Global and Planetary Change 145 (2016) 42–56

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Holocene fire regimes and treeline migration rates in sub-arctic Canada

Kyle C. Sulphur [a,b,*], Shantal A. Goldsmith [a], Jennifer M. Galloway [b], Andrew Macumber [c], Fritz Griffith [d], Graeme T. Swindles [e], R. Timothy Patterson [c], Hendrik Falck [f], Ian D. Clark [d]

[a] Department of Geoscience, University of Calgary, Calgary, Alberta, Canada
[b] Natural Resources Canada, Geological Survey of Canada, Calgary, Alberta, Canada
[c] Ottawa-Carleton Geoscience Centre, Carleton University, Ottawa, Ontario, Canada
[d] Department of Earth and Environmental Sciences, University of Ottawa, Ottawa, Ontario, Canada
[e] School of Geography, University of Leeds, United Kingdom
[f] Northwest Territories Geological Survey, Yellowknife, Northwest, Territories, Canada

ARTICLE INFO

Article history:
Received 7 October 2015
Received in revised form 9 August 2016
Accepted 9 August 2016
Available online 10 August 2016

Keywords:
Holocene
Palynology
Paleoecology
Treeline
Northwest Territories
Fire

ABSTRACT

Holocene climate change resulted in major vegetation reorganization in sub-arctic Canada near modern treeline. However, little is known of the effects of long-term climate change on boreal forest composition and fire regimes below treeline in this region. We present a high-resolution vegetation and fire history from two sites within the modern boreal forest in the central Northwest Territories, Canada, to provide new insight on sub-arctic vegetation response to Holocene climate dynamics and the role of fire in boreal ecosystems. Palynological analysis of sediments retrieved from Waite and Danny's lakes (informal) is used to reconstruct regional vegetation dynamics and boreal fire regimes. The longer Danny's Lake record documents treeline expansion beginning at ca. 7430–7220 cal yr BP. Integration of our new data with previous work shows that treeline expanded between ca. 4050 cal. yr BP and ca. 3840 cal yr BP at a rate of ca. 50 m/yr in response to the 1–2 °C increase in temperature estimated for the Holocene Thermal Maximum. Forest fires were relatively frequent during the early Holocene, before declining in frequency in response to development of cooler and wetter climate conditions associated with the Neoglacial (beginning after ca. 2200–2320 cal yr BP). We document a trend of increasing fire frequency in the 20th century that is correlated with warming at this time. These dynamics south of modern treeline provide insight into factors creating heterogeneity in plant community responses to large-scale climate events in high northern latitudes and suggest that large scale reorganization of boreal vegetation and fire regimes can be expected over the coming decades.

1. Introduction

The large areal extent of the northern boreal forest affects the radiative balance of Earth by acting as a sink in the global carbon cycle (Ahlgren and Ahlgren, 1960; Bonan et al., 1992; Juday et al., 2005). The northern treeline is linked to the summer position of the Arctic Front, which is the southern boundary of the cold, dry arctic air. Through this connection with the Arctic Front, the northern treeline is linked to ocean-atmospheric phenomena and teleconnections (Bryson, 1966; Moser and MacDonald, 1990; Allan et al., 1996). Due to connections between latitudinal treeline and climate, factors influencing boreal forest composition and treeline position are important for climate research. To better understand and forecast climate-terrestrial feedback effects, we look to past climate events and their specific effects on the boreal forest.

Our new data and integration with previous work provides insight into rates of boreal terrestrial ecosystem change in response to climate variability in an ecologically sensitive sub-arctic region. Rates of ecosystem change are critical for understanding how systems will respond in coming decades to current and forecasted climate change. We also document changes in regional forest fire history in sub-arctic Canada. This is important because forest fires shape forest communities through elimination and because lightning produced during summer storms is the primary ignition source for boreal forest fires (Kochtubajda et al., 2006). Due to the link between summer storms and forest fires, fire history is likely to reflect climate changes. For instance, longer, warmer and drier summer months are linked to an increase in lightning-initiated forest fire occurrences (Kochtubajda et al., 2006).

Previous studies across the sub-arctic, including Canada, Sweden, Finland, Norway, and Russia document mid-Holocene northern treeline expansion and subsequent late Holocene contraction. In Russia, postglacial forests covered the landscape by ca. 9000 to 8000 cal yr BP at relatively high latitudes (60° N) but began to retreat by ca. 4000 to 3000 cal yr BP (MacDonald et al., 2000). In Sweden, Finland, and

* Corresponding author at: Department of Geoscience, University of Calgary, Canada.
E-mail address: kcsulphu@ucalgary.ca (K.C. Sulphur).

http://dx.doi.org/10.1016/j.gloplacha.2016.08.003
0921-8181/

Norway, treeline expansion occurred at ca. 6300 cal yr BP, and was followed by retreat at ca. 4500 cal yr BP (Barnekow, 1999; Barnett et al., 2001; Barnekow and Sandgren, 2001; Bergman et al., 2005).

Increased solar insolation centred at ca. 10,000 cal yr BP left much of northwestern North America ice free and covered by birch-shrub tundra, while eastern North America remained covered by the Laurentide Ice Sheet (Berger and Loutre, 1991; Overpeck et al., 1987; Dyke, 2005). By ca. 7000 cal yr BP, boreal forest or forest tundra stretched across most of western and central North America and by ca. 5000 cal yr BP, boreal forests had expanded at least 150 km north of current position in North America. Modern day North American latitudinal treeline limit was reached between ca. 4000 to 3000 cal. yr BP, with regional variation (Dyke, 2005).

Circumpolar forest expansion occurred in response to elevated temperatures regionally associated with the Holocene Thermal Maximum summer insolation anomaly peaked 12–10 ka, but the effects were expressed in a time-transgressive manner following the final melting of the Laurentide Ice Sheet. These temperature effects began to manifest at ca. 11,000 cal yr BP in Alaska and the northwestern Northwest Territories (NWT) and later in central and eastern Canada between ca. 7000 to ca. 5000 cal yr BP (Kaufman et al., 2004). The Holocene Thermal Maximum was expressed at Carleton Lake (central NWT) between ca. 4000 to 6000 cal yr BP (Upiter et al., 2014).

Estimates of Holocene Thermal Maximum warming from Alaska, central northern Canada, Baffin Island, Labrador, Sweden, Finland, Norway, and Russia suggest a temperature increase of 1–2 °C during its expression (MacDonald et al., 1993; Edwards et al., 1996; Pienitz et al., 1999; Barnett et al., 2001; Barnekow and Sandgren, 2001; Seppa and Birks, 2002; MacDonald et al., 2000; Kerwin et al., 2004; Kaufman et al., 2004; Clegg et al., 2010; Upiter et al., 2014).

To better understand the response of boreal forest ecosystems to climate change, we focus on the central NWT of sub-arctic Canada to reconstruct regional vegetation and forest fire regime over the last ca. 9000 years. We know based on previous work that this region experienced treeline expansion and contraction during the mid-Holocene (Moser and MacDonald, 1990; MacDonald et al., 1993; Pienitz et al., 1999; Huang et al., 2004; Dyke, 2005; Upiter et al., 2014). However, little is known of vegetation dynamics below treeline and the role of forest fires remains poorly understood in boreal systems in general and not known at all for the central NWT in particular. Study of sites below modern treeline can provide information on vegetation reorganization within forest communities during episodes of treeline movement and must be used to study the role of fire in boreal landscape change (Larsen and MacDonald, 1998).

High resolution study of lake sediments can provide insight into rates of vegetation change in response to climate variability. Understanding rates of change are particularly important for accurate prediction of terrestrial ecosystem response to current and forecasted change. We present a decadal-to-centennial scale resolution analysis of pollen, spores, and microscopic charcoal preserved in well-dated sediment cores retrieved from Danny's Lake (informal name) located 30 km south of modern treeline and Waite Lake (informal name) located 80 km south of modern treeline in the central Northwest Territories, Canada (Fig. 1b). These lakes are located along the Tibbitt to Contwoyto Winter Road, a 600 km long winter ice road that is critical to the continued success of the Canadian natural resource industry (Galloway et al., 2010a; Macumber et al., 2011). These areas are of particular interest from a socio-economic perspective because use of the winter road has been affected by recent climate change. **We aim to reconstruct regional vegetation dynamics, including the rate of treeline migration and changes in boreal forest fires in sub-arctic Canada in response to Holocene climate change**. Results from our high-resolution paleoecological study of two new lakes are integrated with previously published paleoecological work on nearby Toronto, Waterloo, Queen's, McMaster, UCLA and Carleton lakes (Moser and MacDonald, 1990; MacDonald et al., 1993; Pienitz et al., 1999; Huang et al., 2004; Upiter et al., 2014) as well as carbon and nitrogen isotope analyses (Griffith, 2014) and grain-size data (Macumber, 2015) from Danny's Lake.

2. Regional setting

Danny's Lake (63° 28′32″N, 112°32′15″ W) is located ~30 km south of latitudinal treeline within the boreal forest of the central Canadian sub-arctic (Fig. 1b; Dyke, 2005). Danny's Lake has a maximum depth of 9 m, a surface area of ~20 ha, and a catchment size of ~400 ha (Macumber et al., 2011). Danny's Lake is not connected to other lakes by any major river or streams. Waite Lake (62°50′59″ N, 113°19′39″W) is located within the boreal forest approximately 80 km south of treeline (Fig. 1b; Dyke, 2005). Waite Lake has a maximum depth of 11 m and a surface area of 685 ha (Macumber et al., 2011). Both lakes lie within the Slave Geological Province of the Precambrian Shield and are underlain by amphibolite-grade paragneiss to quartz biotite schists (Davis et al., 1996). Topography of both sites is characterized by gentle hills covered with forest composed of black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), and dwarf birch (*Betula nana*). Climate is continental, characterized by long, cold winters and brief, warm summers. Data from the nearest weather station in Yellowknife document mean January temperatures of −26.8 °C and mean July temperatures of 16.8 °C and a mean annual precipitation of 302.8 mm (based on records from 1971 to 2000; National Climate Data and Information Archive). Both sites are located within the discontinuous permafrost zone (Brown, 1967).

3. Materials and Methods

3.1. Core Collection

A 118-cm long freeze core was collected from a 4.4 m deep sub-basin of Danny's Lake in March 2010 (Fig. 1c; Macumber et al., 2011). A 2-m long freeze core was obtained from the southern basin of Waite Lake from a water depth of 1.8 m in March 2009 (Galloway et al., 2010a). The sediment-water interface of the Waite Lake freeze was not captured by the freeze core. To obtain these surface sediments we returned to the same site in August 2011 and obtained a 36-cm long sediment core using a Glew corer with an internal barrel diameter of 6 cm (Glew, 1991; Glew et al., 2001).

3.2. Chronology

Twenty-five AMS radiocarbon ages were obtained from bulk sediment from the Danny's Lake sediment core. Ten AMS radiocarbon dates were obtained from nine bulk sediment samples and one terrestrial plant macrofossil from Waite Lake sediment core (obtained using the freeze corer). Three AMS ages were obtained from bulk sediments of the Waite Lake Glew core (Table 1). All samples were pretreated with a standard hydrochloric acid wash to remove carbonate material Faegri and Iversen (1989).

Analyses were performed using the accelerator mass spectrometer (AMS) at the ^{14}CHRONO Dating Laboratory at Queen's University, Belfast. Age depth relationships for the Danny's Lake sediment core and the Waite Lake sediment core (freeze core) were constructed using the computer program Bacon version 2.2 and the IntCal13 calibration curve (Figs. 2 and 3; Blaauw and Christen, 2011; Reimer et al., 2013; Crann et al., 2015). Radiocarbon ages younger than AD1950 were calibrated using CALIBomb (Reimer et al., 2004) with the NH_zone1.14c dataset (Hua and Barbetti, 2004). The age modeling procedure we used in Bacon is similar to that outlined in Blaauw and Christen (2005) but more numerous and shorter sections were used to generate a more flexible chronology (Blaauw and Christen, 2011).

A mean sediment accumulation rate of 70 yr/cm was used *a priori* in Bacon based on a summary of accumulation rates of sediment in lakes of the study region by Crann *et al.* (2015). Age depth relations in the Waite