Maintaining the role of Canada's forests and peatlands in climate regulation

by Matthew Carlson[1], Jing Chen[2], Stewart Elgie[3], Chris Henschel[4], Álvaro Montenegro[5], Nigel Roulet[6], Neal Scott[7], Charles Tarnocai[8] and Jeff Wells[9]

ABSTRACT

Canada's forest and peatland ecosystems are globally significant carbon stores, whose management will be influenced by climate change mitigation policies such as offset systems. To be effective, these policies must be grounded in objective information on the relationships between land use, ecosystem carbon dynamics, and climate. Here, we present the outcomes of a workshop where forest, peatland, and climate experts were tasked with identifying management actions required to maintain the role of Canada's forest and peatland ecosystems in climate regulation. Reflecting the desire to maintain the carbon storage roles of these ecosystems, a diverse set of management actions is proposed, incorporating conservation, forest management, and forest products.

Key words: forests, peatlands, carbon, Canada, climate change, management, forest products, conservation

RÉSUMÉ

Les écosystèmes du Canada formés par les forêts et les tourbières constituent des réservoirs importants de carbone dont l'aménagement sera influencé par les politiques d'atténuation des effets des changements climatiques comme les systèmes de crédits compensatoires. Ces politiques, si elles se veulent efficaces, doivent être rattachées à des informations objectives sur les relations entre l'utilisation du territoire, la dynamique du carbone de ces écosystèmes et le climat. Dans ce texte, nous présentons les conclusions d'un atelier au cours duquel on a demandé à des experts du secteur des forêts, des tourbières et du climat d'identifier les actions à entreprendre en aménagement pour préserver le rôle régulateur des écosystèmes formés des forêts et des tourbières au Canada face au climat. Tout en reflétant le souci de maintenir le rôle de réservoir de carbone joué par ces écosystèmes, un ensemble d'actions à entreprendre en aménagement est proposé, incorporant la conservation, l'aménagement forestier et les produits forestiers.

Mots clés : forêts, tourbières, carbone, Canada, changements climatiques, aménagement, produits forestiers, conservation

Introduction

International climate agreements, emerging carbon markets, and growing awareness of the implications of climate change have brought attention to the issue of land-use impacts on climate. Governments across Canada are developing rules concerning carbon storage in forests (e.g., offset systems) and establishing positions concerning post-2012 Kyoto rules for forests and carbon. Now is a key time for the development of forest carbon policy. Policies established in the near future could have a large influence on future land-use practices in Canada's forests, and on climate change mitigation. A critical question, then, is what practices are best suited to maintain the role of Canada's forests and peatlands in climate regulation? Incomplete or poorly informed answers to this question have the potential to cause distracting debates and, more detrimentally, counter-productive policy.

In an attempt to provide clear guidance for policy development, a workshop titled "The Role of Canadian Boreal Ecosystems in Climate Regulation" was hosted in late 2007 in Ottawa, Ontario by the Canadian Boreal Initiative, Richard Ivey Foundation, and University of Ottawa's Institute of the Environment. Participating were experts from relevant fields including Canadian forest and peatland carbon budgets, the impact of anthropogenic and natural disturbances on forest and peatland carbon, climate modelling, and climate policy. At the workshop, participants were tasked with seeking consensus on a set of management actions for maintaining the role of Canada's forests and peatlands in climate regulation. Boreal forest and peatland ecosystems were concluded to be important to global climate regulation due to their globally significant carbon stores. The annual forest greenhouse gas balance of boreal ecosystems fluctuates largely due to factors

[1]Canadian Boreal Initiative, 30 Metcalfe Street, Suite 402, Ottawa, Ontario K1P 5L4. E-mail: mcarlson@borealcanada.ca.
[2]Department of Geography and Program in Planning, University of Toronto, 100 George Street, Toronto, Ontario M5S 3G3.
[3]Institute of the Environment, University of Ottawa, 57 Louis Pasteur, Ottawa, Ontario K1N 6N5.
[4]Canadian Parks and Wilderness Society, 250 City Centre Avenue, Suite 506, Ottawa, Ontario K1R 6K7.
[5]Department of Earth and Ocean Science, University of Victoria, PO Box 3065 Stn CSC, Victoria, British Columbia V8W 3V6.
[6]Department of Geography, McGill Univeristy, 805 Sherbrooke Street West, Montreal Quebec H3A 2K6.
[7]Department of Geography, Queen's University, D201 MacKintosh Corry Hall, Kingston, Ontario K7L 3N6.
[8]Agriculture and Agri-Food Canada, K.W. Neatby Building, Rm. 1135, 960 Carling Avenue, Ottawa, Ontario K1A 0C6.
[9]International Boreal Conservation Campaign, 1904 Third Avenue, Suite 305, Seattle, WA 98101, USA.

beyond management control, including natural disturbances and climate variability. However, participants concluded that the greenhouse gas balance is also influenced by forest and land management activities and that climate policy should focus on this portion of the budget. Perhaps surprisingly, participants were able to agree upon a set of recommended management actions over the two-day workshop, suggesting that sufficient knowledge exists to guide the formation of effective policies on the climate impacts of land use in Canada's forest and peatland regions.

The workshop's findings and a summary of relevant literature are presented here to provide a "state of the science" to help inform policy development. The contribution of Canada's forest and peatland ecosystems to climate regulation is first summarized, followed by a description of the recommended management actions. Implications to forest and climate policy are discussed, including the need to balance conservation and active management if the climate regulation roles of Canada's forest and peatland ecosystems are to be maintained.

The Contribution of Canada's Forest and Peatland Ecosystems to Climate Regulation

Canada's forest and peatland ecosystems contribute to climate regulation primarily through carbon dynamics. Plants absorb carbon dioxide (CO_2) through photosynthesis, storing carbon in vegetation and soils, and then release it during decomposition. Disturbance of vegetation and soils, resulting in increased rates of decomposition, can release carbon into the atmosphere as CO_2 and methane (CH_4), both of which are greenhouse gases (GHGs) that contribute to atmospheric warming.

Canada's 4.042 million km^2 of forest ecosystems store an estimated 85 900 megatonnes of Carbon (Mt C)[10], of which more than 80% is stored within the country's boreal region[11] (Kurz and Apps 1999). The majority of forest carbon is stored in the soil layer, with mineral soils in the Subarctic, Boreal and Cordilleran ecoclimatic regions containing approximately 61 000 Mt C (Tarnocai 2000). Peatland ecosystems, which cover 1.136 million km^2 of the country, store 147 000 Mt C (Tarnocai 2006). The defining characteristic of peatlands is the accumulation of organic matter (peat) over long time scales (millennia) due to net primary production that exceeds organic matter decomposition (Wieder *et al.* 2006). As with forests, the majority (93%) of peatland carbon is located within Canada's boreal region (Tarnocai 2006). Combined, Canada's forest and peatland ecosystems store an estimated 232 900 Mt C, almost one-third of the approximately 775 000 Mt C stored in the Earth's atmosphere (Watson *et al.* 2000).

Decomposition is suppressed by Canada's cold climate and abundance of saturated soils, resulting in positive carbon balances for most of Canada's forests and peatlands. The rate of carbon sequestration for perhaps the most thoroughly studied northern peatland is 20 g C per m^2 per year (Roulet *et al.* 2007) which, when applied to all Canadian peatlands, results in an annual sequestration of about 23 Mt C. This estimate is in broad agreement with a regional modeling study, which determined that Canada's wetlands overall absorbed approximately 40 Mt C annually over the last 100 years (Ju *et al.* 2006). Canada's forest ecosystems are also net sinks, sequestering an average of 205 Mt C per year during the period of 1920 to 1989 (Kurz and Apps 1999), which is roughly equivalent to total greenhouse gas emissions in Canada (204 Mt C in 2007 [Environment Canada n.d.]). Long-term variability in fire and insect disturbance rates causes the carbon balance of Canada's forests to vary. Recent and projected high natural disturbance rates suggest a transition from carbon sink to carbon source (Kurz and Apps 1999; Kurz *et al.* 2008a, b), although Canada's forests may remain a sink when the positive effects of climate warming, nitrogen deposition, and elevated atmospheric CO_2 concentrations on carbon sequestration are considered (Chen *et al.* 2003). The future carbon balance of peatlands is also uncertain due to factors like permafrost melting, which is associated with increased CH_4 release and increased CO_2 sequestration (Turetsky *et al.* 2007).

Land-Use Impacts on Climate Regulation

Ecosystem carbon balance is also affected by land-use change and management. Deforestation, forest degradation, and other land-use practices accounted for approximately 20% of global anthropogenic CO_2 emissions during the 1990s (IPPG 2007a). The proportion of Canada's total carbon emissions associated with these activities is substantially lower than this global average, largely due to Canada's low rate of deforestation. Although the rate of deforestation is low on a national scale, it is significant in some regions. Saskatchewan's boreal transition region, for example, experienced an annual deforestation rate of 0.89% between 1966 and 1994, primarily due to agricultural expansion (Hobson *et al.* 2002). Peatland loss also causes emissions, with extraction of peat for horticulture contributing 2 Mt C to Canada's emissions between 1990 and 2000 (Cleary *et al.* 2005).

Forest management is another land use with significant implications for carbon storage. In 2006, 9800 km^2 of timber harvest (CCFM 2008) removed almost 45 Mt C from the landscape (Environment Canada 2008a). The potential carbon emissions from forest harvest remains high despite moderating factors such as long-term carbon storage in forest products, replacement of fossil-fuel intensive products, and potentially higher carbon-sequestration rates of regenerating stands. Globally, the forest sector could contribute significantly to climate change mitigation, providing similar potential to each of the energy, industrial and agricultural sectors (IPPG 2007b). Although the majority of this mitigation potential is in

[10]This paper uses as its unit of measurement "carbon" (which is commonly used in forest climate literature) rather than "carbon dioxide" (which is commonly used in describing emissions from fossil fuel combustion). One tonne of carbon (C) is equivalent to 3.67 tonnes of carbon dioxide (CO_2 eq).

[11]We use the term boreal region to refer to the coniferous-dominated forest biome spanning from the temperate forest in the south to the tundra in the north. We interpret the region to include the Boreal West, Boreal East, Subarctic, Cordilleran and Subarctic Cordilleran ecoclimatic zones which, combined, account for more than 80% of Canada's forest carbon (Kurz and Apps 1999). Our interpretation of the boreal region also overlaps with much of the Boreal and Subarctic wetland regions referred to by Tarnocai (2006). Combined, the Boreal and Subarctic wetland regions store an estimated 97% of Canada's peatland carbon. When the portion not located within the boreal region is excluded, 93% of Canada's peatland carbon is estimated to be boreal.

the tropics, substantial mitigation potential exists in Canada and other developed countries (Nabuurs *et al.* 2007).

Land-use change can also affect the albedo and evapotranspiration potential of the land surface, both of which impact the climate system. Albedo represents the fraction of incoming radiation reflected by a surface. A reduction in albedo means that a larger fraction of the incoming radiative energy is absorbed by the surface, resulting in warming. Evapotranspiration causes local cooling due to latent heat transfer from the surface to the atmosphere. Evapotranspiration can also influence cloud cover which, in turn, affects the amount of energy reaching the surface. Conversion of forested land to agricultural land, non-vegetated land (urban lands, buildings, industrial or commercial infrastructure), or to more open vegetated land (e.g., grassland, degraded forest habitat) all are likely to increase albedo and decrease evapotranspiration, causing both regional cooling and global warming, respectively. Less clear is the balance, especially in boreal regions, between the warming effects from carbon release, reduction of carbon sequestration potential and decreased evapotranspiration as a result of deforestation versus the cooling effect of increased albedo also caused by deforestation. It is likely that forest management, as opposed to deforestation or reforestation, has a limited effect on albedo in Canadian forests, although further research is needed.

Management Actions

Many of the factors responsible for long-term (i.e., decadal) fluctuations in forest and peatland carbon storage are largely beyond management control, including current age class structure, natural disturbances, and climatic variability. In contrast, a variety of options exist for managing land use to mitigate carbon release and enhance carbon storage by these ecosystems. Many of the management actions relate to forests, including reduced deforestation and forest degradation, afforestation, appropriate silvicultural techniques, forest conservation, longer rotations, natural disturbance suppression, carbon storage in wood products, and substitution of wood for more carbon intensive products (Nabuurs *et al.* 2007).

Management actions (Table 1) aimed at minimizing impacts on Canada's forest and peatland carbon pools are now discussed in detail. The recommended actions were identified through consensus among experts during the workshop described in the introduction. Due to the large quantities of carbon at stake, adoption of these practices is an important component of society's response to the challenge presented by climate change.

Reduce deforestation and increase afforestation

Deforestation promotes global warming by releasing carbon stored in forests, peatlands, and organic soils, and the loss of carbon sequestration potential (Nabuurs *et al.* 2007, Bonan 2008). Deforestation also generates local warming through the decrease in evapotranspiration. Although the increased albedo of deforested land also causes a cooling effect, it is unclear whether the cooling is sufficient to offset the warming effects. Further contributing to the warming effect are carbon emissions associated with industrial activities that are often the cause of deforestation (oil, gas, peat extraction). Deforestation can also lower the resilience of forest ecosystems, diminishing their capacity to adapt to climate change (Noss 2001). Deforestation can be reduced by limiting the expansion of agricultural and urban areas into forested regions and reducing the size, number and lifespan of industrial features such as forestry roads, mines, and seismic lines. The level of deforestation in Canada is relatively low by global standards. An estimated 860 km^2 were deforested in Canada in 2006, producing annual emissions of about 5.2 Mt C, which accounts for less than 3% of Canada's greenhouse gas emissions (Environment Canada 2008a).

With afforestation, the climate cooling effect of carbon sequestration is at least partially offset by a reduction in albedo that increases energy absorption in forests relative to deforested land (Betts 2000, Bala *et al.* 2007, Bonan 2008). Whether albedo effects outweigh carbon sequestration effects to cause a warming from afforestation is unclear because of many uncertainties (Davidson and Wang 2004, Wang 2005, Wang *et al.* 2006, Alexeev *et al.* 2007, Bonan 2008, Cook *et al.* 2008, Lawrence and Slater 2008, Lawrence *et al.* 2008). However, recent research using high-resolution satellite data concluded a net cooling effect from afforestation at all latitudes after accounting for albedo effects (Montenegro *et al.* 2009). While afforestation may be a preferred management option in many circumstances due to benefits of biodiversity and other ecosystem services, reducing the amount and pace of deforestation has a more immediate effect on carbon balance because avoided deforestation circumvents the release of large carbon stocks whereas afforestation accumulates biotic carbon gradually through time (Nabuurs *et al.* 2007).

Avoid logging of natural forests (reduce conversion of unmanaged forests to managed forests)

Timber harvest generally reduces the abundance of late seral stands and the average age of the forest, relative to natural forests, by selectively targeting older stands and shortening the overall disturbance cycle (Kurz *et al.* 1998, Didion *et al.* 2007). Total carbon storage increases with stand age (Luyssaert *et al.* 2008) and consequently natural forests generally store more carbon than managed forests (i.e., forests managed for timber production). In Canada's forests, Kurz *et al.* (1998) estimated that the transition from natural to managed forest causes a decrease in forest ecosystem carbon of 4% to 50.6%, depending on forest type, harvest intensity, and disturbance regime in the natural forest. Storage of carbon in forest products can at least partially compensate for the decrease in forest ecosystem carbon, as can post-harvest regeneration of forest biomass if managed forests display higher growth rates than natural forests. However, it is not yet clear whether including these other factors will lead to an increase in net ecosystem carbon storage in managed forests compared to natural forests. Scott *et al.* (2004) estimated that a 40% increase in growth rate relative to an unharvested stand was needed for net carbon storage (i.e., including forest products) in a partially harvested stand in Maine to equal that of an unharvested stand over 30 years. Increases in growth rates of this magnitude are unlikely given that young forests are often sources of carbon as opposed to substantial sinks (Luyssaert *et al.* 2008). Due to the higher carbon storage of natural forests, reducing the conversion of natural forests to managed forests represents significant mitigation potential. However, forest products are needed by society, and can substitute for more energy-intensive products such as cement and steel

Table 1. Recommended forest management actions for minimizing impacts to Canada's forest and peatland carbon pools. Management actions are listed in the order they are discussed in the paper, not by relative impact.

Recommended Management Actions	
Reduce deforestation and increase afforestation	
Avoid logging of natural forests	
Employ forest management practices that enhance carbon storage:	
1.	reduce soil disturbance and maintain coarse woody debris
2.	silvicultural activities to increase productivity and accelerate regeneration
3.	extend rotation periods
Employ forest sector practices to enhance carbon storage and minimize greenhouse gas emissions:	
1.	capture methane emissions from forest products at landfills
2.	increase recycling and switch production to longer lived forest products
3.	use energy in wood waste for power production
Minimize the extraction of peat soils	
Minimize soil disturbance	
1.	minimize ground disturbance in areas with saturated soils
2.	avoid disturbance to permafrost
Reduce the adverse climate impacts of fire and insect disturbances	
1.	suppress fire and insect events where appropriate in the managed forest
2.	restore the natural resilience of forest to disturbance
3.	use salvage logging where appropriate to reduce harvest of undisturbed forest

(Gustavsson *et al.* 2006). Due to the potential carbon benefits of conserving natural forests and substituting forest products for more energy-intensive alternatives, natural forest conservation could be pursued in tandem with a strategy of maintaining or increasing the production of wood products by increasing afforestation and/or maintaining or increasing the volume of timber in forests that are already under management.

Employ forest management practices that enhance carbon storage

Several modifications to forest management can be made to reduce emissions from harvesting, increase productivity (sequestration) and maintain higher carbon stocks at a landscape level. Harvest emissions can be reduced by leaving coarse woody debris on site rather than broadcast burning or slash pile burning. Coarse woody debris can also enhance site nutrient status, though the margin for improvement from business-as-usual practice is small (Graham 2003). Reducing soil disturbance can have a larger positive benefit by both maintaining soil carbon levels and also increasing productivity (Graham 2003).

Tree planting and competition management can accelerate stand establishment, resulting in higher long-term carbon uptake (Colombo *et al.* 2005). Although thinning would not lead to an increase in total volume on the site, it can be used to increase merchantable wood production and quality, which could result in longer-term carbon storage in longer-lived products, or it can be used to produce biomass for bioenergy, which can offset fossil fuel-related emissions. Also beneficial is the protection of advance regeneration during timber harvest which can accelerate regeneration by several decades (Lieffers *et al.* 2003). Fertilization also has the potential to greatly improve tree growth, though the effectiveness depends on many factors, including stand density, species composition, tree size, availability of other nutrients, and the type of fertilizer applied.

Many studies have shown that longer rotation periods increase total carbon storage at the landscape level (Cooper 1982, Harmon *et al.* 1990, Kurz *et al.* 1998, Euskirchen *et al.* 2002, Peng *et al.* 2002). Although the benefit of longer rotation periods is reduced when carbon storage by forest products is considered, the optimal rotation age from a carbon storage perspective remains longer than what is typically used in Canada's managed forests (Seely *et al.* 2002, Hennigar *et al.* 2008, Neilson *et al.* 2008).

Employ forest sector practices to enhance carbon storage and minimize greenhouse gas emissions

In the most comprehensive study of its kind to date for North America, the National Council for Air and Stream Improvement (NCASI) estimated that the manufacture, transport and disposal of Canadian forest products caused greenhouse gas emissions equivalent to 14.5 Mt C in 2005 (Upton *et al.* 2007). Forty-eight percent of the emissions were related to manufacturing, 46% to the release of CH_4 from the decomposition of wood products in landfills, and 6% to the transportation of raw materials and products. Although NCASI estimates that current CH_4 emissions from landfills are more than offset by the rate of growth in the carbon stored in landfills from new inputs, it also predicts that this balance will shift over the long term, resulting in large net emissions. Reducing CH_4 emissions from landfills is therefore an important mitigation activity. This could be achieved by diverting wood from landfills through increased recycling of products, and capturing of CH_4 emissions from landfills. Shifting industry production (and societal consumption) to a greater proportion of longer-lived forest products (e.g., timber instead of paper) would have the dual benefit of avoiding CH_4 emissions from landfills as well as increasing carbon retention in the harvested wood product carbon pool. Processing and transportation can also generate significant CO_2 emissions—sometimes accounting for more than half of the total carbon footprint of forest products (Gower *et al.* 2006). Strategies for reducing manufacturing and transportation emissions include using energy in wood waste to power mill processing and selling forest products to closer markets, respectively. Moreover, adoption of a life-cycle-based carbon accounting approach would create an important incentive to reduce secondary emissions.

Minimize the extraction of peat soils

Peatlands may contribute to climate cooling by persistent CO_2 uptake, or to warming due to persistent CH_4 emission. Peat accumulation for typical northern peatlands is sufficiently large to exceed the warming effect of CH_4 emissions such that northern peatlands have had a net cooling effect of -0.2 to -0.5 Wm^{-2} through the Holocene (Frolking and Roulet 2007). Further, peatlands are predicted to continue to have a cooling effect for millennia unless stored carbon is rapidly lost and/or their structure changes so that the emission of CH_4 relative to uptake of CO_2 is dramatically altered. Natural processes capable of eliminating large quantities of carbon from peatlands are limited to permafrost degradation, or intense fires capable of penetrating deep into peat (Frolking and Roulet 2007), both of which are likely to increase with climate change. Anthropogenic disturbances with the capacity to cause a rapid decline in peatland carbon storage are those that remove peat from wetlands. The approximately 1.3 Mt of peat extracted in Canada in 2000 was associated with annual life cycle emissions of 0.24 Mt C, up 65% from 1990 (Cleary *et al.* 2005). The expansion of other land uses into peatland regions also contributes to the loss of peatland carbon. An example is the mining of oil sands, where organic and mineral soils are removed to access bitumen located within 100 m of the surface. According to satellite imagery, oil sands mines and associated footprints had disturbed 237 km^2 of peatlands in Alberta as of 2009 (Lee and Cheng 2009) compared to the approximately 190 km^2 of peatlands that have been affected by peat extraction in Canada to date (Environment Canada 2008a). Peatland loss is effectively permanent over timescales relevant to climate change mitigation policy. Re-establishing peatland carbon sinks is problematic and restoration efforts may actually increase CO_2 and CH_4 emissions (Glatzel *et al.* 2004, Waddington and Day 2007). Even if the carbon sink of cutover peatlands is re-established, restoration to pre-disturbance carbon levels would be excessively slow given that northern peatlands represent thousands of years of peat accumulation (Frolking and Roulet 2007).

Minimize soil disturbance

Minimize ground disturbance in areas with saturated soils

A primary factor controlling the soil carbon balance is wetness. In wet soils, decomposition is facilitated by soil aeration, such that soil carbon density is predicted to increase exponentially from well-drained to poorly drained forest and wetland regions in Canada (Ju *et al.* 2006). Disturbance of saturated soils should be minimized to avoid soil carbon loss. Mechanical site preparation and prescribed burning can cause carbon release from peatlands by disturbing moss cover, reducing the thickness of the organic layer, and increasing rates of soil organic matter decomposition (McLaughlin *et al.* 2000, Lavoie *et al.* 2005). Changes to the water table associated with forestry operations also influence peatland carbon balance, although the effect is more complex due to opposing effects to soil respiration, methanogenesis, and primary production. The higher water table that follows timber harvest promotes peat accumulation (Lavoie *et al.* 2005), but the overall effect may be climate warming due to increased methane production (Cui *et al.* 2005). Peatland drainage to promote timber production, on the other hand, tends to increase peatland carbon storage because carbon loss from increased soil respiration is more than offset by increased primary production and reduced methane emissions (Minkkinen *et al.* 2002). The effect of drainage is sensitive to local conditions, however, and experimental drainage of a peatland in Quebec, Canada depended on microtopographic elements with global warming potential increasing in hummocks but decreasing in hollows (Strack and Waddington 2007). The water table can also be altered by industrial footprints that act as hydrological boundaries. Roads and pipelines in northern Minnesota were found to block water flow in forested wetlands such that the water table was 0.21 to 0.26 feet higher on the upland side of the disturbances (Boelter and Close 1974). The carbon implications of such impacts have not been studied, however.

Avoid disturbance to permafrost

A large portion of soils in the boreal forest are perennially frozen and have been accumulating carbon for thousands of years through cryoturbation and syngenetic growth. Typical thickness of permafrost found in the boreal region (i.e., discontinuous permafrost zone of the Northern Hemisphere) is 1 m to 50 m (Schuur *et al.* 2008). Globally, permafrost in the northern hemisphere is estimated to contain 1 672 000 Mt of soil carbon (Schuur *et al.* 2008). Future global permafrost thaw with climate change may create a carbon source of up to 1100 Mt C per year due to microbial decomposition (Schuur *et al.* 2009). Disturbance of these soils also results in serious degradation of permafrost and may initiate the release of carbon to the atmosphere. Due to the large quantity of carbon stored in permafrost and the potential sensitivity to land use, disturbance to permafrost should be minimized.

Reduce the adverse climate impacts of fire and insect disturbances

Fire and insect outbreaks emit carbon into the atmosphere through combustion of vegetation and peat (fire) and the decomposition of dead wood (fire and insects). These natural disturbances have been identified as a primary factor in determining whether Canada's forests are a carbon source or sink in a given year (Kurz and Apps 1999, Goodale *et al.* 2002). Forest fires in Canada are estimated to release, on average, 27 Mt C per year through combustion, and emissions from post-fire decomposition may be of a similar size (Amiro *et al.* 2001). In British Columbia alone, it is estimated that the mountain pine beetle epidemic will reduce the forest carbon sink by almost 13 Mt C per year between 2000 and 2020 (Kurz *et al.* 2008a).

Suppress fire and insect events where appropriate in the managed forest

Fire suppression can reduce fire rates in Canada's boreal forests (Cumming 2005), thereby increasing average forest age and carbon storage. Suppression as a strategy to mitigate climate change is not without its problems, however, and must be carefully considered. Other processes associated with natural disturbance such as increased albedo have a cooling effect, thereby offsetting carbon emissions caused by disturbance (Amiro *et al.* 2006, Randerson *et al.* 2006). In addition, suppression efforts may be ineffective under certain conditions. For example, successful suppression of fire has likely increased the severity of extreme insect outbreaks by increasing fuel loads and decreasing species and landscape diversity (McCullough *et al.* 1998). Warm and dry weather can create fire and insect outbreak risks that exceed suppression capacity (Kurz *et al.* 2008b, Morgan *et al.* 2008). Widespread application of direct or indirect suppression is also likely to be cost-prohibitive and would have deleterious impacts to wildlife that are adapted to the forest composition and structure imposed by natural disturbance (Amiro *et al.* 2002). Suppression also generates greenhouse gas emissions due to the high fuel needs of aircraft needed to access and fight fires. Given these limitations, suppression should be limited to the managed forest and carefully planned to ensure it is effective and minimizes ecological impacts.

Restore the natural resilience of forest to disturbance

Forest cover types differ with respect to their susceptibility to fire and insects. Stands of aspen, for example, burn less frequently than coniferous forest in Canada's western boreal region (Cumming 2001) and forest insects typically have preferred host species such as fir (spruce budworm) and lodgepole pine (mountain pine beetle). Anthropogenic activities that alter the abundance or contiguity of disturbance-prone forest types can affect ecosystem carbon storage by changing the resilience of forest ecosystems to natural disturbance. Some activities may reduce natural disturbance rates, such as multi-pass harvest of western boreal forests that fragment fire-prone spruce forests (Cumming 2001). Other land uses, however, may increase susceptibility to natural disturbance. Timber harvest in some forest regions can increase the abundance of disturbance-prone species such as balsam fir that are adapted to colonize disturbed (i.e., harvested) sites (Strutevant *et al.* 2004) and reduce species that resist canopy fires such as sugar maple (Gustafson *et al.* 2004). Fire suppression can also homogenize the forest with negative implications for long-term risk to disturbance. Decades of fire suppression in western Canada allowed large contiguous regions of lodgepole pine to mature and to contribute to the current mountain-pine beetle epidemic (Whitehead *et al.* 2007), which was further exacerbated by climatic changes (Kurz *et al.* 2008a).

To restore or maintain the resilience of forests to natural disturbance, forests should be managed for their natural age-class structure and species diversity. Examples of such strategies include mixedwood management, retaining residual patches of merchantable forest in harvested landscapes, limiting fire suppression, and prescribed fire in protected areas. An added benefit of managing for natural age-class structure and species diversity is that it promotes the conservation of native species by maintaining the natural range of habitat types (Bunnell 1995).

Use salvage logging where appropriate to reduce harvest of undisturbed forest

Salvage logging after fire and insect disturbance can be an effective strategy for reducing overall carbon emissions from disturbed sites if the salvaged wood is used to replace timber harvest from other stands. By contrast, if salvage logging simply increases overall timber harvest it will reduce the carbon benefits and may lead to increased net emissions. But net reductions could still occur, for example, if the harvested wood is used to produce forest products that store carbon for longer periods of time than the residence time of material left at the site, or to replace fossil fuel (for energy) or carbon-intensive products (such as steel).

The effects of salvage logging on soil condition and stand regeneration are relatively unknown, and complete studies on the ecological consequences are lacking (Lindenmayer *et al.* 2008). Salvage logging removes substantially more carbon than what is originally released during a fire (Johnson *et al.* 2005) and can impede forest regeneration (Donato *et al.* 2006). The impact of fire on carbon flux rates may be relatively short-term with the transition from carbon source back to carbon sink occurring as soon as one year post-fire (Amiro *et al.* 2003). Carbon storage benefits associated with salvage logging are therefore primarily due to reduced demand to harvest undisturbed forest. Salvage logging also has numerous negative ecological impacts, including the removal of biological legacies that provide critical habitat for wildlife (Lindenmayer *et al.* 2004), and should be restricted to areas managed for timber harvest and planned to minimize the detrimental effects.

Discussion

As stewards of one of the largest biological carbon stores on the planet, Canadians have an opportunity to contribute to climate change mitigation at an international scale through improved land management. The development of sound policies for maintaining the role of Canada's forest and peatland ecosystems in climate regulation has been elusive, however, in part due to the rapidly evolving, and at times complex, science that is involved. We have endeavoured to add clarity to the policy debate by applying the best available science to recommend a range of management actions for maintaining the role of Canada's forests and peatlands in climate regulation.

At first glance, some of the recommended actions appear inconsistent. Avoiding logging of natural forests, extending rotation periods, and intensive forest management obviously cannot be applied to the same patch of forest. The apparent conflict is due to the carbon storage roles played by both forest products and intact ecosystems, and the high rate of carbon sequestration of young forests. What is needed is a fully informed, balanced and regional perspective that recognizes the opportunity to maintain both forest product and ecosystem carbon pools, while minimizing secondary emissions. Intensive forest management can concentrate timber production on a smaller land area, making it possible to implement ecosystem-based forest management practices (e.g., extended rotation periods) across much of the actively managed forest landscape without impacting the overall timber supply and eliminating the need for further logging of natural forests. This zoning approach to forest land use was first conceived as a strategy to balance biodiversity conservation and timber production (Hunter 1990, Messier *et al.* 2003) and is increasingly being recommended by policy makers in Canada (Senate Subcommittee on the Boreal Forest 1999, Sustainable Ecosystem Working Group 2008).

Climate change poses an enormous threat to existing biodiversity (Thomas *et al.* 2004) and ecological processes (Scholze *et al.* 2006). In Canada, ecosystem changes expected in response to climate change include increased rates of natural disturbance in most regions (Flannigan *et al.* 2005, Balshi *et al.* 2009) and large northward shifts in species' ranges (McKenney *et al.* 2007, Malcolm and Markham 2000). Existing atmospheric greenhouse gas concentrations and oceanic thermal inertia commit us to substantial future climate change (Wigley 2005) regardless of the effectiveness of efforts to reduce greenhouse gas emissions. Management actions intended to maintain the climate regulatory role of ecosystems should therefore be screened to ensure they do not diminish, and better still enhance, the capacity of ecosystems to adapt. This again suggests the need for an approach that balances active management and conservation. The feasibility of managing climate change impacts through interventions such as assisted migration and fuel management is questionable due to their high cost and uncertain effectiveness (Amiro *et al.* 2001, Ricciardi and Simberloff 2009). Thus, the natural resilience of ecosystems must be relied upon across much of Canada's forest landscape. Conservation strategies such as protecting primary forests and providing connectivity parallel to climatic gradients will help maintain the capacity of forest ecosystems to adapt to changing conditions (Noss 2001).

There are few examples of explicit climate change mitigation activities in Canada's forest and peatland sectors, and policy announcements and policy frameworks to support them are just developing. The most dramatic effort to date are commitments made in 2008 by the governments of Ontario and Quebec to protect half of the northern boreal regions of their provinces because of their carbon storage capacity and other important values, accounting for 225 000 km^2 in Ontario alone (Government of Ontario 2008). Most other policy development has focused on the creation of offset frameworks that include forests. The only existing system to date is Alberta's Offset Market, which includes afforestation as a project activity (Alberta Environment 2008). Canada's proposed Offset System for Greenhouse Gases (Environment Canada 2008b) and the Western Climate Initiative (Western Climate Initiative 2008) are both considering the inclusion of forest offset projects, as is Ontario's recently announced cap-and-trade system (Government of Ontario 2009). The Western Climate Initiative also proposes the use of cap-and-trade auction revenue set asides for forestry (Western Climate Initiative 2008). We hope that the management actions recommended here (Table 1) can help to shape these offset systems and other carbon policies that will influence forest carbon management in Canada for years to come.

Once well established, policies most likely to influence management of Canada's vegetation and soil carbon are international climate agreements such as the Kyoto Protocol and its successors. Only a little more than half of Kyoto signatories with binding emissions targets elected to account for carbon fluxes associated with forest management (which is optional under Kyoto). Although the Kyoto Protocol focuses on anthropogenic (i.e., human induced) emissions and removals, the accounting rules require countries to report on the total emissions from managed forests including natural disturbances. In Canada, emissions from natural disturbances such as wildfire and insects have been projected to dominate the greenhouse gas balance of the managed forest (Kurz *et al.* 2008a, b). Given this risk that emissions from natural disturbances will swamp the effects of forest management activities, it is understandable that Canada and other countries did not elect to include forest management as a land-use activity under the Kyoto Protocol. Although natural disturbances are an important driver of the forest carbon balance, their inclusion in carbon accounting limits the ability of climate agreements to create appropriate incentives for changed practices. Climate change mitigation in the forest sector would be promoted by a post-2012 Kyoto framework for Land Use, Land-Use Change and Forestry (LULUCF) that requires mandatory accounting of forest carbon fluxes while protecting signatory nations against the need to account for emissions from natural processes such as wildfires.

Incomplete scientific information should not lead to inaction, but climate change policy decisions must consider uncertainties. The precautionary principle, whereby potential risks to important values should be minimized even in the absence of scientific consensus, should be applied. For example, surprisingly little research has evaluated the impact of roads and other industrial footprints on peatland carbon flux. Until this issue is better understood, industrial development in peatlands should be avoided due to the potential sensitivity of peatland hydrology and the dominant role of hydrology in regulating peatland carbon fluxes. In addition to application of the precautionary principle, research efforts should be directed towards improving our understanding of the effect of management options on the climate regulatory role of forest and peatland ecosystems.

Action to minimize the climate impacts of land use should not occur without considering impacts to the many other ecological and socioeconomic services provided by Canada's forest and peatland ecosystems. Canada has international obligations to conserve its forest biodiversity, and resource extraction from forest ecosystems generates hundreds of thousands of jobs annually. When applied in their entirety, our recommended forest management actions for minimizing impacts to carbon pools should also benefit other ecological and socioeconomic values. For example, the enhancement and concentration of timber production could improve the economic viability of forestry by reducing transportation costs and increasing regeneration. Shifting production to longer-lived but also value-added forest products such as furniture could increase the economic benefits derived from forestry, and generating energy from wood waste is already being adopted due to its economic advantages. Avoiding logging within natural forests will protect intact forest ecosystems that are capable of supporting species sensitive to development such as woodland caribou (Vors *et al.* 2007), as well as retaining a large carbon stock. Extending rotation periods in parts of the managed forest will also enhance carbon storage and conserve biodiversity given the high species richness associated with older forests (Schieck and Song 2006). Due to these and other diverse co-benefits, improved management of Canada's peatland and forest carbon stores will support the broader goal of sustainable management of Canada's vast forest and peatland ecosystems.

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References

Alberta Environment. 2008. Offset Credit Project Guidance Document. Province of Alberta, Edmonton, AB. 30 p. Available at http://environment.alberta.ca/1239.html [Accessed 16 July 2009].

Alexeev, V.A., D.J. Nicolsky, V.E. Romanovsky and D.M. Lawrence. 2007. An evaluation of deep soil configurations in the CLM3 for improved representation of permafrost. Geophys. Res. Lett. 34 L09502, doi:10.1029/2007GL029536.

Amiro, B.D., M.D. Flannigan, B.J. Stocks and B.M. Wotton. 2002. Perspectives on carbon emissions from Canadian forest fires. Forest. Chron. 78(3): 388–390.

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

Amiro, B.D *et al.* 2006. The effect of post-fire stand age on the boreal forest energy balance. Agr. Forest Meteorol. 140: 41–50.

Amiro, B.D., B.J. Stocks, M.E. Alexander, M.D. Flannigan and B.M. Wotton. 2001. Fire, climate change, carbon and fuel management in the Canadian boreal forest. Int. J. Wildland Fire 10: 405–413.

Bala, G., K. Caldeira, M. Wickett, T.J. Phillips, D.B. Lobell, C. Delire and A. Mirin. 2007. Combined climate and carbon-cycle effects of large-scale deforestation. Proc. Nat. Acad. Sci. 104(16): 6550–6555.

Balshi, M.S., A.D. McGuire, P. Duffy, M. Flannigan, J. Walsh and J. Melillo. 2009. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. Global Change Biol. 15(3): 578–600.

Betts, R. A. 2000. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. Nature 408(6809): 187–190.

Boelter, D.H. and G.E. Close. 1974. Pipelines in forested wetlands. J. Forest. 72: 561–563.

Bonan, G.B. 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320(5882): 1444–1449.

Bunnell, F.J. 1995. Forest-dwelling vertebrate faunas and natural fire regimes in British Columbia: patterns and implications for conservation. Conserv. Biol. 9(3): 636–644.

[CCFM] Canadian Council of Forest Ministers. 2008. Compendium of Canadian Forestry Statistics. Available at http://nfdp.ccfm.org [Accessed 17 July 2009].

Chen, J. M., W. Ju, J. Cihlar, D. Price, J. Liu, W. Chen, J. Pan, T. A. Black and A. Barr. 2003. Spatial distribution of carbon sources and sinks in Canada's forests. Tellus B 55(2): 622–642.

Cleary, J., N.T. Roulet and T.R. Moore. 2005. Greenhouse gas emissions from Canadian peat extraction, 1990–2000: a life-cycle analysis. Ambio 34(6): 456–461.

Colombo, S.J., W.C. Parker, N. Luckai, Q. Dang and T. Cai. 2005. The Effects of Forest Management on Carbon Storage in Ontario's Forests. Ontario Ministry of Natural Resources, Sault Ste. Marie, ON. 126 p.

Cook, B.I., G.B. Bonan, S. Levis and H.E. Epstein. 2008. The thermoinsulation effect of snow cover within a climate model. Clim. Dyn. 31(1): 107–124.

Cooper, C. 1982. Carbon storage in managed forests. Can. J. For. Res. 13: 155–166.

Cui, J., C. Li and C. Trettin. 2005. Modeling biogeochemistry and forest management practices for assessing GHGs mitigation strategies in forested wetlands. Environ. Model. Assess. 10: 43–53.

Cumming, S.G. 2001. Forest type and wildfire in the Alberta boreal mixedwood: what do fires burn? Ecol. Appl. 11(1): 97–110.

Cumming, S.G. 2005. Effective fire suppression in boreal forests. Can. J. Forest Res. 35: 772–786.

Davidson, A. and S. Wang. 2004. The effects of sampling resolution on the albedos of dominant land cover types in the North American boreal region. Remote Sens. Environ. 93: 211– 224.

Didion, M., M.-J. Fortin and A. Fall. 2007. Forest age structure as indicator of boreal forest sustainability under alternative management and fire regimes: A landscape sensitivity analysis. Ecol. Model. 200: 45–58.

Donato, D.C., J.B. Fontaine, J.L. Campbell, W.D. Robinson, J.B. Kauffman and B.E. Law. 2006. Post-wildfire logging hinders regeneration and increases fire risk. Science 311(5759): 352.

Environment Canada. 2008a. National Inventory Report: Greenhouse Gas Sources and Sinks in Canada 1990–2006. Environment Canada, Ottawa, Canada. 620 p.

Environment Canada. 2008b. Turning the Corner: Canada's Offset System for Greenhouse Gases. Available at http://www.ec.gc.ca/doc/virage-corner/2008-03/526_eng.htm#intro [Accessed 16 July 2009].

Environment Canada. n.d. Canada's 2007 Greenhouse Gas Inventory – A Summary of Trends. Available at http://www.ec.gc.ca/pdb/ghg/inventory_report/2007/som-sum_eng.pdf [Accessed 28 June 2009].

Euskirchen, E.S., J. Chen, L. Harbin, E. J. Gustafson and T. R. Crow. 2002. Modeling landscape net ecosystem productivity (LandNEP) under alternative management regimes. Ecol. Model. 154(1–2): 75–91.

Flannigan, M., K. Logan, B. Amiro, W. Skinner and B. Stocks. 2005. Future area burned in Canada. Clim. Change 72(1–2):1–16.

Frolking, S. and N.T. Roulet. 2007. Holocene radiative forcing impact of northern peatland carbon accumulation and methane emissions. Global Change Biol. 13: 1079–1088.

Glatzel, S., N. Basiliko and T. Moore. 2004. Carbon dioxide and methane production potentials of peats from natural, harvested and restored sites, eastern Québec, Canada. Wetlands 24(2): 261–267.

Goodale, C.L. *et al.* 2002. Forest carbon sinks in the northern hemisphere. Ecol. Appl. 12(3): 891–899.

Government of Ontario. 2008. Protecting Ontario's Northern Boreal Forest. Available at http://www.premier.gov.on.ca/news/event.php?ItemID=406&Lang=EN [Accessed 20 May 2009].

Government of Ontario. 2009. Moving Forward: A Greenhouse Gas Cap-and-Trade System for Ontario. PIBS 7093e. Queen's Printer for Ontario. 30 p.

Gower, S.T. *et al.* 2006. Following the Paper Trail: The Impact of Magazine and Dimensional Lumber Production on Greenhouse Gas Emissions: A Case Study. The Heinz Centre, Washington, DC.

Graham, P. 2003. Potential Options to Increase Sequestration through Incremental Forest Management Options: Key Data and Research Needs for Analysis. Natural Resources Canada – Canadian Forest Service. 102 p.

Gustafson, E.J., P.A. Zollner, B.R. Sturtevant, H.S. He and D.J. Mladenoff. 2004. Influence of forest management alternatives and land type on susceptibility to fire in northern Wisconsin, USA. Landscape Ecol. 19: 327–341.

Gustavsson, L., R. Madlener, H.-F. Hoen, G. Jungmeier, T. Karjalainen, S. Klöhn, K. Mahapatra, J. Pohjola, B. Solberg and H. Spelter. 2006. The role of wood material for greenhouse gas mitigation. Mitigation and Adaptation Strategies for Global Change 11(5–6): 1097–1127.

Harmon, M.E., W.K. Ferrell and J.F. Franklin. 1990. Effects on Carbon Storage of Conversion of Old-Growth Forests to Young Forests. Science 247(4943): 699–702.

Hennigar, C.R., D.A. MacLean and L.J. Amos-Binks. 2008. A novel approach to optimize management strategies for carbon stored in both forests and wood products. Forest Ecol. and Manag. 256: 786–797.

Hobson, K.A., E.M. Bayne and S.L. Van Wilgenburg. 2002. Large-scale conversion of forest to agriculture in the boreal plains of Saskatchewan. Conserv. Biol. 16(6): 1530–1541.

Hunter, M.L., Jr. 1990. Wildlife, Forests, and Forestry: Principles of Managing Forests for Biological Diversity. Prentice-Hall, Englewood Cliffs, NJ. 370 p.

[IPPG] Intergovernmental Panel on Climate Change. 2007a. Summary for policymakers. *In* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, New York.

_____. 2007b. Summary for policymakers. *In* B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds.). Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, New York.

Johnson, D.W., J.F. Murphy, R.B. Susfalk, T.G. Caldwell, W.W. Miller, R.F. Walker and R.F. Powers. 2005. The effects of wildfire, salvage logging, and post-fire N-fixation on the nutrient budgets of a Sierran forest. Forest Ecol. And Manag. 220(1–3): 155–165.

Ju, W., J.M. Chen, T.A. Black, A.G. Barr, H. McCaughey and N.T. Roulet. 2006. Hydrological effects on carbon cycles of Canada's forests and wetlands. Tellus B 58(1): 16–30.

Kurz, W.A. and M.J. Apps. 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. Ecol. Appl. 9(2): 526–547.

Kurz, W.A., S.J. Beukema and M.J. Apps. 1998. Carbon budget implications of the transition from natural to managed disturbance regimes in forest landscapes. Mitigation and Adaptation Strategies for Global Change 2: 405–421.

Kurz, W.A., C.C. Dymond, G. Stinson, G.J. Rampley, E.T. Neilson, A.L. Carroll, T. Ebata and L. Safranyik. 2008a. Mountain pine beetle and forest carbon feedback to climate change. Nature 452: 987–990.

Kurz, W.A., G. Stinson, G.J. Rampley, C.D. Dymond and E.T. Neilson. 2008b. Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. Proc. Nat. Acad. Sci. 105: 1551–1555.

Lavoie, M., D. Paré and Y. Bergeron. 2005. Impact of global change and forest management on carbon sequestration in northern forested peatlands. Environ. Rev. 13: 199–240.

Lawrence, D.M. and A.G. Slater. 2008. Incorporating organic soil into global climate model. Clim. Dyn. 30(2–3): 145–160.

Lawrence, D.M., A.G. Slater, V.E. Romanovsky and D.J. Nicolsky. 2008. Sensitivity of a model projection of near-surface permafrost degradation to soil column depth and representation of soil organic matter. J. Geophys. Res. 113, F02011, doi:10.1029/2007JF000883.

Lee, P. and R. Cheng. 2009. Bitumen and Biocarbon. Land Use Conversions and Loss of Biological Carbon Due to Bitumen Operations in the Boreal Forests of Alberta, Canada. Global Forest Watch Canada, Edmonton, AB.

Lieffers V. J., C. Messier, P.J. Burton, J.C. Ruel and B.E. Grover. 2003. Nature-based silviculture for sustaining a variety of boreal forest values. *In* P.J Burton, C. Messier, D.W. Smith and W.L. Adamowicz (eds.). Towards Sustainable Management of the Boreal Forest. pp. 481–530. NRC Research Press, Ottawa, ON.

Lindenmayer, D.B., D.R. Foster, J.F. Franklin, M.L. Hunter, R.F. Noss, F.A. Schmiegelow and D. Perry. 2004. Salvage harvesting policies after natural disturbance. Science 303: 1303.

Lindenmayer, D., J.F. Franklin and P.J. Burton. 2008. Salvage Logging and Its Ecological Consequences. Island Press. 246 p.

Luyssaert, S., E.D. Schulze, A. Borner, A. Knohl, D. Hessenmoller, B.E. Law, P. Ciais and J. Grace. 2008. Old-growth forests as global carbon sinks. Nature 455: 213–215.

Malcolm, J.R. and A. Markham. 2000. Global Warming and Terrestrial Biodiversity Decline. WWF, Gland, Switzerland. 34 p.

McCullough, D.G., R.A. Werner and D. Neumann. 1998. Fire and insects in northern and boreal forest ecosystems of North America. Ann. Rev. Entomol. 43:107–127.

McKenney, D.W., J.H. Pedlar, K. Lawrence, K. Campbell and M.F. Hutchinson. 2007. Potential impacts of climate change on the distribution of North American trees. BioScience 57(11): 939–948.

McLaughlin, J.W., M.R. Gale, M.F. Jurgensen and C.C. Trettin. 2000. Soil organic matter and nitrogen cycling in response to harvesting, mechanical site preparation, and fertilization in a wetland with a mineral substrate. Forest Ecol. and Manag. 129: 7–23.

Messier, C., B. Bigué and L. Bernier. 2003. Using fast-growing plantations to promote forest ecosystem protection in Canada. Unasylva 214/215.

Minkkinen, K., R. Korhonen, I. Savolainen and J. Laine. 2002. Carbon balance and radiative forcing of Finnish peatlands 1900–2100 – the impact of forestry drainage. Global Change Biology 8: 785–799.

Montenegro, A., M. Eby, Q. Mu, M. Mulligan, A.J. Weaver, E.C. Wiebe and M. Zhao. 2009. The net carbon drawdown of small scale afforestation from satellite observations. Global and Planetary Change 69(4): 195–204.

Morgan, P., E.K. Heyerdahl and C.E. Gibson. 2008. Multi-season climate synchronized forest fires throughout the 20th century, northern Rockies, USA. Ecology 89(3): 717–728.

Nabuurs, G.J. *et al.* 2007. Forestry. *In* B. Metz, O.R. Davidson, P.R. Bosch, R. Dave and L.A. Meyer (eds.). Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York.

Neilson, E.T., D.A. MacLean, F. Meng, C.R. Hennigar and P.A. Arp. 2008. Optimal on- and off-site forest carbon sequestration under existing timber supply constraints in northern New Brunswick. Can. J. For. Res. 38: 2784–2796.

Noss, R.F. 2001. Beyond Kyoto: forest management in a timber of rapid climate change. Conservation Biology 15(3): 578–590.

Peng C., H. Jiang, M. J. Apps and Y. Zhang. 2002. Effects of harvesting regimes on carbon and nitrogen dynamics of boreal forests in central Canada: a process model simulation. Ecol. Model. 155(2–3): 177–189.

Randerson, J.T. *et al.* 2006. The impact of boreal forest fire on climate warming. Science 314(5802): 1130–1132.

Ricciardi, A. and D. Simberloff. 2009. Assisted colonization is not a viable conservation strategy. Trends in Ecology and Evolution 24(5): 248–253.

Roulet, N.T., P.M. Lafleur, P.J.H. Richard, T.R. Moore, E.R. Humphreys and J. Bubier. 2007. Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. Global Change Biol. 13: 397–411.

Schieck, J. and S.J. Song. 2006. Changes in bird communities throughout succession following fire and harvest in boreal forests of western North America: literature review and meta-analyses. Can. J. of For. Res. 36: 1299–318.

Scholze, M., W. Knorr, N.W. Arnell and I.C. Prentice. 2006. A climate-change risk analysis for world ecosystems. Proc. Nat. Acad. Sci. 103(35): 13116–13120.

Schuur, E.A.G. *et al.* 2008. Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. Bioscience. 58(8): 701–714.

Schuur, E.A.G., J.G. Vogel, K.G. Crummer, H. Lee, J.O. Sickman and T.E. Osterkamp. 2009. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. Nature 459: 556–559.

Scott, N.A., C.A. Rodrigues, H. Hughes, J.T. Lee, E.A. Davidson, D.B. Dail, P. Malerba and D.Y. Hollinger. 2004. Changes in carbon storage and net carbon exchange one year after an initial shelterwood harvest at Howland Forest, ME. Environ. Manage. 33 (Suppl. 1): S9–S22.

Seely, B., C. Welham and H. Kimmins. 2002. Carbon sequestration in a boreal forest ecosystem: results from the ecosystem simulation model, FORECAST. For. Ecol. and Manag. 169: 123–135.

Senate Subcommittee on the Boreal Forest. 1999. Competing Realities: the Boreal Forest at Risk. The Senate of Canada, Ottawa, ON. Available at http://www.parl.gc.ca/36/1/parlbus/commbus/senate/Com-e/bore-e/rep-e/rep09jun99-e.htm [Accessed 16 July 2009].

Strack, M. and J.M. Waddington. 2007. Response of peatland carbon dioxide and methane fluxes to a water table drawdown experiment. Global Biogeochemical Cycles 21, GB 2007, doi:10.1029/2006GB002715.

Strutevant, B.R., P.A. Zollner, E.J. Gustafson and D.T. Cleland. 2004. Human influences on the abundance and connectivity of high-risk fuels in mixed forests of northern Wisconsin, USA. Landscape Ecology 19: 235–253.

Sustainable Ecosystem Working Group. 2008. Terrestrial Ecosystem Management Framework for the Regional Municipality of Wood Buffalo. Cumulative Environmental Management Association. 57 p. Available at http://www.cemaonline.ca/content/view/75/182/ [Accessed 16 July 2009].

Tarnocai, C. 2000. Carbon pools in soils of the Arctic, Subarctic and Boreal regions of Canada. *In* R. Lal, J.M. Kimble and B.A. Stewart (eds.). Global Climate Change and Cold Regions Ecosystems. Advances in Soil Science. pp. 91–103. Lewis Publishers, Boca Raton, FL.

Tarnocai, C. 2006. The effect of climate change on carbon in Canadian peatlands. Global Planet. Change 53: 222–232.

Thomas, C.D. *et al.* 2004. Extinction risk from climate change. Nature 427: 145–148.

Turetsky, M.R., R.K. Wieder, D.H. Vitt, R.J. Evans and K.D. Scott. 2007. The disappearance of relict permafrost in boreal North America: Effects on peatland carbon storage and fluxes. Global Change Biology 13: 1–13.

Upton, B., R. Miner and K. Vice. 2007. The Greenhouse Gas and Carbon Profile of the Canadian Forest Products Industry. Special Report No. 07-09. National Council for Air and Stream Improvement, Research Triangle Park, NC. 27 p.

Vors, L.S., J.A. Schaefer, B.A. Pond, A.R. Rodgers and B.R. Patterson. 2007. Woodland caribou extirpation and anthropogenic landscape disturbance in Ontario. J. Wildlife Manage. 71(4): 1249–1256.

Waddington, J.M. and S.M. Day. 2007. Methane emissions for a peatland following restoration. J. Geophys. Res. 112 G03018, doi:10.1029/2007JG000400.

Wang, S. 2005. Dynamics of land surface albedo for a boreal forest and its simulation. Ecol. Model. 183: 477– 494.

Wang, S., A. P. Trishchenko, K. V. Khlopenkov and A. Davidson. 2006. Comparison of International Panel on Climate Change Fourth Assessment Report climate model simulations of surface albedo with satellite products over northern latitudes, J. Geophys. Res. 111, D21108, doi:10.1029/2005JD006728.

Watson, R.T., I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo and D.J. Dokken. 2000. Special Report on Land Use, Land-Use Change and Forestry. Cambridge, IPCC, UK. 377 p.

Western Climate Initiative. 2008. Design Recommendations for the WCI Regional Cap-and-Trade Program. 48 p. Available at http://www.westernclimateinitiative.org/the-wci-cap-and-trade-program/design-recommendations [Accessed 16 July 2009].

Whitehead, R.J., L. Safranyik and T.L. Shore. 2007. Preventative management. *In* L. Safranyik and W.R. Wilson (eds.). The Mountain Pine Beetle: A Synthesis of Biology, Management, and Impacts on Lodgepole Pine. pp. 173–192. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC.

Wieder, R.K., D.H. Vitt and B.W. Benscoter. 2006. Peatlands and the Boreal Forest. In R.K. Wieder and D.H. Vitt (eds.). Boreal Peatland Ecosystems. pp. 1–8. Springer.

Wigley, T.M.L. 2005. The climate change commitment. Science 307(5716): 1766–1769.