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The effect of post-fire stand age on the boreal forest energy balance

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Abstract

Fire in the boreal forest renews forest stands and changes the ecosystem properties. The successional stage of the vegetation determines the radiative budget, energy balance partitioning, evapotranspiration and carbon dioxide flux. Here, we synthesize energy balance measurements from across the western boreal zone of North America as a function of stand age following fire. The data are from 22 sites in Alaska, Saskatchewan and Manitoba collected between 1998 and 2004 for a 150-year forest chronosequence. The summertime albedo immediately after a fire is about 0.05, increasing to about 0.12 for a period of about 30 years and then averaging about 0.08 for mature coniferous forests. A mature deciduous (aspen) forest has a higher summer albedo of about 0.16. Wintertime albedo decreases from a high of 0.7 for 5- to 30-year-old forests to about 0.2 for mature forests (deciduous and coniferous). Summer net radiation normalized to incoming solar radiation is lower in successional forests than in more mature forests by about 10%, except for the first 1–3 years after fire. This reduction in net radiative forcing is about 12–24 W m^{-2} as a daily average in summer (July). The summertime daily Bowen ratio exceeds 2 immediately after the fire, decreasing to about 0.5 for 15-year-old forests, with a wide range of 0.3–2 for mature forests depending on the forest type and soil water status. The magnitude of these changes is relatively large and may affect local, regional and perhaps global climates. Although fire has always determined stand renewal in these forests, increased future area burned could further alter the radiation balance and energy partitioning, causing a cooling feedback to counteract possible warming from carbon dioxide released by boreal fires.

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1. Introduction

The boreal forest is recognized as having a global influence on climate by reducing winter albedo (Bonan et al., 1992; Thomas and Rowntree, 1992; Viterbo and Betts, 1999) and acting as a carbon sink (Ciais et al., 1995) and water source to the atmosphere. The North American boreal forest includes sparse lichen wood-lands in the northern taiga, and coniferous and deciduous forests that can grow rapidly in the southern regions. The surface characteristics of these forests are also highly variable. This is partly due to the species mix, but is also affected by the growth stage of a forest stand. Global climate models (GCMs) and regional climate models (RCMs) use land surface characteristics to drive the atmosphere–surface feedback, an essential boundary condition to model atmospheric motions. Many of these models use fundamental properties of the ecosystem, such as albedo, leaf-area index (LAI), surface roughness, and vegetation type (e.g., Verseghy et al., 1993; Bonan et al., 1995). They then calculate energy balance exchange from these inputs. One of the difficulties in projecting future climates is under-standing the nature of future surface characteristics. Many of the current characteristics can be assessed using remote sensing on scales that are useful for GCM and RCM inputs. However, we need validation that the modeled energy balances agree with observations. This can be done most directly through measurements of the energy exchange properties of the forest.

Throughout the North American boreal region, forest stands are being continuously renewed by disturbances. These are dominated by fire and insects, with harvesting being important in the southern parts. Other disturbances, such as disease and windthrow are also important but often not readily quantified. Forest fire is common throughout Canada and Alaska, averaging about 3 million ha burned annually in recent decades (Stocks et al., 2002; Murphy et al., 2000). This creates a mosaic of stand ages with different surface characteristics on the landscape. Some of these patches can be quite large; for example, one single Canadian fire in 1995 covered an area of 1 million ha. Hence, we need to characterize the changing state of the surface characteristics and ecosystem properties throughout the life cycle of the forest. We recognize that fire severity is also an important factor in the landscape mosaic, because it dictates the successional trajectory by setting the initial post-fire environment. This affects vegetation establishment as well as dynamics among species. We approximate the succession of forest stands using the chronosequence approach where forest stands of different ages following

fire are studied. Here we focus on energy balance characteristics that drive local, regional and global climates. Many of these concepts have been described in detail by Chapin et al. (2000), especially with regard to vegetation controls in northern ecosystems.

Studies of the post-fire energy balance in the boreal forest have included subarctic sites (Rouse and Kershaw, 1971; Rouse, 1976) and daytime summer conditions from aircraft (Amiro et al., 1999). Tower-based measurements of a 1-year-old jackpine site showed a decrease in net radiation (R_n), sensible heat flux density (H), and latent heat flux density (LE) compared to a mature site whereas a 10-year-old site showed little difference compared to a nearby mature site in summer (Amiro, 2001). Similarly, Alaskan forests in the first decade following fire show reduced summer net radiation, enhanced ground heat flux and lower Bowen ratios compared to older forests (Chambers and Chapin, 2002). Continuous observations over an annual cycle provide evidence that absolute differences in the surface energy budget between early and late successional forests are greatest during spring – because of differences in albedo – and substantial during summer (Liu et al., 2005). Also, the net radiation of boreal forest and tundra ecosystems respond differently following fire, with the tundra showing increased net radiation (Chambers et al., 2005). These individual studies provide some insights into the situation at specific sites.

Over the past few years, there has been a larger effort to explore the effects of fire on the exchange of carbon dioxide between the boreal forest and the atmosphere (e.g., Amiro et al., 2003; Litvak et al., 2003). These studies have also measured energy balance components, which are often overlooked in the presentation of carbon flux results. In the present paper, we have analyzed data sets from all recent studies of post-fire forest environ-ments in the North American boreal forest to provide an integrated view of the changes in the energy balance and surface characteristics with time since fire.

2. Materials and methods

2.1. The research sites

The data sets come from several research groups who have been measuring the energy balance flux components and the radiative surface characteristics of 22 boreal forest sites. These represent a 150-year-old chronose-quence initiated by natural wildfire over a variety of vegetation types. Table 1 outlines the location, the year of origin (year of the most recent stand-replacing fire), the dominant vegetation type and the years of data collection

Table 1
Site characteristics

Sites	Location	Site origin year	Max. LAI	Live canopy height (m)	Dominant species	Measurement years
AK (Liu et al., 2005)	63°54′N, 145°40′W	1920	3.4	4	Black spruce	2002
	63°56′N, 145°27′W	1987	2.6	5	Aspen, willow, low shrubs, herbs	2002
	63°54′N, 145°44′W	1999	1.1	1	Grass, herbs, moss	2002
AK (Chambers and Chapin, 2002)	63°54′N, 145°44′W	1999		0.2		1999
	65°10′N, 147°30′W	1999		0.2	Willow, herbs, low shrubs	1999
	63°48′N 145°06′W	1994		0.5		1998
	63°49′N, 144°59′W	1994		0.5		1998
	63°56′N, 145°27′W	1987		3.5	Aspen, willow, herbs	1999
	63°49′N, 144°59′W	1900		3.4		1999
	65°10′N, 147°30′W	1919		2.5		1999
	65°10′N, 147°30′W	1919		2.5	Black spruce	1999
	65°10′N, 147°30′W	1919		3		1999
MB (Bond-Lamberty et al., 2002a, b)	55°52′N 98°28′W	1850	6	15	Black spruce, moss	2002–2004
	55°54′N 98°31′W	1930	7.5	16	Black spruce, moss, shrub understorey	2002–2004
	55°55′N 98°21′W	1964	3	6	Black spruce, jackpine, aspen, shrub understorey	2002–2004
	55°51′N 98°28′W	1981	2.5	4	Black spruce, jackpine, aspen, shrubs, herbs	2002–2004
	55°54′N 98°58′W	1989	1.5	2	Shrubs, herbs, aspen, jackpine, small black spruce	2002–2004
	55°54′N 98°58′W	1998	1	1	Herbs, alder, small black spruce, jackpine, and aspen	2002–2003
SK (Amiro et al., 2006; Baldocchi and Vogel, 1997; Blanken et al., 1997; Chen et al., 2006; Jarvis et al., 1997)	54°29N 105°49′W	1977	3.4	7	Jackpine, black spruce	2003–2004
	54°15′N 105°53′W	1989	3	4	Jackpine, aspen, black spruce	2001–2004
	54°15′N 105°53′W	1998	1	1	Herbs, aspen, jackpine, black spruce	2001–2004
	53°59′N 105°7′W	1879	4.2	7	Black spruce	2000–2004
	53°54′N 104°41′W	1929	2.5	13	Jackpine	2001–2002
	53°37′N 106°11′W	1919	5.8	21	Aspen	2001–2003

References given describe the sites more thoroughly.

for each site. A larger deciduous component of vegetation is present in the younger sites. We have organized these data sets into contributions from Alaska (AK), Manitoba (MB), and Saskatchewan (SK). The AK data consists of two sets of measurements. Summer observations of surface energy and CO_2 exchange were made at nine sites during 1998 and 1999 (Chambers and Chapin, 2002). Continuous observations were made at two of these same sites (the 1999 and 1987 burn sites) and one additional site during 2002 as a part of a separate study (Liu et al., 2005). The MB sequence includes data from six sites including a control mature site (the BOREAS Northern Old Black Spruce site). However, the data reported in this paper were collected on a separate tower from the long-term measurements at the Northern Old Black Spruce Site (e.g., Goulden et al., 1997). The SK sequence includes data from three sites burned within the past 27 years (Amiro et al., 2006), two evergreen mature sites

(the BOREAS Southern Old Black Spruce site (Jarvis et al., 1997) and the Southern Old Jack Pine site (Baldocchi and Vogel, 1997)) and a deciduous mature site (the BOREAS Southern Old Aspen site, SOA (Blanken et al., 1997)). The SOA site is of particular interest because it is a mature pure aspen forest, which is not common throughout much of the boreal zone. Most older aspen forests have coniferous components with eventual succession to a coniferous-dominated forest. This particular site is at the southern edge of the boreal forest, and provides a deciduous comparison to the coniferous sites of similar age. The four former BOREAS sites are permanent installations, whereas the other sites were operated for periods of several weeks to several years. Each of these sites is relatively flat with ample fetch, although the 1998 SK site has limited fetch in one sector and data were only used when the footprint originated from the appropriate area.

2.2. Measurements and processing

Micrometeorological measurements were made of net radiation (R_n), incoming solar radiation (S), albedo, sensible heat flux density (H), and latent heat flux density (LE), above the vegetation canopy from towers, as well as ground heat flux density (G). The eddy covariance technique was used to measure H and LE, and the half-hourly values were integrated to obtain 24 h (daily) totals of all quantities. The energy storage terms in the air, very small on a daily basis, were not included in the H and LE daily fluxes. The surface soil layer storage term was included in G using measurements of shallow soil temperatures. The specific instrumentation is listed in Table 2. Turbulent flux data were acquired either through dataloggers or computer acquisition systems, at rates varying from 4 to 20 samples s^{-1}, depending on the site. We did not adjust the eddy covariance measurements for energy balance closure; this has a minor effect on our comparisons because closure is of a similar magnitude among sites (0.85–0.9 typically on a daily basis). We did not exclude data during low friction velocities at night because this has negligible impact on daily LE and

only a small potential effect on daily H. Full 24 h data were available without gap filling.

The sites were compared along the chronosequence through normalization of R_n with S (R_n/S). All other components of the energy balance were normalized to R_n as LE/R_n, H/R_n and G/R_n, with the normalization done as the ratio of the daily totals of each component. The normalized daily values during the summertime period, defined from the last week of June to the third week of July (DOY 177 to DOY 205), were used to compute the normalized summertime means and standard errors (i.e., based on the variability among days). This period was selected to ensure the deciduous vegetation had completed the process of full leaf development at all sites, and corresponded to the period where all sites had data. We excluded days where the daily R_n was less than 1/2 the maximum value during the period to compare clear-sky conditions (i.e., differential cloud among sites was factored out). This left a data set with a mean number of days per site of 23 that included 40 site-years. The albedo data are based on daily totals (i.e., the ratio of total reflected to total incoming solar radiation). The wintertime albedo averages and associated standard errors were calculated

Table 2
Instrumentation configuration at each site

Sites	Origin year	Flux measurement height (m)	Net radiometer	Albedo/solar	Sonic anemometer	Gas analyzer	Soil heat flux plates
AK (Liu et al., 2005)	1920	9.5	REBS Q7	Eppley	CSAT3	LI7500	REBS
	1987	10					
	1999	7.8					
AK (Chambers and Chapin, 2002)	1999	8	REBS Q7	Eppley	Gill Solent	LI6262	REBS
	1999	8					
	1994	7					
	1994	7					
	1987	8					
	1900	7					
	1919	7					
	1919	7					
	1919	7					
MB	1850	20	REBS Q7	Kipp and Zonen CM3	CSAT3	LI7000	Not available
	1930	20					
	1964	12					
	1981	8					
	1989	6					
	1998	6					
SK (Amiro et al., 2006)	1977	12	Kipp and Zonen CNR1	Kipp and Zonen CNR1	CSAT3	LI7500	Thornthwaite
	1989	9	Middleton/CNR1				
	1998	20					LI6262/LI7500
	1879	25	CNR1	CNR1/Eppley	R3	LI6262	Middleton
	1929	28			CSAT3		
	1919	33			R3		

References given describe the instrumentation more thoroughly.

for each site using all the available daily data during the months of January and February (average number of days = 51). These subsets, one for summer and one for winter, were selected to allow meaningful comparisons among the far-reaching sites. Continuous data were not available at all sites to allow for a full annual comparison.

3. Results and discussion

3.1. Albedo

The summertime albedo is about 0.05 immediately after fire, and increases to 0.13 within the first 10 years (Fig. 1). This slowly decreases at most older sites to a value of about 0.07–0.08. The exception is the SOA site, which maintains a summertime albedo of about 0.16 in each of the 3 years. The slight decrease in 2003 may be cause by drought and less leaf area. The development of the forest canopy is largely a function of the stand age, as shown by the leaf-area index (LAI) and height data in Table 2. In fact, regression of height or LAI with stand age is approximately linear and positive, with regression coefficients (r^2) of about 0.5. It is important to note that most of the younger (less than 25 years) sites also have a substantial deciduous component in their canopy and also have a high albedo. Hence, the changes in albedo with time since fire are largely related to both the quantity of vegetation (and canopy structure) as well as the species in the successional trajectory, with deciduous broad-leafed species often being dominant in the early post-fire years. At most of our sites, coniferous pine and spruce dominate

Fig. 2. Wintertime (DOY 1 to DOY 60) daily albedo mean and standard errors. AK = Alaska, MB = Manitoba, SK = Saskatchewan, SOA = Southern Old Aspen site in SK. The line represents an exponential decay curve regression with equation: $y = 0.205 + 0.399\,e^{-0.0561x}$ for the units given in the figure; $r^2 = 0.66$.

in later years, except at the SOA site. We have plotted a linear regression line in Fig. 1 that could be used for modeling purposes for sites older than 12 years, and excluding SOA. We believe that this captures the more typical developments in boreal succession following vegetation establishment although we do not imply a physical basis for the regression.

The wintertime albedo at the older sites is slightly greater than for summer but much greater at sites less than 25 years of age (Fig. 2). We have fitted an exponential decay regression curve to the data, which may be useful for ecosystem modelers. Winter albedo can be as high as 0.7 and is caused by a high reflectance from the snow that is seen through the sparse canopy. The mature deciduous canopy in Saskatchewan has about the same albedo to similarly aged conifer sites. This is not expected but may be caused by similar amounts of snow seen on the ground through the deciduous canopy and on branches of the coniferous canopy at these low winter sun angles. Our albedo measurements are based on daily totals. Some minor latitudinal differences in sun angle do not appear to have a major effect on the trends, since we see similar patterns at any given latitude in Figs. 1 and 2.

3.2. Net radiation

We normalized summertime R_n by S to allow comparisons based on different solar radiation conditions caused by latitude and weather conditions. Fig. 3 shows relatively high values at the very young AK sites, with a lower R_n/S at ages between 10 and 25 years. R_n/S is greater for the mature sites although the SOA site is
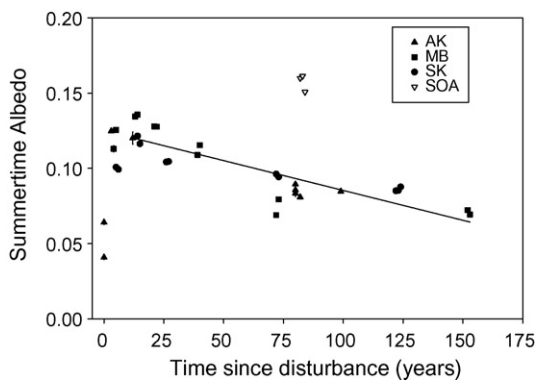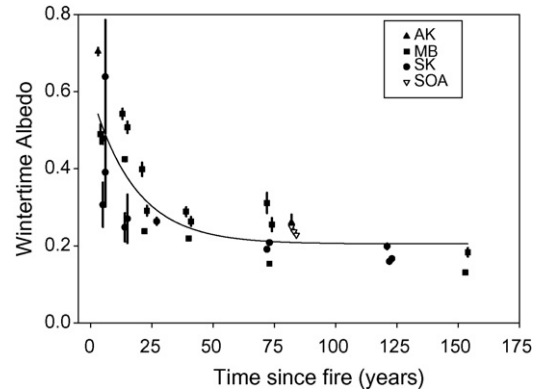

Fig. 1. Summertime (DOY 177 to DOY 205) daily albedo mean and standard errors (error bars are based on variability among days, they are smaller than the point size in most cases). AK = Alaska, MB = Manitoba, SK = Saskatchewan, SOA = Southern Old Aspen site in SK. The line represents a linear regression for times older than 11 years, excluding SOA, with equation: $y = 0.125 - 0.000396x$, for the units given in the figure; $r^2 = 0.74$.
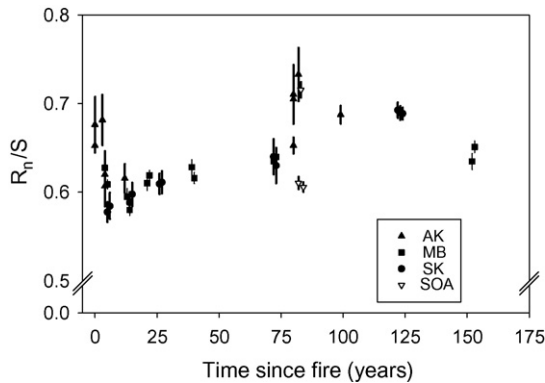
Fig. 3. Summertime (DOY 177 to DOY 205) daily net radiation (R_n) mean and standard errors normalized to the incoming shortwave radiation (S). AK = Alaska, MB = Manitoba, SK = Saskatchewan, SOA = Southern Old Aspen site in SK.
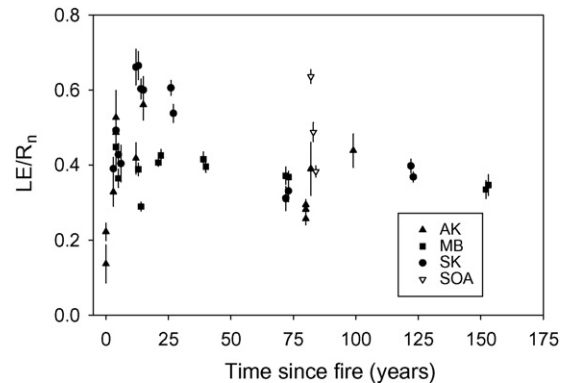

Fig. 4. Summertime (DOY 177 to DOY 205) daily latent heat flux (LE) mean and standard errors normalized to net radiation (R_n). AK = Alaska, MB = Manitoba, SK = Saskatchewan, SOA = Southern Old Aspen site in SK.

slightly lower. Again, the SOA site is more similar to the 10- to 25-year-old sites because of the deciduous components. The higher R_n/S at the very young AK sites is caused largely by the low summertime albedo (Fig. 1) so that a greater portion of the shortwave radiation is absorbed. We do not have measurements of the longwave radiation balance at all of these sites so its contribution to the variation in R_n is not known. We have not attempted to construct regression curves for these data or for the components described in the following sections. The data trends are more complex and do not easily allow for predictive equations without a physical basis for the relationships.

3.3. Latent heat

We normalized LE by R_n to allow comparisons with different amounts of total energy among the sites and to investigate energy partitioning (Fig. 4). LE is about 20% of R_n at the youngest AK sites and increases to about 60% of R_n at sites from 10 to 25 years of age. The rapid increase with age at the start of the chronosequence corresponds to vegetation development with the very youngest sites having much less vegetation. At sites between about 10 and 40 years old, the MB sites tend to have less relative LE than the SK sites. LE at the more mature sites (50–150 years) ranges from about 30 to 60% of R_n. These sites differ not only in vegetation, but also in soil type, hydrology and water status during the measurements. This wide range is partly caused by interannual variability at any given site. For example, the SOA site experienced some very dry years, and 1999 was drier than 1998 at the AK sites. Despite this wide range, it is clear that these mature boreal sites partition close to half of R_n into LE during July on average.

3.4. Sensible heat and ground heat fluxes

The normalized sensible heat flux, H/R_n, is largely complementary to LE/R_n. Although there is more scatter, the 10- to 25-year-old sites have a lower portion of energy partitioned into H than at most older sites (Fig. 5). The large variability at about 80 years contrasts the greater H at some AK sites with the lower H at the SOA site. As in the case of LE, the SOA site varies depending on year because of water availability. The variability in G among sites is about the same as that for LE and H in absolute terms, but this appears greater because of the relative magnitude of the dynamic range (Fig. 6). There is a general decrease with forest age. Data were not available for the MB sites. Although G might be expected to be greater at the young sites with sparser canopies, this is not necessarily the case. The severity of the fire has a major effect on the status of the
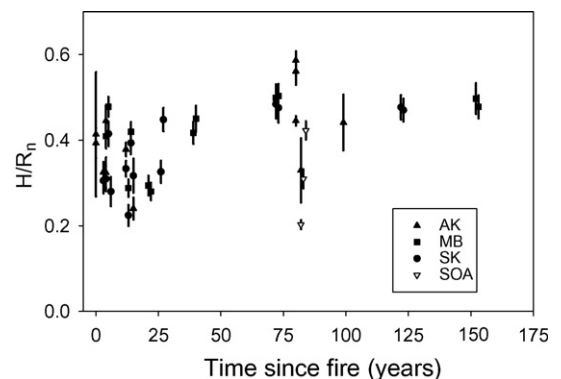

Fig. 5. Summertime (DOY 177 to DOY 205) daily sensible heat flux (H) mean and standard errors normalized to net radiation (R_n). AK = Alaska, MB = Manitoba, SK = Saskatchewan, SOA = Southern Old Aspen site in SK.
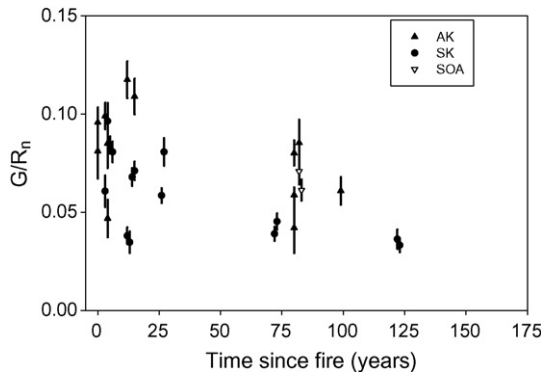
Fig. 6. Summertime (DOY 177 to DOY 205) daily soil heat flux (G) mean and standard errors normalized to net radiation (R_n). AK = Alaska, SK = Saskatchewan, SOA = Southern Old Aspen site in SK.

remaining soil surface organic matter and the successional trajectory. At most of these sites, a ground cover and successional shrubs and seedlings establish quickly after fire such that soil heating may not be much different from older sites. We have no data on heat storage in standing biomass but it is usually small on a daily basis (Saxton and McCaughey, 1988) and likely has minimal impact on the differences among the sites.

3.5. The Bowen ratio

Figs. 4 and 5 show the relative portioning of net radiation into LE and H. However, we have explicitly plotted the daily Bowen ratio (H/LE) as a site-derived quantity (Fig. 7). This shows high values at very young sites with a minimum for sites in the 10–25-year range. There is large variability among sites at about 80 years contrasting the coniferous AK sites with SOA, whereas the MB and SK sites are mid-range at about 1.5. This difference between coniferous and deciduous canopies
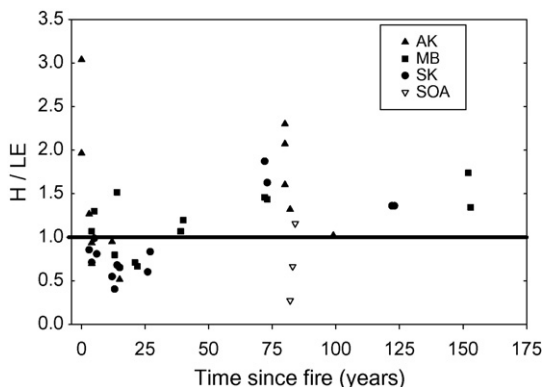

Fig. 7. Summertime (DOY 177 to DOY 205) daily mean Bowen ratio (H/LE). AK = Alaska, MB = Manitoba, SK = Saskatchewan, SOA = Southern Old Aspen site in SK.

follows the differences highlighted by Baldocchi and Vogel (1996) between the SK old jackpine site and a deciduous forest in Tennessee. Their differences were partly attributed to boreal versus temperate forest differences. However, this difference can also occur within the boreal regions depending on forest type and water availability.

4. Implications

Our measurements provide an integrated estimate of the effect of the post-fire environment on the surface energy balance components of the western North American boreal forest. The three main study regions represent both the northern and southern parts of the boreal forest, and include coniferous- and deciduous-dominated ecosystems. The data have been normalized so that they can be compared directly. The chronosequence data show clear patterns with time-since-fire for most parameters. However, the strength and duration of the deciduous phase of the post-fire successional trajectory appears to play a key role in shaping the surface energy balance. For example, the SOA site is clearly different from the coniferous sites of similar age in summer albedo and the Bowen ratio. Table 1 shows that the sites less than 20 years old also have a substantial deciduous tree component. Hence, we believe that the humps in the relationships at ages less than 20 years are mostly because of a deciduous component. This illustrates that the successional species trajectory largely defines the energy balance characteristics, with greater amounts of deciduous trees increasing the summer albedo and LE. This then decreases the Bowen ratio. There is some variability in this generalization, with part of this caused by local site and climate effects. For example, 2002 and 2003 were very dry years at the SK sites and some of the variability in LE among years is caused by local moisture limitations.

There is likely a further complication caused by variability in the magnitude of fire severity among sites. We do not have direct fire severity data, but all fires had replaced the former forest stand, so were at least lethal to trees. There is really no way to experimentally control for differences caused by fire severity, or for edaphic conditions, among the large number of sites compared in the current study. Instead, it is the generalized trends that appear despite local site differences that suggest that successional development is a key factor. This is based on our use of time-since-fire as the hypothetical independent variable in our figures.

We do not imply that the disturbance impact at all post-fire boreal sites follows a conversion from a pre-fire

coniferous forest to post-fire deciduous-dominated forest. In fact, some forests, such as jack-pine stands, often perpetuate themselves. This will still have implications for surface characteristics and energy balance changes because of a low leaf area index in the young stands, and shallow rooting systems that cannot access deep soil moisture reserves. However, we believe that the nature of the successional stand will determine the surface–atmosphere interaction. Some of this responds to feedbacks, such as high LE depleting soil moisture, which in turn controls growth and species composition. But some of the processes are independent, such as distance from a seed source for regeneration of some species following fire (e.g., Green et al., 1999). If much of the energy balance is controlled by the species composition of the stand, this may be additional support for the use of Plant Functional Types (PFTs) in global vegetation models (e.g., Box, 1996; Bugmann, 1996). For example, deciduous broad-leaf and evergreen needle-leaf PFTs form the two main types for much of the North American boreal forest (Nemani and Running, 1996). However, there is often a successional change between these two types that depends on when the most recent fire has occurred. Forest inventory data for Canada indicate that the current deciduous percentage of forest varies from a low of less than 1% in the Taiga Shield ecozone to close to 40% in the Boreal Plains ecozone (Amiro et al., 2001). The western part of the Boreal Shield ecozone has about 5% deciduous, whereas the eastern Boreal Shield ecozone has about 16%. The vegetation variation among ecozones is caused by both environmental differences and disturbance. In addition, Siberian forests behave differently and include more extensive areas of deciduous needle-leafed trees (*Larix* spp.). Irrespective of current vegetation type, fire has the potential to alter the landscape mosaic and affect local, regional and global climates.

Much of the focus on boreal forest change related to climate control has concentrated on albedo effects (Bonan et al., 1992; Betts, 2000). The wintertime albedo difference is more dramatic, but the summertime change with forest age is also important. For the surface energy balance, the overall effect on net radiation is of the order of 10% in summer on a daily basis (see differences in Fig. 3). The period of increased R_n is very short (less than 5 years) so the net fire impact is a decrease in R_n of 1–2 MJ m^{-2} day^{-1} or 12–24 W m^{-2} difference on a daily basis in fire-renewed stands for a few decades. As a comparison, global radiative forcing by enhanced greenhouse gases is of the order of 1–2 W m^{-2} to date (IPCC, 2001). However, the age changes caused by fire are over a limited area and

can create either an increase or decrease in R_n, depending on the successional stage and trajectory. To estimate the full effect, we would need to integrate global fire and forest successional impacts on an annual basis. We expect that these changes would be even larger than those during summer because of the effects of snow cover on albedo during spring (e.g., Liu et al., 2005), and these changes in the surface energy balance may be a more important driver of climate change than the carbon dynamics associated with a changing fire regime. For example, changes in the land system have been highlighted as a contribution to air temperature increases in northern North America (Skinner and Majorowicz, 1999) and modeling experiments clearly show that albedo changes need to be compared to forest carbon sinks to determine net climate effects (Betts, 2000).

The tower data collated in the current study demonstrate that natural stand renewal by fire determines energy partitioning at the local scale, thereby determining microclimates. Larger climate scales can also be affected substantially because fire patch sizes often exceed 10,000 ha in size (Stocks et al., 2002). However, the quantification of the impact on climate is more difficult. Avissar and Schmidt (1998) explored the scale of patches that affect mesoscale circulations and concluded that patches of 5–10 km in extent can be significant. This depends on windspeed, humidity and the magnitude of the surface flux difference. Many of our fires are of sufficient scale to affect these circulations. For our larger boreal fires, it is possible that a whole GCM grid (of the magnitude of 4° latitude) could be affected.

GCM projections of future climates in boreal areas suggest that area burned could double in a $3 \times CO_2$ environment in Canada compared to the recent past (Flannigan et al., 2005). However, there is also evidence that historical area burned in Canada before European influence was greater than in the recent past (Bergeron et al., 2004) and this poses additional uncertainty in the likely future fire regime. If fire increases in the future, we need to consider feedbacks of the fire effects, which include enhanced emissions of combustion carbon to the atmosphere (Amiro et al., 2001), post-fire vegetation changes, and changes in fire severity. A positive feedback scenario is possible with the warming causing more fire, releasing more CO_2, and increasing the warming through elevated atmospheric CO_2 concentrations. However, potential negative feedbacks include more smoke, higher winter albedo at recently burned sites, lower net radiation over successional forests, and higher evapotranspiration that could change cloud cover. Also there may be less fire growth in younger

forests because deciduous-dominated stands tend to have higher moisture contents and slower rates of fire spread. Investigation of these interactions is the next phase in linking of dynamic vegetation models to the GCMs (e.g., Thonicke et al., 2001), and we need to be able to incorporate the appropriate energy balance changes. The modeled results will need to capture the measured changes to the physical environment following fire.

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References

Amiro, B.D., 2001. Paired-tower measurements of carbon and energy fluxes following disturbance in the boreal forest. Global Change Biol. 7, 253–268.

Amiro, B.D., MacPherson, J.I., Desjardins, R.L., 1999. BOREAS flight measurements of forest-fire effects on carbon dioxide and energy fluxes. Agric. For. Meteorol. 96, 199–208.

Amiro, B.D., Todd, J.B., Wotton, B.M., Logan, K.A., Flannigan, M.D., Stocks, B.J., Mason, J.A., Martell, D.L., Hirsch, K.G., 2001. Direct carbon emissions from Canadian forest fires, 1959–1999. Can. J. For. Res. 31, 512–525.

Amiro, B.D., MacPherson, J.I., Desjardins, R.L., Chen, J.M., Liu, J., 2003. Post-fire carbon dioxide fluxes in the western Canadian boreal forest: evidence from towers, aircraft and remote sensing. Agric. For. Meteorol. 115, 91–107.

Amiro, B.D., Barr, A.G., Black, T.A., Iwashita, H., Kljun, N., McCaughey, J.H., Morgenstern, K., Murayama, S., Nesic, Z., Orchansky, A.L., Saigusa, N., 2006. Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada. Agric. For. Meteorol. 136, 237–251.

Avissar, R., Schmidt, T., 1998. An evaluation of the scale at which ground-surface heat flux patchiness affects the convective boundary layer using large-eddy simulations. J. Atmos. Sci. 55, 2666–2689.

Baldocchi, D.D., Vogel, C., 1996. Energy and CO_2 flux densities above and below a temperate broadleaved forest and a boreal pine forest. Tree Physiol. 16, 5–16.

Baldocchi, D.D., Vogel, C.A., 1997. Seasonal variation of energy and water vapor exchange rates above and below a boreal jack pine forest canopy. J. Geophys. Res. 102, 28939–28951.

Bergeron, Y., Flannigan, M., Gauthier, S., Leduc, A., Lefort, P., 2004. Past, current and future fire frequency in the Canadian boreal forest: implications for sustainable forest management. Ambio 33, 356–360.

Betts, R.A., 2000. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. Nature 408, 187–190.

Blanken, P.D., Black, T.A., Yang, P.C., den Hartog, G., Neumann, H.H., Nesic, Z., Novak, M.D., Staebler, R., Lee, X., 1997. Energy balance and canopy conductance of a boreal aspen forest: partitioning overstorey and understorey components. J. Geophys. Res. 102, 28915–28927.

Bonan, G., Pollard, D., Thompson, S.L., 1992. Effects of boreal forest vegetation on global climate. Nature 359, 716–718.

Bonan, G.B., Chapin III, F.S., Thompson, S.L., 1995. Boreal forest and tundra ecosystems as components of the climate system. Clim. Change 29, 145–167.

Bond-Lamberty, B., Wang, C., Gower, S.T., 2002a. Aboveground and belowground biomass and sapwood area allometric equations for six boreal tree species of northern Manitoba. Can. J. For. Res. 32, 1441–1450.

Bond-Lamberty, B., Wang, C., Gower, S.T., Norman, J., 2002b. Leaf area dynamics of a boreal black spruce fire chronosequence. Tree Physiol. 22, 993–1001.

Box, E.O., 1996. Plant functional types and climate at the global scale. J. Veg. Sci. 7, 309–320.

Bugmann, H., 1996. Functional types of trees in temperate and boreal forests: classification and testing. J. Veg. Sci. 7, 359–370.

Chambers, S.D., Chapin III, F.S., 2002. Fire effects on surface–atmosphere energy exchange in Alaskan black spruce ecosystems: implications for feedbacks to regional climate. J. Geophys. Res. 107, 8145 doi:10.1029/2001JD000530.

Chambers, S.D., Beringer, J., Randerson, J.T., Chapin III, F.S., 2005. Fire effects on net radiation and energy partitioning: contrasting responses of tundra and boreal forest ecosystems. J. Geophys. Res. 110, D09106.

Chapin III, F.S., McGuire, A.D., Randerson, J.T., Pielke Sr., R., Baldocchi, D., Hobbie, S.E., Roulet, N., Eugster, W., Kasischke, E., Rastetter, E.B., Zimov, S.A., Running, S.W., 2000. Arctic and boreal ecosystems of western North America as components of the climate system. Global Change Biol. 6 (Suppl. 1), 211–223.

Chen, J.M., Govind, A., Sonnentag, O., Zhang, Y., Barr, A., Amiro, B., 2006. Leaf area measurements at Fluxnet Canada forest sites. Agric. For. Meteorol. 140, 257–268.

Ciais, P., Tans, P.P., Trolier, M., White, J.W.C., Francey, R.J., 1995. A large northern-hemisphere terrestrial CO_2 sink indicated by the C-13/C-12 ratio of atmospheric CO_2. Science 269, 1098–1102.

Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., Stocks, B.J., 2005. Future area burned in Canada. Climatic Change 72, 1–16.

Goulden, M.L., Daube, B.C., Fan, S.-M., Sutton, D.J., Bazzaz, M., Munger, J.W., Wofsy, S.C., 1997. Physiological responses of a black spruce forest to weather. J. Geophys. Res. 102, 28987–28996.

Green, D.F., Zasada, J.C., Sirois, L., Kneeshaw, D., Morin, H., Charron, I., Simard, M.J., 1999. A review of the regeneration dynamics of North American boreal forest tree species. Can. J. For. Res. 29, 824–839.

IPCC (Intergovernmental Panel on Climate Change), 2001. Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, UK.

Jarvis, P.G., Massheder, J.M., Hale, S.E., Moncrieff, J.B., Rayment, M., Scott, S.L., 1997. Seasonal variation of carbon dioxide, water and energy exchanges of a boreal black spruce forest. J. Geophys. Res. 102, 28953–28966.

Litvak, M., Miller, S., Wofsy, S.C., Goulden, M., 2003. Effect of stand age on whole ecosystem CO_2 exchange in the Canadian boreal forest. J. Geophys. Res. 108 (D3), 8225 doi:10.1029/2001JD000854.

Liu, H.P., Randerson, J.T., Lindfors, J., Chapin, F.S., 2005. Changes in the surface energy budget following fire in boreal ecosystems of interior Alaska: an annual perspective. J. Geophys. Res. 110 (D13101) doi:10.1029/2004JD005158.

Murphy, P.J., Mudd, J.P., Stocks, B.J., Kasischke, E.S., Barry, D., Alexander, M.E., French, N.H.F., 2000. Historical fire records in the North American boreal forest. In: Kasischke, E.S., Stocks, B.J. (Eds.), Fire, Climate Change, and Carbon Cycling in the Boreal Forest. Springer, New York, pp. 274–288.

Nemani, R., Running, S.W., 1996. Implementation of a hierarchical global vegetation classification. J. Veg. Sci. 7, 337–346.

Rouse, W.R., 1976. Microclimate changes accompanying burning in subarctic lichen woodland. Arctic Alpine Res. 8, 357–376.

Rouse, W.R., Kershaw, K.A., 1971. The effects of burning on the heat and water regimes of lichen-dominated subarctic surfaces. Arctic Alpine Res. 3, 291–304.

Saxton, W.L., McCaughey, J.H., 1988. Measurement considerations and trends in biomass heat storage of a mixed forest. Can. J. For. Res. 18, 143–149.

Skinner, W.R., Majorowicz, J.A., 1999. Regional climatic warming and associated twentieth century land-cover changes in north-western North America. Climate Res. 12, 39–52.

Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D., Hirsch, K.G., Logan, K.A., Martell, D.L., Skinner, W.R., 2002. Large forest fires in Canada, 1959–1997. J. Geophys. Res. 108 (8149) doi:10.1029/2001JD000484.

Thomas, G., Rowntree, P.R., 1992. The boreal forests and climate. Quart. J. Roy. Meteorol. Soc. 118, 469–497.

Thonicke, K., Venevsky, S., Sitch, S., Cramer, W., 2001. The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model. Global Ecol. Biogeogr. 10, 661–677.

Verseghy, D.L., McFarlane, N.A., Lazare, M., 1993. CLASS—a Canadian land surface scheme for GCMs. II. Vegetation model and coupled runs. Inter. J. Climatol. 13, 347–370.

Viterbo, P., Betts, A.K., 1999. Impact on ECMWF forecasts of changes to the albedo of the boreal forests in the presence of snow. J. Geophys. Res. 104, 27803–27810.