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# Soil respiration in a fire scar chronosequence of Canadian boreal jack pine forest

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## Abstract

To fully understand the carbon (C) cycle impacts of forest fires, both C emissions during the fire and post-disturbance fluxes need to be considered. The latter are dominated by soil respiration ($R_s$), which is still subject to large uncertainties. This research investigates $R_s$ in a boreal jack pine fire scar chronosequence at Sharpsand Creek, Ontario, Canada. During two field campaigns in 2006 and 2007, $R_s$ was measured in a chronosequence of fire scars aged between 0 and 59 years since the last fire. Mean $R_s$ per fire scar was adjusted for soil temperature ($T_s$) and soil moisture ($M_s$) (denoted $\overline{R_S}^{T,M}$). $\overline{R_S}^{T,M}$ ranged from 0.56 $\mu$mol $CO_2/m^2/s$ (32 years post fire) to 8.18 $\mu$mol $CO_2/m^2/s$ (58 years post fire). The coefficient of variation ($CV$) of $\overline{R_S}^{T,M}$ ranged from 20% (16 years post fire) to 56% (58 years post fire). Across the field site, there was a statistically highly significant exponential relationship between $R_s$ adjusted for soil organic carbon ($C_s$) and $T_s$ ($P<0.00001$; $Q_{10}=2.21$) but no effect of $M_s$ on $R_s$ adjusted for $C_s$ and $T_s$ for the range 0.21 to 0.77 volumetric $M_s$ ($P=0.702$). $\overline{R_S}^{T,M}$ decreased significantly ($P=0.030$) after fire (4 to 8 days post fire) in mature forest, though no significant ($P>0.1$) difference could be detected between recently burned (4 to 8 days post fire) and unburned young forest. There were significant differences in $\overline{R_S}^{T,M}$ between recently burned (4 to 8 days post fire) scar age categories that differed in their burn history, with between-fire intervals of 32 vs. 16 years ($P<0.001$) and 32 vs 59 years ($P=0.044$). There was a highly significant exponential increase in $\overline{R_S}^{T,M}$ with time since fire ($r^2=0.999$; $P=0.006$) for the chronosequence 0, 16 and 59 years post fire, and for all these age categories, $\overline{R_S}^{T,M}$ was significantly different from one another ($P<0.05$). The results of this study contribute to a better quantitative understanding of $R_s$ in boreal jack pine fire scars and will facilitate improvements in C cycle modelling. Further work is needed in quantifying autotrophic and heterotrophic contributions to $R_s$ in jack pine systems; in monitoring $R_s$ for extended time periods after fire; and in

measuring different fire-prone forest types.

## 1 Introduction

Soil respiration ($R_s$) refers to carbon dioxide ($CO_2$) efflux at the soil surface and is comprised of both autotrophic ($R_{s(a)}$) (plant roots and associated mycorrhizal fungi) and heterotrophic ($R_{s(h)}$) (microorganisms and soil animals) components. The principal factors controlling $R_s$ are soil organic carbon ($C_s$) (Franzluebbers et al., 2001), density of fine plant roots (Shibistova et al., 2002), soil temperature ($T_s$) (Lloyd and Taylor, 1994) and soil moisture ($M_s$) (Xu et al., 2004). $R_s$ influences nutrient cycling (Zak et al., 1993), carbon (C) balance at ecosystem scale (Curtis et al., 2005) as well as global scale (Raich and Potter, 1995), and can cause C cycle feedbacks to the climate system (Cox et al., 2000). Indeed, globally $R_s$ produces 75 to 120 Pg $CO_2$-C $yr^{-1}$, 11 to 20 times that produced by the combustion of fossil fuels (Hibbard et al., 2005). There has been a substantial amount of $R_s$ research over the last decade, though it remains one of the least understood processes in ecosystem ecology (Luo and Zhou, 2006).

Forest ecosystems sequester, store and release C and have an integral role in the global C balance (Bonan, 2008). The boreal forest, or taiga, is a large terrestrial biome, occupying 45° N to 70° N (Zhang et al., 2003). It has been estimated that boreal forests account for approximately a tenth of Earth's land area (Bonan and Shugart, 1989) and a third of Earth's total forested area (Zhang et al., 2003). Boreal forests contain almost half of the C stored in forest ecosystems (Preston et al., 2006) and between one quarter and one third of global soil C (Dixon et al., 1994). Of the 3150 Pg C believed to be contained in the Earth's soils (Sabine et al., 2003), several hundred Pg are thought to reside in boreal systems (Hobbie et al., 2000). Climate predictions suggest that anthropogenic induced warming will be most pronounced at high latitudes (Kattenberg et al., 1996) and this has recently been demonstrated for Siberia (Balzter et al., 2007). The boreal forest biome is likely to be especially affected by climate change and average atmospheric temperatures may increase by 4 to 6°C in the next

50 to 100 years (IPCC, 2001, 2007). This has led to the suggestion that changes in boreal forest soil C storage could significantly alter the global soil C balance (Ohashi et al., 2005).

Fire is widely regarded as the most significant natural factor controlling succession in the boreal forest biome (Zackrisson, 1977). Boreal forest structure and large fuel loads (Stocks, 1991) commonly result in large and high intensity wildfires (Bond-Lamberty et al., 2004), which can be responsible for releasing millions of tonnes of $CO_2$ to the atmosphere (Amiro et al., 2001; Wang et al., 2001). Forest fires are said to drive much of the C flux dynamics in Siberian and North American boreal forests (Kasischke and Stocks, 2000) and it is reported that between 1959 and 1999 an average of two million ha of Canadian forest had burnt annually (Stocks et al., 2002). Furthermore, there has been a general increase in the amount of Canadian boreal forest burnt throughout the 1980s and 1990s (Amiro et al., 2001). It is likely that climate change will alter the boreal forest fire regime (e.g. an increase in size, frequency or intensity; Kasischke et al., 1995) and there are a number of ways in which this could modify the global C balance. First, it could lead to greater $CO_2$ emissions directly from forest fires, a positive feedback mechanism. Second, it would most likely have a profound effect on the C flux dynamics of boreal forest ecosystems. It is possible that a greater frequency of fires will result in a higher proportion of young, relative to intermediate, mature and older forest and the consequences of this are largely unknown. There is also concern that any change in boreal forest age structure may alter albedo and hence climate (Foley et al., 1994). However, potential scenarios remain uncertain; for instance Flannigan et al. (1998) actually suggest a future reduction in boreal forest fire frequency.

Boreal forests have been extensively studied in the context of C cycling and climate change (Bond-Lamberty et al., 2004), particularly in Canada (Kasischke and Stocks, 2000). C flux research may involve field, laboratory, modelling or remote sensing approaches and are often a combination thereof (Steele et al., 1997; Sullivan et al., 1997; Lo et al., 2001). For example, eddy covariance measurements from $CO_2$ flux towers may be used to measure total ecosystem respiration (Nakai et al., 2008), though often separation of above- and below-ground processes (Bond-Lamberty et al., 2004) provides more detailed insight into C flux dynamics. This is particularly important for improving the accuracy of C cycle models (Kaduk and Heimann, 1996; Crucifix et al., 2005; Huntingford et al., 2008; Sitch et al., 2008). The possibility of changing boreal forest fire regime has led to $R_s$ research being conducted in boreal fire scar chronosequences (Zhuang et al., 2002; Wang et al., 2003; Bond-Lamberty et al., 2004; Czimczik et al., 2006; O'Neil et al., 2006; Singh et al., 2008).

Jack pine (*Pinus banksiana* Lamb.) is a short-lived, early successional species (Yermakov and Rothstein, 2006) and one of nine tree species dominant and widespread in boreal regions of North America (Payette, 1992; Euskirchen et al., 2006). Jack pine covers in excess of $2\times10^{12}$ $m^2$ of predominantly well drained uplands in northern North America (Law and Valade, 1994; Lowe et al., 1994; Striegl and Wickland, 2001; Howard et al., 2004), though the species can also be found in northern temperate regions (Barnes and Wagner, 1996). High population densities and combustible foliage render jack pine systems prone to fire (Rowe and Scotter, 1973; Yermakov and Rothstein, 2006). In fact, boreal jack pine forests have fire return intervals of 40 to 80 years and are one of the most fire prone ecosystems in North America (Carroll and Bliss, 1982; Cogbill, 1985; Desponts and Payette, 1992; Larsen, 1997; Yermakov and Rothstein, 2006).

This study investigates $R_s$ in a boreal jack pine fire scar chronosequence, with the overarching aim of quantifying successional change in $R_s$ with time since fire. There have been some studies of $R_s$ in jack pine fire scar chronosequences, though to date research has rarely involved use of replicate fire scars. In addition, there has yet to be any comparison of $R_s$ in un-burnt vs. burnt scars immediately after fire. Furthermore, there has yet to be any comparison of $R_s$ in recently burnt fire scars that differ in their burn history and previous studies have not adjusted for $T_s$ and $M_s$ when comparing $R_s$ between different fire scar age categories. The results of this study will contribute to a better quantitative understanding of $R_s$ in boreal jack pine systems, facilitate model parameterization and lead to improvements in C cycle models, which are necessary to better understand potential C cycle/climate feedbacks.

## 2 Materials and methods

### 2.1 Field site

Sharpsand Creek is a boreal forest experimental burn site of the Canadian Forest Service located approximately 60 km North of Thessalon, Ontario, Canada (latitude 46°47′ N, longitude 83°20′ W). Since the mid- 1970's, numerous prescribed burns have been carried out on forest plots (0.4 to >3 ha) (Table 1; Figs. 1 to 4). Further data from prescribed burns, e.g. fire weather index system components and fuel consumption are provided in Stocks (1987). Sharpsand Creek is dominated by jack pine, and the availability of replicate, different aged fire scars at similar geographic location minimizes the effect of confounding variables that may influence $R_s$ measurements.

The field site is dominated by jack pine, which grows quickly after fire and out-competes any established sedges or grasses. Fire has the effect of releasing seeds from jack pine cones and this happens immediately after passage of the fire front. Seeds may germinate within days and population densities after fire can reach thousands of jack pine seedlings per ha. Post-fire recovery is dependant on fire intensity. Surface fires of low intensity and flame height may not kill the jack pine trees, though small shrubs and herbs in the under-storey will usually not survive. More intense fires may kill the jack pine trees, but like other boreal species, they remain standing for five to six years in the absence of strong winds. After the trees have fallen to the forest floor, it can take several decades for them to decompose completely by a succession of fungi and bacteria. Small shrubs such as blueberry (*Vaccinium* spp.) and sweet fern (*Comptonia peregrina*) appear around 12 months after fire and are able to thrive in the shady under-storey of the new jack pine stand. In this research, age categories for jack pine at Sharpsand Creek are defined as: young (0 to 20 years, as in Euskirchen et al., 2006); intermediate (20 to 50 years); mature (50 to 90 years) and over-mature (>90 years). At Sharpsand Creek trees are normally harvested after 70 to 80 years.

On 13 May 2007, a prescribed burn was carried out on plot 1B (size=0.9 ha; Figs. 1 and 2) last burnt in a 1948 wildfire. An unprecedented number of spot fires and fire whirl behaviour caused the fire to escape from the plot and burn through large areas of the whole field site. The total area burned from the ensuing wildfire was estimated at 1557 ha. Before 2007, Sharpsand Creek was also subject to the Chapleau-Mississagi wildfire (6 to 8 June 1948) that burnt in excess of 260 000 ha between Thessalon and Chapleau, Ontario (Stocks and Walker, 1973). It is believed that previous wildfires occurred in the Sharpsand Creek area in 1850, 1880, 1901 and 1919 (Stocks, 1987).

## 2.2 Instruments

$R_s$ point measurements were made at Sharpsand Creek with the PP Systems (Hitchin, Hertfordshire, UK) soil respiration system (SRS), which consists of a cylindrical $R_s$ chamber (SRC-1: height=15 cm; diameter=10 cm; ground surface area=78 cm$^2$) connected to an infra-red gas analyser (IRGA) (CIRAS-1) (PP Systems 2003). CIRAS-1 has an absolute precision for $CO_2$ measurements of 0.2 $\mu$mol/mol at 0 ppm and 0.7 $\mu$mol/mol at 2000 ppm (PP Systems 2003). Furthermore, CIRAS-1 has a linearity >1% throughout the measurement range 0 to 9999 $\mu$mol/mol (PP Systems 2003). Two SRS's were serviced approximately two months prior to use in the pilot study (Sect. 2.3.2) and field campaign (FC) 1 (Sect. 2.3.3). A preliminary test (10 June 2006) showed no significant difference in median $R_s$ measured between the two CIRAS-1 IRGA's (Mann Whitney U test: $N$=10 (5+5); $U$=6; $P$=>0.1). Where required, chemical reagents were replaced in the SRS's prior to use in FC 2 (Sect. 2.3.4).

$T_s$ was measured with the Cole Parmer pH/mV/°C Meter and soil moisture voltage ($M_{s(v)}$) with the Delta T ML2 Theta probe connected to a voltmeter (Maplin Electronics Digital Multi Media Sinometer MS8230B). $M_{s(v)}$ values were calibrated to volumetric pore moisture (fraction of pore space) ($\theta p$) obtained from soil cores collected in FC 2 (Sect. 2.3.4) to give an $M_s$ value for each location ($M_s$=1.0252×$M_{s(v)}$). $M_s$ values reported for the field component of this research are thus an estimate of volumetric pore moisture (fraction of pore space).

### 2.3 Experimental design

#### 2.3.1 Sampling regime

Over the pilot study and both FC's at Sharpsand Creek, sampling points for measurements of $R_s$, $T_s$, $M_{s(v)}$ and $C_s$ were arranged as regularly as possible, but some irregularities may have resulted e.g. due to the position of jack pine trees and dead woody debris. Where necessary, soil surface vegetation was removed prior to taking $R_s$ measurements (e.g. litter removed; moss layer peeled back; grasses clipped) in order to minimise autotrophic respiration from the soil surface. Measurements were taken from areas considered representative of the fire scars (in terms of dominant vegetation cover).

#### 2.3.2 Pilot study

The pilot study was conducted on 24 June 2006 in order to estimate the spatial variability of $R_s$ at Sharpsand Creek. The experiment was carried out on fire scar 7 (Table 1; Figs. 1 and 4), burnt experimentally in 1991 and one of the youngest fire scars available at the time. This scar was selected with the assumption that spatial variability of $R_s$ would be greatest in the younger fire scars (Singh et al., 2008). The aim was to collect a large number of $R_s$ measurements in order to obtain an estimate of the coefficient of variation ($CV$) of $R_s$($CV_{R_s}$) for the fire scar.

Thirty sampling points were marked out randomly within an area 30 m×30 m considered to be representative of the fire scar. Concurrent $R_s$ (two independent SRS's) and $T_s$ (at 11.7 cm depth) measurements were taken from each sampling point. $CV_{R_s}$

adjusted for $T_s$ ($CV_{R_S^T}$) was calculated using:

$$CV_{R_S^T} = \frac{\sigma_{R_S^T}}{\overline{R}_s^T} \tag{1}$$

where: $\sigma_{R_S^T}$ is the standard deviation of $R_s$ adjusted for $T_s$; and $\overline{R}_s^T$ is mean $R_s$ adjusted for $T_s$.

Minimum estimated sample size ($N$) of $R_s$ measurements required to be 95% confident the sample $\overline{Rs}^T$ lies within specified fractional errors ($FE$) of the true $\overline{Rs}^T$ was calculated using Eq. (2) (Steele and Torrie, 1960):

$$N \geq \left(\frac{2 * CV_{R_S^T}}{FE}\right)^2 \tag{2}$$

### 2.3.3 Field campaign 1

On 3 July 2006, concurrent $R_s$, $T_s$ (at 11.7 cm depth) and $M_{s(v)}$ (to 6 cm depth) measurements were taken from five fire scars at Sharpsand Creek (Table 1). Two independent CIRAS-1 IRGA's were used, though the same SRC was used for all measurements. Point measurements were carried out on two parallel 10 m line transects (spaced 5 m apart) at 0, 5 and 10 m.

### 2.3.4 Field campaign 2

The burning of large areas of Sharpsand Creek from the escaped prescribed burn on 13 May 2007, provided an opportunity to take $R_s$ measurements from recently burned fire scars as well as from those areas the fire did not affect. Between 17 and 21 May 2007, measurements of $R_s$, $T_s$ (at 2 cm depth) and $M_{s(v)}$ (to 6 cm depth) were taken from 11 fire scars (Table 1). At each fire scar, PVC collars (diameter=10.1 cm;

height=5 cm) were inserted into the soil (2 to 3 cm depth) at least 12 h prior to measuring $R_s$ (Wang et al., 2005) in order to minimize soil disturbance at the time of measurement (Luo and Zhou, 2006). Three parallel 10 m line transects were set up (spaced 5 m apart) and soil collars placed at 0, 5 and 10 m along each of the transects. An additional soil collar was placed randomly within the 10 m×10 m area, making a total of ten soil collars per fire scar. $R_s$ was measured over the soil collar using a single PP systems SRS. After $R_s$, $T_s$ and $M_{s(v)}$ measurements were taken, soil cores (depth=5 cm; volume=132.10 cm$^3$) were delicately extracted from three random collars in each scar and put into labelled, air tight steal soil tins. Each of the soil samples were weighed before, and after oven drying (drying oven model # 1645; Sheldon Manufacturing Inc. of Cornelius, Oregon for John Scientific) at 100°C for 24 h with the tin lid removed (dry weight of the sample and tin was recorded within 15 s of removal from the oven). Laboratory derived volumetric moisture ($\theta$) of each of the samples was calculated by:

$$\theta = \frac{M_d}{M_w} * V_s \tag{3}$$

where $M_d$ is the mass of dry soil; $M_w$ is the mass of wet soil; $V_s$ is the volume of each soil core=132.10 cm$^3$.

Laboratory derived volumetric pore moisture (fraction of pore space) ($\theta p$) was calculated by:

$$\theta p = \frac{\theta}{P_s} \tag{4}$$

where $P_s$ is the porosity of soil=0.38 (McWhorter and Sunada, 1977; value for sand).

Dry soil samples of known weight were placed in a Sybron/Thermdyne muffle oven for 16 h at 375°C in order to oxidise organic matter. Soils were then re-weighed to estimate organic C content (Page et al., 1982; Kalra and Maynard, 1991) expressed as bulk density. During this process, some mass loss may occur through combustion of inorganic C. However, soil inorganic C content e.g. carbonates was assumed to be negligible due to the high level of leaching that occurs in podzolic soils.

## 2.4 Data analyses

### 2.4.1 Soil respiration adjustments for soil temperature

$R_s$ is dependant on some function of $T_s$, $M_s$ and $C_s$ and usually modelled as:

$$R_S = R_0 * f(T_S, M_S) * C_S \quad (5)$$

where $R_0$ is base $R_s$ rate at reference $T_s$ ($T_0$).

To estimate the general $T_s$ and $M_s$ dependence of $R_s$ at Sharpsand Creek, the $R_s$ measurements from FC 2 were used, for which $T_s$, $M_s$ and $C_s$ were known. In order to account for the effect of $C_s$, $R_s$ measurements were first adjusted using:

$$R_S^C = \frac{R_S}{C_S} \quad (6)$$

where $R_S^C$ is $R_s$ adjusted for $C_s$.

$R_s$ is commonly assumed to be exponentially dependant on $T_s$ (Davidson and Janssens, 2006), modelled using a $Q_{10}$ value:

$$R_S = R_0 * Q_{10}^{\wedge}\left(\frac{T_S - T_0}{10}\right) \quad (7)$$

$R_S^C$ was plotted against $T_s$ and an exponential function fitted to derive $Q_{10}$. This indicated a general $T_s$ response of $R_s$ across the field site. $R_s$ adjusted for $C_s$ and $T_s$ ($R_S^{C,T}$) (using $Q_{10}$=2.21 and $T_0$=10°C) versus $M_s$ revealed no effect of $M_s$ on $R_S^{C,T}$ over the range 0.21 to 0.77 $M_s$ (see Sect. 3, 3.2 to 3.3). Since very few $R_s$ measurements had associated $M_s$ values outside the range 0.21 to 0.77 $M_s$ these $R_s$ values were excluded from the analysis. All remaining $R_s$ data from FC's 1 and 2 had associated $M_s$ values in the range 0.21 to 0.77 $M_s$. Therefore $R_s$ measurements used in FC 1 and 2 were adjusted for $T_s$ using:

$$R_0 = \frac{R_S}{Q_{10}^{\wedge}\left(\frac{T_S - T_0}{10}\right)} \quad (8)$$



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where $Q_{10}$=2.21 and $T_0$=10°C.

Note that Eq. (8) accounts for the effects of $T_s$ and $M_s$ but not $C_s$ ($C_s$ was only taken in three locations per fire scar during FC 2). Each $R_s$ measurement yielded an $R_0$ that varied due to differences in $C_s$ between locations. $R_0$ is hereafter referred to as $R_s^{T,M}$, implying $R_s$ has been adjusted for the effects of $T_s$ and $M_s$.

### 2.4.2 Statistical procedures

Statistical analyses were performed in Microsoft Office Excel 2003 and SPSS version 15. For $R_s$ and $C_s$ data obtained in FC 1 and 2, after removing outliers (>1.5**Inter Quartile Range* (IQR)), data were analysed for normality and homogeneity of variances by Kolmogorov-Smirnov and Levene's tests respectively. Since Levene's test indicated significant differences in the variances of both $R_s$ and $C_s$ between fire scar age categories ($F$=25.75; $df$=6, 104; $P$<0.001), the non-parametric Kruskal-Wallis test was used instead of Analysis of Variance (ANOVA) to test for any significant differences in median $R_s^{T,M}$ and $C_s$ between fire scar age categories. Independent samples t tests (Students t test where Levene's $P$>0.05; unequal variance t test (Ruxton, 2006) where Levene's $P$<0.05) were subsequently used to test for significant differences in $\overline{Rs}^{T,M}$ and $\overline{C}_s$ between specific fire scar age categories. $P$ values were corrected for multiple hypotheses testing using the Ryan-Holm step-down Bonferroni procedure (Holm ,1979; Aickin and Gensler, 1996; Ludbrook, 2000) to minimise the occurrence of Type 1 errors. Due to large spatial variability of $R_s$ and $C_s$ measured in the field, and small sample sizes, it was decided to set $\alpha$=0.1; i.e. $P$<0.1 to be statistically significant when comparing $\overline{Rs}^{T,M}$ and $\overline{C}_s$ between fire scar age categories (NS $P$>0.1; *$P$<0.1; **$P$<0.05; ***$P$<0.01). Setting a high $\alpha$ value (compared with e.g. 0.05 used in similar studies of jack pine systems, Weber, 1985; Euskirchen et al., 2003; Singh et al., 2008) increases statistical power, reducing the chance of committing a Type 2 error. Correlations of $R_s^C$ vs. $T_s$, $R_s^{C,T}$ vs. $M_s$ and $\overline{Rs}^{T,M}$ vs. time since fire were performed using linear regression analyses. The fire scars 1975B, 1991NB and 1948NB were chosen to represent the chronosequence 0, 16 and 59 years since fire respectively. 1975B was chosen to represent 0 years, since the burn history more closely matched those of the other scar age categories (1975B, 0 years since most recent fire, *burnt 32 years previously*; 1991NB, 16 years since fire, *burnt 43 years previously*; 1948NB, 59 years since fire, *burnt 29 years previously*).

## 3 Results

### 3.1 Pilot study

Analysis of $R_s$ data from the pilot study suggested high spatial variability in $R_s^T$ ($\overline{R_S}^T$=3.20 $\mu$mol $CO_2/m^2/s$; $\sigma$=1.41 $\mu$mol $CO_2/m^2/s$; $CV$=44%) (two $R_s$ outliers removed due to dubious $R_s$ readings). Table 2 shows estimated minimum sample size ($N$) requirements to be 95% confident that the sample $\overline{R_S}^T$ lies within various $FE$ of the true $\overline{R_S}^T$. For instance, it is estimated that to be 95% confident the sample $\overline{R_S}^T$ lies within 20% of the true $\overline{R_S}^T$, $N$=20 is required.

### 3.2 Soil organic carbon analyses

### 3.3 Soil temperature response of soil respiration

$R_s$ data for which $C_s$ were known were adjusted for $C_s$ ($R_s^C$) and plotted against $T_s$ at 2 cm depth (Fig. 6). There was a significant exponential relationship between $R_s^C$ and $T_s$ (logarithmic transformed linear regression: $N$=28; $df$=27; $r^2$=0.60; $P=1.24\times10^{-6}$); $Q_{10}$=2.21.



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### 3.4 Soil moisture response of soil respiration

$R_s^C$ adjusted for $T_s$ ($R_s^{C,T}$) (using $T_0$=10°C and $Q_{10}$=2.21) vs. $M_s$ revealed no effect of $M_s$ on $R_s^{C,T}$ over the range 0.21 to 0.77 $M_s$ (linear regression: $N$=27; $df$=26; $r^2$=0.006; $P$=0.702) (Fig. 7).

### 3.5 Differences in soil respiration between fire scar age categories

$\overline{R_S}^{T,M}$ along with $N$ and variability coefficients for the fire scar age categories at Sharp-sand Creek are shown in Table 5. In FC 1 $CV_{R_s^{T,M}}$ was higher (56%) in older fire scars (1948†; 58 years since fire) than younger ones (1991†; 15 years since fire) (22%). When comparing the same scar age categories from FC 2, $CV_{R_s^{T,M}}$ was somewhat lower in 1948NB (41%) and slightly lower in 1991NB (20%) compared with FC1, though, $CV_{R_s^{T,M}}$ was still higher in the older scar age category.

For the different fire scar age categories that were all subject to burning in 2007 (1948B; 1975B; 1991B), it appeared that the previously younger fire scar age category (1991B) had lowest $CV_{R_s^{T,M}}$ (26%) followed by 1948B (49%) and 1975B (55%). Although it appeared that burning increases $CV_{R_s^{T,M}}$ immediately after fire (1948NB<1948B; 1991NB<1991B), $CV_{R_s^{T,M}}$ for 1991B was still lower than that obtained for 1948B.

$N$ for 1948† was 12 and this is <minimum $N$=32 to be 95% confident the sample $\overline{R_S}^{T,M}$ lies within 20% of true $\overline{R_S}^{T,M}$ for this scar age category. $N$ for 1948NB was 8 and this is <minimum $N$=17 to be 95% confident the sample $\overline{R_S}^{T,M}$ lies within 20% of the true $\overline{R_S}^{T,M}$ for this scar age category. $N$ for 1948B was 24 and this is <minimum $N$=25 to be 95% confident the sample $\overline{R_S}^{T,M}$ lies within 20% of the true $\overline{R_S}^{T,M}$ for this scar age category. $N$ for 1975B was 27 and this is <minimum $N$=31 to be 95% confident the sample $\overline{R_S}^{T,M}$ lies within 20% of the true $\overline{R_S}^{T,M}$ for this scar age category. $N$ for 1991† was 7 and this is <minimum $N$=20 to be 95% confident the sample $\overline{R_S}^{T,M}$ lies



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within 20% of the true $\overline{R_S}^{T,M}$ for this scar age category (calculations based on the pilot study). However, $N$ for 1991† was 7 and this is >minimum $N$=5 to be 95% confident the sample $\overline{R_S}^{T,M}$ lies within 20% of true $\overline{R_S}^{T,M}$ mfor this scar age category (calculations based on FC 1 as opposed to pilot study). $N$ for 1991NB was 8 and this is >minimum $N$=4 to be 95% confident the sample $\overline{R_S}^{T,M}$ lies within 20% of the true $\overline{R_S}^{T,M}$ for this scar age category. $N$ for 1991B was 25 and this is >minimum $N$=7 to be 95% confident the sample $\overline{R_S}^{T,M}$ lies within 20% of the true $\overline{R_S}^{T,M}$ for this scar age category.

There was evidence of one or more statistically significant differences in median $R_s^{T,M}$ between fire scar age categories (Kruskal-Wallis test: $N$=111; $\chi^2$=67.176; $df$=6; $P$< 0.001), see also Fig. 8). Holm-Bonferroni corrected independent samples t tests revealed significant differences ($\alpha$=0.1) in $\overline{R_S}^{T,M}$ (Table 6; Fig. 8). $\overline{R_S}^{T,M}$ was significantly greater in 1948 than 1991 age categories in both FC 1 (15 vs. 58 years since fire) and FC 2 (16 vs. 59 years since fire) (FC 1: 1948† $\overline{R_S}^{T,M}$=8.18 $\mu$mol $CO_2/m^2/s$; 1991† $\overline{R_S}^{T,M}$=2.61 $\mu$mol $CO_2/m^2/s$; FC 2: 1948NB+$\overline{R_S}^{T,M}$=1.91 $\mu$mol $CO_2/m^2/s$; 1991NB+$\overline{R_S}^{T,M}$=0.79 $\mu$mol $CO_2/m^2/s$. However, $\overline{R_S}^{T,M}$ was significantly greater in FC 1 than FC 2 when comparing the same scar age category (1948NB+ vs. 1948†; 1991NB+ vs. 1991†).

There was a strong significant exponential increase in $\overline{R_S}^{T,M}$ with time since fire (logarithmic transformed linear regression (Ln $R_s$ vs. time since burn): $N$=3;$df$=2; $r^2$=0.999; $P$=0.006); see also Fig. 9.

# 4 Discussion

## 4.1 Spatial variability of soil respiration

### 4.1.1 Interpretation of results

The pilot study indicated high spatial variability in $R_s^T$ ($CV_{R_s^T}$=44%) in a 15 year old fire scar. Moreover, it was estimated that to be 95% confident sample $\overline{R_S}^T$ lies within 20% of the true $\overline{R_S}^T$, $N$=20 is required in 15 year old fire scars. Over FC 1 and 2, $CV_{R_s^{T,M}}$ for the different fire scar age categories ranged from 20% (FC 2; 1991NB; 16 year old scar) to 56% (FC 1; 1948†; 58 year old scar). In FC 1, where soil collars were *not* used for $R_s$ measurements, $CV_{R_s^{T,M}}$ was higher in older fire scars (1948†; 58 years since fire;$CV_{R_s^{T,M}}$=56%; minimum $N$=32 to be 95% confident sample $\overline{R_S}^{T,M}$ lies within 20% of true $\overline{R_S}^{T,M}$) than younger ones (1991†; 15 years since fire; $CV_{R_s^{T,M}}$=22%; minimum $N$=5 to be 95% confident sample $\overline{R_S}^{T,M}$ lies within 20% of true $\overline{R_S}^{T,M}$). When comparing the same scar age categories from FC 2, $CV_{R_s^{T,M}}$ was somewhat lower in 1948NB ($CV_{R_s^{T,M}}$=41%; minimum $N$=17 to be 95% confident sample $\overline{R_S}^{T,M}$ lies within 20% of the true $\overline{R_S}^{T,M}$) and slightly lower in 1991NB ($CV_{R_s^{T,M}}$=20%; minimum $N$=4 to be 95% confident sample $\overline{R_S}^{T,M}$ lies within 20% of the true $\overline{R_S}^{T,M}$) compared with FC 1, though, $CV_{R_s^{T,M}}$ was still higher in the older scar age category. The absence of soil collars may have resulted in greater spatial variability, accounting for higher $CV_{R_s^{T,M}}$ measured in FC 1, though measurements were also taken approximately a year apart.

For the different fire scar age categories that were all subject to burning in 2007, it appeared that the previously younger fire scar age category (1991B) had lowest $CV_{R_s^{T,M}}$

($CV_{R_s^{T,M}}$=26%; minimum $N$=7 to be 95% confident sample $\overline{R_S}^{T,M}$ lies within 20% of the true $\overline{R_S}^{T,M}$) followed by 1948B ($CV_{R_s^{T,M}}$=49%; minimum $N$=25 to be 95% confident sample $\overline{R_S}^{T,M}$ lies within 20% of the true $\overline{R_S}^{T,M}$) and 1975B ($CV_{R_s^{T,M}}$=55%; minimum $N$=31 to be 95% confident sample $\overline{R_S}^{T,M}$ lies within 20% of the true $\overline{R_S}^{T,M}$). Although it appeared that burning increases $CV_{R_s^{T,M}}$ immediately after fire (1948NB<1948B; 1991NB<1991B), $CV_{R_s^{T,M}}$ for 1991B was still lower than that for 1948B, perhaps retaining legacies from pre-fire conditions. The fact that $CV_{R_s^{T,M}}$ for 1975B was higher than that obtained for 1948B and 1991B could imply a high $CV_{R_s^{T,M}}$ in 1975NB (32 years since fire, or an intermediate aged jack pine ecosystem), though this scar age category was unavailable at Sharpsand Creek.

$CV_{R_s^{T,M}}$ may increase immediately after fire due to the patchy effect of burning on the soil (Michaletz and Johnson, 2007). For instance, some areas may be more severely burnt than others and subsequent changes to the physical, chemical and biological properties of soils may have differential consequences on $R_{s(a)}$ and $R_{s(h)}$(Pregitzer and Euskirchen, 2004; Yermakov and Rothstein, 2006). As the stand recovers from disturbance, $CV_{R_s^{T,M}}$ may decrease for some time (lower $CV_{R_s^{T,M}}$ in 15 and 16 year old scars) due to a new cohort of jack pine trees established at approximately the same time and hence all having similar root development (Smirnova et al., 2008). However, with increasing time since fire, differential development of root and/or microbial communities could account for higher $CV_{R_s^{T,M}}$ in mature systems (58 and 59 years since fire). For instance, decreased organic matter quality and altered soil microclimate are believed to suppress organic matter mineralization over successional time in northern forest systems (Bormann and Sidle, 1990; DeLuca et al., 2002; Yermakov and Rothstein, 2006), though this may not occur in complete spatial uniformity.

### 4.1.2 Comparisons with other studies

Minimum $N$ estimated in the pilot study is somewhat larger than that of Singh et al. (2008) who found in their study that $N$=10 is required for estimating $\overline{R}_s$ within a $FE$ of 20% of the true $\overline{R}_s$ for a 15 year old jack pine fire scar. However, results from FC 1 suggest smaller minimum $N$ may be required (1991†; 15 years since fire; $CV_{R_s^{T,M}}$=22%; minimum $N$=5 to be 95% confident sample $\overline{R_S}^{T,M}$ lies within 20% of the true $\overline{R_S}^{T,M}$). Furthermore, results from FC 2 suggest even fewer measurements may be required in jack pine systems 16 years post fire (1991NB; $CV_{R_s^{T,M}}$=20%; minimum $N$=4 to be 95% confident sample $\overline{R_S}^{T,M}$ lies within 20% of true $\overline{R_S}^{T,M}$). However, estimates from Singh et al. (2008) were based on a smaller sampling area (18 m×18 m) and larger $R_s$ sample sizes ($N$=100).

The $CV_{R_s^{T,M}}$ from FC 1 and 2 are consistent with previous studies in jack pine systems that report $CV R_s$ in the range 9 to 61% (Weber, 1985; Striegl and Wickland, 1998, 2001; Singh et al., 2008). However, except recently burned scars, both FC's suggest higher $CV_{R_s^{T,M}}$ in mature as opposed to young jack pine systems. This was also the case in a study by Striegl and Wickland (1998) who found on average $CV_{R_s}$ was 31.3% at old jack pine (age not given) and 30.1% at clear-cut (approximately 6 months to a year after clear-cutting) sites. However, Singh et al. (2008) found that generally $R_s$ at their youngest site (three post fire scar age categories: 6 to 7 years since fire; 15 to 16 years since fire and 27 to 28 years since fire) was most spatially variable, though $R_s$ was not measured in a mature or old jack pine system.

### 4.1.3 Limitations

The absence of soil collars in the pilot study and FC 1 may have resulted in an overestimate of $CV_{R_s^T}$ and $CV_{R_s^{T,M}}$ respectively and hence minimum $N$. Furthermore, the estimate of $CV_{R_s^T}$ for the pilot study is based on adjusting for $T_s$ assuming a $Q_{10}$ of 2, since a generalised $R_s$ vs. $T_s$ relationship had yet to be obtained for the site (obtained during FC 2). Accounting for $M_s$ in addition to $T_s$ may further reduce spatial variability and in this instance, $R_s$ is likely to be controlled primarily by $C_s$ and fine root content. The number of fire scars tested and sampling points within fire scars was not always consistent for FC 1 and 2 and sample sizes and sample area may have been too low to accurately quantify $CV_{R_s^{T,M}}$.

### 4.2 Soil temperature response of soil respiration

#### 4.2.1 Interpretation of results

There was a significant exponential relationship between $R_s^C$ and $T_s$ ($r^2$=0.60; $P$=1.24×10$^{-6}$; $Q_{10}$=2.21) derived from the set of measurements that comprised $T_s$ as well as $C_s$. This implies a more than doubling of $R_s^C$ for every 10°C rise in $T_s$. This $Q_{10}$ is based on a *general* relationship between *total* $R_s$ ($R_{s(a)}$+$R_{s(h)}$) vs. $T_s$, incorporating measurements from *different* aged fire scars.

#### 4.2.2 Comparisons with other studies

Comparing the $T_s$ response of $R_s$ with other studies of jack pine ecosystems, the $Q_{10}$ was remarkably similar to that found by Euskirchen et al. (2006): $Q_{10}$ of 2.2 over three study years; range 1.1 to 2.3. The $Q_{10}$ reported herein is also within the range documented by Striegl and Wickland (1998) (2.02 to 2.68) and Fleming et al. (2006) (1.8 to 2.8). However, two studies report lower $Q_{10}$ values (Euskirchen et al., 2003: 1.67 to 1.92); (Yermakov and Rothstein, 2006: 1.40) and one study reports much higher $Q_{10}$ values (Howard et al., 2004: 3.77 to 7.12), perhaps a result of not effectively accounting for the effects of $C_s$, $M_s$ or fine root content.

Since a general $R_s^C$ vs. $T_s$ exponential relationship fit the Sharpsand Creek field site, implying a constant $Q_{10}$, it may be that $R_s$ does not acclimate to $T_s$. It could be argued that this finding supports the work of Hartley et al. (2008), but disagrees with Bradford et al. (2008), though both these studies were concerned with microbial $R_s$, in contrast to this research which measured total $R_s$.

### 4.2.3 Limitations

There are three main limitations. First, there was no attempt to derive separate $T_s$ responses of $R_{s(a)}$ and $R_{s(h)}$, respectively, since only total $R_s$ was measured. Second, the $R_s$ vs. $T_s$ relationship was not derived separately for individual fire scar age categories, which may have differential $R_{s(a)}$:$R_{s(h)}$ ratios (Wang et al., 2002; Yermakov and Rothstein, 2006). Third, the effects of fine root content were not accounted for, which has been shown to influence $R_s$ (Shibistova et al., 2002).

## 4.3 Soil moisture response of soil respiration

### 4.3.1 Interpretation of results

$R_s^{C,T}$ vs. $M_s$ revealed no significant effect of $M_s$ on $R_s^{C,T}$ over the range 0.21 to 0.77 $M_s$ ($r^2$=0.006; $P$=0.702) to which this study is limited after removal of outliers. This is based on a *general* relationship between *total* $R_s^{C,T}$ ($R_{s(a)}+R_{s(h)}$) vs. $M_s$, incorporating measurements from *different* aged fire scars.

### 4.3.2 Comparisons with other studies

Although most field studies of $R_s$ reveal little response to $M_s$ over broad ranges of intermediate $M_s$ values (Law et al., 1999b; Fang and Moncrieff, 2001; Drewitt et al., 2002), this research is the first to demonstrate this in post-fire jack pine systems. The results are in agreement with Howard et al. (2004) who found that $M_s$ did not improve regression models of $R_s$ vs. $T_s$ in a chronosequence of harvested jack pine. The results are, however, in contrast to a recent study of a jack pine system, which showed $M_s$ dependence of $R_s$ by polynomial functions (Fleming et al., 2006).

### 4.3.3 Limitations

In addition to the limitations outlined in Sect. 4.2.3, there are the following limitations. Firstly, the $M_s$ dependence of $R_s$ was derived after accounting for $T_s$ and is therefore dependant on the validity of the $R_s^C$ vs. $T_s$ relation. Although this research indicated no $M_s$ response of $R_s$ over the range 0.21 to 0.77 $M_s$, the response at low (<0.21) and high (>0.77) $M_s$ was not investigated. For instance, it is likely that as soils approach saturation, $O_2$ becomes limiting to aerobic metabolism and $R_s$ is suppressed (Bernier, 1960; Roberge, 1976; Foster et al., 1980).

## 4.4 Differences in soil respiration between fire scar age categories

### 4.4.1 Interpretation of results

$\overline{R_S}^{T,M}$ was significantly greater in 1948 than 1991 age categories in both FC 1 (15 vs. 58 years since fire; $P$=0.009) and FC 2 (16 vs. 59 years since fire; $P$=0.030) (FC 1: 1948† $\overline{R_S}^{T,M}$=8.18 $\mu$mol $CO_2/m^2/s$; 1991† $\overline{R_S}^{T,M}$=2.61 $\mu$mol $CO_2/m^2/s$; FC 2: 1948NB $\overline{R_S}^{T,M}$=1.91 $\mu$mol $CO_2/m^2/s$; 1991NB $\overline{R_S}^{T,M}$=0.79 $\mu$mol $CO_2/m^2/s$). However, $\overline{R_S}^{T,M}$ was significantly greater in FC 1 than FC 2 when comparing the same scar age category (1948NB vs. 1948†, $P$=0.009; 1991NB vs. 1991†, $P$<0.001). The differences could be a result of measurements being taken a year apart and particularly the absence of soil collars in FC 1, which may have led to an over estimate of soil surface $CO_2$ efflux.

There was a strong significant exponential increase in $\overline{R_S}^{T,M}$ with time since fire ($r^2$=0.999; $P$=0.006) for the chronosequence 1975B ($\overline{R_S}^{T,M}$=0.56 $\mu$mol $CO_2/m^2/s$), 1991NB ($\overline{R_S}^{T,M}$=0.79 $\mu$mol $CO_2/m^2/s$) and 1948NB ($\overline{R_S}^{T,M}$=1.91 $\mu$mol $CO_2/m^2/s$) and for all these age categories $\overline{R_S}^{T,M}$ was significantly different from one another ($P$<0.05).



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An overall increase in $\overline{R_S}^{T,M}$ over successional time could be a result of increased contribution of $R_{s(a)}$ as the vegetation component recovers from disturbance (Wang et al., 2002; Yermakov and Rothstein, 2006).

$\overline{R_S}^{T,M}$ in 1948NB was significantly ($P$=0.030) greater than that obtained for 1948B implying that burning has an immediate affect of decreasing $\overline{R_S}^{T,M}$ in mature jack pine stands, probably as a result of decreased $R_{s(a)}$ (Wang et al., 2002; Yermakov and Rothstein, 2006). However, there was no significant ($P$>0.1) difference when comparing $\overline{R_S}^{T,M}$ for 1991NB vs. 1991B. Though fire may suppress $R_{s(a)}$ in these younger scars, an increase in $R_{s(h)}$ as a result of fire (Pregitzer and Euskirchen, 2004; Yermakov and Rothstein, 2006) could mask this effect and account for no *overall* change in *total* $R_s$. This may be a result of higher $R_{s(h)}$:$R_{s(a)}$ ratios in younger jack pine systems. Although $R_{s(h)}$ may increase as a result of fire in mature jack pine systems, lower $R_{s(h)}$:$R_{s(a)}$ ratios may imply the increase in $R_{s(h)}$ is insufficient to mask the reduction in $R_{s(a)}$ in response to burning. Indeed, absence of a significant ($P$>0.1) difference in $\overline{R_S}^{T,M}$ between 1948B and 1991B (where before burning there *was* a significant difference, see above) is further evidence that fire suppresses $R_s$ in older, but not younger jack pine systems. Where before fire, $\overline{R_S}^{T,M}$ was significantly greater in 58 versus 15 and 59 versus 16 year old scars, fire induced reduction in $\overline{R_S}^{T,M}$ in the older scars could explain the absence of significant differences after fire.

The absence of a 1975NB category prevents any firm conclusions into the effect of fire on $\overline{R_S}^{T,M}$ in 32 year old jack pine systems (intermediate age category), though there was a significant difference between 1975B vs. 1991B ($P$<0.001) and 1975B vs. 1948B ($P$=0.044). This does provide evidence that significant differences in $\overline{R_S}^{T,M}$ *can* occur between previously different aged fire scars that have all been subjected to the same fire. In essence, jack pine stands can retain legacies of pre-fire conditions. The fact that 1975B had significantly lower $\overline{R_S}^{T,M}$ than 1991B or 1948B was possibly due to higher $R_{s(a)}$:$R_{s(h)}$ ratios in 32 year old (or intermediate aged) jack pine systems.

The t tests for significant differences in $\overline{C_s}$ between fire scar age categories revealed a significant difference only between 1948B and 1975B ($P<0.001$) with all other comparisons $P>0.1$). The likely cause is sample sizes being too small resulting in insufficient statistical power to detect significant differences. Therefore it was not appropriate to relate $\overline{C_s}$ to changing $\overline{R_S}^{T,M}$ over successional time.

### 4.4.2 Comparisons with other studies

$\overline{R_S}^{T,M}$ values reported herein are within the range 0.35 to 7.20 $\mu$mol $CO_2/m^2/s$ reported in the literature for jack pine systems (Burke et al., 1997; Savage et al., 1997; Euskirchen et al., 2003). The results of this study also agree with the literature in that the majority of studies have demonstrated a reduction or no change in $R_s$ following fire (Reinke et al., 1981; Weber, 1985, 1990; Fritze et al., 1993; Burke et al., 1997; Sawamoto et al., 2000; Amiro et al., 2003; Singh et al., 2008).

The significantly greater $\overline{R_S}^{T,M}$ in mature (58 to 59 years since fire) compared to young (15 to 16 years since fire) scars (except recently burnt scars) is in agreement with another study of jack pine ecosystems: (63 years since fire >21 years since fire; 63 years since fire >6 years since fire; 20 years sine fire >6 years since fire (Weber 1985; note $\alpha$=0.05 in this study)). Singh et al. (2008) also found that their youngest site generally had significantly lower $R_s$ in a jack pine fire scar chronosequence (6 to 7 years since fire; 15 to 16 years since fire; 27 to 28 years since fire), but although $\overline{Rs}$ was significantly greater in 16 year old vs. 7 year old scars, $\overline{Rs}$ in 16 year old scars was significantly greater than that in 28 year old scars (Singh et al., 2008; note $\alpha$=0.05 in this study).

This research is the first to report a significant exponential increase in $\overline{R_S}^{T,M}$ over successional time in post-fire jack pine systems. In a recent study of a 72 year old jack pine wildfire chronosequence, growing season $R_s$ showed no clear pattern with stand age (Yermakov and Rothstein, 2006).

### 4.4.3 Limitations

There are a number of limitations. Firstly, soil collars were absent in FC 1 which may have led to over-estimated *soil* $CO_2$ efflux. There were no replicate scars available for 1948NB and 1991NB in FC 2, and there were no 1975NB scars available, or intermediate aged jack pine systems.

$R_s$ was adjusted for the generalised $T_s$ and $M_s$ responses and not responses specific to scar age categories, which may have differential $R_{s(a)}$:$R_{s(h)}$ ratios (Wang et al., 2002; Yermakov and Rothstein, 2006). Moreover, there was no attempt to separate $R_{s(a)}$ and $R_{s(h)}$. $R_s$ measurements were made at different times of the day and over a number of days. Although it was attempted to account for $T_s$ and $M_s$, other factors could have influenced $R_s$; for example, $R_s$ can vary temporally at diurnal scales (Xu and Qi, 2001) due to barometric pressure changes (Kimball, 1983).

In this study, $R_s$ sample sizes were small and statistical power may not have been high enough to detect significant differences (Type 2 error) in $\overline{R_S}^{T,M}$ between fire scar age categories. $N$ for 1948† was 12 and this is less than the minimum of $N$=32 to be 95% confident the sample $\overline{Rs}^{T,M}$ lies within 20% of true $\overline{Rs}^{T,M}$ for this scar age category (Sect. 7.2.1). Similarly, $N$ for 1948NB was 8 and not the required $N$=17 to achieve 95% confidence in the mean. $N$ for 1948B was 24, slightly less than the required $N$=25 for a 95% confidence. Also, $N$ for 1975B was 27 and not the required $N$=31 to be 95% confident and $N$ for 1991† was 7 was much smaller than the required $N$=20 to be 95% confident in the mean. However, small sample sizes were in part due to exclusion of outliers necessary for statistical analyses. Finally, the FC's were short and do not replicate measurements temporally e.g. months of the growing season, or over individual years. Temporal variability of $R_s$ can occur at seasonal (Borken et al., 2002) and inter-annual (Irvine and Law, 2002) scales.

## 4.5 Conclusions

The spatial variability of measured $R_s$ was investigated at Sharpsand Creek and $CV_{R_s^{T,M}}$ was estimated to be in the range 20% (FC 2; 1991NB; 16 year old fire scar) to 56% (FC 1; 1948†; 58 year old fire scar). The relationship between measured $R_s^C$ and $T_s$ was investigated at Sharpsand Creek and found to be significantly exponential in form ($r^2$=0.60; $P$=1.24×10$^{-6}$; $Q_{10}$=2.21). The relationship between measured $R_s^{C,T}$ and $M_s$ was investigated at Sharpsand Creek and there was no significant effect of $M_s$ on $R_s^{C,T}$ over the range 0.21 to 0.77 $M_s$ ($r^2$=0.006; $P$=0.702). Our study has detected a fire scar age specific response to fire in jack pine forest. The immediate effect of burning was investigated at Sharpsand Creek and it appeared that measured $\overline{Rs}^{T,M}$ is significantly ($P$=0.030) decreased after burning mature forest, though no significant ($P$>0.1) difference could be detected between recently burned and unburned young forest. $R_s$ was measured in recently burned boreal jack pine fire scar age categories at Sharpsand Creek that differed in their burn history and there was a significant difference in $\overline{Rs}^{T,M}$ for 1975B vs 1991B ($P$<0.001) and 1975B vs. 1948B ($P$=0.044). There was a strong significant exponential increase in $\overline{R_S}^{T,M}$ with time since fire at Sharpsand Creek ($r^2$=0.999; $P$=0.006) for the chronosequence 0, 16 and 59 years post fire, and for all these age categories, $\overline{Rs}^{T,M}$ was significantly different from one another ($P$<0.05). The results of this study contribute to a better quantitative understanding of $R_s$ in boreal jack pine fire scars and will facilitate improvements in C cycle modelling.

## 4.6 Future research

There are numerous implications of this study for future research. Firstly, separating the contributions of $R_{s(a)}$ and $R_{s(h)}$ in jack pine chronosequences would provide more insight into ecosystem physiological response of $R_s$ to fire and post-fire successional changes. The $T_s$ and $M_s$ responses of $R_s$ in jack pine systems needs to be quantified



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for $R_{s(h)}$ and $R_{s(a)}$ and in different aged jack pine systems. This research has shown that $R_s$ may decrease after burning mature but not young jack pine forest, but further work with replicate scars is needed to confirm this. This is particularly important since the proportion of young jack pine ecosystems may increase with future increases in boreal forest fire size, frequency, or intensity. This research has suggested that $R_s$ increases exponentially with successional time since fire in jack pine systems, though further work with replicate fire scars is needed. In addition, monitoring $R_s$ for an extended time period after fire is a fertile avenue for future research.

## Appendix A

### Abbreviations

ANOVA – analysis of variance; B – burnt in 2007; C – carbon; $CO_2$ – carbon dioxide; $C_s$ – soil carbon (note $C_s$ values reported for results of *this* research are an estimate of soil organic carbon); *CV* – coefficient of variation; DC – change in carbon; *df* – degrees of freedom; DT – change in time; FC – field campaign; *FE* – fractional error; *IQR* – inter quartile range; IR – infra red radiation; IRGA – infra-red gas analyser; $M_d$ – mass of dry soil; $M_s$ – soil moisture (note $M_s$ values reported for results of *this* research are an estimate of volumetric pore moisture (fraction of pore space)); $M_{s(v)}$ – soil moisture voltage; $M_w$ – mass of wet soil; $N$ – sample size; NB – not burnt in 2007; NS – not (statistically) significant; $P$ – statistical significance; $P_s$ – soil porosity; PVC – polyvinyl chloride; $Q_{10}$ – rate of (soil) respiration increase for every 10°C rise in (soil) temperature; $R$ – respiration; $R_0$ – base (soil) respiration rate at reference (soil) temperature; $R_s$ – soil respiration; $R_{s(a)}$ – soil autotrophic respiration; $R_s^C$ – soil respiration adjusted for soil organic carbon; $R_s^{C,T}$ – soil respiration adjusted for soil organic carbon and soil temperature; $R_{s(h)}$ – soil heterotrophic respiration; $R_s^T$ – soil respiration adjusted for soil temperature; $R_s^{T,M}$ – soil respiration adjusted for soil temperature and soil moisture;

SRC – soil respiration chamber; SRS – soil respiration system; $T_0$ – reference (soil) temperature at base (soil) respiration rate; $T_s$ – soil temperature; vs. – versus; $V_s$ – volume of soil; $\overline{X}$ – mean; $\sigma$ – standard deviation; $\overline{\sigma}$ – standard error; $\theta$ – laboratory derived volumetric soil moisture; $\theta p$ – laboratory derived volumetric soil pore moisture; $\mu$mol – micromoles; $<$ – less than; $>$ – greater than; † – 2006 field campaign; + – 2007 field campaign.

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**Table 1.** Fire scars at Sharpsand Creek used in the pilot study and field campaigns 1 and 2 of this research.

| Field campaign | Fire scar | Age category † | Burnt in 2007 wildfire? | Time since fire (years) |
|---|---|---|---|---|
| 1 | A | 1948 | no | 58 |
| 1 | B | 1948 | no | 58 |
| 1 | C | 1948 | no | 58 |
| 1 | 2 | 1991 | no | 15 |
| 1+P | 7 | 1991 | no | 15 |
| 2 | A | 1948 | yes | 0 |
| 2 | B | 1948 | yes | 0 |
| 2 | C | 1948 | yes | 0 |
| 2 | 5 | 1975 | yes | 0 |
| 2 | 6 | 1975 | yes | 0 |
| 2 | Ac | 1975 | yes | 0 |
| 2 | 2 | 1991 | yes | 0 |
| 2 | 7 | 1991 | yes | 0 |
| 2 | 8 | 1991 | yes | 0 |
| 2 | 1A | 1948 | no | 59 |
| 2 | 2* | 1991 | no | 16 |

† – excluding fire on 13 May 2007; P – pilot study; 2* – part of scar 2 not burnt in 2007 wildfire. Replicates for 1948 and 1991 age categories not burnt in 2007 unavailable due to the extent of the 2007 wildfire.

**Table 2.** Estimated minimum sample size ($N$) requirements of soil temperature ($T_s$) normalised soil respiration ($R_s^T$) to be 95% confident sample mean $R_s^T$ ($\overline{R_S}^T$) lies within.

| Fractional error acceptance | Estimated minimum $N$ |
|---|---|
| 0.10 | 78 |
| 0.15 | 35 |
| 0.20 | 20 |
| 0.25 | 13 |
| 0.30 | 9 |

$R_s^T$ adjusted to base soil respiration rate at $T_s$=10°C using $Q_{10}$=2.0; based on 28 measurements taken from an area 30 m×30 m from scar 7 (scar age category 1991; 15 years since fire) at Sharpsand Creek, June 2006. $N$ rounded up to nearest integer.

**Table 3.** Descriptive statistics of soil samples analysed for organic carbon ($C_s$) collected from various fire scar age categories at Sharpsand Creek.

| †Scar age category | Time since fire (years) | $N$ replicate scars | $N$ soil samples | $\overline{C_s}$ (g/cm$^3$) | $\sigma_{C_s}$ (g/cm$^3$) | $\overline{\sigma}_{C_s}$ (g/cm$^3$) | $CV_s$ (%) |
|---|---|---|---|---|---|---|---|
| 1948 B | 0 | 3 | 9 | 0.088 | 0.012 | 0.004 | 13.6 |
| 1948 NB | 59 | 1 | 3 | 0.088 | 0.028 | 0.016 | 31.8 |
| 1975 B | 0 | 3 | 8 | 0.060 | 0.014 | 0.005 | 23.3 |
| 1991 B | 0 | 3 | 9 | 0.074 | 0.016 | 0.005 | 21.6 |
| 1991 NB | 16 | 1 | 3 | 0.103 | 0.061 | 0.035 | 59.2 |

Soil samples collected during field campaign 2 (May 2007). † Scar age category corresponds to year of last burn (excluding 2007 burn). B=burnt in 2007; NB=not burnt in 2007. $N$=sample size; $\overline{C_s}$=mean soil organic carbon; $\sigma$=standard deviation; $\overline{\sigma}$=standard error; $CV$=coefficient of variation. 1 outlier removed (>1.5*inter quartile range).



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**Table 4.** Statistical tests for significant differences in mean soil organic C ($\overline{C_s}$) between various fire scar age categories at Sharpsand Creek.

| Fire scar age category comparison | Levene's test | | t test | | | | |
|---|---|---|---|---|---|---|---|
| | *F* | *P* | Type | *t* | *df* | $P_{raw}$ | $P_{adj}$ |
| 1948NB vs. 1948B | 6.432 | 0.030 | UV | 0.041 | 2.242 | 0.971 | 1.0 NS |
| 1948B vs. 1975B | 0.112 | 0.742 | S | 4.602 | 15 | 0.000 | 0.000*** |
| 1991B vs. 1948B | 2.166 | 0.160 | UV | 2.155 | 14.427 | 0.048 | 0.329 NS |
| 1948NB vs. 1975B | 3.832 | 0.082 | S | 2.294 | 9 | 0.047 | 0.329 NS |
| 1991NB vs. 1948 NB | 2.565 | 0.184 | S | −0.401 | 4 | 0.709 | 1.0 NS |
| 1975B vs. 1991B | 0.960 | 0.343 | S | −1.857 | 15 | 0.083 | 0.415 NS |
| 1975B vs. 1991NB | 14.748 | 0.004 | UV | −1.213 | 2.076 | 0.345 | 1.0 NS |
| 1991B vs. 1991NB | 13.818 | 0.004 | UV | −0.824 | 2.098 | 0.493 | 1.0 NS |

Scar age category corresponds to year of last burn (excluding 2007 burn); B=burnt in 2007; NB=not burnt in 2007; vs.=versus; *F*=Levene's test statistic; *P*=statistical significance; NS=not statistically significant; t tests: S=students t test (where Levene's $P>0.05$); UV=unequal variance t test (where Levene's $P<0.05$); *df*=degrees of freedom; *P* values for t tests are 2 tailed; Values to 3 significant figures; $P_{adj}$=Holm-Bonferroni correction for multiple hypothesis testing; NS $P>0.1$; *$P<0.1$; **$P<0.05$; ***$P<0.01$.

**Table 5.** Mean soil respiration ($R_s$) adjusted for soil temperature ($T_s$) and soil moisture ($M_s$) ($\overline{R_S}^{T,M}$) along with sample sizes ($N$) and variability coefficients from various fire scar age categories in field campaigns 1 (2006) and 2 (2007) at Sharpsand Creek.

| Scar age category | $N_1$ | $N_2$ | $\overline{R_S}^{T,M}$ ($\mu$mol $CO_2$/m$^2$/s) | $\sigma_{R_s^{T,M}}$ ($\mu$mol $CO_2$/m$^2$/s) | $\overline{\sigma}_{R_s^{T,M}}$ ($\mu$mol $CO_2$/m$^2$/s) | $CV_{R_s^{T,M}}$ |
|---|---|---|---|---|---|---|
| 1948† | 3 | 12 | 8.18 | 4.60 | 1.33 | 0.56 |
| 1991† | 2 | 7 | 2.61 | 0.58 | 0.22 | 0.22 |
| 1948NB+ | 1 | 8 | 1.91 | 0.79 | 0.28 | 0.41 |
| 1948B+ | 3 | 24 | 0.83 | 0.41 | 0.08 | 0.49 |
| 1975B+ | 3 | 27 | 0.56 | 0.31 | 0.06 | 0.55 |
| 1991NB+ | 1 | 8 | 0.79 | 0.16 | 0.06 | 0.20 |
| 1991B+ | 3 | 25 | 0.91 | 0.24 | 0.05 | 0.26 |

$T_s$ adjustment: $Q_{10}$=2.21; reference $T_s$=10°C; $M_s$ adjustment: exclusion of $R_s$ values with associated $M_s$ outside the range 0.21 to 0.77 volumetric $M_s$; scar age category=year of last burn (not including 2007 wildfire); † Field campaign 1 (2006); + field campaign 2 (2007); NB=not burnt in 2007; B=burnt in 2007; $N_1$=number of replicate scars; $N_2$=number of $R_s$ measurements; $\sigma$ – standard deviation; $\overline{\sigma}$ – standard error of mean; $CV$ – coefficient of variation.



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**Table 6.** t tests comparing mean soil respiration ($R_s$) adjusted for soil temperature ($T_s$) and soil moisture ($M_s$) ($\overline{R_S}^{T,M}$) between various scar age categories at Sharpsand Creek.

| Fire scar age category | Levene's test | | | t test | | | |
|---|---|---|---|---|---|---|---|
| Comparison | $F$ | $P$ | Type | $t$ | $df$ | $P_{raw}$ | $P_{adj}$ |
| 1948† vs. 1991† | 9.793 | 0.006 | UV | 4.130 | 11.598 | 0.001 | 0.009*** |
| 1948NB+ vs. 1948B+ | 10.332 | 0.003 | UV | 3.713 | 8.289 | 0.006 | 0.030** |
| 1948NB+ vs. 1975B+ | 24.943 | 0.000 | UV | 4.719 | 7.632 | 0.002 | 0.014** |
| 1948B+ vs. 1975B+ | 1.547 | 0.219 | S | 2.632 | 49.0 | 0.011 | 0.044** |
| 1948NB+ vs. 1991NB+ | 20.228 | 0.001 | UV | 3.943 | 7.599 | 0.005 | 0.030** |
| 1948B+ vs. 1991B+ | 6.297 | 0.016 | UV | −0.849 | 36.571 | 0.402 | 0.402 NS |
| 1975B+ vs. 1991NB+ | 6.325 | 0.017 | UV | 2.693 | 22.530 | 0.013 | 0.044** |
| 1975B+ vs. 1991B+ | 2.917 | 0.094 | S | 4.533 | 50.0 | 0.000 | 0.000*** |
| 1991NB+ vs. 1991B+ | 2.269 | 0.142 | S | −1.370 | 31.0 | 0.181 | 0.362 NS |
| 1948† vs. 1948NB+ | 9.643 | 0.006 | UV | −4.615 | 11.958 | 0.001 | 0.009*** |
| 1991† vs. 1991NB+ | 6.255 | 0.027 | UV | 8.020 | 6.826 | 0.000 | 0.000*** |

$T_s$ adjustment: $Q_{10}$=2.21; reference $T_s$=10°C; $M_s$ adjustment: exclusion of $R_s$ values with associated $M_s$ outside the range 0.21 to 0.77 volumetric $M_s$; scar age category=year of last burn (not including 2007 wildfire); † field campaign 1 (2006); + field campaign 2 (2007); NB=not burnt in 2007; B=burnt in 2007; "Type": S=students t test (where Levene's $P$>0.05); UV=unequal variance t test (where Levene's$P$<0.05). $P_{adj}$=Holm-Boferroni adjustment for multiple hypothesis testing; $P$ values 2 tailed; NS $P$>0.1; *$P$<0.1; **$P$<0.05; ***$P$<0.01.



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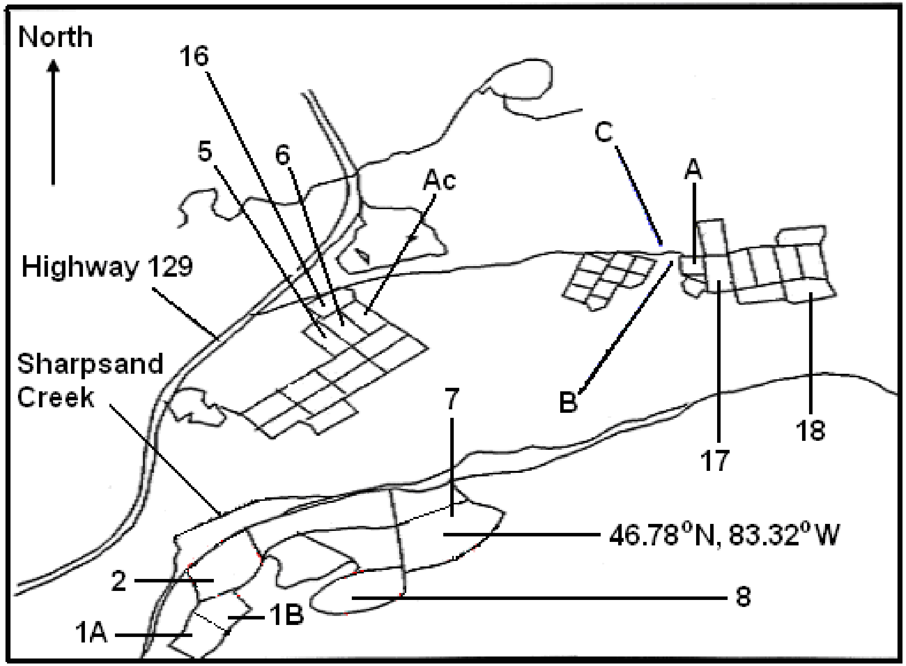


**Fig. 1.** Organisation of fire scars at Sharpsand Creek last burnt* in: 1948 wildfire (1A, 1B, A, B, C); 1975 prescribed burns (5, 6, Ac); 1981 prescribed burns (16, 17, 18); 1991 prescribed burns (2, 7, 8). *Excluding 13 May 2007 prescribed burn at 1B and subsequent wildfire across large areas of whole field site.



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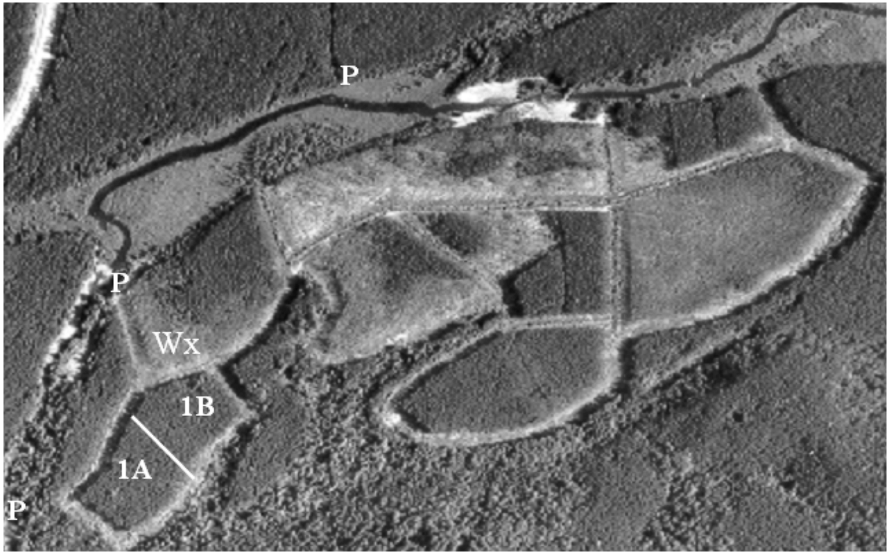


**Fig. 2.** Aerial photograph (1992) of part of Sharpsand Creek field site. The fire scars and fire breaks around their perimeter are clearly visible. Scar 1A was last burnt in a 1948 wildfire. On 13 May 2007, a prescribed burn was carried out on scar 1B (previously burnt in 1948 wildfire). “Wx” represents the location of a Canadian Forest Service weather station. “P” represents the location of water pumps used in fire suppression. Source: Ontario Ministry of Natural Resources.



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**Fig. 3.** Photograph (taken in June 2006) inside scar A at Sharpsand Creek, last burnt in a 1948 wildfire.



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**Fig. 4.** Photograph (taken in June 2006) inside scar 7 at Sharpsand Creek, last burnt experimentally in 1991.


**Fig. 5.** Mean soil organic carbon ($\overline{C_s}$) for five scar age categories at Sharpsand Creek. Soil samples collected during field campaign 2 (May 2007). Scar age category corresponds to year of last burn (excluding 2007 burn). B=burnt in 2007; NB=not burnt in 2007. Error bars represent mean±2 standard errors. Same letters are significantly different from one another ($\alpha$=0.1).

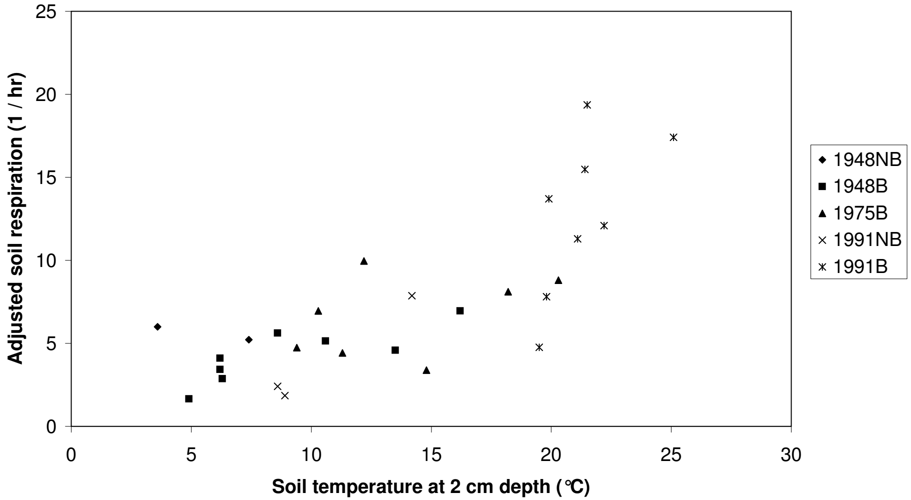


**Fig. 6.** Soil respiration ($R_s$) adjusted for soil organic carbon ($C_s$) ($R_s^C$) versus soil temperature ($T_s$) at 2 cm depth. $R_s^C = R_s / C_s$. Exponential function: $R_s^C = 2.0542 \exp(0.0794 {*} T_s)$; $Q_{10} = 2.21$. Ln $R_s^C$ versus $T_s$ linear regression: $N = 28$; $df = 1, 26$; $r^2 = 0.60$; $P = 1.24 \times 10^{-6}$. Based on measurements taken across Sharpsand Creek field site in May 2007.

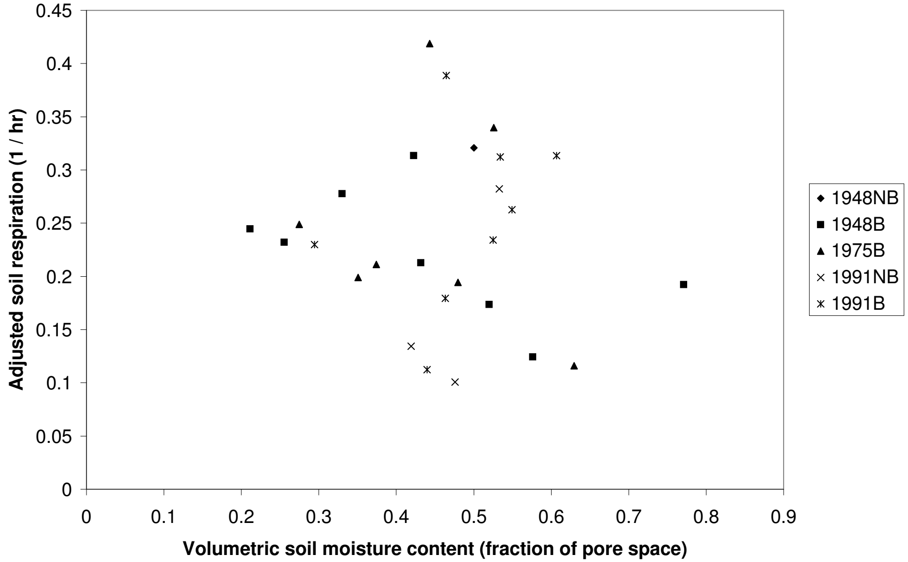


**Fig. 7.** Adjusted soil respiration ($R_s$) versus volumetric soil moisture ($M_s$). $R_s$ adjusted for soil organic carbon ($C_s$) ($R_s/C_s$), then adjusted for $T_s$ (base $T_s$=10°C; $Q_{10}$=2.21). Linear regression: $N$=27; $df$=26; $r^2$=0.006; $P$=0.702.

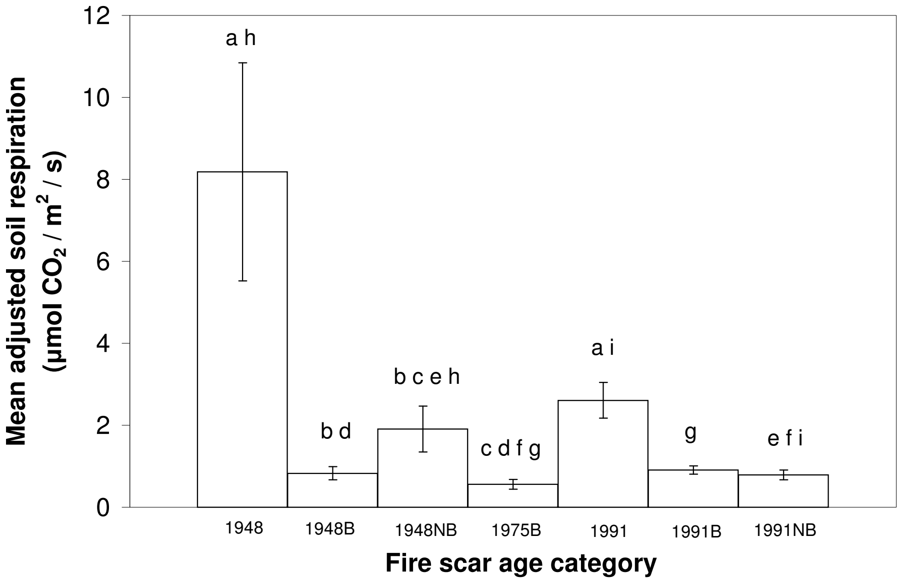


**Fig. 8.** Mean soil respiration (soil surface $CO_2$ efflux) adjusted for soil temperature ($T_s$) and soil moisture ($M_s$) ($\overline{R_S}^{T,M}$) for various fire scar age categories at Sharpsand Creek. $T_s$ adjustment: $Q_{10}$=2.21; reference $T_s$=10°C; $M_s$ adjustment: exclusion of $R_s$ values with associated $M_s$ outside the range 0.21 to 0.77 volumetric $M_s$; data collected over field campaign 2 (2007) except 1948 and 1991 categories – data collected during field campaign 1 (2006). Scar age category corresponds to year of last burn (excluding 2007 burn). NB=not burnt in 2007; B=burnt in 2007. Error bars represent mean±2 standard errors.

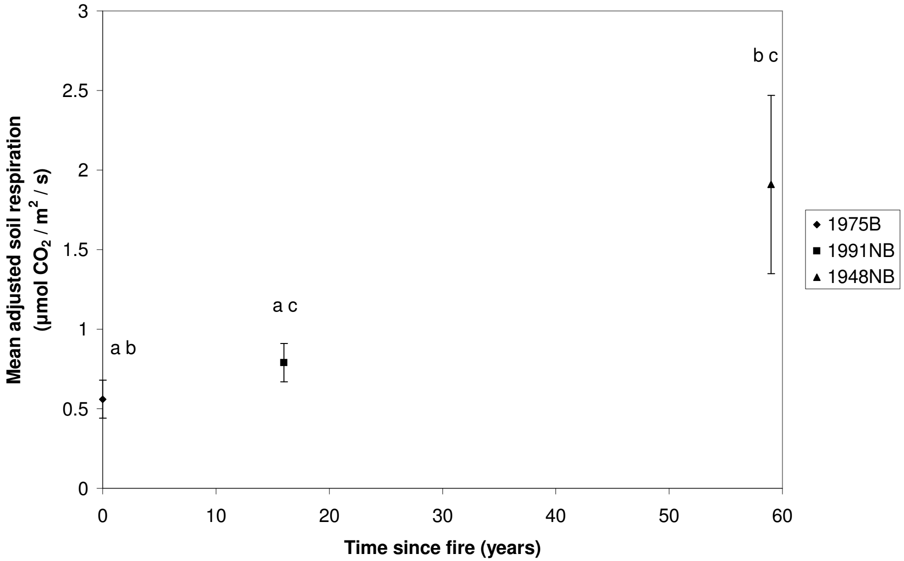


**Fig. 9.** Mean soil respiration (soil surface $CO_2$ efflux) adjusted for soil temperature ($T_s$) and soil moisture ($M_s$) ($\overline{R_S}^{T,M}$) versus time ($t$) since last fire at Sharpsand Creek. Based on three scar age categories: 1975B (0 years since fire), 1991NB (16 years since fire), 1948NB (59 years since fire). $T_s$ adjustment: $Q_{10}$=2.21; reference $T_s$=10°C; $M_s$ adjustment: exclusion of $R_s$ values with associated $M_s$ outside the range 0.21 to 0.77 volumetric $M_s$; measurements made during field campaign 2 (May 2007). Empirical function: $\overline{R_S}^{T,M}$=0.5629 exp(0.0207*t); transformed linear regression (Ln $R_s$ vs. time since burn): $N$=3; $df$=2; $r^2$=0.999; $P$=0.006. Error bars represent mean±2 standard errors.