

**Combating Climate Change Through Boreal Forest Conservation:
Resistance, Adaptation, and Mitigation**

A Technical Report for Greenpeace Canada
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Introduction

The boreal forest is the largest forest ecosystem in the world, covering approximately 25 million km² of land, or 11% of the earth's terrestrial surface (Esseen *et al.* 1997). In Canada, it covers some 5 million km², or 20% of the worldwide total, and includes some of the last large areas of wilderness forest on the planet where large-scale anthropogenic impacts are absent and where natural disturbance regimes prevail (Bryant *et al.* 1997). A critical feature of the boreal forests is that although annual precipitation is often low, it generally exceeds evapotranspiration. This characteristic, in conjunction with a post-glacial geomorphology and relatively cold temperatures, is ultimately responsible for Canada's 1.5-2 million lakes, immense wetland areas, and carbon-rich organic soils that predominate over much of the region. Unlike most temperate and tropical forests, where much of the pool of carbon is stored in live tree tissues, an average of 84% of the carbon in boreal forests is in soils (IPCC 2000).

Canada's vast boreal forest is heterogeneous, with variation in forest structure and species composition largely driven by climatic gradients. Two such gradients are critical: a south-to-north gradient of decreasing solar radiation and related variables (decreasing temperature and light intensity and increasing sun angles and seasonal photoperiod variation) and an east-to-west gradient of decreasing precipitation and increased frequency of natural fire ignition. When combined with periods of drought, lightning is capable of initiating large forest fires, which are one of the most important forces driving boreal vegetation dynamics (Payette 1992). Natural fire return intervals across the Canadian boreal forest range from under 50 years in dry regions to >500 years in moist regions (Zasada *et al.* 1997, Bergeron *et al.* 2001). Paleo-ecological studies suggest that within a given area, the fire return interval can fluctuate over long time scales; for example, the mixed-wood boreal forests of northwestern Quebec have experienced periods of both relatively long (>300 y) and short (<100 y) fire cycles over the last 1000 years (Bergeron *et al.* 1999).

This biophysical context is critical to understanding both boreal forest conservation and the potential impacts of global climate change on the forest. There is general consensus among climate modellers that pole-ward regions of the globe, including the boreal region, will experience the largest increases in temperature under global warming (IPCC 2007). Because climate gradients are closely related to boreal forest structure, species composition, and dynamics, one can infer large and rapid changes within the boreal forest (Malcolm *et al.* 2002; Hamann and Wang 2006). Another critical point is that ancient, primary or “old growth” forests (i.e., forests characterized by completion of the life-cycles of individual trees and subsequent gap-phase dynamics), which represent large carbon stores, can be very common where fire return intervals are long. For this reason, boreal forest conservation efforts that focus on protection of landscapes can have large implications for carbon budgets. Finally, given the importance of soil carbon in boreal forest ecosystems, and the potential for release of this carbon and resulting exacerbation of global climate change, any analysis of the role of boreal forests in a climate change context must carefully consider this feature.

Purpose and scope of the review

The purpose of this review is to examine the potential role of forest conservation in Canada's boreal region as a strategy to mitigate global climate change. Historically, changes in land use, primarily deforestation, have contributed enormous quantities of carbon to the planet's atmosphere, approximately 22% of the overall total from 1850-2000 (156 PgC; Houghton 2003). This figure encapsulates three important points: (1) land-use change, principally deforestation, contributes directly and substantially to the increasing atmospheric CO₂ concentrations and hence to global warming; (2) avoiding net CO₂ emissions from forests can substantially mitigate greenhouse-gas-related climate change; and (3) forest conservation measures alone can potentially result in at least 5 to 10% reductions in total Canadian CO₂ emissions. However, these figures understate the case for forest conservation in a climate change context in at least one very important respect: whereas Canada's boreal forest at present are not a major source of carbon, depending upon how we manage them they have the potential to become one. The

world's boreal forests are home to an immense pool of carbon, approximately one-quarter of the planet's terrestrial carbon stock, which if liberated even in part has the potential to seriously exacerbate human-induced climate change from other sources. This theme was the focus of a 1997 Greenpeace report entitled “The Carbon Bomb”, which noted that climate change and forest harvesting in combination could potentially result in large increases in Canada’s CO₂ emissions, mainly through releases of carbon held in northern soils. While the “carbon bomb” argument remains compelling, recent scientific work provides a number of additional strong arguments for conserving boreal forest as a means of fighting climate change.

This report is broken into four main sections. First, we review recent evidence that climate change is already having important effects on boreal forest ecosystems. Second, we outline the effects of industrial-scale logging and development on boreal forest ecosystems, with a focus on their potential to exacerbate global warming. Third, we outline mechanisms whereby intact boreal forest landscapes are better able to resist and adapt to climate change impacts than forests subjected to anthropogenic impacts. Finally, we enumerate the ways in which intact boreal forest landscapes may directly act to mitigate climate change effects.

Climate change is already affecting the boreal forest

Although boreal forest trees are commonly temperature limited and might be expected to show increased growth under moderate temperature increases, there is recent evidence of reduced growth and survival of boreal tree species under recent warming. Species are showing evidence of direct effects of climate change such as increased temperature stress, drought stress, and freeze-thaw damage. The boreal forest as an ecosystem is experiencing increased fire frequencies and pest damage. There is also increasing evidence of systematic changes in boreal wildlife consistent with a climate change signal, including shifts in species ranges and behaviours.

The boreal forest is experiencing increased temperature stress

Tree growth in boreal forests is commonly enhanced by warm growing seasons. This well-established relationship has been supported by numerous long-term studies (Briffa *et al.* 1995; Jacoby *et al.* 1996). However, in theory, the relationship between growth and temperature should be “humped” in form, showing an optimum temperature (Woodward 1987). Along these lines, studies suggest that while climate warming may increase boreal forest growth initially, warming beyond some threshold will result in growth reductions. Recent studies suggest that this point has already been reached, and that the boreal forest is no longer benefiting from warmer temperatures. A survey of over 300 northern sites found that wood density was no longer responding to increasing temperature as predicted by a linear model (Briffa *et al.* 1998). A number of studies also indicate reduced diameter increments in response to warmer growing seasons (Barber *et al.* 2000; Wilmking *et al.* 2004, 2005). In Alaska, D’Arrigo and colleagues (2004) found that white spruce trees responded positively to small increases in temperature, but that growth declines were observed for July-August mean temperatures greater than 11.3°C, a temperature exceeded on average since the mid-1960s. If temperatures continue to increase, more and more species will be pushed outside of ideal temperature conditions.

Climate change is expected to result in an increased growing season length as well as increased growing season temperatures, both of which are expected to increase tree growth potential. However, remote sensing studies suggest that whereas certain tundra communities have responded to warmer spring and summer temperatures by an earlier onset of growth, the boreal forest has not shown this pattern (Goetz *et al.* 2005). Increased winter precipitation observed in many parts of the boreal forest may delay the snow-free season and subsequent “spring greening”, and so may contribute to recent changes in temperature-growth relationships (Vaganov *et al.* 1999).

The boreal forest is experiencing increased temperature-induced drought stress

As temperatures increase, water availability declines. Water limitation has been linked to growth declines across the boreal forest (Barber *et al.* 2000; Wilmking and Juday 2005). White spruce (*Picea glauca*), one of the most widespread and important trees of the Canadian boreal, is particularly sensitive to moisture limitation beyond a critical temperature threshold of 2°C above local temperatures (Calef *et al.* 2005). In northwestern Alberta, aspen (*Populus tremuloides*) populations are currently experiencing dieback and stunted growth following recent drought events (Hogg *et al.* 2002). As temperatures continue to rise, water is expected to become a limiting factor for many biological processes, particularly in the drier parts of the boreal forest in west-central Canada.

The boreal forest may experience increased freeze-thaw damage

Trees are particularly sensitive to temperature fluctuations near the freezing point, which can result in “frost burn” and other injuries related to ice-crystal formation. Climate model predictions are consistent in predicting relatively large increases in winter temperatures, and as a consequence, increased frequencies of freeze-thaw events at northern latitudes (IPCC 2007). Climate warming is thus predicted to increase the risk of freeze-thaw damage in boreal tree species (Cannell and Smith 1986; Hanninen 2006). Warm spring temperatures also result in earlier needle dehardening, rendering trees

vulnerable to late spring frosts (Hanninen *et al.* 2005). Red spruce (*Picea rubens*) and sugar maple (*Acer saccharum*) are particularly sensitive to late spring frosts, with severe frost events associated with substantial needle or leaf loss (Saxe *et al.* 2001). Low rates of growth have been recorded in Alberta aspen populations following unusually warm winters and increased frequency of freeze-thaw events (Hogg *et al.* 2002). Early onset of photosynthesis in response to warm conditions may potentially elicit further damage due to low-light conditions (Saxe *et al.* 2001). Although most damage will be limited to late winter and early spring, warmer autumn temperatures may prevent needles from hardening enough for the cold winters, resulting in further needle loss (Saxe *et al.* 2001).

The boreal is experiencing increased fire frequency

Warmer and drier conditions increase the frequency, duration, and intensity of forest fires. Increases in fire frequency have been noted across the boreal forest, particularly in the last 30 years (Stewart *et al.* 1998; Goetz *et al.* 2005). Chapin and colleagues (2000) reported a doubling of area burned in North America in the last 20 years, in parallel with increasing temperatures. Podur and colleagues (2002) took fire protection into account in their analysis of fire dynamics in Canada during 1918-2000, and found a significant increase in fire activity. Declining forests under increased temperature and drought stress provide greater fuel quality and quantity, thus increasing fire severity (Stewart *et al.* 1998). This trend toward increased fire frequency, duration, and intensity is predicted to increase as temperatures warm (Flannigan *et al.* 2005).

The boreal is experiencing increased pest outbreaks

Warmer winters improve over-wintering success for many insect species. Warmer temperatures year-round also enhance the population growth rate of most insect pests (Stewart *et al.* 1998). Cool summers in Alberta were linked to reduced defoliation events in aspen populations (Hogg *et al.* 2002). A widespread outbreak of mountain pine beetle (*Dendroctonus ponderosae*) across the western boreal forest in Canada has been linked to

enhanced over-wintering success as a result of warmer winter temperatures (Stahl *et al.* 2006). Other boreal insect pests for which increased impacts have been shown or are predicted include the spruce bark beetle (*Ips typographus*) (Wermielinger 2004) and all three major defoliating insects: spruce budworm (*Choristoneura sumiferana*), jack pine budworm (*Choristoneura pinus*), and forest tent caterpillar (*Malacosoma disstria*) (Volney and Fleming 2000). Insect-related timber losses are commonly much higher than fire-related losses in the Canadian boreal, and the most recent recorded insect-related losses in forest area are some 8-fold higher than the area burned (Compendium of Canadian Forestry Statistics 2007). Existing pest problems are predicted to further increase with additional climate warming (Stewart *et al.* 1998; Volney and Fleming 2000).

Climate change is directly and indirectly impacting boreal wildlife

Climate change is predicted to have a number of effects on boreal animal species. With increasing temperatures, many species will shift their ranges northward, a process which has already been documented for some species (e.g., Kerr and Packer 1998). Most boreal taxa are expected to show geographic range contractions as temperature zones shift northward and boundaries (such as water bodies and the treeline) are encountered (Kerr and Packer 1998). More southerly temperate-zone species are predicted to move northward into the boreal forest as temperatures increase (Kerr and Packer 1998), with potentially disruptive effects on current boreal communities. Warmer temperatures could also lead to lower snowfall levels (Schmitz *et al.* 2003), with the potential to disrupt a number of wildlife species. For example, snow depth is a critical predictor of woodland caribou survival (Rupp *et al.* 2006) and of the lynx-snowshoe hare population cycle (Schmitz *et al.* 2003).

As climate shifts, it is assumed in most models that the plant communities upon which animal communities depend will shift northwards (Hamann and Wang 2006; Iverson and Prasad 1998). Although many models operate under the assumption that current plant communities will re-establish themselves over time, it has also been suggested that novel

assemblages will be created as plants move at different rates (Solomon and Kirilenko 1997). This could result in increased and novel patterns of competition among animal species (Kerr and Packer 1998). Perhaps of equal importance is the potential mismatch between rates of shifts in climate zones and the rates at which plant species are able to respond (Malcolm *et al.* 2002, 2005). Distributions of tree species in Ontario are projected to shift northward over the next 100 years at rates that are much higher than those that tree species are likely to attain. In fact, the required rates were reminiscent of those observed for the “weediest” of invading plant species with the largest dispersal distances (Malcolm *et al.* 2005). In contrast to plants, animal populations can typically shift ranges quickly, increasing the possibility of mismatches between appropriate climatic conditions and other habitat features. Such mismatches have been observed to result in increased mortality for bird populations (Martin 2001). In other cases, mismatches may occur when predators and their food sources respond differently to climatic cues. Visser *et al.* (1998) found that the needs of the great tit (*Parus major*) for its offspring and the peak of its prey abundance no longer were synchronous due to differential responses to earlier springs. As detailed above, climate change also will likely result in increases in fire- and insect-related disturbance, both of which may be exacerbated when trees are stressed. Such changes in forest disturbance regimes also could have dramatic effects on wildlife. All of these factors will likely impact the distribution and survival of boreal wildlife species, including those of special conservation concern, such as woodland caribou (*Rangifer tarandus*), wood bison (*Bison bison athabascae*), grey wolf (*Canis lupus*), and American marten (*Martes americana*).

Industrial-scale logging in the boreal forest can worsen climate change impacts

Industrial-scale logging has important effects on the carbon budget of the boreal forest, changing vegetation biomass and structure, altering debris levels, and impacting the soil (Covington 1981; Howard *et al.* 2004; Kohv and Liira 2005). Several authors have discussed the general pattern of carbon stock change following disturbance and have divided this process into four stages (Kurz and Apps 1999; Harden *et al.* 2000; Wang *et al.* 2003). In the first stage, disturbances remove vegetative biomass and add large amounts of debris to the detritus pool. In the second stage, the vegetation begins to re-grow, but high levels of decomposition dominate. In the third stage, rapid re-growth leads to high levels of carbon being sequestered in the ecosystem. In the last stage biomass accumulation begins to diminish as the stand ages, although net carbon sequestration can continue. In this section, we will examine the effects of industrial-scale logging on the carbon pools of the boreal forest and implications for climate change.

Logging in the boreal results in a large release of carbon from both vegetation and soils

The fact that old growth forests contain more carbon than younger forests is well established (Harmon *et al.* 1990). Mature boreal forests can contain over 80 Mg C/ha in the aboveground vegetative layer (Finer *et al.* 2003; Wang *et al.* 2003) and when these sites are harvested this component is reduced to almost inconsequential levels (Finer *et al.* 2003). While not all sites contain this amount of carbon, if an intermediate level of 40 Mg/ha is used (see Houghton 2005a) and is projected across approximately 900,000 ha of boreal forest harvested annually, roughly 3.6×10^7 Mg of carbon is removed from the Canadian boreal forest each year by logging activities.

Some authors have advanced the argument that much of the carbon removed by harvesting is stored for long time periods in forest products (Skog and Nicholson 1998; Colombo *et al.* 2006). However, large accumulations of carbon in forest products generally only occur in simulations when unrealistically long estimates are used for product half-life. For example, Colombo *et al.* (2006) assume carbon losses of forest

products of <25% in 100 years in Ontario, implying a half-life of >240 years. In contrast, product half-life values from other studies range from 1-3 years for paper to 30-50 years for sawnwood, with IPCC “good practice” defaults of 2 and 35 years, respectively (Buchanon and Levine 1999, IPCC 2003). Analyses for Douglas-fir (*Pseudotsuga menziesii*) forests presented by Harmon *et al.* (1990) suggest that following harvests most carbon is either stored in short-term products such as paper or is lost during harvesting and processing, and only a small fraction ends up in longer-term products such as dimensional lumber (Houghton 2005b). Harvested carbon may also ultimately be stored in landfills; however, considerable uncertainty remains on decomposition rates in this pool, with few measurements available (Barlaz 2003, IPCC 2007), and also a high potential for increased methane emissions in the landfill environment. Changes in municipal landfill practices, including increased use of incineration, seem likely to reduce carbon residence time, making estimates based on historical data inappropriate.

In addition to largely eliminating carbon stocks represented by living trees, clearcut harvesting also results in much lower levels of woody debris than natural disturbances such as fire or defoliation (Tinker and Knight 2000) and this can have important consequences for the soil because woody debris is an important source of carbon for long-term soil carbon storage (Manies *et al.* 2005). Woody debris levels are drastically reduced when naturally disturbed sites undergo salvage logging, as shown by Johnson *et al.* (2005), who found that more carbon was lost from the stand by salvage logging than the fire event itself. Forest regeneration may also be compromised by salvage logging in some circumstances (Donato *et al.* 2006, Lindenmayer and Noss 2006). More intense fibre removal, for example during biofuel harvesting, has the potential to remove large amounts of carbon that would otherwise remain in the ecosystem (Rudolphi and Gustafsson 2005)

Whether the soil compartment undergoes significant carbon loss due to logging is still controversial: some studies have shown significant soil losses following harvest (Covington 1981; Peltoniemi *et al.* 2004), whereas others have failed to find such losses (Fitzsimmons *et al.* 2004). This uncertainty in part reflects difficulties in separating the

effects of harvesting on different carbon pools and problems associated with using comparisons among different-aged sites to reconstruct changes over time at a single site (Kolari *et al.* 2004). However, removal of the tree component exposes the soil to an extreme shift in energy balance, resulting in warmer conditions favouring increased decomposition (Carrasco *et al.* 2006). This loss is reflected in flux studies that have found that young regenerating forests are losing carbon (Pypker and Fredeen 2002; Amiro *et al.* 2006; Fredeen *et al.* 2007). In some cases logged stands may take decades to recover a positive carbon balance (Federer 1984).

Overall, large amounts of carbon can be lost following harvesting in boreal regions. Fredeen *et al.* (2005) found that total carbon stocks were reduced by up to 54% in spruce forests following harvest. Kolari *et al.* (2004) found that sites 4 years following harvest contained 80 Mg C/ha less than 75 year old stands of Scots pine. Howard *et al.* (2004) found that a 5-year-old jack pine site had 40 Mg C/ha less in aboveground stocks than a 79-year-old stand. Considering the extent of harvest across the Canadian boreal forest, with nearly 900,000 ha harvested a year (CFS 2006), the implications of this carbon loss are tremendous. Even greater losses of carbon could potentially be triggered by logging activities in northern forests if changes in drainage and increased ignition probabilities resulted in large-scale peat fires. The Indonesian peat fires of 1997 are estimated to have contributed 13-40% of the global carbon emissions from fossil fuels in that year (Page *et al.* 2002).

Logged areas experience slow recovery of carbon stocks following harvest

Conventional clearcut harvesting results in a large and immediate loss of carbon from the boreal ecosystem. The resulting vegetation carbon pools are negligible, the soil is disturbed, and a moderate woody debris component remains. What happens next is a very slow recovery of carbon to pre-harvest levels, in many cases taking well over a century (Yarie and Van Cleave 1983; Bond-Lamberty *et al.* 2006). Initially there is a period of time where the ecosystem continues to lose carbon as decomposition of the woody debris

and soil outpaces re-growth of the vegetation, with this period often lasting more than 10 years (Schulze *et al.* 1999; Fredeen *et al.* 2007).

As a stand ages and matures, it will undergo a period of high fibre production (Goulden *et al.* 1998); however, it takes a considerable amount of time for intermediate-aged forests to approach the total carbon sequestration levels found in old growth. Yarie and Van Cleave (1983) estimated that white spruce stands were accumulating carbon at well over 200 years of age; similarly, Bond-Lamberty *et al.* (2006) showed that 140 year old black spruce were still sequestering carbon. However, most harvesting is conducted using shorter rotation lengths, typically from 50 to 100 years (Price *et al.* 1997; Kopra and Fyles 2005), preventing forests from recovering to pre-harvest carbon levels. Relatively short rotation lengths are reflected in a recent shift towards a younger age structure in much of the Canadian boreal (Kurz and Apps 1999; Harvey *et al.* 2002). In order to stabilize carbon levels in the Canadian boreal, it is estimated that rotation lengths would need to be extended to well over 100 years, particularly in regions with lower natural fire frequency (Peng *et al.* 2002)

Logging can result in permafrost loss and soil saturation

Soil that remains frozen throughout the year is called permafrost, which covers approximately 24% of the exposed land area of the northern hemisphere (Zhang *et al.* 1999). Over 60% of the permafrost region is composed of thin, low-ice content soil profiles, much of which can support thick vegetation cover including boreal forests (Zhang *et al.* 1999). Logging removes the protective cover of the forest vegetation, exposing cold and frozen soil to incoming solar radiation and high temperatures (Eugster *et al.* 2000). As permafrost melts, the exposed soil becomes increasingly saturated with water (Chapin *et al.* 2000). Without the high water demands of trees, these water-saturated landscapes experience increased peat formation and rising water tables, a process known as paludification (Crawford *et al.* 2003; Morishita *et al.* 2005). Previously forested areas can be rapidly converted to large, expanding bog landscapes through

paludification; these landscapes are then largely resistant to forest establishment (Crawford *et al.* 2003).

Permafrost loss and soil saturation at large scales are potentially large sources of greenhouse gases, and are expected to exacerbate global warming (Camill and Clark 1998; Eugster *et al.* 2000). As frozen soil thaws, respiration increases rapidly, contributing carbon to the atmosphere. Water-logged soil emits large amounts of methane, a particularly potent greenhouse gas, due to increases in anaerobic respiration under low-oxygen conditions (Chapin *et al.* 2000). Both permafrost loss and paludification are projected to increase under current climate change projections (Camill and Clark 1998; IPCC 2007).

Logging alters community composition and reduces functional diversity of boreal forests

Logging inevitably results in a decrease in the representation of older stands in the landscape (Bergeron *et al.* 1999), and there is unequivocal evidence of large-scale effects of logging on species composition in boreal forests. Through much of the southern Canadian boreal, large-scale logging has resulted in a conversion of conifer-dominated systems to systems dominated by early-successional hardwoods, in particular aspen (*Populus tremuloides*) and/or paper birch (*Betula papyrifera*) (Hearnden *et al.* 1992, Carleton 2000, Jackson *et al.* 2000, Friedman and Reich 2005). In both cases, there are likely to be significant reductions in “functional diversity” of boreal forests, in particular a reduction in the coniferous tree component. Reduced functional diversity is expected to result in significant changes in ecosystem function, including altered patterns of productivity, hydrological balance, litter decomposition, and mineral nutrient cycling (Diaz and Cabido 2001). Although experimental work is limited, there is evidence that functional diversity is related to many aspects of ecosystem function in boreal forests (Carleton and MacLellan 1994, Wardle *et al.* 1997, Fenton *et al.* 2005).

Logging may or may not result in a decrease in total plant species richness in boreal systems; in some cases, logged areas show a transient increase in species richness and

diversity (Haeussler *et al.* 2002, Kemball *et al.* 2005, Hart and Chen 2006). The main cause of this pattern is an increase in frequency and abundance of opportunistic woody and herbaceous species in logged areas (Kemball *et al.* 2005, Hart and Chen 2006), sometimes including non-native species. Conversely, shade-tolerant plant species tend to decrease following logging, as do species associated with organic substrates and coarse woody debris (Thompson *et al.* 2003).

Silvicultural treatments associated with logging, in particular manipulations of the soil environment, may have effects as profound as those of tree cutting. Post-harvest treatments designed to facilitate regeneration often include mechanical site preparation and broadcast burning of slash. Such treatments are commonly associated with strong changes in species composition that can persist for decades (Haeussler *et al.* 1999, Bock and Van Rees 2002). Roads and other infrastructure for access may also have large impacts on boreal forest structure and function (Forman and Alexander 1998, Trombulak and Frissell 2000). In addition to forest areas directly and permanently removed by construction of roads and yarding areas, roads alter drainage patterns and other aspects of the physical environment, provide a corridor for invasion of exotic species, and provide increased access by humans who further impact the forest through hunting and fishing activities and fire ignition. Impacts of non-logging development on boreal forests, such as seismic survey lines, may also have large impacts on boreal forest structure and composition that persist for many decades (Lee and Boutin 2006).

Logging results in losses of wildlife species of conservation concern

While some species of boreal animals are generalists in that they can use a wide range of habitats, many species specialize on certain habitat types. The loss of a seral stage from an area, or of certain habitat features such as woody debris, can have important consequences for forest wildlife. Sufficient cover of mature and old growth forests is necessary for some species to be present in the landscape (Fisher and Wilkinson 2005), including a number of boreal species of special conservation concern such as the woodland caribou and the American marten (Brassard and Chen 2006).

Many studies have documented the effects of habitat loss and fragmentation on various species of animals (Fahrig and Merriam 1994; Fahrig 1997; Bender *et al.* 1998; Schmiegelow and Monkkonen 2002). There are a number of reasons for this loss, including outright habitat loss, the creation of barriers to movement (Shirley 2006), edge effects such as higher levels of predation and reduced interior habitat (Fahrig 1997), reductions in genetic variation, and higher susceptibility to local extinction following disturbance (Fahrig and Merriam 1994). Such losses and fragmentation of critical habitat types becomes of even greater concern in a changing climate, when habitat connectivity may be critical in permitting climate-induced migration. Logging typically has a homogenizing influence in landscapes in that a lower diversity of forest types and ages is present in post-logged than natural landscapes, especially with regard to late-seral forest types and associated habitat features (e.g., Malcolm *et al.* 2004). This not only has the effect of homogenizing the suite of resources available to species, providing fewer opportunities for plasticity under changed conditions, but also can result in losses of rare habitat types and populations that can serve as important source populations in facilitating migration. Such outlier populations have the potential to greatly increase the abilities of populations to migrate in response to warming (Clark 1998).

Box 1. The Southern Boreal Forest

The southern boreal forest is an area of special interest for conservation, containing the most diverse assemblages of species within the boreal forest (Vucetich *et al.* 2000). A number of bird, mammal and tree species reach their northern limit in the southern boreal forest, forming diverse communities with the more northern boreal elements (Goldblum and Rigg 2005; Hamann and Wang 2006; Kellman 2004). This creates a unique ecosystem that is not easily replaced. In addition, the southern boreal has suffered under a long history of anthropogenic influence, with very little late-seral boreal forest remaining (Boucher *et al.* 2006). Harvesting intensities are much higher in the south than north, and the forest landscape is much more fragmented (Achard *et al.* 2006; Young *et al.* 2006).

In the context of climate change, conservation of the dwindling intact areas of southern boreal forest takes on added importance as a valuable source of pre-adapted southern species and genotypes (Jump and Penuelas 2005). Boreal species that have southern distributions will have pre-adapted genotypes that will be able to take advantage of warming climate conditions in more northerly landscapes (Saxe *et al.* 200; Jump and Penuelas 2005). These genotypes have the potential to migrate from the southern boreal forest and travel north over many generations (Malcolm *et al.* 2002; Jump and Penuelas 2005). Deciduous tree species, which may benefit especially from increasing temperatures, may contribute negative feedbacks to warming through reduced albedo, increased evapotranspiration, and increased carbon uptake (Chapin *et al.* 2000; Eugster *et al.* 2000).

Maintenance of forested north-south corridors is essential for successful northward migration (Malcolm *et al.* 2002; Jump and Penuelas 2005). Both southern boreal species and southern boreal genotypes are essential for the resistance and adaptation of the boreal forest to climate change. In a climate change context, if the southern boreal is not sufficiently protected, the long-term function and persistence of the northern boreal forest is in doubt.

Intact boreal forest landscapes are more resistant and better able to adapt to climate change

Maintenance of intact boreal forest landscapes, with a relatively high incidence of late-seral and old growth stands, is likely to be important in promoting continued ecosystem stability in the face of climate change. Late-seral boreal forest stands are better able to resist climate change through their ability to moderate the microclimates experienced by individual trees and animals. The relatively high species and genetic diversity of intact forest landscapes, and the higher reproductive capacity of constituent trees, may also allow boreal forest ecosystems as a whole to withstand disturbance events, including those triggered by climate change.

The moderated microclimate of intact forests limits temperature stress, drought stress, and freeze-thaw damage

Intact forests buffer regional climate regimes by acting as heat sinks in the summer and heat sources in the winter (Noss 2001). The soil in intact forests is generally several degrees cooler in late spring and summer and several degrees warmer in late fall and winter than in open areas, delaying freeze-up in autumn and snowmelt in the spring (Rivers and Lynch 2004). When compared to bare ground, such as following a clear-cut harvest, forested soils have a thicker permafrost layer which is more stable over time (Stewart *et al.* 1998). Intact forests store and release water between times of water excess and water stress, which has the effect of compensating for irregular precipitation. In the spring, intact forests show an earlier onset and extended duration of snowmelt compared with bare ground systems (Sturm *et al.* 2005). Spring water availability is therefore more stable and less water is lost from the forest ecosystem. Given the predicted increase in extreme precipitation and drought events across boreal landscapes, the rapid loss of water from clear-cut and bare ground systems may delay recovery of disturbed and logged forests (IPCC 2007). Because intact forests are buffered from temperature extremes, intact forests are also likely to experience reduced freeze-thaw damage in both spring and fall. In experimentally manipulated forests, seedlings planted under the shelter of existing

forest stands experience reduced frost damage and show improved growth when compared with exposed seedlings (Nilsson *et al.* 2006).

The biodiversity of intact forests enable these communities to withstand climatic change and related disturbance events

Biodiversity can be viewed as insurance against unknown future changes and disturbances. Intact forest landscapes with a higher proportion of late-seral stands have greater genetic and species diversity than second-growth forests (Mosseler *et al.* 2003) and may serve as source populations for disturbance-sensitive species. Ecological theory in general predicts that forests with a greater variety of species are more likely to persist over time, as species are not affected by disturbance equally (Walker 1992; de Grandpre and Bergeron 1997). The more species an ecosystem has, the more overlap in functional niches between species, limiting the effect of a disturbance event on the forest as a whole (Walker 1992; Noss 2001). Boreal forests have only a few dominant tree species, and declines in boreal tree species diversity may thus have particularly large consequences. Widespread conversion of boreal mixedwood forests to aspen-dominated forests is predicted following industrial logging (Hearndon *et al.* 1992; Friedman and Reich 2005), a conversion projected to be intensified by climate change itself (Malcolm *et al.* 2005). This increase in single species dominance is likely to result in boreal forests that are extremely sensitive to climatic or biotic impacts on aspen (Hogg *et al.* 2002).

Maintenance of high genetic diversity within species is also likely to enhance population resistance to climate change and related disturbance events (Noss 2001). Kelly *et al.* (2003) found that European birch (*Betula lenta*) possessed “warm” year and “cool” year genotypes, improving the survival of the species under differing climatic outcomes (Jump and Penuelas 2005; Kelly *et al.* 2003). The presence of alternate genotypes for differing conditions also is found in old growth jack pine (Gauthier *et al.* 1996). Higher levels of genetic variation found in intact forest landscapes are expected to enhance the ability of boreal forest communities to persist despite changing climates and increased frequencies of disturbance events (Noss 2001; Frelich and Reich 2003; Jump and Penuelas 2005).

The genetic diversity of intact boreal forest landscapes also is likely to enhance adaptive responses to climate change. Boreal forest populations have always been under strong selective pressure to adapt to local climates (Saxe *et al.* 2001; Jump and Penuelas 2005). For example, “warm year” genotypes will likely increase in frequency under warming conditions (Kelly *et al.* 2003) over a much shorter time-scale than northward migration of southern pre-adapted genotypes (Jump and Penuelas 2005). Intact boreal forest landscapes also are likely to facilitate gene flow between species populations, which is essential for continued adaptation and migration (Jump and Penuelas 2005). Habitat patches must be close enough for pollen or propagules to disperse between them, a critical concern in fragmented boreal landscapes (Jump and Penuelas 2005).

The presence of reproductively mature trees enables intact forests to recover from direct and indirect climatic disturbance events

Forests with more reproductively mature trees are better able to replace lost individuals following disturbance events. Although some important boreal tree species, in particular black spruce and aspen, reproduce primarily through vegetative (asexual) means, reproduction through seed is necessary to ensure recolonization of completely deforested patches and to ensure genetic variation within populations (Lloyd *et al.* 2005; Romme *et al.* 2005). Reproductive maturity in boreal forest trees may require decades; for example, spruce species generally require c. 30 years to produce seed in quantity (Burns and Honkala 1990). Unlike clearcut logging, many natural disturbance events, such as forest fires or insect outbreaks, leave a substantial portion of reproductively mature trees behind (Stewart *et al.* 1998). These individuals are able to rebuild the ecosystem without human intervention, producing seedlings pre-adapted to the unique environment into which they are born.

Reproductively mature trees are able to produce large amounts of locally-adapted seedlings within one growing season, which may enhance forest regeneration. Intact forest landscapes with a higher proportion of mature trees may be better able to adapt to

changing climates by producing “warm year” and “warmer year” genotypes under progressively increasing temperature conditions (Kelly *et al.* 2003; Jump and Penuelas 2005). Seed produced under warm conditions gives rise to seedlings that are better adapted to warmer climates, while still adapted to local environmental conditions such as soil type, nutrient availability, and light competition (Saxe *et al.* 2001). Such seedlings are therefore better adapted to local conditions than southern genotypes that have migrated north (Jump and Penuelas 2005). Warm-adapted seedlings delay dehardening and flushing in the spring to protect against freeze-thaw damage, and are also able to take advantage of the late-season growing conditions through delayed growth cessation (Saxe *et al.* 2001).

Intact boreal forests will be able to migrate more quickly in response to climate change

As temperatures rise, the climate conditions that characterize the boreal biome will shift northwards. For plant species to migrate in any direction, forest fragments must be close enough to enable gene flow between them (Noss 2001; Jump and Penuelas 2005). Intact, contiguous boreal forest will be best able to keep up with rapidly changing climate conditions because of high connectivity and abundant propagule production (Noss 2001). Tree species with their northern limit in the boreal are predicted to increase in abundance within their current range, while also gaining new habitat in the north (Hamann and Wang 2006). Sugar maple and many other deciduous species are likely to benefit from both temperature increases and projected precipitation changes in the boreal forest (Goldblum and Rigg 2005; Kellman 2004). Conifer species may have even more to gain from increasing temperatures, and are predicted to expand into tundra landscapes (Saxe *et al.* 2001; Jump and Penuelas 2005; Lloyd 2005). Northward shifts in the forest-tundra boundary have been recorded in Alaska, and arctic shrub cover has been increasing north of the treeline (Lloyd and Fastie 2003; Tape *et al.* 2006). Within existing treeline populations, provided that water is available, tree growth and tree fertility have both increased with rising temperature (Gamache and Payette 2004; Stewart *et al.* 1998).

Wildlife survival and adaptation under climate change is greater in intact forest landscapes

Climate change is projected to cause a shift towards younger age classes and increasing fragmentation (Flannigan *et al.* 2000) and may thus mimic some of the effects of large-scale logging disturbances on wildlife populations. Interactions with habitat loss due to timber harvest are accordingly expected to result in even higher likelihoods of extinction for species reliant on late-seral stands (Kerr and Packer 1998). Conversely, conservation of intact boreal forest landscapes would give wildlife the greatest chance to persist under climate change.

Under climate change, wildlife will face environment shifts that are more rapid than those encountered in much of the paleological record (Malcolm *et al.* 2005; IPCC 2007). In order to survive in a changing environment, species must either migrate or adapt. In terms of migration, intact forests provide the corridors necessary for migration of many species. An example of this is the southern flying squirrel, which has migrated north through the more contiguous forests of south-eastern Ontario, but not the more fragmented south-western sections (Gray 2005) allowing it to extend far to the north of its historic range (Bowman *et al.* 2005). While modern harvesting methods have attempted to mimic natural disturbance by leaving corridors and retention blocks, they are insufficient for many species (Potvin and Bertrand 2004) and many studies recommend widening corridors and leaving larger blocks in order for better survival and utilization rates (Potvin and Bertrand 2004; Lopez *et al.* 2006).

A wealth of recent evidence indicates that many animal species are already responding to climate change, exhibiting earlier breeding seasons (Reale *et al.* 2003), earlier arrival of migrants (Tottrup *et al.* 2006) and multiple generations per season. However, if change is too rapid, species may not be able to adapt their behaviours and/or breeding phenologies rapidly enough (Fahrig and Merriam 1994). Intact forest landscapes have the ability to slow the rate of change upon a landscape, by moderating local climate and by providing

alternate habitats (Noss 2001). This slowed rate of change is expected to aid in the adaptation of boreal wildlife to climatic shifts.

Intact boreal forest landscapes will mitigate climate change

Intact boreal forests sequester carbon and are home to large carbon stores

Large amounts of carbon are stored in the northern boreal forest ecosystems (Tans *et al.* 1990), which contain up to one-quarter of global terrestrial carbon stocks (IPCC 2000). Recently however, there has been a growing controversy as to whether boreal forests in Canada continue to sequester carbon (Kurz and Apps 1999; Ju *et al.* 2006) or have become net carbon sources (Myneni *et al.* 2001; Goodale *et al.* 2002; Goetz *et al.* 2005). The reason given for the switch to an overall carbon source has been an increase in disturbance regimes, either through increases in insect defoliation, or increases in fire disturbance (Myneni *et al.* 2001; Goetz *et al.* 2005). This situation is exacerbated by continued high levels of logging, as it can represent approximately 25% of Canadian boreal forest area lost in a given year (Kurz and Apps 1999). Industrial-scale logging likely results in even higher carbon losses since harvest is conducted in high-volume areas containing higher levels of carbon, and removes woody debris that would otherwise remain following natural disturbances (Kurz *et al.* 1998).

A traditional view has been that late-seral forests are carbon neutral (Desai *et al.* 2005); however, recent studies indicate that many old forests continue to sequester carbon. For example, Griffis *et al.* (2003) found that old growth spruce, aspen, and jack pine forests were all moderate carbon sinks, absorbing 35-122 g C m⁻² per year. Bond-Lamberty *et al.* (2004) found black spruce continued to sequester carbon for well over a century. Law *et al.* (2001) and Carey *et al.* (2001) found similar results in mature ponderosa pine and subalpine forests, respectively. Recent studies of ancient temperate forests also have documented surprisingly large carbon sinks (Knobl *et al.* 2003, Paw *et al.* 2004; Winner *et al.* 2004; Guan *et al.* 2006); likewise, old growth tropical forests also appear to operate as strong carbon sinks (Malhi *et al.* 1998, Loescher *et al.* 2003, Takanashi *et al.* 2005). This is an important result as it indicates that forest removal not only results in losses in above- and below-ground carbon stocks, but also in lower sequestration until the regenerating forest returns to pre-harvest rates of net carbon uptake.

The effect of climate change on carbon sequestration rates is uncertain. Some studies have indicated that carbon sequestration rates may increase with warming and increased atmospheric CO₂ concentrations (White *et al.* 2000), whereas others have predicted decreases in carbon uptake (Yarie and Parton 2005). Still others have concluded that boreal forests will become carbon sources in the future (Lindroth *et al.* 1998; Makipaa *et al.* 1999). The response of late-seral forests to climate change also will depend on the specific suite of tree species present (Yarie and Parton 2005) and site conditions (Bergeron *et al.* 2007). It is important to remember, however, that maintaining old growth forest cover is important irrespective of sequestration rates because such forests contain the largest stocks of carbon (Harmon *et al.* 1990). While replacement of old stands may result in higher local net primary productivity (NPP) and net ecosystem productivity (NEP) rates (i.e. increased rate of carbon sequestration) due to greater growth in young- and intermediate-aged stands (Law *et al.* 2003; Coursolle *et al.* 2006), on a regional scale, industrial-scale logging results in less carbon within the landscape (Fredeen *et al.* 2005), with some stands taking more than a century to recover to pre-harvest carbon levels and many young stands acting as carbon sources for more than a decade following harvest (Pypker and Fredeen 2002; Wirth *et al.* 2002; Amiro *et al.* 2006).

Intact forests are slowing permafrost melt and soil saturation in response to rising temperatures

As permafrost melts, newly thawed soil releases carbon through soil respiration. In the western boreal forest, 1.6- and 30-fold increases in CO₂ and CH₄ are associated with permafrost melt (Turetsky *et al.* 2002). Intact forests buffer regional climate conditions and insulate permafrost from warm air temperatures (Stewart *et al.* 1998; Eugster *et al.* 2000). The permafrost layer is thicker and more stable throughout the year under intact forests in comparison to adjacent tundra or clear-cut landscapes (Stewart *et al.* 1998; Iwahana *et al.* 2005). Increases in air temperatures of only 1-2 degrees have the potential to thaw out large expanses of discontinuous permafrost, an outcome that may be delayed

several decades by maintaining high vegetation cover (Camill and Clark 1998; Eugster *et al.* 2000; Osterkamp *et al.* 2000). Although widespread permafrost melt is likely given the rapid warming across the boreal, intact forest cover may delay thaw by decades or even centuries (Camill and Clark 1998). Intact boreal forests thus mitigate a serious positive feedback to warming by reducing the rate at which greenhouse gases are emitted from thawing northern soils (Eugster *et al.* 2000).

The saturation of northern soils following permafrost melt is predicted to increase methane release through soil anaerobic respiration (Chapin *et al.* 2000). Predicted increases in precipitation across the boreal region may exacerbate this potentially serious positive feedback to climate warming. Forested systems generally have lower soil moisture content than bare ground or tundra systems, likely due to the high water demands of forest vegetation (Iwahana *et al.* 2005, Morishita *et al.* 2005). This reduced soil moisture content is associated with reduced methane release in forested sample plots (Morishita *et al.* 2005). Expansion and intensification of boreal forest species above the northern treeline, which will be facilitated by adjacent intact forests to the south, is therefore likely to enhance carbon sequestration through reduced permafrost melt and reductions in water saturation of northern soils (Saxe *et al.* 2001).

Box 2: Boreal feedbacks to Climate Change

Over the next 50-100 years, the Earth's boreal regions are projected to experience an increase in temperature of 4-10°C as the planet's atmosphere undergoes a doubling or even tripling of atmospheric CO₂ concentrations (IPCC 2007). On a physiological level, boreal forests may respond positively to increased CO₂ levels and temperature provided that water is available, and this has been highlighted as a possible negative feedback that may decrease rates of climate change (Makipaa *et al.* 1999). However there are a number of other possible feedbacks that could override these effects. In this section, we highlight some of the feedbacks that may influence the extent and timing of climate change.

Changes in the fire regimes

Although fire is a natural component of boreal ecosystems, large-scale changes are projected to occur in Canadian boreal fire regimes due to climate change. Overall fire frequency is expected to increase; however, the degree of change depends on the climate model used and the boreal region examined (Stocks *et al.* 1998; Flannigan *et al.* 2005). Where fire frequency and intensity increases, large amounts of CO₂ may be released into the atmosphere (Wang *et al.* 2003). This effect may in part be mitigated by higher NEP in recovering stands and higher albedo of recently burned areas, but in the short term it would constitute a positive feedback (Stocks *et al.* 1998). In the long term, the overall carbon balance will depend on the fire return interval (Randerson *et al.* 2006). In some areas, such as the eastern boreal region, fire frequency may decline due to increased precipitation (Flannigan *et al.* 2005). This would likely allow these forests to increase in average age and hence sequester more carbon over time.

Changes in vegetation phenology

In areas of existing boreal forest, an earlier onset of spring may allow NPP to increase through increased photosynthesis, although recent remote sensing studies have not detected this effect in Canadian boreal forests (Goetz *et al.* 2005). In some areas NPP will decrease due to temperature stress and drought, lowering carbon uptake particularly during late-season drought periods (Barber *et al.* 2000).

Soil warming

Soil warming in boreal regions has the potential to create a very large positive feedback in the global carbon cycle (Goulden *et al.* 1998). The boreal forest contains large amounts of carbon in the soil, with an overall average of approximately 84% of total ecosystem carbon (Dixon *et al.* 1994; IPCC 2000). If warming of the boreal soil occurs, increased levels of CO₂ could be added to the atmosphere due to enhanced decomposition (Carrasco *et al.* 2006). While some of this CO₂ feedback will be mitigated by increased carbon inputs from vegetation (Jones *et al.* 2005), the overall change will likely be negative with strong regional differences (Jones *et al.* 2005). Additionally, changes in soil moisture regimes that promote drying of inundated areas could result in rapid decomposition of organic soil layers (Preston *et al.* 2006)

If warming occurs on permafrost areas of the northern boreal forest, profound changes are likely to occur (Gorham 1991) as large amounts of organic matter are exposed to decomposition. This newly thawed organic matter is highly susceptible to decomposition since it is thought to have a large labile component (Dutta *et al.* 2006). For example, Turetsky *et al.* (2002) found a 1.6-fold increase in soil CO₂ efflux and a 30-fold increase in CH₄ efflux following permafrost melt. The duration of CO₂ and methane emissions is likely to depend strongly on the moisture regime of the permafrost. In areas where drying occurs due to drought or drainage, CO₂ emissions would increase, but CH₄ emissions would be reduced (Moore and Knowles 1989). In areas where the water table is maintained, CH₄ emissions could remain high over a decade or more (Gorham 1991).

Logging and human land-use

As the boreal forest experiences warming, some areas may undergo dieback (Hogg *et al.* 2002), or experience greater rates of disturbance (Stocks *et al.* 1998). Less drastic changes such as reduced growth rates may also occur (Spittlehouse 2005). These changes may force the logging industry to modify their logging practices. If these changes occur it would have important implications for the carbon balance of the boreal ecosystem.

Some proposed forest management efforts could help mitigate climate change effects. The use of provenances with a wider range of tolerance, planting mixed provenances, and planting of more climatically adapted provenances could help mitigate climate changes by maintaining productivity (Ledig and Kitzmiller 1992; Spittlehouse and Stewart 2003). However, because of the uncertainty associated with climate change some forest managers are unwilling to risk lower current productivity for possible higher levels in the future (Spittlehouse 2005).

Other potential management decisions in response to climate change impacts may result in positive feedbacks. In areas experiencing increasing disturbance from fire or insects, salvage logging is likely (Spittlehouse and Stewart 2003), removing more carbon which otherwise would have remained in the woody debris and eventually transferred in part to the soil pools (Manies *et al.* 2005). Additionally, if previously harvested areas further degrade due to climate change, timber companies may look to unlogged areas for timber supplies. As detailed above, increased logging in intact forest areas results not only in carbon emissions related to losses of live trees and soil, but potentially in increases in fire frequency due to increased human initiation of fires. If more logging occurs in permafrost areas, the process of permafrost melting may accelerate (Camill and Clark 1998), resulting in increased CO₂ and CH₄ emissions.

Box 3: Albedo and other non-carbon climatic feedbacks

Although the vast majority of literature related to land-use in relation to climate change has focused on emissions of CO₂ and other greenhouse gases, forests interact with climate via other mechanisms as well. Albedo is defined as the ratio of radiation reflected into space relative to total radiation intercepted by an ecosystem. In general, forested ecosystems have a lower albedo than non-forested areas, an effect that is particularly pronounced for coniferous forests during periods of snow-cover. Removal of trees from logging and other disturbances can thus result in a cooling effect that is especially pronounced in boreal forests during winter (Bonan *et al.* 1992). A recent study by Bala *et al.* (2007), the first to consider climate effects of deforestation mediated by both carbon

and radiation, received considerable media attention, reporting a finding that deforestation of the boreal region would result in climatic cooling due to albedo effects. The Bala *et al.* study concluded that “afforestation projects in high latitudes would be counterproductive in mitigating global-scale warming”.

The physical basis for albedo effects analyzed by Bala *et al.* (2007) and Bonan *et al.* (1992) is well-established; however, these simulation studies do not represent realistic biological dynamics associated with deforestation. Both studies rely essentially on a “biome substitution” to simulate deforestation: i.e., the physical attributes of boreal forests are replaced with those of a boreal grassland or agricultural system. This modeling strategy has several critical limitations. First, there is no possibility for losses of soil carbon to be associated with forest harvest. As detailed above, this is an unrealistic assumption; since the vast majority of carbon in boreal forest ecosystems is belowground, this assumption may drastically understate potential carbon losses. Second, “biome substitution” does not allow for forest re-growth. At a landscape scale, large-scale logging in the boreal would not actually result in a replacement of boreal forests with grasslands, but rather replacement of old boreal forests with young, regenerating stands. This would almost certainly result in only small changes in albedo, but large losses of carbon. Third, modeling studies have not used actual data on albedo of post-disturbance boreal forests in simulations. Following fire disturbance there is generally a short-term reduction in growing-season albedo due to blackened surfaces (Amiro *et al.* 2006). In each of these aspects, modeling studies to date, such as that of Bala *et al.* (2007), have over-estimated the potential cooling effects of albedo changes, and under-estimated potential carbon losses associated with boreal deforestation.

Studies that would more realistically examine the climate consequences of alternative scenarios for boreal forest conservation management are an important research priority. Changes in albedo following forest harvest are complex and influenced by many factors, including exposure and duration snow cover, stand structure, surface roughness, and forest species composition (Ni and Woodcock 2000; Davidson and Wang 2005; Amiro *et al.* 2006). In addition, changes in disturbance regimes that might give rise to changes in

albedo would have large consequences for non-CO₂ radiative forcing agents, such as methane, nitrous oxide, and ozone (Bala *et al.* 2007). In the southern boreal forest, increased disturbance levels and dieback of some species associated with climate change will likely alter vegetation composition (Hogg and Bernier 2005). With a possible shift to grassland and deciduous species, this could result in a negative feedback through increased albedo, although these water-limited systems might have lower carbon storage (Hogg and Bernier 2005). Expansion of the boreal into tundra regions will cause an increase in vegetative carbon stocks (Wilmking *et al.* 2005); however, northward spread of the treeline would result in a lowering of the albedo, and a possible positive feedback to climate change (Betts 2000; Callaghan *et al.* 2004). In addition, soil carbon stores could be reduced during the shift from tundra to forested areas (Wilmking *et al.* 2005). In summary, modeling studies do suggest important climatic effects driven by albedo changes in boreal forests, but the science on this topic remains preliminary.

Conservation of the Canadian boreal forest in global perspective

The present review has outlined several inter-related topics that together argue that conservation of Canada's boreal forest is important in mitigating global climate change and in resisting and adapting to climate change already occurring in this biome. Due to climatic constraints on productivity, Canada's boreal forests are unlikely to serve as strong carbon sinks relative to temperate or tropical forests. However, the vast carbon stocks represented by organic soils in the Canadian boreal represent a serious threat to the future global climate. Since climate change effects are predicted to be most pronounced in the boreal region, efforts to maintain or enhance the ability of Canada's boreal forests to adapt to climate change are critical. Enhanced conservation of Canada's boreal can serve as "insurance" to limit carbon emissions and to avoid negative consequences of climate change on forest regeneration, maintenance of permafrost, and biodiversity.

In the global perspective, the contributions of the forest sector to combating climate change are almost certainly greatest in the tropics. Most of the carbon emissions attributable to deforestation derive from tropical forests (Houghton 2005b). In addition,

potential rates of carbon sequestration are highest in this biome, and there is increasing evidence that intact old-growth tropical forests operate as strong carbon sinks (Loescher *et al.* 2003; Stephens *et al.* 2007). However, Canada is unique as the only Western developed country with vast areas of intact “frontier” forests. Although the underlying biology is profoundly different, the decisions that Canada makes regarding forest conservation in relation to climate change will undoubtedly influence decisions globally, including those of developing countries in the tropics.

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