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Boreal lichen woodlands: A possible negative feedback to climate change in eastern North America

P.Y. Bernier[a,*], R.L. Desjardins[b], Y. Karimi-Zindashty[b], D. Worth[b], A. Beaudoin[a], Y. Luo[c], S. Wang[d]

[a] Canadian Forest Service, Natural Resources Canada, Québec, QC, Canada
[b] Agriculture and Agrifood Canada, Ottawa, ON, Canada
[c] Meteorological Service of Canada, Environment Canada, Ottawa, ON, Canada
[d] Canada Centre for Remote Sensing, Natural Resources Canada, Ottawa, ON, Canada

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ABSTRACT

Because of successive forest fires, closed-canopy black spruce forests are susceptible to a shift towards open lichen–spruce woodlands in parts of the boreal forest of eastern North America. The shift from dark black spruce canopies to pale lichen ground cover offers a dramatic contrast in reflectance that may compensate for the CO_2 emissions from forest fires in terms of radiative forcing. We have therefore looked at the climate change feedback that would result from the generation of lichen woodlands through changes in albedo and in stored carbon. Using albedo estimates based on MODIS imagery and incoming solar radiation for the period between 2000 and 2008 along with forest biomass estimates for eastern Canada, we have estimated that net radiative forcing for the conversion from closed-canopy coniferous forests to open lichen woodlands would be about $-0.12\,\mathrm{nW\,m^{-2}\,ha^{-1}}$, and would therefore generate a cooling effect in the atmosphere. Based on current estimates of area in open lichen woodlands within the closed-canopy black spruce–moss forests of eastern Canada, we estimate that a current net forcing of $-0.094\,\mathrm{mW\,m^{-2}}$ has already arisen from such conversions. As projections of future climate have been linked to increased probability of forest fires, the generation of open lichen woodlands provides a possible negative feedback to climate change. Results also suggest that carbon sequestration through the afforestation of boreal lichen woodlands may not provide a climate change mitigation benefit.

1. Introduction

The boreal forest is Canada's largest forest ecosystem, occupying 35% of the total Canadian land area and 77% of Canada's total forest land (Natural Resources Canada, 2010). Fire regularly disturbs the boreal forest in Canada, leaving behind a temporary landscape of burnt trees and blackened earth. On average, about 9000 forest fires consume 2.1 million hectares annually in this ecosystem. While destructive, forest fires are a necessary and natural aspect of the life cycle of the boreal forest, releasing nutrients and rejuvenating the forest. The dominant tree species of the boreal forest are adapted and can regenerate following fires. Aspen (*Populus tremuloides*) regenerates vegetatively and abundantly from its root system following a fire, while black spruce (*Picea mariana*) and jack pine (*Pinus banksiana* Lamb.) have serotinous or semi-serotinous cones and heat-tolerant seeds that ensure a rapid re-seeding of the ground where these species are present (Elliott-Fisk, 2000). Black spruce is a slow-growing species that can take 25 years to reach sexual maturity (Morneau and Payette, 1989). In eastern Canada, where pure stands of this species dominate the high-latitude boreal forest, a first burn or harvest followed by a second burn before trees reach sexual maturity may therefore eliminate or strongly reduce the tree cover, depending on the fire intensity. In well-drained landscapes of coarse glacial deposits, the now open ground often becomes covered with various species of lichens, mostly of the *Cladina* and *Cladonia* genus, creating stable open lichen woodland ecosystems that persist over time (Girard et al., 2008).

Each land cover type has its own surface reflectivity, or albedo. When snow free, the boreal forest has an albedo of 9–11%, which tends to be less than that of other forest types and grasslands, which usually is in the 10–20% range. This difference in albedo is accentuated in winter, as snow blankets landscapes with sparse forest cover, resulting in an albedo in the range of up to 78%, but will tend to fall through a densely forested landscape, leaving the absorptive branches exposed and resulting in an albedo in the range of 10–26% (Betts, 2000; Betts et al., 2007a). Therefore, a change in land cover type has a direct effect on albedo, which in turn influences the local

* Corresponding author at: Canadian Forest Service, Natural Resources Canada, PO Box 10380, Stn. Ste-Foy, Québec, QC, Canada G1V 4C7.
E-mail address: pbernier@rncan.gc.ca (P.Y. Bernier).

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radiation budget. This change can be expressed in terms of radiative forcing, which is defined as the disturbance of net irradiance at the tropopause after allowing the stratospheric temperature to readjust to radiative equilibrium (Chapter 6 in IPCC, 2001).

Radiative forcing is often used to combine the effects of different agents, such as greenhouse gases, with a change in albedo into one metric that describes the net impact on climate. For instance, Betts (2000) showed that the radiative forcing of carbon sequestration and albedo change associated with afforestation/reforestation could be compared, and Pielke et al. (2002) estimated that for the boreal forest of North America this forcing ranged from 0.05 to 0.2 $nW\,m^{-2}\,ha^{-1}$. At the global level, a nominal climate sensitivity of 0.75 °C per $W\,m^{-2}$ of radiative forcing on a global scale has been reported by Hansen et al. (2008).

Air temperature is increasing within the boreal region of Canada (Jones and Moberg, 2003), which may lead to an increase in the future area of forest burnt annually (Flannigan et al., 2005). In the boreal forest of eastern Canada, the burn rate since 1940 has decreased compared with historical rates (Le Goff et al., 2007), but predictions for a $2 \times CO_2$ climate scenario suggest a 38% increase in future burn rates compared with current rates across the coniferous forest of Québec (Bergeron et al., 2006). It has been speculated that a climate change-induced increase in forest fires could lead to a positive climate feedback as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) released during combustion promote further warming and burning (Kurz et al., 1995; Metsaranta et al., 2010). However, the larger impact may be through the change in surface albedo following a burn, particularly in early spring when solar radiation is increasing and snow still blankets recently burnt areas, whereas in forested areas most of the snowfall passes through or falls off the canopy, leaving the more absorptive branches exposed (Betts and Ball, 1997). Such a difference in albedo may result in a net cooling during winter (Bonan et al., 1992; Brovkin et al., 2004; Claussen et al., 2001; Ganopolski et al., 2001). Over the multiple decades required for forest regrowth, simulations suggest that the negative feedback of albedo could outweigh the positive feedback effects of CO_2 emissions from the combustion of organic matter (Randerson et al., 2006).

In the boreal forest of eastern Canada, the change in albedo following repeated fires may be particularly important because the ground cover of open lichen woodlands is very pale in colour with high albedo, and because these open systems are stable and not easily recolonised by trees. The increased rate of creation of open lichen woodlands through projected increases in fire frequency may therefore provide a negative feedback to climate change. The objectives of the present work were to evaluate the net radiative forcing resulting from the loss of biomass carbon to the atmosphere and the increase in albedo resulting from the creation of open lichen woodlands in the closed-canopy forest domain, and to assess the potential net radiative forcing effect of increased lichen woodland extent as a result of increased fire frequency. Results are also interpreted in terms of afforestation of open lichen woodlands.

2. Materials and methods

2.1. Study location

The study area is located in the boreal forest of the province of Québec, Canada, and consists of the closed-canopy black spruce–moss bioclimatic domain (Robitaille and Saucier, 1998), located roughly between 49°N and 50°30′N latitude, and covering an area of about 412,400 km^2 (Saucier et al., 2009). This area is characterised by a low mean annual temperature (−2.5 °C to 0.0 °C), with annual precipitation increasing from west to east, from about 700–1200 mm. The dominant tree species is *P. mariana* (black spruce) with a variable abundance of *P. banksiana* (jack pine) and *P. tremuloides* (quaking aspen) in the dryer western portion of the domain, and of *Abies balsamea* (balsam fir) and *Betula papyrifera* (paper birch) in the wetter eastern portion of the domain. With the notable exception of the James Bay lowlands, most of these landscapes are underlain by coarse glacial deposits draped over hilly terrain.

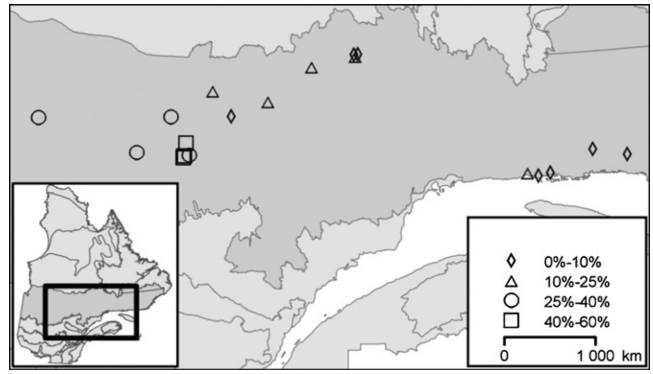

Fig. 1. Location of the reference blocks selected for the local dominance of one of four target cover densities of black spruce–lichen stand types. The darker shaded area corresponds to the black spruce–moss bioclimatic domain of the Quebec forest ecological classification of Robitaille and Saucier (1998).

The historical fire return interval for this region varies across the landscape from about 140 years in the west to 280 years or more in the east. The tendency since 1940 has been a decrease in the fire frequency, with a doubling of the fire return interval to nearly 600 years in the east (Bergeron et al., 2006; Le Goff et al., 2007). Simulations done for $2 \times CO_2$ and $3 \times CO_2$ scenarios suggest a return to historical burn rates and possibly an increase in frequency above the historical rates for the western portions of the domain, with return intervals of 80 years for the $3 \times CO_2$ scenario (Flannigan et al., 2005). Lichen woodlands are scattered in portions of this bioclimatic domain and have been expanding into the closed-canopy boreal forest for the past 1500 years. A possible cause of this expansion could be the drier late-Holocene conditions for this region (Jasinski and Payette, 2005), although fire risk seems to have been declining in the eastern boreal forest over the past 7000 years (Hély et al., 2010).

2.2. Selection of reference blocks

Albedo values were determined for four forest types with a lichen ground cover, and with different canopy cover densities: 0–10%, 10–25%, 25–40% and 40–60%. The computation of albedo started with the selection of reference blocks for each cover density on a forest cover map that was developed as part of the Earth Observation for Sustainable Development (EOSD) project led by the Canadian Forest Service and funded by the Canadian Space Agency (Wulder et al., 2008). Location of the reference blocks is shown in Fig. 1. The *circa* 2000 land cover classification of Canada was completed in 2007 based on Landsat TM and ETM multispectral scenes. Within this national framework, the Enhancement-Classification Method (ECM) (Beaubien et al., 1999) was applied over the province of Québec using three Landsat spectral bands (red, NIR and MIR) from an assembly of 100 Landsat scenes acquired between 1998 and 2003. ECM was used to produce a detailed land cover map of Québec at a 25-m resolution with 52 thematic classes. These classes were further aggregated into the 23 EOSD thematic classes to be compliant with the national-level EOSD legend (Wulder et al., 2008).

In our study, we used the detailed version of the land cover map of Québec to depict the forest covers of interest, i.e.