

## Introduction. The boreal forest and global change

The boreal forest is the second largest biome in the world containing 33% of the Earth's forest cover (FAO 2001) of which approximately 25% is natural. It is circumpolar and shares similar taxa across its range. It has approximately 20 300 identified species. Along with the tropics, the boreal forest is both a major depository and at times a major source of carbon. However, unlike most ecosystems in the world, the boreal forest is still sparsely populated by humans and therefore largely intact. It is one of the few biomes in which large predator–prey systems are still widely operational, invasive species are few by proportion, and large-scale natural disturbances such as wildfire and epidemic insects still occur extensively at their natural frequencies and patterns.

Indigenous peoples often make up the majority of the sparse human population and many are dependent on resources available from the native vegetation and animal life, including the widespread reindeer herding of northern Eurasia. Human impacts by indigenous peoples are often light, except where herding is part of their lifestyle. First World impact is relatively recent (Angelstam *et al.* 1995) and involves natural resource extraction, particularly wood fibre, oil and gas, and minerals.

The boreal forest is one of the last settlement frontiers. Although small-scale agricultural settlements began advancing into the boreal forest more than 400 years ago in Eurasia, in North America, forest clearing for agriculture has occurred only in the past 100 years or so and mostly along the southern fringe. The economy of the settlements in the southern boreal is based on mixed farming with supplemental employment in resource extraction industries. The growing season is short and in many areas the boreal forest soils are thin, acidic and unsuitable for agriculture. Thus, even with climate warming, such areas are unlikely to become heavily settled. Currently, settlement populations within the boreal zone are small and far from large markets. For example, approximately 80% of the Canadian boreal forest is still unfragmented by settlements or roads (Smith & Lee 2000).

However, the boreal forest is an important source of forest products such as lumber and paper. It should be noted here that harvesting of trees in the boreal forest does not generally result in deforestation since harvested areas (even clear-cuts) regenerate their tree cover, although the tree species composition may change, depending on the harvesting and post-harvest practices. On the other hand, the damming of rivers to supply hydroelectric power to southern non-boreal regions does produce significant loss of forested area

(e.g. the James Bay hydroelectric project in north-western Quebec involves three river basins and the upper catchment of two other rivers over an area that is larger than the state of New York).

The boreal forests are at the latitude where most of the global warming is predicted to occur. There is now ample evidence that this change in climate is occurring (Hansen *et al.* 1999, 2006; IPCC 2001, 2007; Hassol 2004). These changes will affect all of the major biophysical processes in the boreal from hemispheric, synoptic, mesoscale, boundary-layer meteorology/climatology, fluvial, hillslope, basin and terrain geomorphology and hydrology, soil development and genesis, to biogeochemical cycles and population dynamics of organisms. However, even a basic understanding of the environmental and ecological processes in the boreal forest is rudimentary and shallow in comparison to that of many other ecosystems. There have been only a few notable and successful large-scale research programmes in the boreal forest (e.g. BOR-EAS). This is probably due to the lack of many national and international cooperative organizations that encourage and fund long-term research in any integrated biogeoscience strategy. The objective of this special issue is: (i) to present some of the current research and understanding on a subset of the biophysical processes mentioned above as well as the present state and limitations of our understanding and (ii) to demonstrate the need for a more integrated interdisciplinary approach to the study of this large circumpolar biome owing to the complexity of interactions and feedbacks among the various processes.

Understanding the impacts of climate change on the hydrology of the boreal forest has both scientific and economic relevance. As the paper in this issue by Woo *et al.* (2008) explains, freshwater inputs to the Arctic Ocean have important implications for the formation of sea ice which, in turn, has climatic feedback effects through the involvement of latent heat flux as well as the change in albedo and hence net radiation. Although several studies have reported twentieth century increases in streamflow of Eurasian rivers that drain to the Arctic Ocean (e.g. Peterson *et al.* 2002), northward-flowing rivers in North America do not appear to show a similar trend (e.g. Déry & Wood 2005; Aziz & Burn 2006). Woo *et al.* examined through hydrologic modelling the effects of climate change on streamflow in the North American boreal forest as well as showing the impacts of flow regulation on flow regime. While the effects of climate change on streamflow need to be considered in assessing the impacts of human activities, such as major water projects (e.g. building of dams and water diversions) and *in situ* uses of water (e.g. for oil extraction from the Athabasca oil sands), Woo *et al.* noted that these anthropogenic

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impacts generally overwhelm any effects of climate change predicted by the model simulations.

Climate-induced hydrologic changes (e.g. precipitation, evapotranspiration, permafrost melting) affect not only streamflow but also the water levels of boreal peatlands and lakes. Northern peatlands play an important role in the global carbon cycle: they contain 80% of the soil carbon stock in Western Canada (Syed *et al.* 2006) and 25–35% of the world's soil carbon (Humphreys *et al.* 2006; Roulet *et al.* 2007). They are both an important source of the greenhouse gas CH<sub>4</sub>, a product of anaerobic decomposition (fermentation) of organic matter, and a sink for atmospheric CO<sub>2</sub>, since the plant tissues produced from photosynthetic carbon fixation are incompletely decomposed under water and result in accumulation of carbon as peat. Vegetated lake littoral, although covering a smaller area than bogs and fens, has also been shown to be an important source of CH<sub>4</sub> (Bergstrom *et al.* 2007). Whether the boreal zone is a net source or sink for atmospheric carbon thus largely depends on the balance between emission of CO<sub>2</sub> and CH<sub>4</sub> through aerobic and anaerobic respiration/decomposition and uptake and storage of CO<sub>2</sub> in photosynthesis/primary production (e.g. Zhuang *et al.* 2007; see also Kurz *et al.* 2008). Water table depth provides a critical control on this carbon exchange in the boreal forest (Dunn *et al.* 2007; Pelletier *et al.* 2007); exposure of submerged peat through drawdown of the water table (either as a result of climate change or human activities) results in aerobic decomposition of peat (Jaatinen *et al.* 2007), thus returning the stored carbon to the atmosphere as CO<sub>2</sub>. Furthermore, climate warming is increasing the rate of emissions of atmospheric carbon (both CH<sub>4</sub> from increased anaerobic decomposition and CO<sub>2</sub> from increased aerobic respiration) from boreal peatlands faster than increasing carbon sequestration through net primary production (Johansson *et al.* 2006; Zhuang *et al.* 2007). The explanation is that warmer temperatures and a longer growing season are not correlated with an increase in annual net carbon uptake, probably due to the offsetting increases in ecosystem respiration (Dunn *et al.* 2007; Kurz *et al.* 2008).

Since the boreal forest is estimated to store more carbon than the temperate and tropical forests combined (Kasischke & Stocks 2000), potential changes in the carbon balance of the boreal forest resulting from global warming are addressed in this issue by Kurz *et al.* (2008). They use a stand- and landscape-level model of forest carbon dynamics to simulate changes in net ecosystem productivity (net primary production minus respiration/decomposition) under scenarios of varying changes (positive and negative) in growth and decomposition. Furthermore, climate-related changes to rates of forest disturbance (largely by fire but also by insect or pathogen outbreaks) have also been hypothesized. Any disturbance that kills trees causes a decrease in the carbon sink due to loss of photosynthetic capacity as well as increasing the emission of CO<sub>2</sub> from oxidation (either through combustion or decomposition) of dead plant tissues that represent a long period of carbon accumulation and storage. Owing to the large areas of boreal forest that burn each year (see Johnson 1992; Achard *et al.*

2008), fire plays a very significant role in the boreal carbon cycle. Thus, Kurz *et al.* (2008) also set up varying scenarios of fire disturbance for model simulations. Their simulations showed that increased growth rates in response to climate warming could compensate for equivalent losses by fire only if decomposition rates remained unchanged. However, since decomposition rate is temperature-dependent, when decomposition rate was allowed to change in response to temperature, the increase in primary production could not compensate for any increased loss of forest to fire.

Given the significant amount of carbon sequestered in the boreal forest (in both trees and forest soils), both tree growth and the areal extent of forest cover would affect the capacity of the boreal forest to function as a carbon sink. Two expected responses of the boreal forest to climate warming are an increase in tree growth (due to a longer growing season) and increased tree recruitment at treeline with a resulting northward advance of the latitudinal treeline into areas of tundra. With regard to the first response of enhanced tree growth, the article by Briffa *et al.* (2008) investigated spatial and temporal patterns of tree-growth variability in northwest Eurasia over the past 2000 years. They first show that year-to-year variation in tree growth (as measured by width of tree rings) in Eurasia over the period of available instrumental temperature records is associated with variation in local summer temperature. They then use tree-ring chronologies to infer spatial and temporal patterns of warming and cooling from the ring widths. While there is some regional variation in these patterns, widespread patterns are also evident. Their results show that the twentieth century warming in this region has been greater than that of any past warm period (e.g. the Medieval Warming). Finally, they looked at the concordance of the temporal pattern of ring growth with general circulation model (GCM) simulations of temperature change over the past 250 years; one simulation used only 'natural' forcings while the other included the additional forcing of increasing greenhouse gas concentrations in the atmosphere. Somewhat surprisingly, despite evidence in the literature of the significant forcing by increased atmospheric greenhouse gases, the tree-ring patterns were in better concordance with the first simulation using only natural forcings.

The second expected response of the boreal forest to global warming is both enhanced recruitment in treeline populations and migration of treeline position into the tundra region since the limiting factors for tree growth at high latitudes and altitudes are summer temperature and growing season length, both of which should increase with continued warming. Enhanced tree recruitment and advance of treeline into current tundra areas would be expected to produce a positive feedback, enhancing the warming, because the albedo of forested areas is significantly lower (and net radiation consequently higher) than that of tundra. MacDonald *et al.* (2008) review the recent literature on treeline dynamics in northern Eurasia. They report studies of tree fossils, found in northern Russia significantly north of the current treeline, whose radiocarbon dates place them during the Holocene Thermal Maximum 7000–10 000 cal. yr BP. Furthermore, dendrochronological studies

of dead trees indicate elevation shifts in treeline over the past two millennia with the highest elevations during the Medieval Warm Period (*ca* AD 600–1300), a subsequent descent during the Little Ice Age (*ca* AD 1500–1800), and another ascent since the late nineteenth century. Although there has been an increase in tree recruitment and upslope movement of forest cover in response to twentieth century warming, the treeline has not yet recovered from its retreat during the Little Ice Age. MacDonald *et al.* (2008) discuss anticipated future changes in treeline position in the context of these past movements in response to climate change. They conclude that there may be some short-term lags in forest development by decades following warming as well as development of transient communities with unique species compositions, but anticipated northern forest extension could approximate the northern forest limits experienced during the Holocene Thermal Maximum.

However, the boreal forest–tundra boundary is influenced not only by climate but also by fire. Payette *et al.* (2008) present evidence to show that current lichen–tundra sites at the forest–tundra ecotone along the eastern coast of Hudson Bay were converted from forest cover to tundra over the past 2000 years as a result of repeated fires. Deforestation accelerated during the Little Ice Age through the combined impact of climatic cooling and increased fire frequency, resulting in downslope movement of the treeline. As MacDonald *et al.* (2008) note about the Eurasian treeline, the North American treeline has also not recovered from the retreat of forest and expansion of tundra that occurred during the Little Ice Age. MacDonald *et al.* (2008) list a number of reasons why it may be more difficult for tree establishment at the Eurasian treeline in response to the current warming than for past major warm periods; Payette *et al.* (2008) would add fire occurrence to their list.

Most of the studies that have hypothesized an increase in fire frequency in the boreal forest in response to climate warming have been based on the recent increase in large fires concurrent with rising temperatures as well as general circulation model simulations of changes in temperature. However, previous studies had shown the causal connection between large-fire years and the occurrence of mid-tropospheric blocking high pressure systems in North America that produce the drying conditions conducive to uncontrollable high intensity fires (Johnson & Wowchuk 1993). In this issue, Macias & Johnson (2008) show that the frequency of these blocking highs in the North American boreal forest is controlled by the dynamics of large-scale teleconnection patterns (the Pacific Decadal Oscillation/El Niño–Southern Oscillation and the Arctic Oscillation). They also note that warming itself is not a predictor of increased fires since, as shown in previous studies, fire frequency across the North American boreal forest decreased as the Little Ice Age came to an end in the late nineteenth century (Johnson 1992; Bergeron & Archambault 1993). The study by Macias & Johnson (2008) provides not only evidence for the link between decadal-scale changes in the teleconnection patterns (e.g. the Pacific Decadal Oscillation (PDO) index) and the increased fire

frequency in the late twentieth century but also an explanation of why the pattern of fire variability and fire–climate relationships changes at different time scales from centennial/decadal to interannual.

In North America, most of the boreal forest is still relatively intact, not accessible by road, and most of the area burned is attributable to lightning-caused fires. This is not necessarily the case for large areas of the Eurasian boreal forest. In this issue, Achard *et al.* (2008) investigated fire occurrence in a 543 Mha area of forest cover in Russia within which they recognize 38% as intact forest and the remaining 62% as non-intact forest. They used satellite data to determine the number and areal extent of fires in the period 2002–2005. Owing to the lack of data on the causes of fires, the extent of disturbance by natural (non-anthropogenic) fires was estimated from the occurrence of fires within their ‘intact’ forest areas. Assuming that natural (lightning-caused) fires would affect the non-intact forest to a similar degree, they inferred the proportion of burned areas attributable to anthropogenic fires from the difference between the fire event density of intact and non-intact forest areas. Achard *et al.* (2008) conclude from their results that approximately 87% of the area burnt in non-intact forest is attributable to human causes. Note that, unlike the estimates provided here for the Russian boreal forest, the statistics on the proportion of area burned by natural- and anthropogenic-caused fires in the North American and Scandinavian boreal forest are generally based on known causes of ignition (Stocks 1991). However, if we accept the estimates by Achard *et al.* as reasonable, then it means that human-caused fires play a much bigger role in the boreal forest of Eurasia than of North America.

Another difference between the Eurasian and North American boreal forest is the extent of forest management. While forest products are an important natural resource in the Canadian boreal forest, most of this forest is publicly owned and more than half has not yet been allocated to industrial use. As indicated earlier, approximately 80% remains unfragmented by roads. On the other hand, Kellomäki *et al.* (2008) note that the European boreal forest (especially in Scandinavia) is intensively managed for the forest industry. Owing to the impact of potential changes to this resource in response to climate change, there has been recognition of the need for adaptive management and the inclusion of such potential changes in development of forest management strategies. Kellomäki *et al.* (2008) thus used a forest ecosystem simulation model to study the sensitivity of managed boreal forest to increasing CO<sub>2</sub> and accompanying changes to temperature and precipitation. They looked at the impacts of changing climate on tree growth, stocking, species composition, cutting drain and carbon sequestration. Their results showed significant changes to tree growth and species composition that would require adaptive changes in forest management as well as increased carbon sequestration in upland forests.

In addition to forest management, the European boreal forest (again, particularly in Scandinavia) has also been affected more by agricultural settlement and use for animal husbandry (reindeer herding). Thus, although in contrast to other ecosystems in Europe, the

boreal forest has had sparse human populations, it has had a longer period of significant human impact than the North American boreal forest and most of the European boreal forest would not be considered natural. As a result, Granström & Niklasson (2008) note the importance of assessing and understanding past and potential human impacts in order to better predict the ecosystem's response to climate change. Given the importance of fires in the boreal forest and the ability of humans to exert an influence through fire far beyond that expected from such sparse populations, Granström & Niklasson address the issue of human control of historic fire regimes in the boreal forest, primarily in Scandinavia. They suggest that human impacts might be better assessed by examining changes in spatial and temporal patterns of fires (e.g. locations of fires relative to the landscape physiognomy, season of fires as indicated in fire scars, etc.) and not just fire frequency (the focus of most fire history studies). Furthermore, the authors discuss how the different cultures of resident populations (e.g. hunting, herding, forestry) could result in different human impacts on boreal fire regimes.

Aside from herded reindeer, the boreal forest is home to large numbers of species of insects, birds and mammals. Not only would these animals be directly affected by changes in climate and fire but also they would be indirectly affected by climate change effects on any species, plant or animal, upon which they rely for food or with which they otherwise interact. In this issue, Mysterud *et al.* (2008) discuss some of these direct and indirect interactions. For example, the cold boreal climate can directly cause animals such as deer and moose to expend more energy for thermoregulation and to move through deep snow, thus potentially affecting body mass loss and survivorship, especially of calves and yearlings. Indirectly, the climate affects plant phenology, thus influencing the availability of forage. In order to predict the potential impacts of climate change on boreal faunal species, it is important to understand these direct and indirect effects of climate change on individual species. Thus, Mysterud *et al.* (2008) present a method for assessing the relative importance of these direct and indirect climate effects. They use the example of red deer populations in Norway to illustrate how hierarchical Bayesian modelling can be used to investigate direct and indirect effects of climate on autumn body mass. The authors conclude that plant phenology development during the summer is more important in predicting animal body condition and survival than climatic factors, like snow depth.

Mysterud *et al.*'s article, therefore, underlines the importance of looking at plant phenology and how it could be affected by climate change. A key indirect effect, particularly in a highly seasonal environment as the boreal, that is addressed by Post & Forchhammer's article in this issue is the possible development of a mismatch in timing between animal migration or reproduction and the pulsed peak in their food availability (i.e. plant phenology; Post & Forchhammer 2008). Such a mismatch could occur either if the timing of one is cued by temperature and the other by day length, or if the ability of different species to respond to changing climate differs. The result of this trophic

mismatch could be reproductive failure or reduced recruitment. Post & Forchhammer examined the case of caribou calving in West Greenland and showed that a more rapid progression of the plant growing season resulting from increasing spring temperature and earlier snowmelt results in a greater trophic mismatch between caribou calving and plant phenology. As a consequence, a progression of the plant growing season by approximately two weeks resulted in a fourfold increase in offspring mortality, and a sevenfold drop in offspring production. Trophic mismatch seems to occur not only in ungulates but also in other vertebrates as well. Most studies, so far, have concentrated on songbirds and migratory birds (Visser *et al.* 1998), but it is probable that other species are affected as well.

The contributed papers in this issue point to the importance of looking at all scales and processes involved to better understand the effects of global climate change on the boreal ecosystem. They also provide further understanding on some of the concerns that governments, NGOs and the public should consider in any policy discussions regarding development and management in the boreal zone. While just a small sampling of the studies on this topic, these studies represent the complexity of climate change related responses and driving forces and all of their interactions. For example, it is interesting to note that the study by Mysterud *et al.* (2008) related snow accumulation patterns and resulting plant growth during summer to the winter North Atlantic Oscillation (NAO) Index. Thus, as Macias Fauria & Johnson showed the role of atmospheric teleconnection patterns (Pacific Decadal Oscillation/El Niño-Southern Oscillation and Arctic oscillation) to fire occurrence in the boreal, so Mysterud *et al.* (2008) show the role of the NAO teleconnection to plant phenology and indirectly red deer body mass accumulation in summer. These studies illustrate clearly the obvious need for more integrative studies that show an awareness of other related processes from different disciplines (i.e. no split between physical and biological sciences).

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## REFERENCES

- Achard, F., Eva, H. D., Mollicone, D. & Beuchle, R. 2008 The effect of climate anomalies and human ignition factor on wildfires in Russian boreal forests. *Phil. Trans. R. Soc. B* **363**, 2331–2339. (doi:10.1098/rstb.2007.2203)
- Angelstam, P., Majewski, P. & Bondrup-Nielsen, S. 1995 West-East cooperation in Europe for sustainable boreal forest. *Water Air Soil Pollut.* **82**, 3–11. (doi:10.1007/BF01182813)
- Aziz, O. I. A. & Burn, D. H. 2006 Trends and variability in the hydrological regime of the Mackenzie River Basin. *J. Hydrol.* **319**, 282–294. (doi:10.1016/j.jhydrol.2005.06.039)

- Bergeron, Y. & Archambault, S. 1993 Decrease of forest fires in Quebec's southern boreal zone and its relation to global warming since the "Little Ice Age". *Holocene* **3**, 255–259.
- Bergstrom, I., Makela, S., Kankaala, P. & Kortelainen, P. 2007 Methane efflux from littoral vegetation stands of southern boreal lakes: an upscaled regional estimate. *Atmos. Environ.* **41**, 339–351. (doi:10.1016/j.atmosenv.2006.08.014)
- Briffa, K. R., Shshov, V. V., Melvin, T. M., Vaganov, E. A., Grudd, H., Hantemirov, R. M., Eronen, M. & Naurzbaev, M. M. 2008 Trends in recent temperature and radial tree growth spanning 2000 years across northwest Eurasia. *Phil. Trans. R. Soc. B* **363**, 2271–2284. (doi:10.1098/rstb.2007.2199)
- Déry, S. J. & Wood, E. F. 2005 Decreasing river discharge in northern Canada. *Geophys. Res. Lett.* **32**, L10401. (doi:10.1029/2005GL022845)
- Dunn, A. L., Barford, C. C., Wofsy, S. C., Goulden, M. L. & Daube, B. C. 2007 A long-term record of carbon exchange in boreal black spruce forest: means, responses to inter-annual variability, and decadal trends. *Global Change Biol.* **13**, 577–590. (doi:10.1111/j.1365-2486.2006.01221.x)
- FAO 2001 *Production yearbook 1999*. Food and Agriculture Organization of the United Nations, vol 53. Stastical series no. 156. Rome, Italy: FAO.
- Granström, A. & Niklasson, M. 2008 Potentials and limitations for human control over historic fire regimes in the boreal forest. *Phil. Trans. R. Soc. B* **363**, 2353–2358. (doi:10.1098/rstb.2007.2205)
- Hansen, J., Ruedy, R., Glascoe, J. & Sato, M. 1999 GISS analysis of surface temperature change. *J. Geophys. Res.* **104**, 30 997–31 022. (doi:10.1029/1999JD900835)
- Hansen, J., Ruedy, R., Sato, M. & Lo, K. 2006 GISS surface temperature analysis global temperature trends: 2005 summation. NASA Goddard Institute for Space Studies, New York, NY. See <http://data.giss.nasa.gov/gistemp/2005/>.
- Hassol, S. 2004 *Impacts of a warming Arctic: Arctic climate impact assessment*. Cambridge, UK: Cambridge University Press.
- Humphreys, E. R., Lafleur, P. M., Flanagan, L. B., Hedstrom, N., Syed, K. H., Glenn, A. J. & Granger, R. 2006 Summer carbon dioxide and water vapor fluxes across a range of northern peatlands. *J. Geophys. Res.-Biogeosci.* **111**, G04011. (doi:10.1029/2005JG000111)
- Intergovernmental Panel on Climate Change (IPCC) 2001 *Climate change 2001: the scientific basis*. Cambridge, UK: Cambridge University Press.
- Intergovernmental Panel on Climate Change (IPCC) 2007 *Climate change 2007: the physical science basis summary for policymakers*. Geneva, Switzerland: World Meteorological Organization.
- Jaatinen, K., Fritze, H., Laine, J. & Laiho, R. 2007 Effects of short- and long-term water-level drawdown on the populations and activity of aerobic decomposers in a boreal peatland. *Global Change Biol.* **13**, 491–510. (doi:10.1111/j.1365-2486.2006.01312.x)
- Johansson, T., Malmer, N., Crill, P. M., Friborg, T., Aerman, J. H., Mastepanov, M. & Christensen, T. R. 2006 Decadal vegetation changes in a northern peatland, greenhouse gas fluxes and net radiative forcing. *Global Change Biol.* **12**, 2352–2369. (doi:10.1111/j.1365-2486.2006.01267.x)
- Johnson, E. A. 1992 *Fire and vegetation dynamics: studies from the North American boreal forest*. Cambridge, UK: Cambridge University Press.
- Johnson, E. A. & Wowchuk, D. R. 1993 Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. *Can. J. Forest Res.* **23**, 1213–1222. (doi:10.1139/x93-153)
- Kasischke, E. S. & Stocks, B. J. 2000 *Fire, climate change, and carbon cycling in the boreal forest*. New York, NY: Springer.
- Kellomäki, S., Peltola, H., Nuutinen, T., Korhonen, K. T. & Strandman, H. 2008 Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. *Phil. Trans. R. Soc. B* **363**, 2341–2351. (doi:10.1098/rstb.2007.2204)
- Kurz, W. A., Stinson, G. & Rampley, G. 2008 Could increased boreal forest ecosystem productivity offset carbon losses from increased disturbances? *Phil. Trans. R. Soc. B* **363**, 2261–2269. (doi:10.1098/rstb.2007.2198)
- MacDonald, G. M., Kremenetski, K. V. & Beilman, D. W. 2008 Climate change and the northern Russian treeline zone. *Phil. Trans. R. Soc. B* **363**, 2285–2299. (doi:10.1098/rstb.2007.2200)
- Macias Fauria, M. & Johnson, E. A. 2008 Climate and wildfires in the North American boreal forest. *Phil. Trans. R. Soc. B* **363**, 2317–2329. (doi:10.1098/rstb.2007.2202)
- Mysterud, A., Yoccoz, N. G., Langvatn, R., Petterelli, N. & Stenseth, N. C. 2008 Hierarchical path analysis of deer responses to direct and indirect effects of climate in northern forest. *Phil. Trans. R. Soc. B* **363**, 2359–2368. (doi:10.1098/rstb.2007.2206)
- Payette, S., Filion, L. & Delwaide, A. 2008 Spatially explicit fire-climate history of the boreal forest-tundra (Eastern Canada) over the last 2000 years. *Phil. Trans. R. Soc. B* **363**, 2301–2316. (doi:10.1098/rstb.2007.2201)
- Pelletier, L., Moore, T. R., Roulet, N. T., Garneau, M. & Beaulieu-Audy, V. 2007 Methane fluxes from three peatlands in the La Grande Riviere watershed, James Bay lowland, Canada. *J. Geophys. Res. Biogeosci.* **112**, G01018. (doi:10.1029/2006JG000216)
- Peterson, B. J., Holmes, R. M., McClelland, J. W., Vörösmarty, C. J., Lammers, R. B., Shiklomanov, A. I., Shiklomanov, I. A. & Rahmstorf, S. 2002 Increasing river discharge to the Arctic Ocean. *Science* **298**, 2171–2173. (doi:10.1126/science.1077445)
- Post, E. & Forchhammer, M. C. 2008 Climate change reduces reproductive success of an Arctic herbivore through trophic mismatch. *Phil. Trans. R. Soc. B* **363**, 2369–2375. (doi:10.1098/rstb.2007.2207)
- Roulet, N. T., Lafleur, P. M., Richard, P. J. H., Moore, T. R., Humphreys, E. R. & Bubier, J. 2007 Contemporary carbon balance and Late Holocene carbon accumulation in a northern peatland. *Global Change Biol.* **13**, 397–411. (doi:10.1111/j.1365-2486.2006.01292.x)
- Smith, W. & Lee, P. (eds) 2000 *Canada's forests at a crossroads: an assessment in the year 2000*, Washington, DC: World Resources Institute.
- Stocks, B. J. 1991 The extent and impact of forest fires in northern circumpolar countries. In *Global biomass burning: atmospheric, climatic, and biospheric implications* (ed. J. S. Levine), pp. 197–202. Cambridge, MA: The MIT Press.
- Syed, K. H., Flanagan, L. B., Carlson, P. J., Glenn, A. J. & Van Gaalen, K. E. 2006 Environmental control of net ecosystem CO<sub>2</sub> exchange in a treed, moderately rich fen in northern Alberta. *Agric. Forest Meteorol.* **140**, 97–114. (doi:10.1016/j.agrformet.2006.03.022)
- Visser, M. E., van Noordwijk, A. J., Tinbergen, J. M. & Lessells, C. M. 1998 Warmer springs lead to mistimed reproduction in great tits (*Parus major*). *Proc. R. Soc. B* **265**, 1867–1870. (doi:10.1098/rspb.1998.0514)
- Woo, M.-k., Thorne, R., Szeto, K. & Yang, D. 2008 Streamflow hydrology in the boreal region under the influences of climate and human interference. *Phil. Trans. R. Soc. B* **363**, 2251–2260. (doi:10.1098/rstb.2007.2197)
- Zhuang, Q., Melillo, J. M., McGuire, A. D., Kicklighter, D. W., Prinn, R. G., Steudler, P. A., Feizer, B. S. & Hu, S. 2007 Net emissions of CH<sub>4</sub> and CO<sub>2</sub> in Alaska: implications for the region's greenhouse gas budget. *Ecol. Appl.* **17**, 203–212. (doi:10.1890/1051-0761(2007)017[0203:NEOCAC]2.0.CO;2)