Greenpeace is an independent, campaigning organization which uses non-violent, creative confrontation to expose global environmental problems and to focus attention on solutions essential to a green and peaceful future. Founded in Canada in 1971, Greenpeace is now the world's largest membership-based environmental organization, with offices operating in 40 countries and more than 2.8 million members worldwide.

www.greenpeace.ca

Greenpeace Canada

33 Cecil Street, **Toronto**, Ontario, M5T 1N1
454, avenue Laurier Est, 3e étage, **Montréal** (Québec) H2J 1E7
1726 Commercial Drive, **Vancouver**, British Columbia, V5N 4A3
6238 - 104 Street NW, **Edmonton**, Alberta, T6H 2K9

1 800 320-7183

100%

Turning Up the Heat: Global Warming and the Degradation of Canada's Boreal Forest

Turning Up the Heat

Global Warming and the Degradation of Canada's Boreal Forest

www.greenpeace.ca

Published by Greenpeace Canada
March 2008
ISBN: 978-0-9732337-6-6

Authors

Christy Ferguson, *Greenpeace Canada*
Elizabeth A. Nelson, *University of Toronto*
Geoff G. Sherman, *University of Toronto*

Design and layout

Brigitte Binet

Acknowledgements

The authors would like to thank the many individuals and organizations who helped to produce this report.

Dr. Jay Malcolm and Dr. Sean Thomas of the University of Toronto Faculty of Forestry contributed immensely to the research and review of this report.

Richard Brooks, Melissa Filion, Kim Fry, Rolf Skar, Dr. Janet Cotter, Dr. Jeff Wells, Phil Aikman, and Nicolas Mainville all gave valuable feedback on various drafts.

Dr. Christoph Thies, Oliver Salge, and Justin Podur reviewed and commented on the technical report on which this report is based in part.

Cheryl Johnstone copy edited the text, and Aladdin Diakun helped with production.

Finally, we would like to thank Global Forest Watch, the Boreal Songbird Initiative, and CPAWS Wildlands League for providing maps, graphics, and photos.

Photos credits: Todd Korol/Aurora/Getty Images, Garth Lenz, J Henry Fair, J.D. Taylor, Ducks Unlimited, Jay Forsyth, Daniel J. Cox/NaturalExposures.com, CP/Thunder Bay Chronicle/Jamie Smith

Printed on 100 per cent post-consumer recycled, chlorine-free paper that is manufactured with wind-generated energy.

100%

Table of contents

Glossary

Aboveground carbon: The carbon stored in a forest's aboveground biomass (i.e., in its trees and plants), as opposed to the carbon stored in its soils.

Albedo: The ratio of radiation an ecosystem reflects into space relative to the radiation it intercepts.

Carbon: An element present in all organic compounds. Represented by the symbol "C". Carbon is present in the atmosphere as carbon dioxide (CO_2) gas.

Carbon dioxide: A greenhouse gas. Represented by the symbol "CO_2".

Carbon sequestration: The removal and storage of carbon from the atmosphere.

Carbon sink: An ecosystem that removes more carbon dioxide from the atmosphere than it emits.

Carbon source: An ecosystem that emits more carbon dioxide into the atmosphere than it removes.

Carbon stock, or store: The carbon stored within an ecosystem.

Deforestation: The direct, human-induced conversion of forested land to non-forested land.

Disturbance: An event that causes a change in structure or composition of a forest. A disturbance can be natural (e.g., fire, insect outbreak) or human-caused (e.g., logging).

Fragmentation: The breakup of an intact forest area, e.g., by logging or road building.

Greenhouse gas: A gas that contributes to the greenhouse effect. Carbon dioxide, methane, nitrous oxide, and three groups of fluorinated gasses (sulphur hexafluoride, hydrofluorocarbons and perfluorocarbons) are all greenhouse gasses.

Intact forest: An area of forest in its natural state, unbroken by roads or other human infrastructure. Describes non-treed areas within the forest zone (e.g., swamps and peatlands) in addition to treed areas.

Methane: A greenhouse gas. Represented by the symbol "CH_4".

Paludification: A process whereby newly melted soils become saturated with water.

Peat: An accumulation of partially decayed vegetation matter, formed when decaying plant matter from mosses, sedges, grasses, shrubs, or trees accumulates in permanently waterlogged conditions. Peat forms in wetlands or peatlands, also referred to as bogs, moors, muskegs, and mires.

Permafrost: Soil that remains frozen throughout the year.

Executive summary

Canada's Boreal Forest is dense with life. Richly populated with plants, birds, animals, and trees; home to hundreds of communities; and a wellspring of fresh water and oxygen, the Boreal has long been recognized as a critically important ecosystem. But as rising temperatures threaten to destabilize the planet, the potential of the Boreal's carbon-rich expanses to mitigate global warming continues to be underestimated.

Based in part on a comprehensive review of scientific literature by researchers at the University of Toronto[1], this report examines the complex relationship between global warming and Canada's Boreal Forest. It finds that the intact areas of the Boreal are not only actively helping to slow global warming, but are also helping the forest itself to resist and recover from global warming impacts. These unfragmented areas are also helping trees, plants, and animals to migrate and adapt in response to changing climate conditions.

At the same time, however, it finds that logging is destabilizing the Boreal Forest in ways that may exacerbate both global warming and its impacts. The forest products industry and government regulators adamantly deny that logging in Canada's Boreal affects the climate. But research shows that when the forest is degraded through logging and industrial development, massive amounts of greenhouse gasses are released into the atmosphere, and the forest becomes more vulnerable to global warming impacts like fires and insect outbreaks. In many cases, these impacts cause even more greenhouse gasses to be released, driving a vicious circle in which global warming degrades the Boreal Forest, and Boreal Forest degradation advances global warming. If left unchecked, this could culminate in a catastrophic release of greenhouse gasses known as "the carbon bomb".

For these reasons, the report concludes that greenhouse gas emissions must be drastically reduced and that intact areas of Canada's Boreal Forest must be protected—for the sake of the forest, and for the sake of the climate.

Global warming is already having an impact on Canada's Boreal Forest

With global warming causing warmer, drier conditions in parts of the Boreal Forest, droughts, forest fires, and insect infestations are all on the rise. Drought stress has already increased, particularly in western Canada[2,3], as have forest fires. While fires are a natural part of the Boreal ecosystem, they're becoming longer, more frequent, and more intense as time goes on[4, 5, 6]—and the more intense forest fires get, the more carbon they release into the atmosphere[7]. Warmer temperatures are also leading to destructive insect outbreaks. The damage caused by the mountain pine beetle and other major defoliating insects in the Boreal is already severe, and is projected to increase as temperatures continue to rise[8, 9]. Lastly, while early predictions suggested that warmer temperatures would enhance tree growth, more recent research shows that higher temperatures are actually reducing the growth and survival of some Boreal trees[10, 11, 12].

Global warming is predicted to cause additional problems in the Boreal as well. As tree, plant, and animal species migrate at different rates to adapt to changing temperatures, for example, interdependent relationships may be disrupted[13].

These disruptions, combined with other predicted problems, could lead to die-offs in species already at risk, including the woodland caribou, the wolverine, and the American marten.

Large intact areas of the Boreal Forest better resist and recover from global warming impacts

Research suggests that intact areas of the Boreal Forest—those areas that remain in their natural states—will be better able to resist and recover from global warming impacts than those areas fragmented by roads, logging, mining, or other human activity. By maintaining stable local climates, intact forests shield the trees, plants, and animals within them from the rapid and sometimes erratic changes happening in the broader climate, giving them more time to migrate and adapt[14]. And when trees, plants, and animals do migrate, intact forests provide the contiguous corridors they need in order to do so successfully[15]. Further, because they tend to have more mature trees and higher levels of biodiversity compared to areas that have been logged, intact areas of the Boreal Forest will be better able to resist and recover from global warming impacts such as drought, forest fires, and insect outbreaks[16, 17, 18, 19, 20].

While the more southern areas of the Boreal Forest have already been severely fragmented by logging and development, research shows that protecting what remains of these biologically rich areas is essential for facilitating the adaptation and migration that will allow the vast intact areas of the northern Boreal to survive in a changing climate[21, 22].

Intact areas of the Boreal Forest are helping to mitigate global warming

The Boreal plays a vital role in curbing global warming by absorbing carbon dioxide out of the atmosphere and storing it in its trees and soils. Canada's Boreal Forest stores an estimated 186 billion tonnes of carbon[23], an amount equal to 27 years worth of carbon emissions from the burning of fossil fuels worldwide[24]. Eighty-four per cent of this is stored in the forest's soils[25].

Intact areas of the Boreal are also helping to mitigate global warming by slowing the melt of Canada's expansive areas of permafrost. When permafrost melts, large quantities of carbon dioxide and methane—a greenhouse gas 21 times more potent than carbon dioxide—are released into the atmosphere[26, 27]. Given the rapid warming happening across the Boreal, widespread permafrost melt is likely[28]. But research shows that intact forest cover may delay thawing by decades or even centuries[29, 30, 31].

Logging is destabilizing the Boreal Forest and contributing to global warming

With over 750,000 hectares (1.85 million acres) of the Boreal Forest cut every year[32], logging is exacting a considerable toll on the climate. An estimated 36 million tonnes of aboveground carbon is directly removed from the Boreal each year by logging alone—more carbon than is emitted each year by all the passenger vehicles in Canada combined[33]. And this number doesn't account for the additional carbon lost from the forest's soils, or for the 68,000 hectares (168,028 acres) deforested each year through the construction of logging roads and landings[34, 35]. Further, research shows that logged areas continue to emit carbon long after the trees have been removed—often for 10 years or more—as the amount of carbon emitted through decomposition and decay outstrips the amount of carbon absorbed by young, growing trees[36, 37].

Logging also contributes to carbon dioxide and methane emissions by accelerating permafrost melt, and weakens the forest's ability to resist and recover from global warming impacts. By reducing the diversity of the forest, logging makes it more vulnerable to diseases, insect outbreaks, and other threats. And by eliminating the intact corridors that animals, trees, and plants need in order to migrate and adapt, it reduces the ability of the ecosystem as a whole to function and thrive.

Setting the carbon bomb

If left unchecked, these problems could culminate in a catastrophic scenario known as "the carbon bomb": a massive release of greenhouse gasses into the atmosphere driven, for example, by a widespread outbreak of forest or peat fires. As Greenpeace first warned in its 1994 report *The Carbon Bomb*, because Canada's Boreal Forest contains so much carbon, a rapid release into the atmosphere could cause a disastrous spike in global emissions.

Solutions

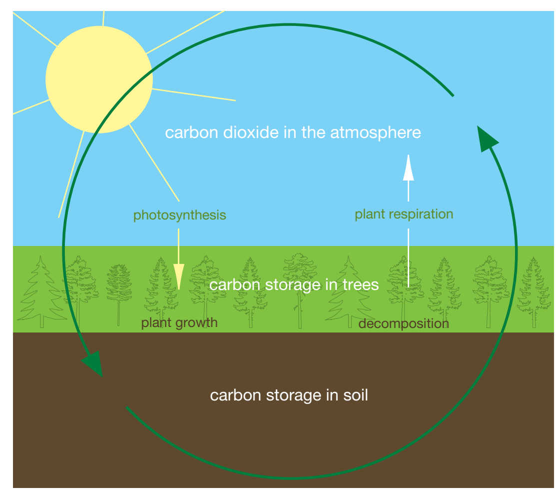
Reducing greenhouse gas emissions from fossil fuels and stopping tropical deforestation have both been widely recognized as measures essential for curbing global warming. As this report shows, safeguarding Canada's Boreal Forest is vital as well. Yet under current legislation, only 8.1 per cent of the large intact areas of Canada's Boreal are protected from industrial development, while more than 45 per cent of its treed areas are under license to logging companies. Greenpeace is calling on government and industry decision-makers around the world to help protect Canada's Boreal Forest from destructive industrial development. Only through immediate and comprehensive action can we save what's left of the Boreal, and ensure that the global climate remains a liveable one.

The carbon cycle

Carbon is one of the most common elements on earth. It exists in biological materials as carbon (C), and in the atmosphere as carbon dioxide (CO_2). It is so common, in fact, that life on earth is described as "carbon-based". Carbon moves naturally between its four major pools—vegetation, soils, fossil fuels, and the atmosphere—in a process known as the carbon cycle.

All organisms, whether living or dead, exchange carbon with their surroundings. Trees, for example, absorb carbon dioxide from the atmosphere through photosynthesis, store it as carbon within their tissues and fluids, then return it to the atmosphere as carbon dioxide through respiration.

In a natural ecosystem, this process is largely a balanced one. But fossil fuel burning, deforestation, and other human activities have caused massive amounts of stored carbon to be released into the atmosphere very rapidly, amplifying the greenhouse effect and disrupting the Earth's climate.



Introduction

Global warming is believed to be the most serious environmental threat facing the planet today. From fires to floods to hurricanes, its impacts are already being felt around the world. And leading climate scientists warn that if we allow global temperatures to rise more than 2 degrees Celsius above the global norm, up to 30 per cent of plant and animal species risk extinction, and about 15 per cent of ecosystems are likely to be seriously affected[38].

Forests play an essential role in regulating the global climate. They sequester and store carbon, they conserve biodiversity, and they stabilize local climates. But the world's last great forests—the Amazon, the Congo, the Boreal, the Paradise forests of Asia-Pacific—are all actively threatened by logging and other industrial activity. While due attention is starting to focus on tropical forests, the role of northern forests in mitigating global warming continues to be underestimated.

In 1994, Greenpeace published a report titled *The Carbon Bomb: Global Warming and the Fate of the Northern Boreal Forests*, which called on policy and decision makers to "radically rethink and change energy policies and logging practices in boreal forest countries in order to protect and preserve the climate and biodiversity"[39]. Fourteen years later, that call is even more urgent. Since *The Carbon Bomb* was published, scientific consensus around the reality and risks of global warming has solidified, public support for solutions has rallied, and the consequences of ignoring a looming crisis have become all too real. But political and corporate action have been weak. And as a result, greenhouse gas emissions continue to rise, while the forest continues to be degraded. Between 1990 and 2005, Canada's greenhouse gas emissions rose by 25 per cent (to 32.7 per cent over Canada's Kyoto target)[40]; and 41 per cent of the treed area of the Boreal Forest has already been fragmented by logging and industrial development[41].

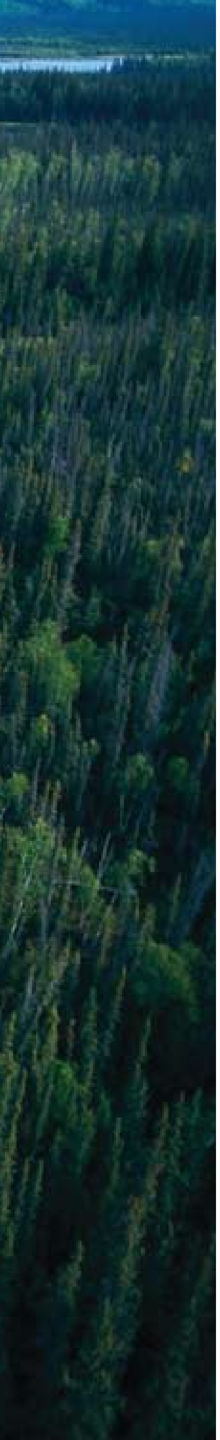
This new report is based in part on a comprehensive review of scientific literature by researchers at the University of Toronto[42] and therefore reflects the most current state of knowledge on the relationship between global warming and the Boreal Forest. We urge government and industry decision-makers in Canada and abroad to consider its findings seriously, and to take the immediate action necessary to protect the forest and the climate.

By the numbers

- At 545 million hectares, or **5.45 million square kilometres** (1.3 billion acres), Canada's Boreal Forest encompasses almost **53 per cent** of Canada's total landmass, and includes **90 per cent** of Canada's remaining intact forest landscapes.
- Over the next **50–100 years**, the Earth's boreal regions could experience temperature increases of between **4 and 10 degrees Celsius**[43].
- Canada's Boreal Forest stores **186 billion tonnes** of carbon[44], equal to 27 years' worth of global carbon emissions from the burning of fossil fuels[45].
- An average of **84 per cent** of the carbon in the Boreal Forest is stored in its soils[46].
- Mature areas of the Boreal can contain over **80 tonnes** of carbon per hectare in their trees and aboveground vegetation[47, 48].
- Research has shown that some Boreal trees continue to accumulate carbon at well **over 200 years of age**[49].
- As much as **7,600,000 hectares** (18,780,000 acres) of forest—an area larger than Ireland—burn in Canada each year[50].
- According to one study, the area of North American Boreal burned by forest fires **doubled** between 1970 and 1990[51].
- The area of forest lost to insects in the Boreal is up to **eight times** greater than the area burned by forest fires[52].
- Over **750,000 hectares** (1.85 million acres) of the Boreal Forest—an area almost six times larger than New York City— is logged every year[53].
- Roughly **30 million tonnes** of aboveground carbon are removed from Canada's Boreal Forest each year by logging alone—more carbon than is emitted each year by all the passenger vehicles in Canada combined[54].
- In addition, an estimated **68,000 hectares**, or 168,028 acres, per year—an area larger than the city of Toronto[55, 56]—is directly deforested for the construction of logging roads and landings.
- In many cases it takes **over 100 years** for the carbon stocks in logged forests to return to pre-logging levels[59, 60].
- Increases in air temperature of only **1–2 degrees Celsius** have the potential to thaw out large expanses of discontinuous permafrost[61].
- In the western Boreal Forest, a **1.6-fold** increase in carbon dioxide release and a **30-fold** increase in methane release associated with melting permafrost have already been documented[62].
- Under current legislation, only **8.1 per cent** of the large intact areas of Canada's Boreal Forest are protected from industrial development[63].
- More than **45 per cent** or **154 million hectares** (382 million acres), of the treed area of the Boreal is under license to logging companies[64].

Canada's Boreal Forest

Canada's Boreal Forest stretches across the country, from the Yukon Territory in the west to the province of Newfoundland and Labrador in the east. At 545 million hectares, or 5.45 million square kilometres (1.3 billion acres), it encompasses almost 53 per cent of Canada's total landmass, and includes 90 per cent of Canada's remaining intact forest landscapes. Its treed area covers 310 million hectares (766 million acres), while the remaining 235 hectares (581 million acres) comprise peatlands and other treeless areas.



The Boreal Forest encompasses a diverse and awe-inspiring landscape of granite outcrops, lakes, rivers, and marshes, interspersed with pine, spruce, fir, aspen, and poplar forests. Numerous wildlife species, including moose, caribou, lynx, bear, wolverine, and wolf, live in its vast expanses. At least three billion birds, including eagles, hawks, owls, and geese, accounting for 30 per cent of North America's songbirds and 40 per cent of its waterfowl, nest in its forested areas and wetlands.

Canada's Boreal Forest also contains a rich cultural legacy and is a source of sustenance for many of the indigenous peoples of Canada—the First Nations and Métis. Almost 80 per cent of Canada's more than one million aboriginal people live in more than 600 communities in Canada's forest regions, the majority in the Boreal Forest. Many of these communities depend on the wilderness, water, and wildlife of these places for their livelihoods and cultures.

Global warming and the Boreal Forest

Over the next 50–100 years, the Earth's boreal regions could experience temperature increases of between 4 and 10 degrees Celsius[65]. As the planet's atmosphere undergoes a doubling or even tripling of atmospheric CO_2 concentrations[66], the Boreal Forest will come under increasing stress. Climate modellers generally agree that the pole-ward regions of the globe, including the Boreal Forest, will experience the largest increases in temperature under global warming[67].

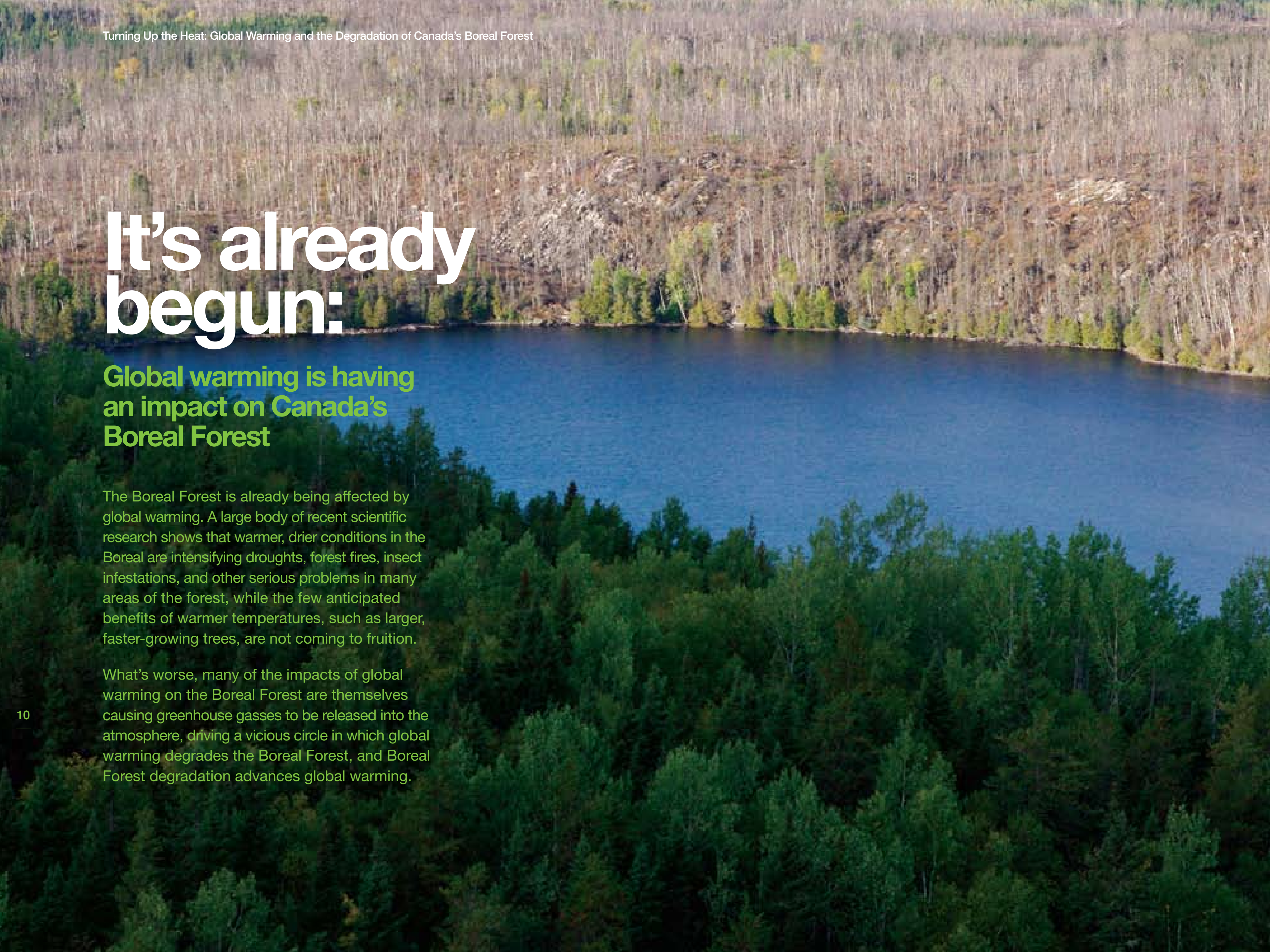
These temperature increases are likely to hit the Boreal Forest hard, as its physical and ecological characteristics are closely tied to variations in climate. Canada's Boreal Forest is vast, and its structure and composition vary across the landscape.

This variance is largely driven by two climatic gradients: one south-to-north, and one east-to-west. From south to north, solar radiation decreases, as do temperature and light intensity; from east to west, precipitation decreases and the frequency of natural fires increases. Because the Boreal Forest is so closely tied to these climate gradients, it is likely to undergo large and rapid changes under warming conditions[68, 69].

The Earth's green crown

Canada's Boreal Forest is immense, but it comprises only a fifth of the great boreal forest that encircles the northern hemisphere. In its entirety, the global boreal forest covers 25 million square kilometres of land, or 11 per cent of the Earth's land surface[70]. Sometimes called "the Earth's green crown", it ranges from Alaska in the far west, throughout Canada, across Norway, Sweden, and Finland, through Russia, and into parts of China, Mongolia, the northern Korean Peninsula, and northern Japan. Worldwide, the boreal forest holds an immense pool of carbon—approximately one quarter of the planet's land-based carbon stock[71].

While this report is focussed on Canada's Boreal Forest, its findings are of great relevance for boreal regions throughout the world. The boreal forests of Northern Europe, Russia, and Asia are closely related to Canada's Boreal Forest. As the world's climate continues to warm, these forests are likely to undergo similar impacts. Ultimately, therefore, a pan-boreal perspective is needed to safeguard the world's great northern forests and the enormous stores of carbon contained within them. The conclusions and recommendations made in this report, while in many ways specific to Canada's Boreal Forest, should serve as a resource for research and action in boreal regions worldwide.

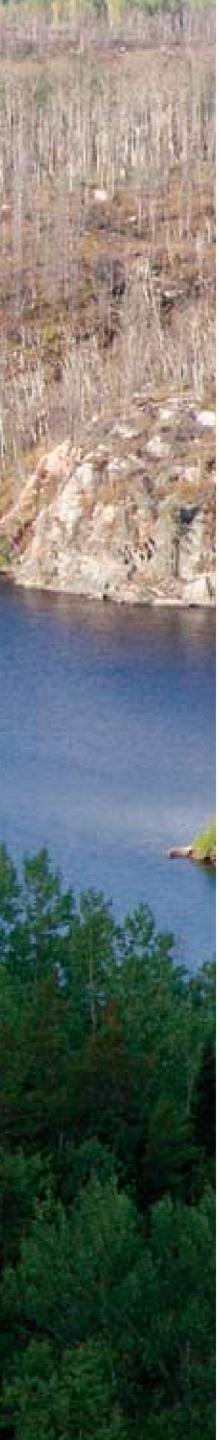


It's already begun:

Global warming is having an impact on Canada's Boreal Forest

The Boreal Forest is already being affected by global warming. A large body of recent scientific research shows that warmer, drier conditions in the Boreal are intensifying droughts, forest fires, insect infestations, and other serious problems in many areas of the forest, while the few anticipated benefits of warmer temperatures, such as larger, faster-growing trees, are not coming to fruition.

What's worse, many of the impacts of global warming on the Boreal Forest are themselves causing greenhouse gasses to be released into the atmosphere, driving a vicious circle in which global warming degrades the Boreal Forest, and Boreal Forest degradation advances global warming.



Drought is increasing

In the Boreal, when temperatures increase, so does the potential for water limitation. With temperatures rising due to global warming, drought stress has already increased in parts of the Boreal Forest, particularly in western Canada—and tree growth and carbon sequestration have already begun to suffer as a result.

Lack of water has already been linked to growth declines and reduced carbon absorption across the Boreal Forest[72, 73]. In northwestern Alberta, for example, recent droughts have resulted in dieback and stunted growth in aspen trees[74]. Likewise, drought stress has been correlated with range limitations and reduced growth in white spruce, one of the most widespread and important trees in the Canadian Boreal, when temperatures cross a critical threshold of two degrees above the local norm[75].

As temperatures continue to rise, lack of water availability is expected to play a continuing role in limiting the growth and survival of Boreal trees—especially in the drier parts in west-central Canada—compromising the health of the forest as well as its ability to sequester carbon.

Forest fires are becoming more frequent and more intense

Forest fires are a natural and integral part of the Boreal ecosystem, and a critical driver of its vegetation dynamics[76]. But as temperatures continue to rise, these fires are becoming longer, more frequent, and more intense—resulting in widespread carbon emissions across the region.

In the Canadian Boreal, fires recur anywhere from once every 50 years in dry regions, to once every 500 or more years in moist regions[77, 78]. Under the current changes in environmental conditions, however, the forest's fire cycles are speeding up.

As much as 7,600,000 hectares (18,780,000 acres) of forest—an area larger than Ireland—burn in Canada each year[79]. While fire cycles and trends vary regionally, with more fires occurring in western Canada than eastern Canada, for example, the increasing frequency of fires across the Boreal overall has been well documented, especially over the last 30 years[80, 81, 82], as has the increase in area burned by these fires. According to one study, the area of North American Boreal burned by forest fires doubled between 1970 and 1990[83].

The intensity of fires is increasing as well. The damage and degradation caused by warmer temperatures and drier conditions is providing more and better-quality fuel for forest fires, increasing their intensity and severity[84]. This is important in the context of global warming because, while particularly hot, intense fires often lead to strong forest regeneration, they also exact a particularly large toll in terms of carbon emissions. When fire frequency and intensity increase, correspondingly larger amounts of carbon dioxide are released into the atmosphere[85].

As temperatures continue to warm, the trend toward more frequent, longer, more intense fires in parts of the Boreal is projected to continue[86], driving the vicious circle wherein global warming causes carbon to be released from the forest, and the carbon that's released worsens global warming.

Insect outbreaks are spreading across the country

Insect outbreaks are another devastating impact of global warming on the Boreal Forest. Historically, many species of insects common to the Boreal died off during the winter months when temperatures reached low levels. Under global warming, however, winter temperatures are not reaching their usual lows, and many insects are surviving throughout the winter where they wouldn't have in the past[87]. The result is increased insect population growth, and severe damage to forests across Canada.

The highest-profile example of these climate-induced insect outbreaks is the ongoing mountain pine beetle outbreak in the western provinces of British Columbia and Alberta. Where the mountain pine beetle's population and range have historically been limited by freezing winters, warmer temperatures have allowed it to survive over the winter months[88] (see Figure 1). The resulting devastation has been intense. According to the most recent recordings, the area of forest lost to insects in the Boreal is up to eight times greater than the area burned by forest fires[89]. The pine beetle is currently moving east across the country, doing more and more damage to the Boreal Forest. In addition to the mountain pine beetle, the spruce bark beetle and all three major defoliating insects—spruce budworm, jack pine budworm, and forest tent caterpillar—have all been shown or are projected to have increased impacts on the forest as a result of climate warming[90, 91].

Like drought and fire, the problems caused by the mountain pine beetle, the budworm, and other insects are only expected to increase as climate warming continues[92, 93].

Trees in some areas are growing more slowly and are at risk of experiencing more damage

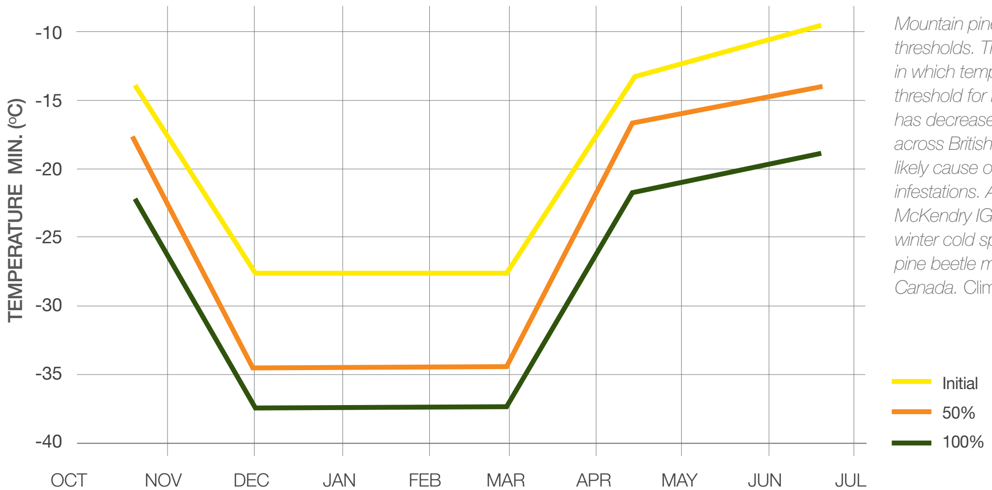
Recent evidence shows that warming temperatures are reducing the growth and survival of some Boreal trees. This is somewhat surprising because in the past, Boreal trees have often thrived in warm growing seasons. In fact, the well-established relationship between warmer temperatures and enhanced tree-growth[94, 95] once led to speculation that climate warming would lead to larger, faster-growing trees, especially in the more northern climes of the Boreal Forest. Further study, however, has revealed that the relationship between temperature and growth in Boreal trees is neither linear nor indefinite. In other words, it's not necessarily true that the warmer it gets in the Boreal, the bigger and faster trees will grow.

Instead, it appears that trees have optimum temperatures above which growth starts to level out or decline[96]. A study of spruce trees in Alaska, for example, demonstrated that white spruce trees had responded positively to small increases in temperature but then declined when mean temperatures rose above a critical threshold[97] (see Figure 2). Along these lines, research suggests that while climate warming may increase Boreal Forest growth initially, warming beyond a certain threshold will actually result in growth reductions. Some studies suggest that this point has already been reached, and that the Boreal is no longer benefiting from warmer temperatures. A 1998 survey of over 300 high-latitude sites across North America and Eurasia, for example, found that wood density was no longer responding to increasing temperature as predicted by a linear model[98]. A number of studies also show reductions in tree diameter in response to warmer growing seasons[99, 100]. As the climate warms, temperature thresholds may be reached for an increasing number of species, reducing growth rates across the Boreal Forest.

Warming temperatures can compromise tree survival as well. When temperatures fluctuate close to the freezing point, ice-crystal formation can give trees "frost burn" and other injuries. Climate warming is predicted to increase the risk of freeze-thaw damage in Boreal tree species[101, 102], especially given the relatively large increases in winter temperatures in northern latitudes consistently predicted by climate models[103]. This damage, combined with reduced growth and the damage caused by drought stress, high fire frequency, and pest damage, means that on balance Boreal trees will suffer, not thrive, under warming conditions.

Figure 1

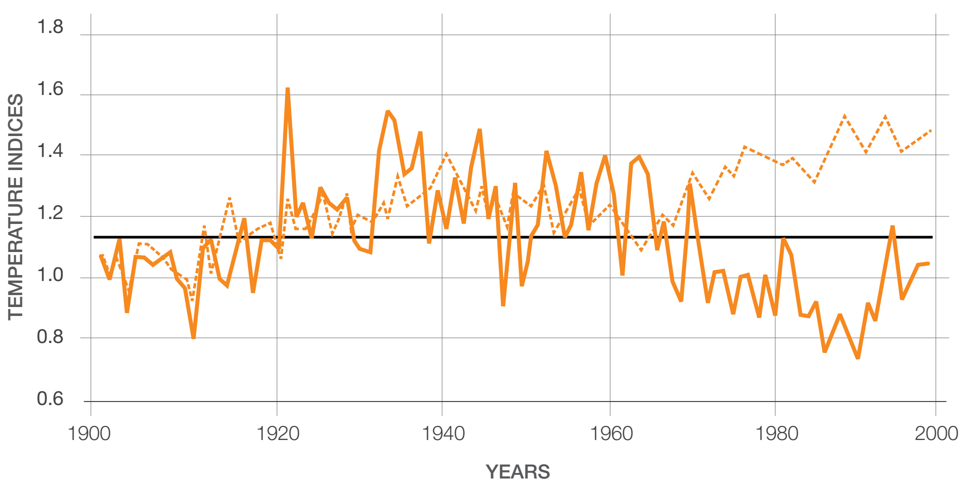
Mountain pine beetle cold-mortality thresholds



Mountain pine beetle (MPB) cold-mortality thresholds. The annual number of days in which temperatures fell below the threshold for mountain pine beetle mortality has decreased over the last fifty years across British Columbia, and this is the likely cause of dramatic increases in infestations. After Stahl K, Moore RD, McKendry IG (2006). Climatology of winter cold spells in relation to mountain pine beetle mortality in British Columbia, Canada. Climate Research *32, 13.*

Figure 2

Predicted and observed growth in Alaskan white spruce over time



Predicted and observed annual tree ring increments of Alaskan white spruce over the last 100 years. The dashed line represents expected tree ring growth based on local temperature data, and the solid line represents actual tree ring growth. These results suggest that above a temperature threshold of 11.3 degrees Celsius, ring growth is no longer positively related to temperature. After D'Arrigo RD, Kaufmann RK, Davi N, Jacoby GC, Laskowski C, Myneni RB, Cherubini P (2004). Thresholds for warming-induced growth decline at elevational tree line in the Yukon Territory, Canada. Global Biogeochemical Cycles *18.*

Wildlife habitats are shifting

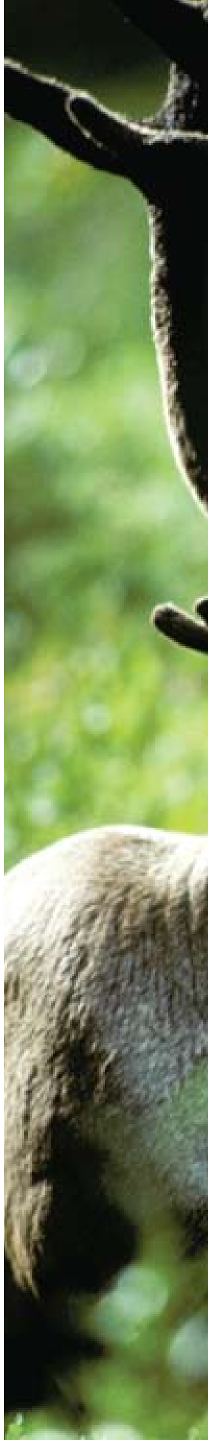
Under global warming, animals and birds will face environmental shifts more rapid than those encountered in much of the paleological record[104, 105]. In the Boreal, many animals will respond to increasing temperatures by shifting their ranges northward[106]. While this will help them to survive under changing conditions, no species can travel north indefinitely. Water bodies and the treeline will act as boundaries for many species as they move northward, resulting in overall range contractions[107].

Of course, climate adaptations won't be confined to the Boreal. As Boreal species are migrating north to cope with a warming climate, more southerly temperate-zone species will likely be moving north as well, a dynamic which may cause conflicts and disruptions[108]. There are 25 species, for example, that have ranges bound by the Arctic Ocean to the north and that are likely to face pressure from species migrating from the south. Described in one paper as "the species with nowhere to go," these include the arctic fox, the red fox, the grey wolf, the caribou, the moose, the muskox, the grizzly bear, the black bear, the polar bear, the lynx, and the wolverine[109].

Further, it is assumed in most models that as temperatures warm and animals move northward, the plants upon which animals depend will shift northward as well[110, 111], resulting in communities that essentially remain the same but shift northward over time. Unfortunately, the migrations of different plant and wildlife species are unlikely to happen at the same rates[112]. Because mismatches in rate of shift are likely to occur among interdependent species, substantial problems could result[113, 114], including increased novel patterns of competition among animal species[115].

Furthermore, animal populations can typically shift range much more quickly than can plant populations, increasing the possibility of mismatches between appropriate climate conditions and other necessary habitat features: an animal species may move north to cope with increasing temperatures, only to find that the plant species necessary to sustain it have not yet made the same shift. Such mismatches have already resulted in increased mortality for bird populations[116]. These sorts of mismatches could occur among different animal populations as well, disrupting predator-prey relationships[117].

Research suggests that lower snowfall levels[118] could reduce the survival of species such as the threatened woodland caribou[119], the lynx, and the snowshoe hare[120]. Add this to the fire- and insect-related disturbances detailed above, and wildlife, including the woodland caribou, the wolverine, and the American marten (all federally listed species of special conservation concern[121]), could face die-offs due to global warming.

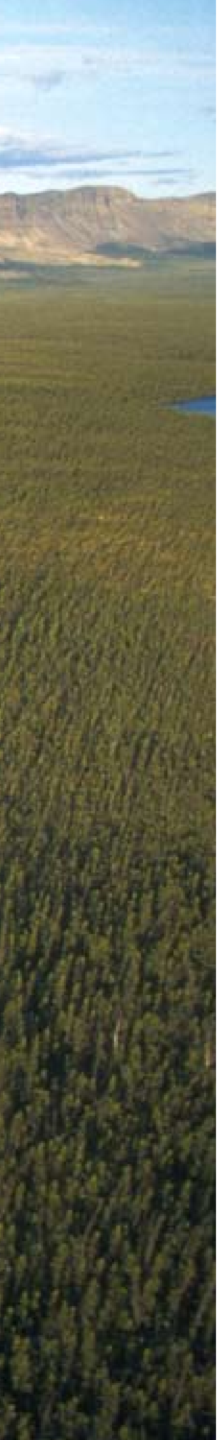


Bigger is better:

Large intact areas of the Boreal Forest better resist and recover from climate impacts

As detailed above, the Boreal Forest is already being affected by global warming, and it is at risk of undergoing even more serious impacts if current trends continue. The frequency and intensity of drought, fire, and insect outbreaks are already rising in some parts of the Boreal, while the health and survival of trees, plants, and wildlife are declining. Global warming is degrading the forest, while Boreal Forest degradation, in turn, is contributing to global warming.

Not all landscapes are equally vulnerable, however. Research suggests that intact areas of the Boreal Forest—those areas that remain in their natural states—will be better able to resist and recover from climate impacts than those areas fragmented by human activity. Forests that are unmarred by roads, logging operations, powerlines, or other imposed infrastructure have an ability to moderate the local climates experienced by individual trees and animals, have higher levels of biodiversity, and have more reproductively mature trees. All these factors make intact forests crucial to slowing global warming and mitigating its impacts.



Intact forests moderate local climates

Large intact forest landscapes create their own microclimates, and these microclimates buffer the forest, its trees and its wildlife from many of the shifts and extremes felt in the broader regional climate. By maintaining stable local climates, intact forests shield trees, plants, and animals from the rapid and sometimes erratic changes happening in the broader climate, and create a slower rate of shift that allows more time for adaptation and migration.

By absorbing heat in the summer and radiating heat in the winter, intact forests maintain more stable temperatures throughout the year, reducing temperature stress and freeze-thaw damage in both spring and fall[122,123]. They also stabilize temperatures by keeping the soil several degrees cooler in late spring and summer and several degrees warmer in late fall and winter compared to the soil in open areas such as clearcuts, delaying freezing in autumn and snowmelt in the spring[124].

Another way microclimates protect forests from climate impacts is by limiting drought stress. Compared to other forests, intact forests store more water when it's in excess and release water when it's in shortage, thus compensating for irregularities. As well, because snow melt starts sooner and lasts longer in intact forests compared to the bare-ground areas found in clearcut forests[125], the former have more stable supplies of water year-round. Clearcut and bare-ground areas lose water rapidly—something which may delay the recovery of disturbed and logged forests[126], especially given the projected increase in extreme precipitation and drought events across the Boreal Forest.

Intact forests have higher levels of biodiversity

The more genetic diversity a forest has, both within and among tree and plant species, the greater likelihood that forest has of resisting and surviving climate impacts. Tree and plant biodiversity helps intact forests to withstand existing global warming impacts, and acts as insurance against unknown future changes and disturbances.

Ecological theory in general predicts that forests with a greater variety of species are more likely to persist over time[127, 128]. This is because not all species are affected by disturbances in the same way. The greater the number of tree and plant species found in a forest, the more limited an impact any single disturbance will have on the forest as a whole[129, 130]. This is particularly important in the case of the Boreal, since it is naturally dominated by only a few tree species and is therefore especially vulnerable to species diversity loss. Because intact Boreal Forest landscapes have greater tree species diversity than managed, second-growth Boreal Forest landscapes[131], they are expected to be more resilient in the face of disturbances[132, 133, 134].

In addition to diversity *between* species, research has shown that high genetic diversity *within* any given species is likely to enhance that species' resistance to global warming impacts[135] and its ability to adapt to shifting climate conditions. Studies have found that European birch, for example, possesses "warm year" and "cool year" genotypes that improve its survival under differing conditions[136, 137]. "Warm year" seeds give rise to seedlings that are better adapted to warmer climates, while still adapted to local environmental conditions such as soil type and nutrient availability[138, 139]. Such seedlings are therefore better adapted to local conditions than southern genotypes that have migrated north[140].

Intact forests with a higher proportion of mature trees may be able to continue this type of adaptation by producing "warm year" and "warmer year" genotypes as temperatures rise[141, 142].

Intact forests provide corridors for plant and tree migration

As temperatures rise, the climate conditions that characterize the Boreal biome will shift northward, and many plant and tree species will respond to these shifting climate conditions by migrating northward along with them. Conifer species, for example, are predicted to expand into tundra landscapes as temperatures warm[143, 144, 145]. The forest-tundra boundary has already moved north in Alaska, and arctic shrub cover has been increasing north of the treeline as well[146,147].

This kind of migration is slow, however, and requires certain conditions. In order for it to occur, genes must be able to flow between forest stands. Intact forest landscapes help facilitate this flow[148], whereas fragmented landscapes may impede it[149]. Because of their high connectivity and their abundant production of seeds, cones, and other propagules, landscapes within the Boreal Forest that are intact and contiguous will be best able to keep up with rapidly changing climate conditions[150].

Intact forests regenerate more successfully

In addition to resisting and adapting to climate impacts, intact forests are better able than fragmented forests to regenerate after natural disturbances have occurred.

This is largely because intact forests tend to have more reproductively mature trees than do fragmented forests. This is true even where natural disturbances such as forest fires and insect outbreaks have occurred. Unlike clearcut logging, where the largest and oldest trees are targeted for cutting, many natural disturbances leave a substantial proportion of reproductively mature trees behind[151]. Mature trees are the most robust in the face of climate disturbances; and once the disturbances subside, they are the most able to repopulate the area.

By producing seedlings that are genetically adapted to the unique environment into which they are born, these mature trees help a forest to recover better than it would with human intervention. Because manually planted seedlings may have been imported from another region or microclimate, they are less likely to thrive than their naturally seeded native counterparts.

Intact forests help wildlife to migrate and adapt

Intact forest landscapes give wildlife the best chances of surviving in a rapidly changing environment, by providing functional corridors for migration and stabilized local climates for adaptation over time.

Intact forests help wildlife migrate by providing the kind of contiguous travel corridors that are lacking in fragmented forests. The southern flying squirrel, for example, has migrated north through the more contiguous forests of south-eastern Ontario, allowing it to extend far to the north of its historic range[152], but has failed to migrate through the more fragmented sections in the south-west[153]. While modern logging methods have attempted to mimic natural disturbances by leaving corridors and retention blocks, studies have shown that these are insufficient for many species[154].

Intact forests help wildlife to adapt, as well. A wealth of recent evidence indicates that many animal species are already responding to global warming by exhibiting earlier breeding seasons[155], earlier migration[156], and multiple generations per season. If change is too rapid, however, species may not be able to adapt quickly enough to keep up[157]. Intact forest landscapes help this situation by slowing the rate of change across the landscape, moderating the local climate, and providing alternate habitats[158].

Large intact forest landscapes in Canada's Boreal Forest

Data Sources:
Global Forest Watch Canada; Government of Canada, Natural Resources Canada / Earth Sciences Sector / Canada Centre for Remote Sensing; Global Land Cover Facility (2000), www.landcover.org; Canadian Boreal Inititive (CBI), Canada's Boreal Region (2003) www.borealcanada.ca

Note: Large Intact Boreal Forests Landscapes represents a contiguous mosaic of natural ecosystems greater than 50,000 hectares in the Boreal Forest landscape, essentially undisturbed by human influence. This map was generated through the use of Landsat imagery acquired during the approximate epochs of 1990 and 2000.

Produced by Global Forest Watch Canada, November, 2007.

Projection:	Central Meridian: -95.0
Lambert Conformal Conic	Standard Parallel 1: 49.0
False Easting: 0.0	Standard Parallel 2: 77.0
False Northing: 0.0	Latitude of Origin: 49.0

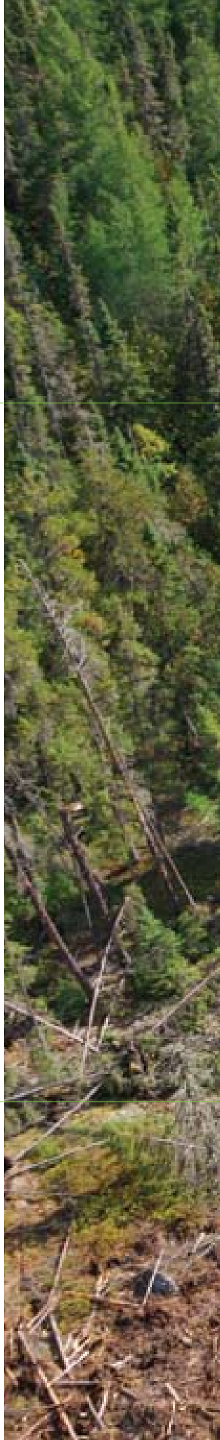
Save the south, protect the north

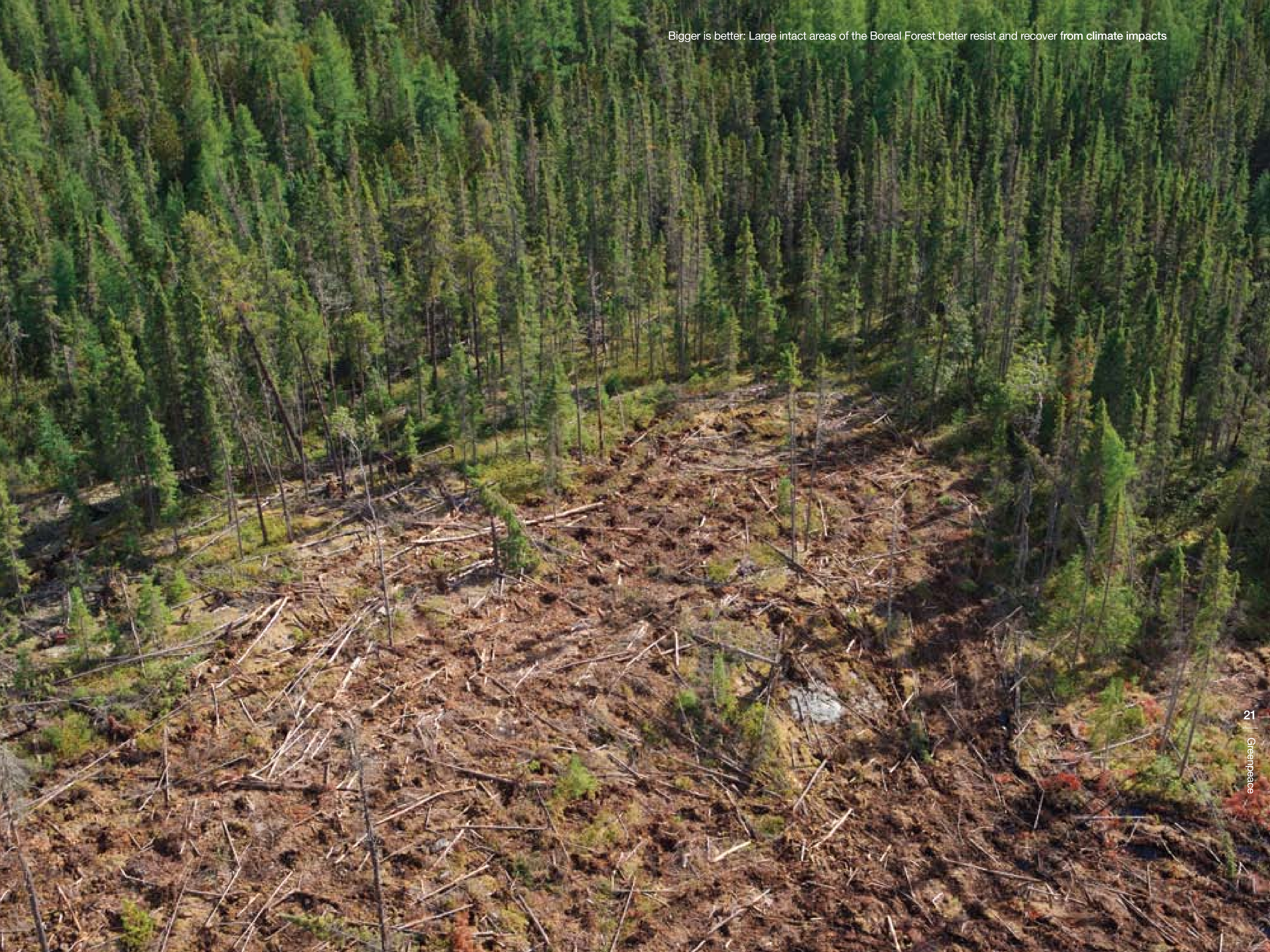
Most of the remaining intact forest landscapes in North America are part of the northernmost expanses of Canada's Boreal Forest. More remote, less accessible, and as yet unallocated for industrial logging, these northern areas have undergone far less fragmentation than the more southern reaches of the forest. For this reason, they appear at first glance to provide the best opportunities for conservation. In the context of global warming, however, failing to protect what remains of the more fragmented south directly jeopardizes the future of the vast north.

The more southern areas of the Boreal Forest have long been subject to human influence and impacts, and as a result little mature forest remains[159]. Owing to closer proximity to roads, mills, towns, and transportation infrastructure, logging in the southern Boreal has long been more intense, and its forest landscape is much more heavily fragmented[160, 161]. According to satellite imagery, for example, less than 26 per cent of the commercial or southern Boreal Forest in the province of Ontario remains intact[162]. Still, the more southern areas house a unique biological richness, containing the most diverse assemblages of species within the Boreal[163].

This high level of biodiversity makes protecting the southern Boreal essential, even though its remaining forest landscapes are smaller and more fragmented than those farther north. A number of bird, mammal, and tree species reach their northern limit in the southern Boreal Forest, intermingling with Boreal species that are at their southern limit to form diverse communities[164, 165, 166]. This intersection of southern and northern Boreal plants and wildlife creates a unique ecosystem that cannot be replaced.

In the context of global warming, however, conservation of the dwindling intact areas of the more southern Boreal Forest takes on added importance, as it becomes essential for facilitating the adaptation and migration that will allow the northern Boreal to survive in a changing climate. The many plant and tree species that straddle the northern and southern areas of the Boreal will be able to use pre-adapted genotypes from southern areas to survive in warming conditions in more northerly landscapes[167, 168]. These genotypes have the potential to migrate north over many generations, but this cannot occur unless wide, intact forested north-south corridors are maintained[169, 170].





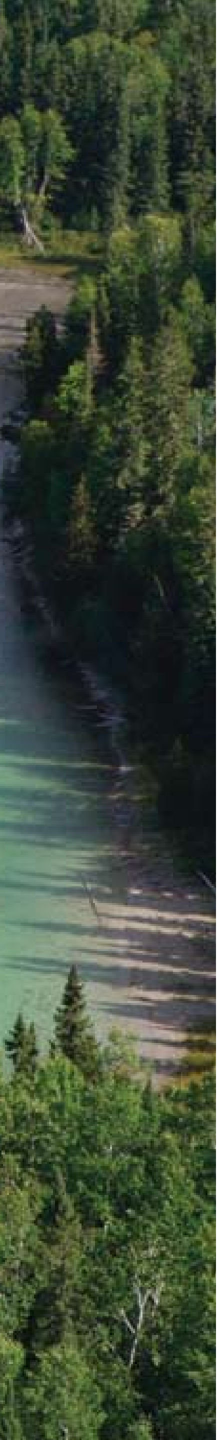
Bigger is better: Large intact areas of the Boreal Forest better resist and recover from climate impacts

Storing carbon, slowing melt:

Intact Boreal landscapes are mitigating global warming

As we have seen, the intact areas of Canada's Boreal Forest have the potential to help the forest as a whole to resist and recover from the negative impacts of global warming. By stabilizing the local climate and housing diverse species and genotypes, they help plants and animals alike to adapt, migrate, and ultimately survive under rapidly changing conditions.

At the same time, intact Boreal Forest landscapes are playing a key role in mitigating global warming itself on a global scale. By storing massive amounts of carbon and slowing permafrost melt, intact areas of the Boreal Forest are slowing the release of carbon and methane into the atmosphere, curbing the overall feedback loop between forest degradation and global warming.



Intact forests sequester and store carbon

The Boreal Forest stores massive amounts of carbon. In fact, the world's boreal forest ecosystems contain almost a quarter of the world's land-based carbon stocks[171, 172]. According to one estimate, Canada's Boreal Forest stores 186 billion tonnes of carbon[173], equal to 27 years' worth of global carbon emissions from the burning of fossil fuels[174].

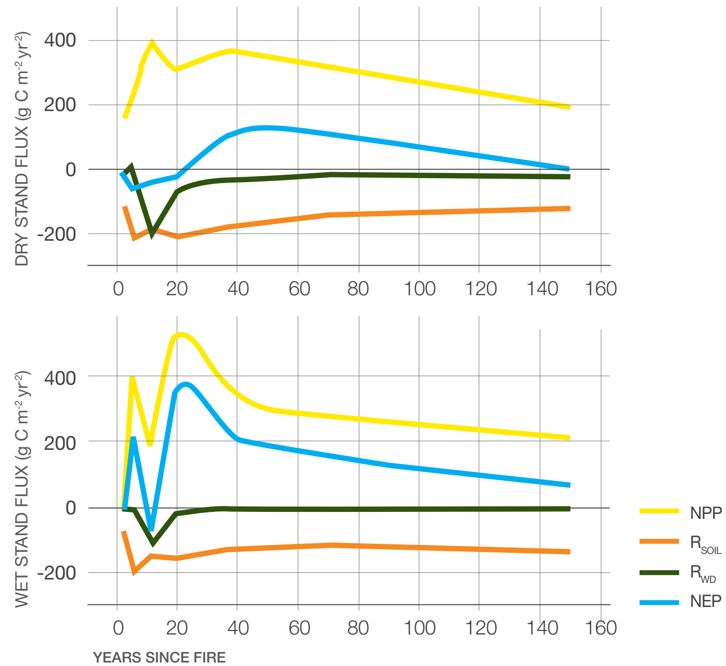
In most temperate and tropical forests, carbon is stored mainly in live tree tissues. In Canada's Boreal, however, it is soils that serve as the primary carbon storehouses over much of the region. With 1.5 to 2 million lakes and enormous peatlands stretching across its landscape, the Boreal is rich in belowground carbon. An average of 84 per cent of the carbon in the Boreal Forest is stored in its soils[175].

Trees still play an important role in carbon sequestration, however—even more so than previously believed. Traditionally, mature forests have largely been viewed as carbon neutral[176], meaning that once a forest had reached maturity, it was assumed to have stopped sequestering carbon. More recently, however, studies have found that many forests continue to sequester carbon as they age. One such study, for example, found that old-growth spruce, aspen, and jack pine forests were all moderate carbon sinks[177]. Another found that black spruce continued to sequester carbon for over 140 years[178] (see Figure 3), and others found similar results in mature ponderosa pine and subalpine forests[179, 180]. Another estimated that white spruce stands were still accumulating carbon at well over 200 years of age[181]. This appears to hold for other forest types as well. Recent studies of ancient temperate forests have documented surprisingly large carbon sinks[182, 183, 184, 185]; and old-growth tropical forests appear to operate as strong carbon sinks as well[186, 187, 188].

These findings are important, as they mean that forest cutting and removal not only results in losses in existing carbon stocks, but also results in lowered sequestration until the regenerating forest returns to previous carbon storage levels.

Figure 3

Carbon absorption and respiration in black spruce over time



Black spruce chronosequence showing net ecosystem productivity (NEP, or carbon absorption by plants), net primary productivity (NPP, or carbon absorption by plants and carbon release by soils), and respiration (R). Mature stands continued to show positive NEP for over 140 years, particularly in wetter stands. After Bond Lamberty B, Gower ST, Goulden ML, McMillan A (2006). Simulation of boreal black spruce chronosequences: Comparison to field measurements and model evaluation. Journal of Geophysical Research Biogeosciences *111.*

Is the Boreal a net carbon sink or a net carbon source?

Recently, questions have been raised about whether Canada's Boreal Forest remains an overall carbon sink[189,190], or whether it has become an overall carbon source[191, 192, 193, 194]. As discussed above, many of the impacts of global warming on the Boreal Forest are causing carbon to be released into the atmosphere, tipping the balance between how much carbon the forest absorbs from the atmosphere in a given year and how much it releases back into the atmosphere.

The documented switch from a net carbon sink to a net carbon source has been attributed primarily to increased fire and insect outbreaks under changing climate conditions[195, 196, 197], but the situation is exacerbated by high levels of logging. While natural disturbance levels can vary greatly, logging represents about 25 per cent of the Canadian Boreal Forest area lost in a given year[198]; and because industrial-scale logging is conducted in high-volume, high-carbon areas (that is, older-growth stands) and removes future woody debris that would remain on the forest floor under natural circumstances, researchers have concluded that it likely results in disproportionately high carbon losses compared to natural disturbances like forest fires and insect outbreaks[199]. Logging, therefore, appears to be playing an important role in the possible conversion of Canada's Boreal Forest from an overall carbon sink to an overall carbon source.

It is important to understand, however, that regardless of whether the Boreal Forest is a net sink or a net source on an annual basis, it continues to store massive amounts of carbon. In order to maintain and promote carbon storage, therefore, it remains essential to protect the Boreal, especially its most carbon-rich intact and old-growth areas[200].

Intact forests slow permafrost melt and methane release

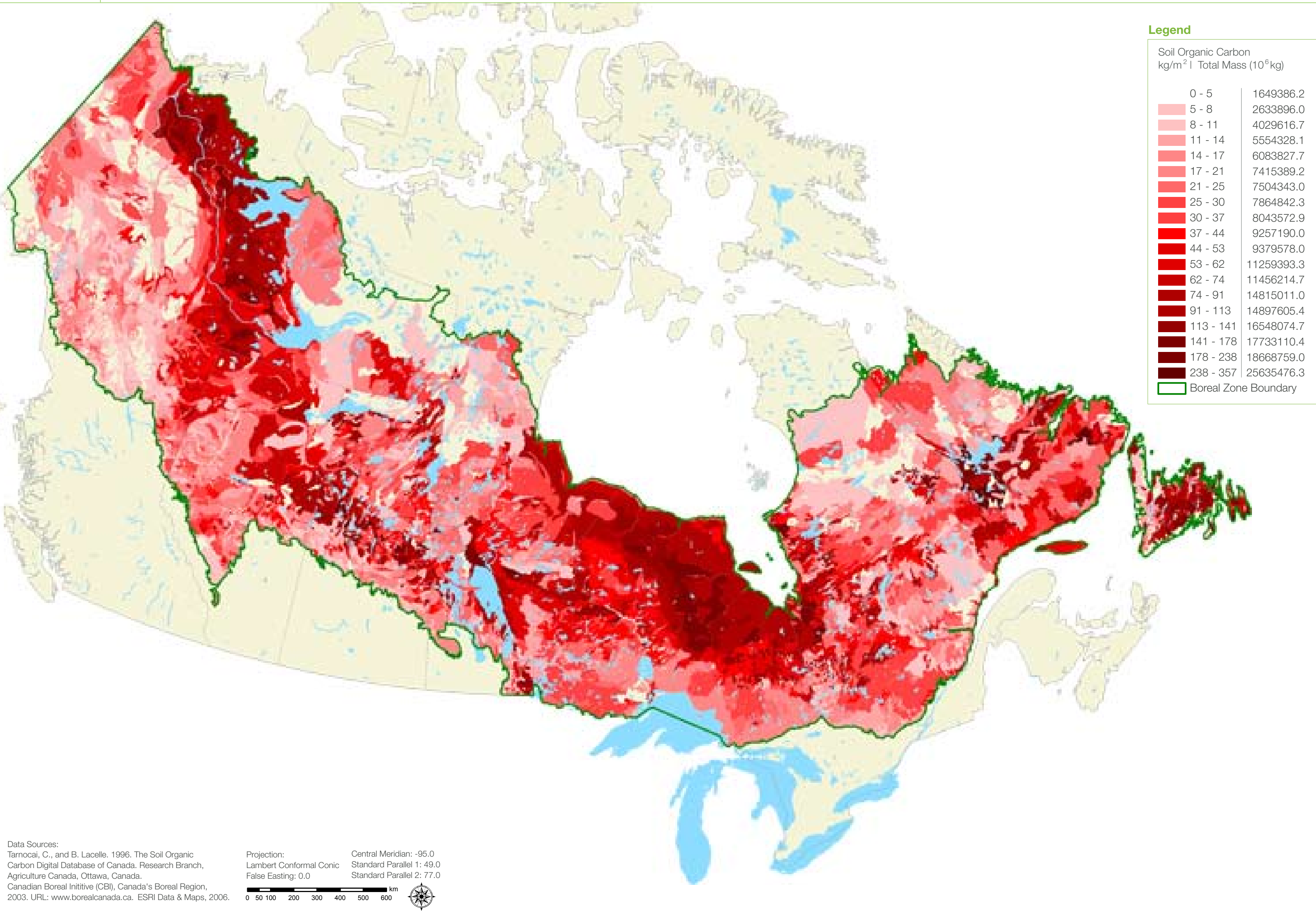
In addition to storing carbon, intact Boreal Forest landscapes are helping mitigate global warming by slowing permafrost melting. Permafrost—soil that remains frozen throughout the year—covers approximately 24 per cent of the exposed land area of the northern hemisphere[201]. Over 60 per cent of the permafrost area is capable of supporting thick vegetation cover, including forests[202].

Permafrost melt and the soil saturation that results could exacerbate global warming by releasing large amounts of greenhouse gasses into the atmosphere[203, 204]. As permafrost melts, it releases carbon dioxide and methane into the atmosphere through rapid soil respiration and paludification, a process whereby newly melted soils become saturated with water. When paludification occurs, the water-logged soil emits large amounts of methane, a greenhouse gas 21 times more potent than carbon dioxide[205, 206]. According to current global warming projections, both permafrost loss and paludification are expected to increase[207, 208]. In the western Boreal Forest, a 1.6-fold increase in carbon dioxide release and a 30-fold increase in methane release associated with melting permafrost have already been documented[209].

Given the rapid warming across the Boreal, widespread permafrost melt is likely—increases in air temperature of only 1–2 degrees Celsius have the potential to thaw out large expanses of discontinuous permafrost[210]. But intact forest cover may delay this thaw by decades or even centuries[211, 212, 213]. Intact forests' moderated microclimates insulate permafrost from warming air temperatures[214, 215], and the permafrost layer under intact forests is thicker and more stable throughout the year compared to the permafrost under adjacent tundra or clearcut landscapes[216, 217].

Intact forests may also reduce the amount of methane released from permafrost when it does melt. The soil in forested areas generally stores less moisture than bare ground or tundra areas because of the high water demands of forest vegetation[218, 219]. In sample plots, this reduced soil moisture content has been associated with reduced methane release[220].

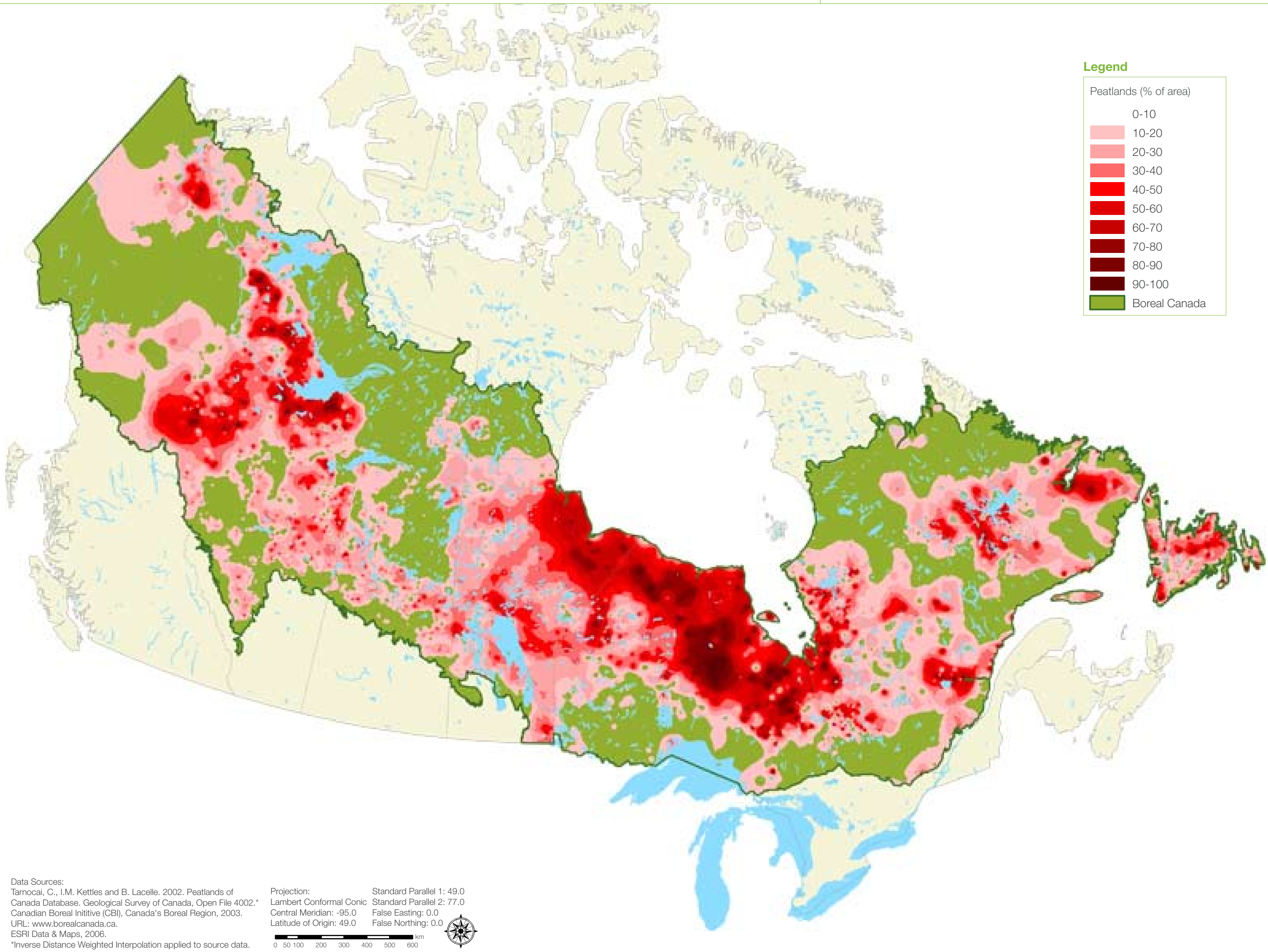
Soil organic carbon in Canada's Boreal Forest



Data Sources:
Tarnocai, C., and B. Lacelle. 1996. The Soil Organic Carbon Digital Database of Canada. Research Branch, Agriculture Canada, Ottawa, Canada.
Canadian Boreal Inititive (CBI), Canada's Boreal Region, 2003. URL: www.borealcanada.ca. ESRI Data & Maps, 2006.

Projection:
Lambert Conformal Conic
False Easting: 0.0
Central Meridian: -95.0
Standard Parallel 1: 49.0
Standard Parallel 2: 77.0

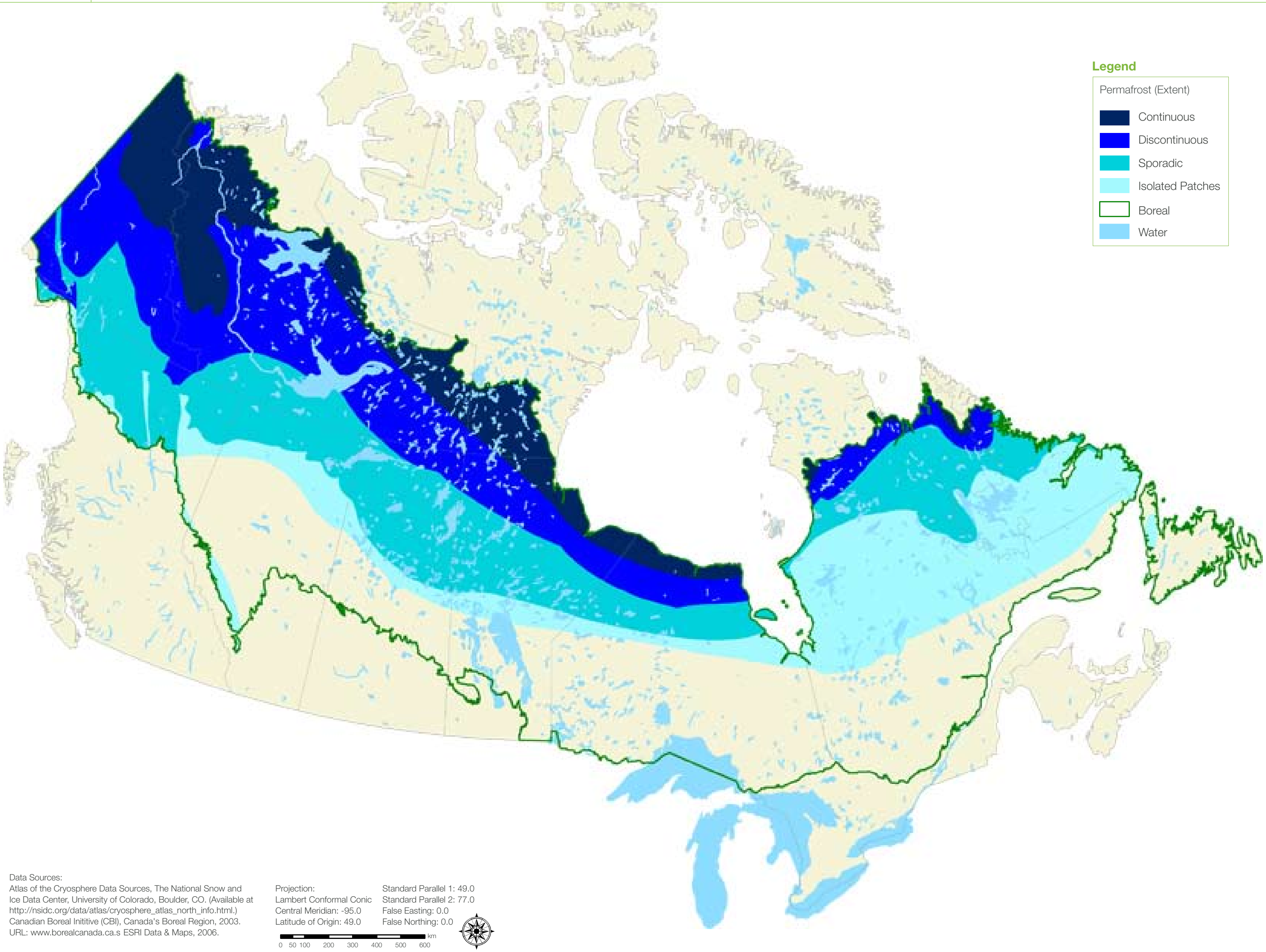
Peatlands in Canada's Boreal Forest



Data Sources:
Tarnocai, C., I.M. Kettles and B. Lacelle. 2002. Peatlands of Canada Database. Geological Survey of Canada, Open File 4002.*
Canadian Boreal Inititive (CBI), Canada's Boreal Region, 2003.
URL: www.borealcanada.ca.
ESRI Data & Maps, 2006.
*Inverse Distance Weighted Interpolation applied to source data.

Projection:
Lambert Conformal Conic
Central Meridian: -95.0
Latitude of Origin: 49.0
Standard Parallel 1: 49.0
Standard Parallel 2: 77.0
False Easting: 0.0
False Northing: 0.0

Permafrost in Canada's Boreal Forest



Data Sources:
Atlas of the Cryosphere Data Sources, The National Snow and Ice Data Center, University of Colorado, Boulder, CO. (Available at http://nsidc.org/data/atlas/cryosphere_atlas_north_info.html.)
Canadian Boreal Inititive (CBI), Canada's Boreal Region, 2003.
URL: www.borealcanada.ca.s ESRI Data & Maps, 2006.

Projection:
Lambert Conformal Conic
Central Meridian: -95.0
Latitude of Origin: 49.0

Standard Parallel 1: 49.0
Standard Parallel 2: 77.0
False Easting: 0.0
False Northing: 0.0

The albedo effect

Although most of the literature related to global warming and forests focuses on the storage and release of greenhouse gasses, forests interact with the climate via other mechanisms as well. Primary among these is a phenomenon known as the albedo effect. Albedo describes the extent to which an ecosystem absorbs or reflects back the sun's rays. Defined as the ratio of radiation reflected into space relative to the total radiation intercepted by an ecosystem, albedo essentially describes the reflectivity of an area. Areas with high albedo reflect large amounts of solar radiation back into space, whereas areas with low albedo absorb large amounts of radiation. This is relevant to global warming because forests tend to have low albedo compared to non-forested areas, especially during periods of snow cover. And low-albedo areas—that is, areas that absorb large amounts of heat—can contribute to climate warming.

One recent study on this subject received considerable media attention in Canada and abroad: it reported a finding that deforestation of the Boreal would result in climate cooling due to the albedo effect. The 2007 study by Bala *et al.* concluded that "afforestation projects in high latitudes would be counterproductive in mitigating global-scale warming"[221]. This study was preceded by a 1992 study that concluded that removal of trees from logging and other disturbances could result in a cooling effect, especially pronounced in boreal forest areas during the winter[222].

These studies, while interesting, are misleading. By over-estimating the potential cooling effects of albedo following logging, and under-estimating the potential carbon losses associated with Boreal deforestation, they paint an unrealistic picture. These shortcomings stem from the studies' bases in limited models and simulations.

Both the 2007 study and the 1992 study rely on direct biome substitution to simulate deforestation—that is, they rely on a modelling scenario whereby they replace the physical attributes of an area of boreal forest with the physical attributes of a grassland, then compare the properties of the two. This modelling strategy has several critical limitations.

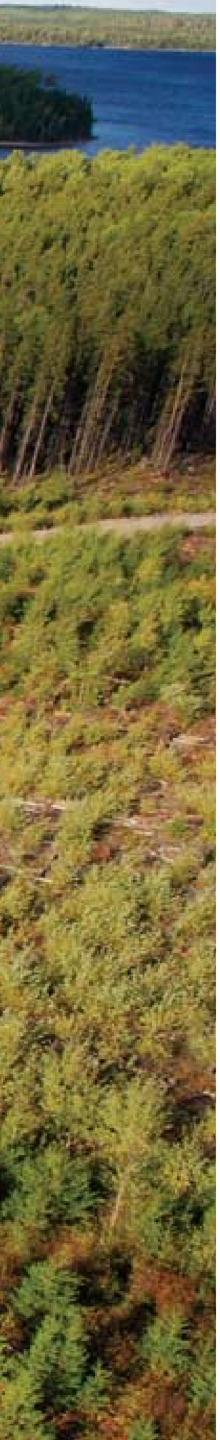
First, it doesn't account for the losses of soil carbon associated with logging. Because most carbon in the Boreal Forest is stored belowground, the potential carbon losses associated with logging or other types of forest clearing may have been drastically underestimated. Second, biome substitution does not take into account forest re-growth. In reality, large-scale logging in the Boreal would not result in a replacement of forests with grasslands, but rather in a replacement of old, mature forests with young, regenerating stands. This would almost certainly result in large losses of carbon, with only small changes in albedo. Third, neither of these modelling studies has used actual data on the albedo of post-disturbance boreal forest landscapes in their simulations. Changes in albedo are complex and influenced by many factors, including exposure and duration of snow cover; stand structure; surface roughness; and forest species composition[223, 224, 225]. Following fire, for example, there is generally a short-term reduction in growing-season albedo due to blackened surfaces[226,227].

While forested areas do generally absorb more solar radiation than non-forested areas, this dynamic alone does not rationalize the deforestation of the Boreal. Even if deforestation did reduce the albedo of an area (which is not clear based on the research done to date), this would not compensate for the massive amounts of greenhouse gas release and lost sequestration potential that would result.

Making a bad situation worse:

The destabilizing role of logging

The Boreal Forest is being destabilized by global warming. Climate gradients are shifting, plants and animals are migrating, and fire cycles are accelerating. Where intact landscapes have the potential to slow these changes and stabilize both the climate and the forest, industrial-scale logging has the potential to do just the opposite. By releasing carbon, fragmenting the landscape, reducing biodiversity, and accelerating permafrost loss, logging in Canada's Boreal Forest may both worsen global warming and weaken the forest's ability to withstand its impacts.



Logging releases massive amounts of carbon

As discussed above, old-growth forests contain more carbon than younger forests (see the section "Intact forests sequester and store carbon", above)[228]. In addition to the massive amounts of carbon stored in their soils, mature areas of the Boreal can contain over 80 tonnes of carbon per hectare in their trees and aboveground vegetation[229, 230]. When these areas are logged, this aboveground carbon content is reduced to almost inconsequential levels[231]. While some government and industry analysts claim that the aboveground carbon removed by logging is stored in forest products, this argument does not hold (see the section "Do forest products store carbon?", below).

In addition to largely eliminating the carbon stocks represented by living trees, clearcut logging results in much lower levels of woody debris than would result from natural disturbances such as fire or insect-caused defoliation[232]. This has serious consequences for carbon storage because as woody debris decomposes, much of the carbon within it becomes part of the soils beneath. In this way, woody debris is the source of much of the carbon eventually stored for long periods in the forest's soil[233].

Woody debris levels are reduced even more drastically when forests are subjected to salvage logging (that is, logging following a natural disturbance such as fire or a pine beetle outbreak). One study, for example, found that more carbon was lost from salvage logging after a forest fire than from the fire itself[234, 235]. Intensive extraction projects such as biofuel harvesting have the potential to do extensive damage as well, removing large amounts of carbon that would otherwise remain in the ecosystem[236].

Just how much belowground carbon is lost from soils during logging remains a matter of some debate: some studies have shown significant losses of soil carbon following logging[237, 238], while others have failed to find such losses[239, 240]. What is clear, however, is that when trees are removed, the underlying soil is subjected to an extreme increase in heat exposure. Previously sheltered by trees, the soil is suddenly warmed by direct sunlight, leading to warmer conditions and increased soil decomposition[241]. This decomposition results in carbon emissions, as reflected in studies that have found that young, regenerating forests are losing carbon[242, 243, 244]. In some cases it takes decades before logged stands start sequestering more carbon through growth than they're emitting through decay[245].

All these factors lead to large carbon losses when forests are logged. One study found that total carbon stocks were reduced by up to 54 per cent in spruce forests following logging[246]. Another found that sites assessed four years after logging contained 80 tonnes of carbon per hectare less than 75-year-old stands of Scots pine[247]. Yet another found that a five-year-old jack pine site had 40 tonnes of aboveground carbon per hectare less than a 79-year-old stand[248].

Considering the extent of logging across Canada's Boreal Forest, the implications of this carbon loss are dramatic. Over 750,000 hectares (1.85 million acres) are logged every year[249]—an area almost seven-and-a-half times larger than New York City. While carbon levels vary across the landscape, if an intermediate level of 40 tonnes of carbon per hectare of aboveground carbon is used[250] and is projected across the approximately 750,000 hectares of Boreal Forest logged in Canada each year, then roughly 30 million tonnes of aboveground carbon are removed from Canada's Boreal Forest every year by logging alone—more carbon than is emitted each year by all the passenger vehicles in Canada combined[251]. And this doesn't even include the carbon lost from the forest's soils.

Logged areas continue to emit carbon for years

In addition to the carbon removed during logging itself, research shows that forests continue to emit carbon after they've been logged—often for 10 years or more—because of the damage and decay incurred through logging[252, 253]. As the decomposition of soils and woody debris outpaces the re-growth of trees and other vegetation, carbon continues to be lost, making many young, regenerating stands carbon emission sources for more than a decade following logging[254, 255, 256].

Government and industry documents, however, are increasingly characterizing young regenerating forests as active carbon sinks that draw large amounts of carbon out of the atmosphere. A Natural Resources Canada fact sheet titled "Does Harvesting in Canada's Forests Contribute to Global warming?", for example, claims that logging does not cause substantial carbon emissions because "harvested areas regenerate to become forests again, so that in any year there is substantial new storage of carbon occurring in the areas previously harvested"[257]. An article in an industry magazine goes further: "Indeed, there is a case for cutting more forest. This is not to condone the indiscriminate felling of old forests; they have enormous value as eco-systems full of irreplaceable life forms. Let us be clear, though: they absorb far less carbon dioxide than younger, fast-growing stands. And in a time of increasingly rapid global warming, we desperately need to increase CO_2 absorption"[258].

While replacing old stands with young ones may result in higher annual sequestration rates locally for the period when those young- and intermediate-aged stands are growing fastest[259, 260], this cannot compensate for the carbon lost during and after logging through the loss of carbon-dense old-growth trees, and the disturbance and warming of carbon-rich soils. The fact is that industrial logging results in less carbon remaining within the ecosystem[261].

One study, for example, found that old-growth forest plots held up to 2.9 times more carbon than second-growth forests[262].

In many cases it takes over a century for the carbon stocks in logged forests to return to pre-logging levels[263, 264]. These forests' carbon-storage potential is often cut short, however, as most logging in Canada's Boreal Forest is conducted using rotation lengths between 50 and 100 years[265, 266]—at least twice the rate of pre-industrial fire regimes[267]—preventing logged forests from ever achieving their maximum sequestration and storage potential[268].

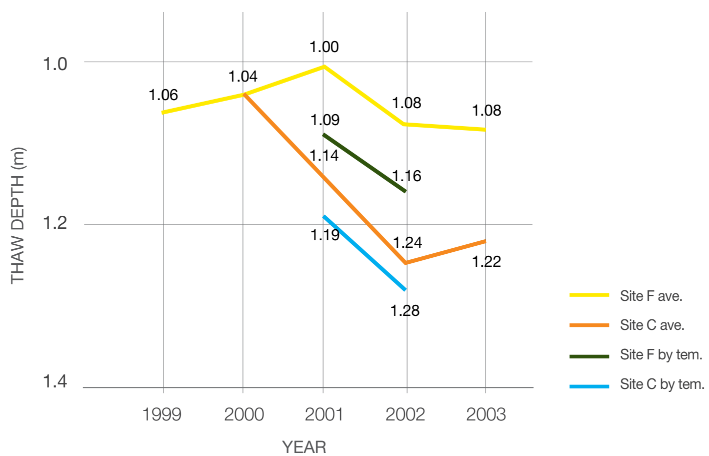
Logging accelerates permafrost loss and methane release

Whereas intact forests slow permafrost melt, logging accelerates it. By removing the protective cover of forest vegetation, logging in permafrost areas exposes the cold and frozen soil to higher temperatures and solar radiation[269], accelerating melting and, as a consequence, greenhouse gas release (for example, see Figure 4). Industrial logging has been occurring in permafrost areas in Scandinavia and Siberia for decades, and has more recently begun in discontinuous permafrost areas in Canada. Research shows that further expansion north would have dramatic consequences, including rapid bog expansion, methane release, and carbon dioxide release.

When permafrost melts, the newly thawed soil becomes saturated with water[270]. Without the high water demands of trees this effect is exaggerated, and logged areas experience increased bog formation and rising water tables[271, 272]. Not only does this release methane into the atmosphere, but the large, rapidly expanding bog landscapes that replace previously forested areas are largely resistant to forest regeneration[273], making the re-establishment of forest difficult if not impossible. Further, as the frozen ground thaws, soil respiration increases rapidly, contributing additional carbon to the atmosphere[274].

Figure 4

Permafrost loss as a result of clearcut logging



Average maximum thaw depths were determined by pounding a steel rod into the ground in forested (Site F) and clearcut (Site C) sample plots. For 2001 and 2002, maximum thaw depths were also determined by temperature profile. After Iwahana G, Machimura T, Kobayashi Y, Fedorov AN, Konstantinov PY, Fukuda M (2005). Influence of forest clear cutting on the thermal and hydrological regime of the active layer near Yakutsk, eastern Siberia. Journal of Geophysical Research *110.*

Logging reduces the functional diversity of forests

Industrial-scale logging alters the structure and function of the Boreal Forest, reducing its diversity and, as a consequence, its resilience against climate impacts. By replacing a naturally diverse forest with one made up of uniformly aged trees with similar genetic make-ups, logging makes forests more vulnerable to diseases, insect outbreaks, and other threats.

In general, landscapes that have been logged are less diverse than natural landscapes, both in terms of species and in terms of the ages of their trees[275]. Industrial logging decreases the prevalence of older stands across the landscape[276], while increasing the prevalence of single-species dominance[277, 278]. Through much of the southern Boreal, extensive logging has already resulted in a conversion of conifer-dominated systems to systems dominated by certain hardwoods, particularly aspen and/or paper birch[279, 280, 281, 282].

The physical, chemical, and mechanical manipulations of the soil that go along with industrial logging are partly responsible for this species conversion. Slash—or woody debris—burning and the use of heavy machinery, for example, are associated with strong changes in species composition that can persist for decades[283, 284].

Roads and other infrastructure created to facilitate logging access can have large impacts on the structure and function of the Boreal Forest as well[285, 286]. In addition to the direct and permanent deforestation caused by the construction of roads and yards (amounting to an estimated 68,000 hectares, or 168,028 acres, per year, an area larger than the city of Toronto[287,288]), roads alter drainage patterns and other aspects of the physical environment, provide a corridor for the invasion of exotic species, and provide increased access to humans who further affect the forest through hunting, fishing, and fire ignition.

Other types of industrial development, such as seismic survey lines, may have similarly large and long-lasting impacts as well[289].

In all these ways, logging is homogenizing the Boreal Forest. The result is forests that are sensitive to impacts on those few species that remain. The conversion of mixed-wood forests to aspen-dominated forests in the Boreal, for example, has resulted in forests that are vulnerable to any disease or insect infestation that affects aspen trees[290]. This type of vulnerability is especially important in the context of increasingly frequent and severe climate impacts.

Logging removes natural wildlife habitats

Logging not only extirpates some wildlife species from their natural habitats but may also reduce their ability to adapt and migrate under changing climate conditions, putting numerous species in peril. By altering the composition of the forest, logging removes the habitat features many species need to survive; and by fragmenting the landscape, it leaves them without some of the options that would otherwise allow them to adapt under changing conditions.

While some Boreal animals can survive in a wide range of habitats, many others require very particular habitat types. Because of this, the homogenizing effects logging brings about in the structure and composition of a forest may have strong, negative consequences for wildlife. When the plants and trees comprising an area change, whether in terms of species makeup or in terms of age structure, the food and shelter available to wildlife change—sometimes in ways that make a previously hospitable area uninhabitable. Woodland caribou and American marten, for example, cannot thrive in an area without sufficient old-growth forest cover[291, 292].

Habitat fragmentation lowers species survival as well[293, 294, 295, 296]. There are a number of reasons for this, including outright habitat loss, the creation of barriers to movement[297], "edge effects" such as higher levels of predation and reduced interior habitat[298], reductions in genetic variation, and higher susceptibility to local extinction following disturbance[299]. An average herd of woodland caribou, for example, requires 9,000 square kilometres (5592 square miles) of undisturbed wilderness, an area larger than most parks in Canada, and at least a 12-kilometre (7.5-mile) buffer between its habitat and forestry operations to survive[300]. The woodland caribou is now federally listed as a threatened species, with a Boreal population believed to number fewer than 33,000 animals[301].

In a changing climate, the habitat fragmentation caused by logging becomes an even greater concern for wildlife, since intact corridors and connectivity are critical in facilitating climate-induced migration, as discussed above. Without sufficient corridors, an "island scenario" can be created, where pockets of intactness remain but animal and plant species are unable to successfully migrate between them.

Do forest products store carbon?

Recently, the Canadian forest products industry and government regulators have been arguing that when forests are logged, the carbon stored within them is not released into the atmosphere, but is instead stored for long periods of time in forest products[302, 303, 304]. Essentially, they claim that through manufacturing, carbon is transferred from living forests to forest products. Some go as far as to argue that logging Canada's Boreal Forest actually helps to slow global warming, because the carbon stored in mature trees is transferred to long-lasting forest products, and then those trees are replaced with young, growing saplings which quickly absorb more carbon[305].

According to one government fact sheet, for example, the "combination of harvest and regrowth along with the storage of carbon in long-lasting forest products means that our forest management practices do not result in substantial emissions"[306]. This argument does not live up to scientific scrutiny.

First, the simulations used to support the claim that carbon is stored in forest products use unrealistically long estimates of product half-life. For example, Colombo *et al.*[307] assume that forest products lose less than 25 per cent of their carbon over 100 years, implying a half-life of over 240 years. By contrast, the "good practice" defaults set by the United Nations Intergovernmental Panel on Climate Change (IPCC) for analyses of this type are two years for paper and thirty-five years for sawn wood[308]—a far cry from the 240 years used by industry and government studies in the province of Ontario. Other studies use product half-lives of between one and three years for paper, and between thirty and fifty years for sawn wood[309].

Second, this argument assumes that most if not all of the carbon from a logged forest is transferred to long-lasting forest products. Analyses of Douglas-fir forests suggest that after logging, most carbon is either stored in short-lived products such as paper, or lost during logging and processing—only a small fraction ends up in longer-term products such as dimensional lumber[310, 311]. Some of the logged carbon may also end up "stored" in landfills when products are disposed of; but little is known about how quickly forest products decompose in landfills[312,313], and the potential for increased methane emissions from decomposing products is high. Additionally, the increased use of incineration in municipal waste management seems likely to reduce the period of carbon storage in products sent to landfill, making estimates based on historical data inappropriate.

Third, this argument does not account for the additional carbon loss incurred through the road building, forest fragmentation, and storehouse damage associated with logging. As noted above, in addition to forests directly logged, an estimated 68,000 hectares (168,028 acres) per year is deforested through the construction of logging roads and landings[314, 315]. Because these areas are permanently deforested, they represent a permanent loss of carbon storage potential.

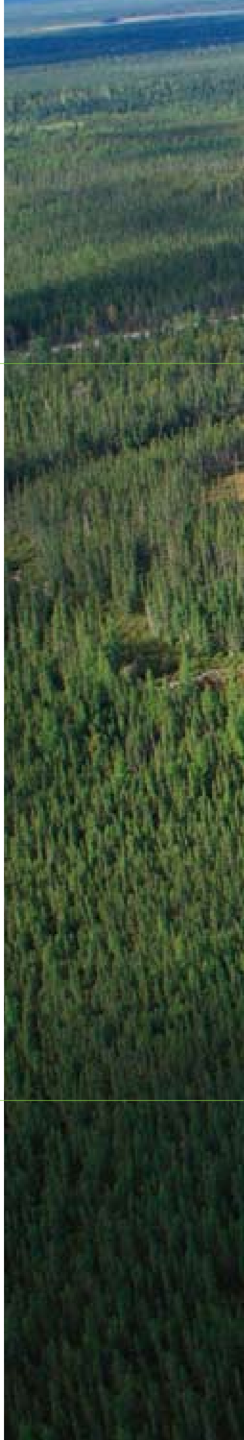
Lastly, this argument fails to account for the secondary emissions caused by the transportation, transformation, and distribution of forest products.

Deforestation vs. forest degradation

In lay terms, the word deforestation is used to describe any cutting or clearing of trees. Technically, however, deforestation refers only to the direct, human-caused conversion of forested land to non-forested land—for example, the conversion of a forest to urban or agricultural land or to roads[316].

According to the explanatory notes accompanying the definition of deforestation by the Food and Agriculture Organization (FAO) of the United Nations, "the term specifically excludes areas where the trees have been removed as a result of harvesting or logging … unless logging is followed by the clearing of the remaining logged-over forest for the introduction of alternative land uses, or the maintenance of the clearings through continued disturbance, forests commonly regenerate, although often to a different, secondary condition"[317]. In this way deforestation is distinguished from forest fragmentation, which refers to the breakup of an intact forest area through logging, road-building, or other industrial activity; and from forest degradation, which refers more generally to the impoverishment of a forest area.

This difference in definitions is highly relevant with reference to technical reports, policy mechanisms, and carbon accounting schemes that deal with forests and global warming. The frequently quoted IPCC figure which attributes approximately one fifth of global emissions to deforestation[318], for example, does not include emissions caused by forest fragmentation, degradation, or soil decay. Care must therefore be taken in the understanding and use of these terms.



The carbon bomb

Forest fires, insect outbreaks, permafrost melting, and logging in Canada's Boreal Forest have the potential to worsen global warming, while industrial development has the potential to weaken the Boreal's resistance and resilience in the face of global warming's intensifying impacts. If left unchecked, this situation could culminate in a catastrophic scenario known as "the carbon bomb".

The carbon bomb describes a massive release of greenhouse gasses into the atmosphere, driven, for example, by a widespread outbreak of forest or peat fires. As Greenpeace first warned in its 1994 report, *The Carbon Bomb*, because Canada's Boreal Forest contains 186 billion tonnes of carbon[319]—27 times the world's annual fossil fuel emissions—a rapid release of its carbon into the atmosphere could cause a disastrous spike in emissions.

The drought and decay being caused by global warming, combined with the fragmentation caused by logging, have the potential to create a tinderbox in Canada's north. Already, researchers are documenting an overall shift in the Boreal Forest from a net carbon sink to a net carbon source, due primarily to the increasing frequency and intensity of fires under warming climate conditions[320]. The more that intact forests are fragmented and degraded, the more susceptible the Boreal will become to these fires, and the more intense the fires themselves are likely to become.

By altering drainage patterns and other conditions, logging in the northern Boreal could trigger even more damage, through large-scale peat fires. Because 84 per cent of the carbon in the Boreal Forest is stored in its soils, peat fires would be disastrous in terms of climate emissions. Such events are not unprecedented. In 1997, peat fires ignited across Indonesia, releasing between 0.87 and 2.57 billion tonnes of carbon into the atmosphere—an estimated 13–40 per cent of the global carbon emissions from fossil fuels in that year[321]. While these fires were ignited by storms, the conditions for their ignition and spread were created in part by rapid industrial development. In 1995, the naturally waterlogged peatlands were logged and drained to create massive rice plantations. When a long drought came in 1997, the dried-out peat caught fire, releasing thousands of years' worth of stored carbon in a matter of months[322].

Logging and other industrial projects in Canada's Boreal Forest may be setting us up for a similar disaster. The drier and more fragmented the forest and its peatlands become, the more susceptible they will be to widespread, intense fires that threaten the rapid release of thousands of years' worth of accumulated carbon from the Boreal's trees and soils.

If protected, Canada's Boreal Forest can continue to play its crucial role in storing carbon, moderating local climates, and slowing permafrost melt. But if logging and industrial development continue to cut into forests at their current pace and global temperatures continue to rise, the Boreal Forest could turn from one of the world's most important carbon sinks to one of the world's biggest carbon sources.

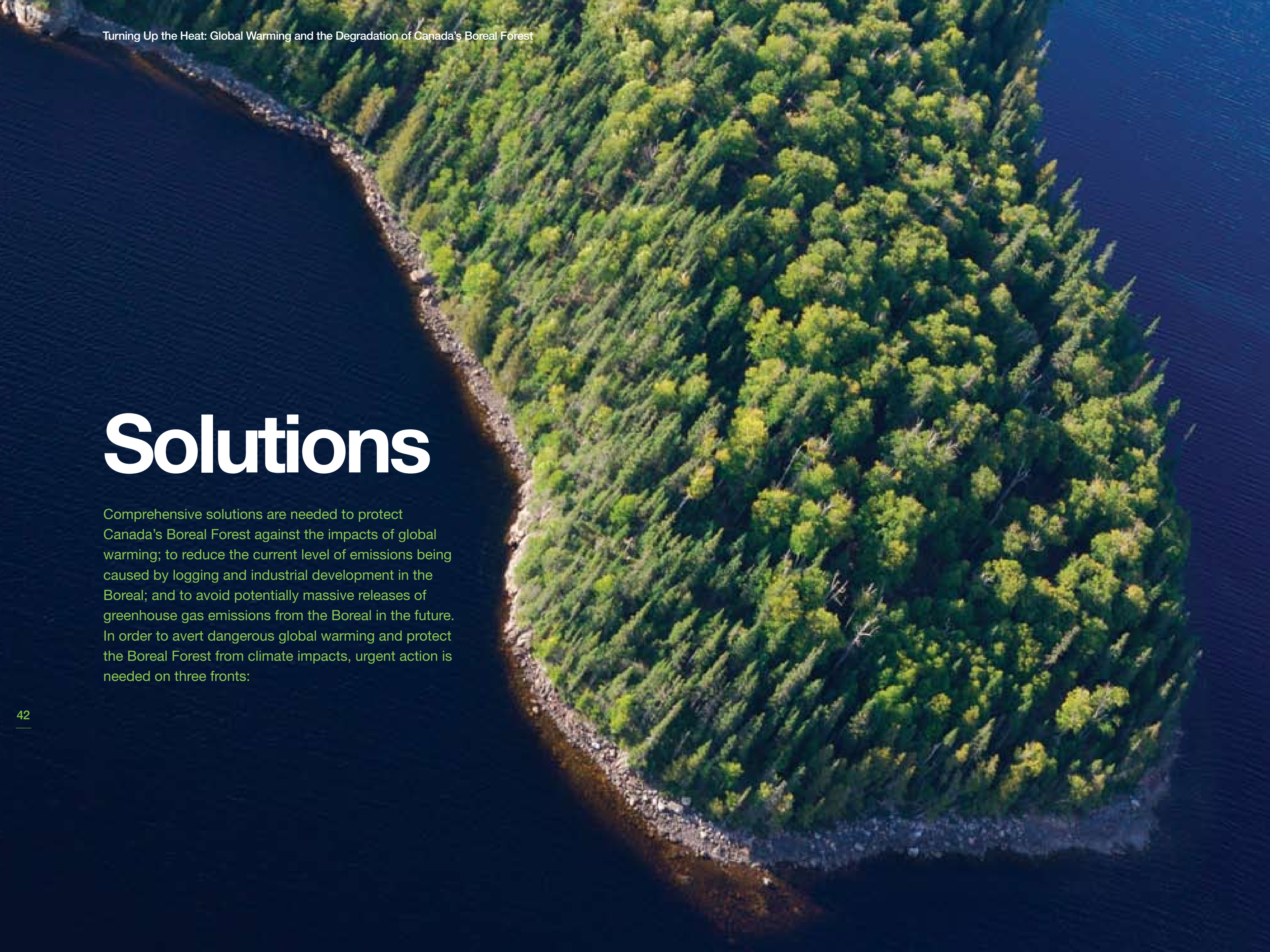
And the enormous stocks of carbon locked away in the Boreal's trees and soils could become a serious threat to the global climate.

The domino effect

The Boreal, the Amazon, the Congo, the Paradise forests of Asia-Pacific—in a changing climate, the fates of all these great forests are linked. Forest ecosystems currently store about one-and-a-half times as much carbon as is present in the atmosphere. As the climate warms and deforestation and forest degradation accelerate, more and more of this stored carbon is being released into the atmosphere, driving feedback loops that compromise the survival of all the world's forests.

Deforestation is one of the main causes of global warming, second only to practices in the energy sector. According to the IPCC, it accounts for about a fifth of all global emissions—more than the emissions from all the world's cars, trucks, and airplanes combined. Deforestation also results in less forest area to reabsorb the carbon emitted to the atmosphere. Tropical forests in particular play a powerful role in mitigating the growing change in the climate, but they are rapidly being destroyed by industrial logging and deforestation for plantations and agriculture.

Already, rising global temperatures—caused in part by deforestation—are disrupting forest ecosystems around the world in ways that are provoking a feedback of more greenhouse gas emissions into the atmosphere through forest dieback, forest fire, and other means. Tropical forests in particular are critical to climate regulation, acting as a global cooling mechanism through the carbon they store, absorb, and cycle. But if temperatures continue to increase, tropical rainforests and peatlands could become sources of greenhouse gas emissions—increasing the likelihood that the Boreal will continue to transition from an annual carbon sink to an annual carbon source.



Solutions

Comprehensive solutions are needed to protect Canada's Boreal Forest against the impacts of global warming; to reduce the current level of emissions being caused by logging and industrial development in the Boreal; and to avoid potentially massive releases of greenhouse gas emissions from the Boreal in the future. In order to avert dangerous global warming and protect the Boreal Forest from climate impacts, urgent action is needed on three fronts:

1 Intact areas of Canada's Boreal Forest must be protected.

As detailed in this report, intact areas of Canada's Boreal Forest are actively helping to slow global warming, both by storing massive amounts of carbon and by slowing permafrost melt and methane release. But with global temperatures on the rise, intact forests' abilities to resist and recover from global warming impacts and to help trees, plants, and wildlife to adapt and migrate under changing climate conditions are proving just as crucial.

When the Boreal Forest is degraded through logging and industrial development, not only are massive amounts of greenhouse gasses released into the atmosphere, but the forest becomes increasingly vulnerable to global warming impacts like fires and insect outbreaks—in many cases, impacts that themselves cause more greenhouse gasses to be released. At the same time, animals, birds, and trees lose the stability they need in order to adapt and the corridors they need in order to migrate. In short, when the Boreal Forest is degraded by logging, both the climate and the forest face dramatic consequences.

Yet under current legislation, only 8.1 per cent of the large intact areas of Canada's Boreal Forest are protected from industrial development[323]. Meanwhile, 45 per cent, or 154 million hectares (382 million acres), of the treed area of the Boreal is under license to logging companies, mainly in the biologically diverse southern areas of the Boreal Forest[324]. Many of the last remaining intact pockets of the more southern Boreal are slated for logging in coming years and the immense intact areas of the north are facing increasing risk of fragmentation through expanded logging, mining, and oil and gas development. What remains is in urgent need of protection.

That is why Greenpeace is calling for a government-imposed, industry-supported moratorium on industrial development in all intact areas of Canada's Boreal Forest.

A moratorium would make the most important areas of the Boreal off-limits to logging and other industrial development until an acceptable, comprehensive, science-based plan for its future management and protection is agreed to by First Nations, communities, governments, environmental organizations, and industry—a plan that's sustainable for communities, for wildlife, and for the planet.

2 Greenhouse gas emissions from fossil fuels must be reduced.

To protect the Boreal Forest and the carbon stored within it, global warming must be slowed, through a drastic reduction in greenhouse gas emissions. The burning of fossil fuels is the number one contributor to greenhouse gas emissions, accounting for about 75 per cent of emissions worldwide[325]. To curb global warming, therefore, the use of coal, oil, and gas must be drastically reduced, especially in the industrialized world, where emissions are the highest. The Greenpeace Energy Revolution scenario shows that emissions from the power sector can be reduced by 50 per cent by 2050 if a massive uptake of sustainable renewable energy options, a doubling of energy efficiency, and a decentralization of energy generation systems are achieved[326]. Greenpeace is calling for industrialized-country emissions to be reduced by 18 per cent from 1990 levels for the second Kyoto commitment period, and by 30 per cent by the third period, covering 2018–2022[327].

3 Tropical deforestation must be stopped.

Second only to reducing fossil fuel burning, curbing tropical deforestation is one of the quickest, most effective ways to reduce greenhouse gas emissions. In addition to preserving global biodiversity, protecting these forests is crucial to stabilizing the climate, and therefore crucial to protecting the Boreal from intensifying global warming impacts. Greenpeace is calling for an end to deforestation in Indonesia and the Amazon rainforest—by far the two largest sources of greenhouse gas emissions from deforestation.

Conclusion

Canada has a critical opportunity to help slow global warming by protecting the Boreal Forest. But it is an opportunity which, if ignored, could turn into a serious liability. Because the Boreal stores so much carbon in its soils, trees, and peatlands, its potential to contribute to the solution is darkly underlaid with the potential to worsen the problem.

If Canada's Boreal Forest is protected, it will continue to sequester and store carbon, and its intact landscapes will continue to help protect the forest and its inhabitants from the intensifying impacts of global warming. But if industrial development is allowed to continue its trajectory north, then what remains of the Boreal's pristine expanses will be scarred with roads and clearcuts, it will become more and more vulnerable to insect outbreaks, fires, and melting, and the masses of carbon locked away in its soils and trees may be released into the atmosphere.

In 1994, Greenpeace urged policy and decision makers to radically rethink energy policies in industrialized countries and logging practices in the Boreal Forest. Since then, fourteen years have passed without sufficient action on either front. We cannot continue to watch and wait: leading climate scientists warn that if we're to avert dangerous climate change, global greenhouse gas emissions must reach their peak by 2015 and then decline dramatically by mid-century[328]. Governments and industry around the world must take immediate action to save what is left of Canada's Boreal Forest, and to ensure that the global climate remains a liveable one.

Endnotes

1 Nelson, E.A., G.G. Sherman, J.R. Malcolm, and S.C. Thomas (2007). *Combating climate change through boreal forest conservation: Resistance, adaptation, and mitigation.* A technical report for Greenpeace Canada.

2 Barber VA, Juday GP, Finney BP (2000). Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature* 405, 668-673.

3 Wilmking M, Juday GP (2005). Longitudinal variation of radial growth at Alaska's northern treeline—Recent changes and possible scenarios for the 21st century. *Global and Planetary Change* 47, 282-300.

4 Stewart RB, Wheaton E, Spittlehouse DL (1998). Climate change: Implications for the boreal forest. In: *Emerging air issues for the 21st century: The need for multidisciplinary management*. *Proceedings.* Speciality conference, Sep. 22–24, 1997, Calgary. AB. Legge AH, Jones LL (eds.). Air and Waste Management Assoc., Pittsburg, PA, pp 86-101.

5 Goetz SJ, Bunn AG, Fiske GJ, Houghton RA (2005). Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance. *Proceedings of the National Academy of Sciences of the United States of America* 102, 13521-13525.

6 Podur JJ, Martell DL, Knight K (2002). Statistical quality control analysis of forest fire activity in Canada. *Canadian Journal of Forest Research* 32,195-205.

7 Wang CK, Bond-Lamberty B, Gower ST (2003). Carbon distribution of a well- and poorly-drained black spruce fire chronosequence. *Global Change Biology* 9, 1066-1079.

8 Wermielinger B (2004). Ecology and management of the spruce bark beetle *Ips typographus*—A review of recent research. *Forest Ecology and Management* 202, 67-82.

9 Volney WJA, Fleming RA (2000). Climate change and impacts of boreal forest insects. *Agriculture Ecosystems and Environment* 82: 283-294.

10 Woodward FI (1987). *Climate and plant distribution*. Cambridge University Press, Cambridge, UK.

11 Cannell MGR, Smith RI (1986). Climatic warming, spring budburst and frost damage on trees. *Journal of Applied Ecology* 23, 177-191.

12 Hanninen H (2006). Climate warming and the risk of frost damage to boreal forest trees: Identification of critical ecophysiological traits. *Tree Physiology* 26, 889-898.

13 Kerr J, Packer L (1998). The impact of climate change on mammal diversity in Canada. *Environmental Monitoring and Assessment* 49, 263-270.

14 Noss RF (2001). Beyond Kyoto: Forest management in a time of rapid climate change. *Conservation Biology* 15, 578-590.

15 Jump AS, Penuelas J (2005). Running to stand still: Adaptation and the response of plants to rapid climate change. *Ecology Letters* 8, 1010-1020.

16 Mosseler A, Major JE, Rajora OP (2003). Old-growth red spruce forests as reservoirs of genetic diversity and reproductive fitness. *Theoretical and Applied Genetics* 106, 931-937.

17 Noss RF (2001). Beyond Kyoto: Forest management in a time of rapid climate change. *Conservation Biology* 15, 578-590.

18 Frelich LE, Reich PB (2003). Perspectives on development of definitions and values related to old-growth forests. *Environmental Reviews* 11, S9-S22.

19 Jump AS, Penuelas J (2005). Running to stand still: Adaptation and the response of plants to rapid climate change. *Ecology Letters* 8, 1010-1020.

20 Stewart RB, Wheaton E, Spittlehouse DL (1998). Climate change: Implications for the boreal forest. In: *Emerging air issues for the 21st century: The need for multidisciplinary management*. *Proceedings.* Speciality conference, Sep. 22–24, 1997, Calgary. AB. Legge AH, Jones LL (eds.). Air and Waste Management Assoc., Pittsburg, PA, pp 86-101.

21 Saxe H, Cannell MGR, Johnsen B, Ryan MG, Vourlitis G (2001). Tree and forest functioning in response to global warming. *New Phytologist* 149, 369-399.

22 Jump AS, Penuelas J (2005). Running to stand still: Adaptation and the response of plants to rapid climate change. *Ecology Letters* 8, 1010-1020.

23 M.J. Apps, W.A. Kurz, R.J. Luxmoore, L.O. Nilsson, R.A. Sedjo, R. Schmidt, L.G. Simpson, and T.S. Vinson (1993). Boreal forests and tundra. *Water, Air, and Soil Pollution* 70, 39-53.

24 Global carbon emissions during 2000–2005 averaged around 7.2 million metric tonnes per year. (International Panel on Climate Change [IPCC]) [2007]. Summary for policymakers. In: *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller [eds.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.)

25 M.J. Apps, W.A. Kurz, R.J. Luxmoore, L.O. Nilsson, R.A. Sedjo, R. Schmidt, L.G. Simpson, and T.S. Vinson (1993). Boreal forests and tundra. *Water, Air, and Soil Pollution* 70, 39-53.

26 Chapin FS, McGuire AD, Randerson J, Pielke R, Baldocchi D, Hobbie SE, Roulet N, Eugster W, Kasischke E, Rastetter EB, Zimov SA, Running SW (2000). Arctic and boreal ecosystems of western North America as components of the climate system. *Global Change Biology* 6, 211-223.

27 Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate change 2007*. IPCC third assessment report. IPCC Secretariat, Geneva.

28 Camill P, Clark JS (1998). Climate change disequilibrium of boreal permafrost peatlands caused by local processes. *American Naturalist* 151, 207-222.

29 Camill P, Clark JS (1998). Climate change disequilibrium of boreal permafrost peatlands caused by local processes. *American Naturalist* 151, 207-222.

30 Eugster W, Rouse WR, Pielke RA, McFadden JP, Baldocchi DD, Kittel TGF, Chapin FS, Liston GE, Vidale PL, Vaganov E, Chambers S (2000). Land-atmosphere energy exchange in Arctic tundra and boreal forest: Available data and feedbacks to climate. *Global Change Biology* 6, 84-115.

31 Osterkamp TE, Viereck L, Shur Y, Jorgenson MT, Racine C, Doyle A, Boone RD (2000). Observations of thermokarst and its impact on boreal forests in Alaska, USA. *Arctic Antarctic and Alpine Research* 32, 303-315.

32 Canadian Forest Service (CFS) (2006). National Forestry Database Program. http://nfdp.ccfm.org/index_e.php.

33 Environment Canada (2006). *National inventory report: Greenhouse gas sources and sinks in Canada, 1990–2004*. Submission to the United Nations Framework Convention on Climate Change.

34 Colombo CJ, Parker WC, Lukai N, Dang Q, Cai T (2003). *The effects of forest management on carbon storage in Ontario's forests*. Climate change research report (CCRR-03). Ontario Ministry of Natural Resources Applied Research and Development Branch. Queens Printer for Ontario. Ontario, Canada. 82.

35 ForestEthics (2007). *Canada's forest industry: Setting the record straight*. http://www.forestethics.org/downloads/FPACwhitepaper.pdf.

36 Schulze ED, Lloyd J, Kelliher FM, Wirth C, Rebmann C, Luhker B, Mund M, Knohl A, Milyukova IM, Schulze W, Ziegler W, Varlagin AB, Sogachev AF, Valentini R, Dore S, Grigoriev S, Kolle O, Panfyorov MI, Tchebakova N, Vygodskaya NN (1999). Productivity of forests in the Eurosiberian boreal region and their potential to act as a carbon sink—A synthesis. *Global Change Biology* 5, 703-722.

37 Fredeen AL, Waughtal JD, Pypker TG (2007). When do replanted sub-boreal clearcuts become net sinks for CO_2? *Forest Ecology and Management* 239, 210-216.

38 Intergovernmental Panel on Climate Change (IPCC), Working Group II (2007). *Climate change 2007: Impacts, adaptation and vulnerability*. Working Group II contribution to the fourth assessment report of the Intergovernmental Panel on Climate Change. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.), Cambridge University Press, Cambridge, UK.

39 Greenpeace International (1994). *The carbon bomb: Global warming and the fate of the northern boreal forests*. Stichting Greenpeace Council, Amsterdam, the Netherlands.

40 Environment Canada. *National inventory report, 1990–2005: Greenhouse gas sources and sinks in Canada*. A summary of trends.

41 Analysis produced by Global Forest Watch Canada, 2008.

42 Nelson, E.A., G.G. Sherman, J.R. Malcolm, and S.C. Thomas (2007). *Combating climate change through boreal forest conservation: Resistance, adaptation, and mitigation.* A technical report for Greenpeace Canada.

43 Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate change 2007*. IPCC third assessment report. IPCC Secretariat, Geneva.

44 M.J. Apps, W.A. Kurz, R.J. Luxmoore, L.O. Nilsson, R.A. Sedjo, R. Schmidt, L.G. Simpson, and T.S. Vinson (1993). Boreal forests and tundra. *Water, Air, and Soil Pollution* 70, 39-53.

45 Global carbon emissions during 2000–2005 averaged around 7.2 million metric tonnes per year. (International Panel on Climate Change [IPCC]) [2007]. Summary for policymakers. In: *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller [eds.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.)

46 M.J. Apps, W.A. Kurz, R.J. Luxmoore, L.O. Nilsson, R.A. Sedjo, R. Schmidt, L.G. Simpson, and T.S. Vinson (1993). Boreal forests and tundra. *Water, Air, and Soil Pollution* 70, 39-53.

47 Finer L, Mannerkoski H, Piirainen S, Starr M (2003). Carbon and nitrogen pools in an old-growth, Norway spruce mixed forest in eastern Finland and changes associated with clear-cutting, *Forest Ecology and Management* 174, 51-63.

48 Wang CK, Bond-Lamberty B, Gower ST (2003). Carbon distribution of a well- and poorly-drained black spruce fire chronosequence. *Global Change Biology* 9, 1066-1079.

49 Yarie J, Van Cleve K (1983). Biomass productivity of white spruce stands in interior Alaska. *Canadian Journal of Forest Research* 13, 767-772.

50 Canadian Forest Service (2007). Forest fire facts and questions. March 2007. Natural Resources Canada. http://www.nofc.forestry.ca/fire/facts_e.php/.

51 Chapin FS, McGuire AD, Randerson J, Pielke R, Baldocchi D, Hobbie SE, Roulet N, Eugster W, Kasischke E, Rastetter EB, Zimov SA, Running SW (2000). Arctic and boreal ecosystems of western North America as components of the climate system. *Global Change Biology* 6, 211-223.

52 National Forestry Database Program (2007). Canadian compendium of forestry statistics. June 2007. http://nfdp.ccfm.org/compendium/index_e.php/.

53 Canadian Forest Service (CFS) (2006). National Forestry Database Program. http://nfdp.ccfm.org/index_e.php.

54 Environment Canada (2006). *National inventory report: Greenhouse gas sources and sinks in Canada, 1990–2004*. Submission to the United Nations Framework Convention on Climate Change.

55 Colombo CJ, Parker WC, Lukai N, Dang Q, Cai T (2003). *The effects of forest management on carbon storage in Ontario's forests*. Climate change research report (CCRR-03). Ontario Ministry of Natural Resources Applied Research and Development Branch. Queens Printer for Ontario. Ontario, Canada. 82.

56 ForestEthics (2007) *Canada's forest industry: Setting the record straight*. http://www.forestethics.org/downloads/FPACwhitepaper.pdf.

57 Schulze ED, Lloyd J, Kelliher FM, Wirth C, Rebmann C, Luhker B, Mund M, Knohl A, Milyukova IM, Schulze W, Ziegler W, Varlagin AB, Sogachev AF, Valentini R, Dore S, Grigoriev S, Kolle O, Panfyorov MI, Tchebakova N, Vygodskaya NN (1999). Productivity of forests in the Eurosiberian boreal region and their potential to act as a carbon sink—A synthesis. *Global Change Biology* 5, 703-722.

58 Fredeen AL, Waughtal JD, Pypker TG (2007). When do replanted sub-boreal clearcuts become net sinks for CO_2? *Forest Ecology and Management* 239, 210-216.

59 Yarie J, Van Cleve K (1983). Biomass productivity of white spruce stands in interior Alaska. *Canadian Journal of Forest Research* 13, 767-772.

60 Bond-Lamberty B, Gower ST, Goulden ML, McMillan A (2006). Simulation of boreal black spruce chronosequences: Comparison to field measurements and model evaluation. *Journal of Geophysical Research—Biogeosciences* 111.

61 Camill P, Clark JS (1998). Climate change disequilibrium of boreal permafrost peatlands caused by local processes. *American Naturalist* 151, 207-222.

62 Turetsky MR, Wieder RK, Vitt DH (2002). Boreal peatland C fluxes under varying permafrost regimes. *Soil Biology & Biochemistry* 34, 907-912.

63 Analysis produced by Global Forest Watch Canada, 2008.

64 Analysis produced by Global Forest Watch Canada, 2008.

65 Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate change 2007*. IPCC third assessment report. IPCC Secretariat, Geneva.

66 Ibid.

67 Ibid.

68 Malcolm JR, Markham A, Neilson RP, Garaci M (2002). Estimated migration rates under scenarios of global climate change. *Journal of Biogeography* 29, 835-849.

69 Hamann A, Wang TL (2006). Potential effects of global climate change on ecosystem and tree species distribution in British Columbia. *Ecology* 87, 2773-2786.

70 Esseen PA, Ehnström B, Ericson L, Sjöberg K (1997). Boreal forests. *Ecological Bulletin* 46, 16-47.

71 Intergovernmental Panel on Climate Change (IPCC) (2000). *Land-use, land-use change and forestry. Special report*. Cambridge University Press, Cambridge.

72 Barber VA, Juday GP, Finney BP (2000). Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature* 405, 668-673.

73 Wilmking M, Juday GP (2005). Longitudinal variation of radial growth at Alaska's northern treeline—Recent changes and possible scenarios for the 21st century. *Global and Planetary Change* 47, 282-300.

74 Hogg EH, Brandt, James P, Kochtubajda B (2002). Growth and dieback of aspen forests in northwestern Alberta, Canada, in relation to climate and insects. *Canadian Journal of Forest Research* 32, 823.

75 Calef MP, McGuire AD, Epstein HE, Rupp TS, Shugart HH (2005). Analysis of vegetation distribution in Interior Alaska and sensitivity to climate change using a logistic regression approach. *Journal of Biogeography* 32, 863-878.

76 Payette S (1992). Fire as a controlling process in the North American boreal forest. In: Shugart HH, Leemans R, Bonan GB (eds.), *A systems analysis of the global boreal forest*. Cambridge University Press, New York, pp 144-169.

77 Zasada JC, Gordon AG, Slaughter CW, Duchesne LC (1997). *Ecological considerations for the sustainable management of the North American boreal forests*. Interim report. International Institute for Applied Systems Analysis, Laxenburg, Austria.

78 Bergeron Y, Gauthier S, Kafka V, Lefort P, Lesieur D (2001). Natural fire frequency for the eastern Canadian boreal forest: Consequence for sustainable forestry. *Canadian Journal of Forest Research* 31, 384-391.

79 Canadian Forest Service (2007). Forest fire facts and questions. March 2007. Natural Resources Canada. http://www.nofc.forestry.ca/fire/facts_e.php/.

80 Stewart RB, Wheaton E, Spittlehouse DL (1998). Climate change: Implications for the boreal forest. In: *Emerging air issues for the 21st century: The need for multidisciplinary management*. *Proceedings.* Speciality conference, Sep. 22–24, 1997, Calgary. AB. Legge AH, Jones LL (eds.). Air and Waste Management Assoc., Pittsburg, PA, pp 86-101.

81 Goetz SJ, Bunn AG, Fiske GJ, Houghton RA (2005). Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance. *Proceedings of the National Academy of Sciences of the United States of America* 102, 13521-13525.

82 Podur JJ, Martell DL, Knight K (2002). Statistical quality control analysis of forest fire activity in Canada. *Canadian Journal of Forest Research* 32,195-205.

83 Chapin FS, McGuire AD, Randerson J, Pielke R, Baldocchi D, Hobbie SE, Roulet N, Eugster W, Kasischke E, Rastetter EB, Zimov SA, Running SW (2000). Arctic and boreal ecosystems of western North America as components of the climate system. *Global Change Biology* 6, 211-223.

84 Stewart RB, Wheaton E, Spittlehouse DL (1998). Climate change: Implications for the boreal forest. In: *Emerging air issues for the 21st century: The need for multidisciplinary management*. *Proceedings.* Speciality conference, Sep. 22–24, 1997, Calgary. AB. Legge AH, Jones LL (eds.). Air and Waste Management Assoc., Pittsburg, PA, pp 86-101.

85 Wang CK, Bond-Lamberty B, Gower ST (2003). Carbon distribution of a well- and poorly-drained black spruce fire chronosequence. *Global Change Biology* 9, 1066-1079.

86 Flannigan MD, Logan KA, Amiro BD, Skinner WR, Stocks BJ (2005). Future area burned in Canada. *Climatic Change* 72, 1-16.

87 In addition to warmer winter temperatures, warmer temperatures year-round have also been shown to enhance the population growth rate of most insect species. (Stewart RB, Wheaton E, Spittlehouse DL [1998]. Climate change: Implications for the boreal forest. In: *Emerging air issues for the 21st century: The need for multidisciplinary management*. *Proceedings.* Speciality conference, Sep. 22-24, 1997, Calgary. AB. Legge AH, Jones LL [eds.]. Air and Waste Management Assoc., Pittsburg, PA.)

88 Stahl K, Moore RD, McKendry IG (2006). Climatology of winter cold spells in relation to mountain pine beetle mortality in British Columbia, Canada. *Climate Research* 32, 13.

89 National Forestry Database Program (2007). Canadian compendium of forestry statistics. June 2007. http://nfdp.ccfm.org/compendium/index_e.php/.

90 Wermielinger B (2004). Ecology and management of the spruce bark beetle *Ips typographus*—A review of recent research. *Forest Ecology and Management* 202, 67-82.

91 Volney WJA, Fleming RA (2000). Climate change and impacts of boreal forest insects. *Agriculture Ecosystems and Environment* 82: 283-294.

92 Stewart RB, Wheaton E, Spittlehouse DL (1998). Climate change: Implications for the boreal forest. In: *Emerging air issues for the 21st century: The need for multidisciplinary management*. *Proceedings.* Speciality conference, Sep. 22–24, 1997, Calgary. AB. Legge AH, Jones LL (eds.). Air and Waste Management Assoc., Pittsburg, PA, pp 86-101.

93 Volney WJA, Fleming RA (2000). Climate change and impacts of boreal forest insects. *Agriculture Ecosystems and Environment* 82: 283-294.

94 Briffa KR, Jones PD, Schweingruber FH, Shiyatov SG, Cook ER (1995). Unusual twentieth-century summer warmth in a 1,000-year temperature record from Siberia. *Nature* 376, 156.

95 Jacoby GC, D'Arrigo RD, Davaajamts T (1996). Mongolian tree rings and 20th-century warming. *Science* 273, 771.

96 Woodward FI (1987). *Climate and plant distribution*. Cambridge University Press, Cambridge, UK.

97 D'Arrigo RD, Kaufmann RK, Davi N, Jacoby GC, Laskowski C, Myneni RB, Cherubini P (2004). Thresholds for warming-induced growth decline at elevational tree line in the Yukon Territory, Canada. *Global Biogeochemical Cycles* 18.

98 Briffa KR, Schweingruber FH, Jones PD, Osborn TJ, Shiyatov SG, Vaganov EA (1998). Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature* 391, 678-682.

99 Barber VA, Juday GP, Finney BP (2000). Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature* 405, 668-673.

100 Wilmking M, Juday GP, Barber VA, Zald HSJ (2004). Recent climate warming forces contrasting growth responses of white spruce at treeline in Alaska through temperature thresholds. *Global Change Biology* 10, 1724-1736.

101 Cannell MGR, Smith RI (1986). Climatic warming, spring budburst and frost damage on trees. *Journal of Applied Ecology* 23, 177-191.

102 Hanninen H (2006). Climate warming and the risk of frost damage to boreal forest trees: Identification of critical ecophysiological traits. *Tree Physiology* 26, 889-898.

103 Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate change 2007*. IPCC third assessment report. IPCC Secretariat, Geneva.

104 Malcolm JR, Puric-Mladenovic D, Shi H (2005). Projected tree distributions, tree migration rates, and forest types in Ontario under a 2°C global temperature rise. Pp. 52-99 In: *Implications of a 2°C global temperature rise for Canada's natural resources* (T Tin, ed.). WWF-World Wide Fund For Nature, Gland, Switzerland.

105 Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate change 2007*. IPCC third assessment report. IPCC Secretariat, Geneva.

106 E.g., Kerr J, Packer L (1998). The impact of climate change on mammal diversity in Canada. *Environmental Monitoring and Assessment* 49, 263-270.

107 Kerr J, Packer L (1998). The impact of climate change on mammal diversity in Canada. *Environmental Monitoring and Assessment* 49, 263-270.

108 Ibid.

109 Ibid.

110 Hamann A, Wang TL (2006). Potential effects of global warming on ecosystem and tree species distribution in British Columbia. *Ecology* 87, 2773-2786.

111 Iverson LR, Prasad AM (1998). Predicting abundance of 80 tree species following global warming in the eastern United States. *Ecological Monographs* 68, 465-485.

112 Solomon AM, Kirilenko AP (1997). Global warming and terrestrial biomass: What if trees do not migrate! *Global Ecology and Biogeography Letters* 6, 139-148.

113 Malcolm JR, Markham A, Neilson RP, Garaci M (2002). Estimated migration rates under scenarios of global climate change. *Journal of Biogeography* 29, 835-849.

114 Malcolm JR, Puric-Mladenovic D, Shi H (2005). Projected tree distributions, tree migration rates, and forest types in Ontario under a 2°C global temperature rise. Pp. 52-99 In: *Implications of a 2°C global temperature rise for Canada's natural resources* (T Tin, ed.). WWF-World Wide Fund For Nature, Gland, Switzerland.

115 Kerr J, Packer L (1998). The impact of climate change on mammal diversity in Canada. *Environmental Monitoring and Assessment* 49, 263-270.

116 Martin TE (2001). Abiotic vs. biotic influences on habitat selection of coexisting species: Climate change impacts? *Ecology* 82, 175-188.

117 E.g., Visser ME, van Noordwijk AJ, Tinbergen JM, Lessells CM (1998). Warmer springs lead to mistimed reproduction in great tits (*Parus major*). In: *Proceedings of the Royal Society of London, Series B—Biological Sciences* 265, 1867-1870.

118 Schmitz OJ, Post E, Burns CE, Johnston KM (2003). Ecosystem responses to global climate change: Moving beyond color mapping. *Bioscience* 53, 1199-1205.

119 Rupp TS, Olson M, Adams LG, Dale BW, Joly K, Henkelman J, Collins WB, Starfield AM (2006). Simulating the influences of various fire regimes on caribou winter habitat. *Ecological Applications* 16, 1730-1743.

120 Schmitz OJ, Post E, Burns CE, Johnston KM (2003.) Ecosystem responses to climate change: Moving beyond color mapping. *Bioscience* 53, 1199-1205.

121 Government of Canada Committee on the Status of Endangered Species in Canada (2007). Government of Canada, December 2007. http://www.cosewic.gc.ca/.

122 Noss RF (2001). Beyond Kyoto: Forest management in a time of rapid climate change. *Conservation Biology* 15, 578-590.

123 Nilsson U, Örlander G, Karlsson M (2006). Establishing mixed forests in Sweden by combining planting and natural regeneration; Effects of shelterwoods and scarification. *Forest Ecology and Management* 237, 301-311.

124 Rivers AR, Lynch AH (2004). On the influence of land cover on early Holocene climate in northern latitudes. *Journal of Geophysical Research-Atmospheres* 109, D21114.

125 Sturm M, Douglas T, Racine C, Liston GE (2005). Changing snow and shrub conditions affect albedo with global implications. *Journal of Geophysical Research-Biogeosciences,* 110, G01004.

126 Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate change 2007*. IPCC third assessment report . IPCC Secretariat, Geneva.

127 Walker BH (1992). Biodiversity and Ecological Redundancy. *Conservation Biology* 6, 18-23.

128 de Grandpre L, Bergeron Y (1997). Diversity and stability of understorey communities following disturbance in the southern boreal forest. *Journal of Ecology* 85, 777.

129 Walker BH (1992). Biodiversity and ecological redundancy. *Conservation Biology* 6, 18-23.

130 Noss RF (2001). Beyond Kyoto: Forest management in a time of rapid climate change. *Conservation Biology* 15, 578-590.

131 Mosseler A, Major JE, Rajora OP (2003). Old-growth red spruce forests as reservoirs of genetic diversity and reproductive fitness. *Theoretical and Applied Genetics* 106, 931-937.

132 Noss RF (2001). Beyond Kyoto: Forest management in a time of rapid climate change. *Conservation Biology* 15, 578-590.

133 Frelich LE, Reich PB (2003). Perspectives on development of definitions and values related to old-growth forests. *Environmental Reviews* 11, S9-S22.

134 Jump AS, Penuelas J (2005). Running to stand still: Adaptation and the response of plants to rapid climate change. *Ecology Letters* 8, 1010-1020.

135 Noss RF (2001). Beyond Kyoto: Forest management in a time of rapid climate change. *Conservation Biology* 15, 578-590.

136 Jump AS, Penuelas J (2005). Running to stand still: Adaptation and the response of plants to rapid climate change. *Ecology Letters* 8, 1010-1020.

137 Kelly CK, Chase MW, de Bruijn A, Fay MF, Woodward FI (2003). Temperature-based population segregation in birch. *Ecology Letters* 6, 87-89.

138 Saxe H, Cannell MGR, Johnsen B, Ryan MG, Vourlitis G (2001). Tree and forest functioning in response to global warming. *New Phytologist* 149, 369-399.

139 Boreal forest populations have always been under strong selective pressure to adapt to local climates[a, b]. For example, "warm year" genotypes will likely increase in frequency under warming conditions[c] over a much shorter timescale than northward migration of southern pre-adapted genotypes.[d]

[a] Saxe H, Cannell MGR, Johnsen B, Ryan MG, Vourlitis G (2001). Tree and forest functioning in response to global warming. *New Phytologist* 149.

[b] Jump AS, Penuelas J (2005). Running to stand still: Adaptation and the response of plants to rapid climate change. *Ecology Letters* 8.

[c] Kelly CK, Chase MW, de Bruijn A, Fay MF, Woodward FI (2003). Temperature-based population segregation in birch. *Ecology Letters* 6.

[d] Jump and Penuelas (2005). Idem.

140 Jump AS, Penuelas J (2005). Running to stand still: Adaptation and the response of plants to rapid climate change. *Ecology Letters* 8, 1010-1020.

141 Kelly CK, Chase MW, de Bruijn A, Fay MF, Woodward FI (2003). Temperature-based population segregation in birch. *Ecology Letters* 6, 87-89.

142 Jump AS, Penuelas J (2005). Running to stand still: Adaptation and the response of plants to rapid climate change. *Ecology Letters* 8, 1010-1020.

143 Saxe H, Cannell MGR, Johnsen B, Ryan MG, Vourlitis G (2001). Tree and forest functioning in response to global warming. *New Phytologist* 149, 369-399.

144 Jump AS, Penuelas J (2005). Running to stand still: Adaptation and the response of plants to rapid climate change. *Ecology Letters* 8, 1010-1020.

145 Lloyd AH (2005). Ecological histories from Alaskan tree lines provide insight into future change. *Ecology* 86, 1687-1695.

146 Lloyd AH, Fastie CL (2003). Recent changes in treeline forest distribution and structure in interior Alaska. *Ecoscience* 10, 176-185.

147 Tape K, Sturm M, Racine C (2006). The evidence for shrub expansion in Northern Alaska and the Pan-Arctic. *Global Change Biology,* 12, 686-702.

148 Jump AS, Penuelas J (2005). Running to stand still: Adaptation and the response of plants to rapid climate change. *Ecology Letters* 8, 1010-1020.

149 Ibid.

150 E.g., Noss RF (2001). Beyond Kyoto: Forest management in a time of rapid climate change. *Conservation Biology* 15, 578-590.

151 Stewart RB, Wheaton E, Spittlehouse DL (1998). Climate change: Implications for the boreal forest. In: *Emerging air issues for the 21st century: The need for multidisciplinary management*. *Proceedings.* Speciality conference, Sep. 22–24, 1997, Calgary. AB. Legge AH, Jones LL (eds.). Air and Waste Management Assoc., Pittsburg, PA, pp 86-101.

152 Bowman J, Holloway GL, Malcolm JR, Middel KR, and Wilson PJ (2005). Northern range boundary dynamics of southern flying squirrels: Evidence of an energetic bottleneck. *Canadian Journal of Zoology* 83, 1486–1494.

153 Gray PA (2005). Impacts of climate change on diversity in forested ecosystems: Some examples. *Forestry Chronicle* 81, 655-661.

154 Potvin F, Bertrand N (2004). Leaving forest strips in large clearcut landscapes of boreal forest: A management scenario suitable for wildlife? *Forestry Chronicle* 80, 44-53.

155 Reale D, McAdam AG, Boutin S, Berteaux D (2003). Genetic and plastic responses of a northern mammal to climate change. *Proceedings of the Royal Society of London, Series B—Biological Sciences* 270, 591-596.

156 Tottrup AP, Thorup K, Rahbek C (2006). Patterns of change in timing of spring migration in North European songbird populations. *Journal of Avian Biology* 37, 84-92.

157 Fahrig L, Merriam G (1994). Conservation of fragmented populations. *Conservation Biology* 8, 50-59.

158 Noss RF (2001). Beyond Kyoto: Forest management in a time of rapid climate change. *Conservation Biology* 15, 578-590.

159 Boucher Y, Arseneault D, Sirois L (2006). Logging-induced change (1930–2002) of a preindustrial landscape at the northern range limit of northern hardwoods, eastern Canada. *Canadian Journal of Forest Research* 36, 505.

160 Achard F, Mollicone D, Stibig H, Aksenov D, Laestadius L, Li Z, Popatov P, Yaroshenko A (2006). Areas of rapid forest-cover change in boreal Eurasia. *Forest Ecology and Management* 237, 322-334.

161 Young JE, Sánchez-Azofeifa GA, Hannon SJ, Chapman R (2006). Trends in land cover change and isolation of protected areas at the interface of the southern boreal mixedwood and aspen parkland in Alberta, Canada. *Forest Ecology and Management* 230, 151-161.

162 Analysis produced by Global Forest Watch Canada, 2007.

163 Vucetich JA, Reed DD, Breymeyer A, Degórski M, Mroz GD, Solon J, Roo-Zielinska E, Noble R (2000). Carbon pools and ecosystem properties along a latitudinal gradient in northern Scots pine (*Pinus sylvestris*) forests. *Forest Ecology and Management* 136, 135-145.

164 Goldblum D, Rigg LS (2005). Tree growth response to climate change at the deciduous-boreal forest ecotone, Ontario, Canada. *Canadian Journal of Forest Research* 35, 2709-2718.

165 Hamann A, Wang TL (2006). Potential effects of climate change on ecosystem and tree species distribution in British Columbia. *Ecology* 87, 2773-2786.

166 Kellman M (2004). Sugar maple (*Acer saccharum* Marsh.) establishment in boreal forest: Results of a transplantation experiment. *Journal of Biogeography,* 31, 1515-1522.

167 Saxe H, Cannell MGR, Johnsen B, Ryan MG, Vourlitis G (2001). Tree and forest functioning in response to global warming. *New Phytologist* 149, 369-399.

168 Jump AS, Penuelas J (2005). Running to stand still: Adaptation and the response of plants to rapid climate change. *Ecology Letters* 8, 1010-1020.

169 Malcolm JR, Markham A, Neilson RP, Garaci M (2002). Estimated migration rates under scenarios of climate change. *Journal of Biogeography* 29, 835-849.

170 Jump AS, Penuelas J (2005). Running to stand still: Adaptation and the response of plants to rapid climate change. *Ecology Letters* 8, 1010-1020.

171 Tans PP, Fung IY, Takahashi T (1990). Observational constraints on the global atmospheric CO_2 budget. *Science* 247, 1431-1438.

172 Intergovernmental Panel on Climate Change (IPCC) (2000). *Land-use, land-use change and forestry. Special report*. Cambridge University Press, Cambridge.

173 M.J. Apps, W.A. Kurz, R.J. Luxmoore, L.O. Nilsson, R.A. Sedjo, R. Schmidt, L.G. Simpson, and T.S. Vinson (1993). Boreal forests and tundra. *Water, Air, and Soil Pollution* 70, 39-53.

174 Global carbon emissions during 2000–2005 averaged around 7.2 million metric tonnes per year. (International Panel on Climate Change [IPCC]) [2007]. Summary for policymakers. In: *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller [eds.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.)

175 M.J. Apps, W.A. Kurz, R.J. Luxmoore, L.O. Nilsson, R.A. Sedjo, R. Schmidt, L.G. Simpson, and T.S. Vinson (1993). Boreal forests and tundra. *Water, Air, and Soil Pollution* 70, 39-53.

176 Desai AR, Bolstad PV, Cook BD, Davis KJ, Carey EV (2005). Comparing net ecosystem exchange of carbon dioxide between an old-growth and mature forest in the upper Midwest, USA. *Agricultural and Forest Meteorology* 128, 33-55.

177 Griffis TJ, Black TA, Morgenstern K, Barr AG, Nesic Z, Drewitt GB, Gaumont-Guay D, McCaughey JH (2003). Ecophysiological controls on the carbon balances of three southern boreal forests. *Agricultural and Forest Meteorology* 117, 53-71.

178 Bond-Lamberty B, Wang CK, Gower ST (2004). Net primary production and net ecosystem production of a boreal black spruce wildfire chronosequence. *Global Change Biology* 10, 473-487.

179 Law BE, Thornton PE, Irvine J, Anthoni PM, Van Tuyl S (2001). Carbon storage and fluxes in ponderosa pine forests at different developmental stages. *Global Change Biology* 7, 755-777.

180 Carey EV, Sala A, Keane R, Callaway RM (2001). Are old forests underestimated as global carbon sinks? *Global Change Biology* 7, 339-344.

181 Yarie J, Van Cleve K (1983). Biomass productivity of white spruce stands in interior Alaska. *Canadian Journal of Forest Research* 13, 767-772.

182 Knohl A, Schulze ED, Kolle O, Buchmann N (2003). Large carbon uptake by an unmanaged 250-year-old deciduous forest in Central Germany. *Agricultural and Forest Meteorology* 118, 151-167.

183 Paw U, Kyaw T, Falk M, Suchanek TH, Ustin SL, Chen J, Park Y-S, Winner WE, Thomas SC, Hsiao TC, Shaw RH, King TS, Pyles RD, Schroeder M, Matista AA (2004). Carbon dioxide exchange between an old-growth forest and the atmosphere. *Ecosystems* 7, 513-524.

184 Winner WE, Thomas SC, Berry JA, Bond BJ, Cooper CE, Hinckley TM, Ehleringer JR, Fessenden JE, Lamb B, McCarthy S, McDowell NG, Phillips N, Williams M (2004). Mechanisms of canopy carbon gain and water use: Analysis of old-growth conifers in the Pacific Northwest. *Ecosystems* 7, 482-497.

185 Guan DX, Wu JB, Zhao XS, Han SJ, Yu GR, Sun XM, Jin CJ (2006). CO_2 fluxes over an old, temperate mixed forest in northeastern China. *Agricultural and Forest Meteorology* 137, 138-149.

186 Malhi Y, Nobre AD, Grace J, Kruijt B, Pereira MGP, Culf A, Scott S (1998). Carbon dioxide transfer over a Central Amazonian rain forest. *Journal of Geophysical Research—*Atmospheres 103, 31593-31612

187 Loescher HW, Oberbauer SF, Gholz HL, Clark DB (2003). Environmental controls on net ecosystem-level carbon exchange and productivity in a Central American tropical wet forest. *Global Change Biology* 9, 396-412

188 Takanashi S, Kosugi Y, Tani M, Matsuo N, Mitani T, Nik AR (2005). Characteristics of the gas exchange of a tropical rain forest in peninsular Malaysia. *Phyton* 45, 61-66.

189 Kurz WA, Apps MJ (1999). A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecological Applications* 9, 526-547.

190 Ju WM, Chen JM, Black TA, Barr AG, McCaughey H, Roulet NT (2006). Hydrological effects on carbon cycles of Canada's forests and wetlands. *Tellus Series B—Chemical and Physical Meteorology* 58, 16-30.

191 Myneni RB, Dong J, Tucker CJ, Kaufmann RK, Kauppi PE, Liski J, Zhou L, Alexeyev V, Hughes MK (2001). A large carbon sink in the woody biomass of northern forests. *Proceedings of the National Academy of Sciences of the United States of America* 98, 14784-14789.

192 Goodale CL, Apps MJ, Birdsey RA, Field CB, Heath LS, Houghton RA, Jenkins JC, Kohlmaier GH, Kurz W, Liu SR, Nabuurs GJ, Nilsson S, Shvidenko AZ (2002). Forest carbon sinks in the Northern Hemisphere. *Ecological Applications* 12, 891-899.

193 Goetz SJ, Bunn AG, Fiske GJ, Houghton RA (2005). Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance. *Proceedings of the National Academy of Sciences of the United States of America* 102, 13521-13525.

194 Bond-Lamberty B, Peckham SD, Ahl DE, Gower ST (2007). Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature* 450, 89-93.

195 Myneni RB, Dong J, Tucker CJ, Kaufmann RK, Kauppi PE, Liski J, Zhou L, Alexeyev V, Hughes MK (2001). A large carbon sink in the woody biomass of Northern forests. *Proceedings of the National Academy of Sciences of the United States of America* 98, 14784-14789.

196 Goetz SJ, Bunn AG, Fiske GJ, Houghton RA (2005). Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance. *Proceedings of the National Academy of Sciences of the United States of America* 102, 13521-13525.

197 Bond-Lamberty B, Peckham SD, Ahl DE, Gower ST (2007). Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature*, 450, 89-93.

198 Kurz WA, Apps MJ (1999). A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecological Applications* 9, 526-547.

199 Kurz WA, Beukema SJ, Apps MJ (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.

200 Harmon ME, Ferrell WK, Franklin JF (1990). Effects on carbon storage of conversion of old-growth forests to young forests. *Science* 247, 699-702.

201 Zhang T, Barry RF, Knowles K, Heginbottom JA, Brown (1999). Statistics and characteristics of permafrost and ground ice distribution in the Northern Hemisphere. *Polar Geography* 23, 147-169.

202 Ibid.

203 Camill P, Clark JS (1998). Climate change disequilibrium of boreal permafrost peatlands caused by local processes. *American Naturalist* 151, 207-222.

204 Eugster W, Rouse WR, Pielke RA, McFadden JP, Baldocchi DD, Kittel TGF, Chapin FS, Liston GE, Vidale PL, Vaganov E, Chambers S (2000). Land-atmosphere energy exchange in Arctic tundra and boreal forest: Available data and feedbacks to climate. *Global Change Biology* 6, 84-115.

205 Chapin FS, McGuire AD, Randerson J, Pielke R, Baldocchi D, Hobbie SE, Roulet N, Eugster W, Kasischke E, Rastetter EB, Zimov SA, Running SW (2000). Arctic and boreal ecosystems of western North America as components of the climate system. *Global Change Biology* 6, 211-223.

206 Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate change 2007*. IPCC third assessment report. IPCC Secretariat, Geneva.

207 Camill P, Clark JS (1998). Climate change disequilibrium of boreal permafrost peatlands caused by local processes. *American Naturalist* 151, 207-222.

208 Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate change 2007*. IPCC third assessment report. IPCC Secretariat, Geneva.

209 Turetsky MR, Wieder RK, Vitt DH (2002). Boreal peatland C fluxes under varying permafrost regimes. *Soil Biology & Biochemistry* 34, 907-912.

210 Camill P, Clark JS (1998). Climate change disequilibrium of boreal permafrost peatlands caused by local processes. *American Naturalist* 151, 207-222.

211 Ibid.

212 Eugster W, Rouse WR, Pielke RA, McFadden JP, Baldocchi DD, Kittel TGF, Chapin FS, Liston GE, Vidale PL, Vaganov E, Chambers S (2000). Land-atmosphere energy exchange in Arctic tundra and boreal forest: Available data and feedbacks to climate. *Global Change Biology* 6, 84-115.

213 Osterkamp TE, Viereck L, Shur Y, Jorgenson MT, Racine C, Doyle A, Boone RD (2000). Observations of thermokarst and its impact on boreal forests in Alaska, USA. *Arctic Antarctic and Alpine Research* 32, 303-315.

214 Stewart RB, Wheaton E, Spittlehouse DL (1998). Climate change: implications for the boreal forest. In: *Emerging air issues for the 21st century: The need for multidisciplinary management*. *Proceedings.* Speciality conference, Sep. 22–24, 1997, Calgary. AB. Legge AH, Jones LL (eds.). Air and Waste Management Assoc., Pittsburg, PA, pp 86-101.

215 Eugster W, Rouse WR, Pielke RA, McFadden JP, Baldocchi DD, Kittel TGF, Chapin FS, Liston GE, Vidale PL, Vaganov E, Chambers S (2000). Land-atmosphere energy exchange in Arctic tundra and boreal forest: Available data and feedbacks to climate. *Global Change Biology* 6, 84-115.

216 Stewart RB, Wheaton E, Spittlehouse DL (1998). Climate change: Implications for the boreal forest. In: *Emerging air issues for the 21st century: The need for multidisciplinary management*. *Proceedings.* Speciality conference, Sep. 22–24, 1997, Calgary. AB. Legge AH, Jones LL (eds.). Air and Waste Management Assoc., Pittsburg, PA, pp 86-101.

217 Iwahana G, Machimura T, Kobayashi Y, Fedorov AN, Konstantinov PY, Fukuda M (2005). Influence of forest clear-cutting on the thermal and hydrological regime of the active layer near Yakutsk, eastern Siberia. *Journal of Geophysical Research* 110.

218 Ibid.

219 Morishita T, Hatano R, Takahashi K, Kondrashov LG (2005). Effect of deforestation on CH4 uptake in Khabarovsk, Far East, Russia. *Phyton-Annales Rei Botanicae,* 45, 267-274.

220 Ibid.

221 Bala G, Caldeira K, Wickett M, Phillips TJ, Lobell DB, Delire C, Mirin A (2007). Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences* 104, 6550-6555.

222 Bonan GB, Pollard D, Thompson SL (1992). Effects of boreal forest vegetation on global climate. *Nature* 359, 716-718.

223 Ni WG, Woodcock CE (2000). Effect of canopy structure and the presence of snow on the albedo of boreal conifer forests. *Journal of Geophysical Research-Atmospheres* 105, 11879-11888.

224 Davidson A, Wang SS (2005). Spatiotemporal variations in land surface albedo across Canada from MODIS observations. *Canadian Journal of Remote Sensing* 31, 377-390.

225 Amiro BD, Barr AG, Black TA, Iwashita H, Kljun N, McCaughey JH, Morgenstern K, Murayama S, Nesic Z, Orchansky AL, Saigusa N (2006). Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada. *Agricultural and Forest Meteorology* 136, 237-251.

226 Ibid.

227 In addition, changes in disturbance regimes that might give rise to changes in albedo would have large consequences for non-carbon dioxide radiative forcing agents (agents that force change in climate by altering the energy of the Earth's atmosphere), such as methane, nitrous oxide, and ozone. (Bala G, Caldeira K, Wickett M, Phillips TJ, Lobell DB, Delire C, Mirin A [2007]. Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences* 104, 6550-6555.)

228 Harmon ME, Ferrell WK, Franklin JF (1990). Effects on carbon storage of conversion of old-growth forests to young forests. *Science* 247, 699-702.

229 Finer L, Mannerkoski H, Piirainen S, Starr M (2003). Carbon and nitrogen pools in an old-growth, Norway spruce mixed forest in eastern Finland and changes associated with clear-cutting, *Forest Ecology and Management* 174, 51-63.

230 Wang CK, Bond-Lamberty B, Gower ST (2003). Carbon distribution of a well- and poorly-drained black spruce fire chronosequence. *Global Change Biology* 9, 1066-1079.

231 Finer L, Mannerkoski H, Piirainen S, Starr M (2003). Carbon and nitrogen pools in an old-growth, Norway spruce mixed forest in eastern Finland and changes associated with clear-cutting, *Forest Ecology and Management* 174, 51-63.

232 Tinker DB, Knight DH (2000). Coarse woody debris following fire and logging in Wyoming lodgepole pine forests. *Ecosystems* 3, 472-483.

233 Manies KL, Harden JW, Bond-Lamberty BP, O'Neill KP (2005). Woody debris along an upland chronosequence in boreal Manitoba and its impact on long-term carbon storage. *Canadian Journal of Forest Research* 35, 472-482.

234 Johnson DW, Murphy JF, Susfalk RB, Caldwell TG, Miller WW, Walker RF, Powers RF (2005). The effects of wildfire, salvage logging, and post-fire N-fixation on the nutrient budgets of a Sierran forest. *Forest Ecology and Management* 220, 155-165.

235 In addition to exacerbating carbon loss from fires, research has shown that salvage logging may also impair forest regeneration. (Donato DC, Fontaine JB, Campbell JL, Robinson WD, Kauffman JB, Law BE [2006]. Post-wildfire logging hinders regeneration and increases fire risk. *Science* 311, 352-352. Lindenmayer DB, Noss RF [2006]. Salvage logging, ecosystem processes, and biodiversity conservation. *Conservation Biology* 20, 949-958.)

236 Rudolphi J, Gustafsson L (2005). Effects of forest-fuel harvesting on the amount of deadwood on clear-cuts. Scandinavian Journal of Forest Research 20, 235-242.

237 Covington WW (1981). Changes in forest floor organic-matter and nutrient content following clearcutting in northern hardwoods. *Ecology* 62, 41-48.

238 Peltoniemi M, Makipaa R, Liski J, Tamminen P (2004). Changes in soil carbon with stand age—An evaluation of a modelling method with empirical data. *Global Change Biology* 10, 2078-2091.

239 Fitzsimmons MJ, Pennock DJ, Thorpe J (2004). Effects of deforestation on ecosystem carbon densities in central Saskatchewan, Canada. *Forest Ecology and Management* 188, 349-361.

240 This uncertainty in part reflects difficulties in separating the effects of logging on different carbon pools, and problems associated with using comparisons among different aged sites to reconstruct changes over time at a single site. (Kolari P, Pumpanen J, Rannik U, Ilvesniemi H, Hari P, Berninger F [2004]. Carbon balance of different aged Scots pine forests in Southern Finland. *Global Change Biology* 10, 1106-1119.)

241 Carrasco JJ, Neff JC, Harden JW (2006). Modeling physical and biogeochemical controls over carbon accumulation in a boreal forest soil. *Journal of Geophysical Research-Biogeosciences* 111.

242 Pypker TG, Fredeen AL (2002) Ecosystem CO_2 flux over two growing seasons for a sub-boreal clearcut 5 and 6 years after harvest. *Agricultural and Forest Meteorology* 114, 15-30.

243 Amiro BD, Barr AG, Black TA, Iwashita H, Kljun N, McCaughey JH, Morgenstern K, Murayama S, Nesic Z, Orchansky AL, Saigusa N (2006). Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada. *Agricultural and Forest Meteorology* 136, 237-251.

244 Fredeen AL, Waughtal JD, Pypker TG (2007). When do replanted sub-boreal clearcuts become net sinks for CO_2? *Forest Ecology and Management* 239, 210-216.

245 Federer CA (1984). Organic-matter and nitrogen-content of the forest floor in even-aged northern hardwoods. *Canadian Journal of Forest Research* 14, 763-767.

246 Fredeen AL, Bois CH, Janzen DT, Sanborn PT (2005). Comparison of coniferous forest carbon stocks between old-growth and young second-growth forests on two soil types in central British Columbia, Canada. *Canadian Journal of Forest Research* 35, 1411-1421.

247 Kolari P, Pumpanen J, Rannik U, Ilvesniemi H, Hari P, Berninger F (2004). Carbon balance of different aged Scots pine forests in Southern Finland. *Global Change Biology* 10, 1106-1119.

248 Howard EA, Gower ST, Foley JA, Kucharik CJ (2004). Effects of logging on carbon dynamics of a jack pine forest in Saskatchewan, Canada. *Global Change Biology* 10, 1267-1284.

249 Canadian Forest Service (CFS) (2006). National Forestry Database Program. http://nfdp.ccfm.org/index_e.php.

250 See Houghton RA (2005). Aboveground forest biomass and the global carbon balance. *Global Change Biology* 11, 945-958.

251 Environment Canada (2006). *National inventory report: Greenhouse gas sources and sinks in Canada, 1990–2004*. Submission to the United Nations Framework Convention on Climate Change.

252 Schulze ED, Lloyd J, Kelliher FM, Wirth C, Rebmann C, Luhker B, Mund M, Knohl A, Milyukova IM, Schulze W, Ziegler W, Varlagin AB, Sogachev AF, Valentini R, Dore S, Grigoriev S, Kolle O, Panfyorov MI, Tchebakova N, Vygodskaya NN (1999). Productivity of forests in the Eurosiberian boreal region and their potential to act as a carbon sink—A synthesis. *Global Change Biology* 5, 703-722.

253 Fredeen AL, Waughtal JD, Pypker TG (2007). When do replanted sub-boreal clearcuts become net sinks for CO_2? *Forest Ecology and Management* 239, 210-216.

254 Pypker TG, Fredeen AL (2002). Ecosystem CO_2 flux over two growing seasons for a sub-boreal clearcut 5 and 6 years after harvest. *Agricultural and Forest Meteorology* 114, 15-30.

255 Wirth C, Czimczik CI, Schulze ED (2002). Beyond annual budgets: Carbon flux at different temporal scales in fire-prone Siberian Scots pine forests. *Tellus* 54B, 611-630.

256 Amiro BD, Barr AG, Black TA, Iwashita H, Kljun N, McCaughey JH, Morgenstern K, Murayama S, Nesic Z, Orchansky AL, Saigusa N (2006). Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada. *Agricultural and Forest Meteorology* 136, 237-251.

257 Natural Resources Canada (2007). Does harvesting in Canada's forests contribute to global warming? Canadian Forest Service science-policy notes. Her Majesty the Queen in Right of Canada, May 1, 2007.

258 Bayliss, M (2007). Countering the eco-claptrap. *Tissue World*, October/November 2007, 3.

259 Law BE, Sun OJ, Campbell J, Van Tuyl S, Thornton PE (2003). Changes in carbon storage and fluxes in a chronosequence of ponderosa pine. *Global Change Biology* 9, 510-524.

260 Coursolle C, Margolis HA, Barr AG, Black TA, Amiro BD, McCaughey JH, Flanagan LB, Lafleur PM, Roulet NT, Bourque CPA, Arain MA, Wofsy SC, Dunn A, Morgenstern K, Orchansky AL, Bernier PY, Chen JM, Kidston J, Saigusa N. (2006). Late-summer carbon fluxes from Canadian forests and peatlands along an east-west continental transect. *Canadian Journal of Forest Research* 36, 783-800.

261 Fredeen AL, Bois CH, Janzen DT, Sanborn PT (2005). Comparison of coniferous forest carbon stocks between old-growth and young second-growth forests on two soil types in central British Columbia, Canada. *Canadian Journal of Forest Research* 35, 1411-1421.

262 Ibid.

263 Yarie J, Van Cleve K (1983). Biomass productivity of white spruce stands in interior Alaska. *Canadian Journal of Forest Research* 13, 767-772.

264 Bond-Lamberty B, Gower ST, Goulden ML, McMillan A (2006). Simulation of boreal black spruce chronosequences: Comparison to field measurements and model evaluation. *Journal of Geophysical Research—Biogeosciences* 111.

265 Price DT, Halliwell DH, Apps MJ, Kurz WA, Curry SR (1997). Comprehensive assessment of carbon stocks and fluxes in a Boreal-Cordilleran forest management unit. *Canadian Journal of Forest Research* 27, 2005-2016.

266 Kopra K, Fyles J (2005). *Nutrient budgeting for jack pine plantations in Northern Ontario*, SFMN Research Note Series #6. Sustainable Management Forest Network. Edmonton, Alberta, Canada.

267 Bergeron Y, Flannigan M, Gauthier S, Leduc A, Lefort P (2004). Past, current and future fire frequency in the Canadian Boreal Forest: Implications for sustainable forest management. Royal Swedish Academy of Sciences. *Ambio*, Vol 33, No 6, August 2004.

268 These relatively short rotation lengths are reflected in a recent shift towards a younger overall age structure in much of Canada's Boreal Forest. (Kurz WA, Apps MJ [1999]. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecological Applications* 9, 526-547. Harvey BD, Leduc A, Gauthier S, Bergeron Y [2002]. Stand-landscape integration in natural disturbance-based management of the southern boreal forest. *Forest Ecology and Management* 155, 369-385.)

269 Eugster W, Rouse WR, Pielke RA, McFadden JP, Baldocchi DD, Kittel TGF, Chapin FS, Liston GE, Vidale PL, Vaganov E, Chambers S (2000). Land-atmosphere energy exchange in Arctic tundra and boreal forest: Available data and feedbacks to climate. *Global Change Biology* 6, 84-115.

270 Chapin FS, McGuire AD, Randerson J, Pielke R, Baldocchi D, Hobbie SE, Roulet N, Eugster W, Kasischke E, Rastetter EB, Zimov SA, Running SW (2000). Arctic and boreal ecosystems of western North America as components of the climate system. *Global Change Biology* 6, 211-223.

271 Crawford RMM, Jeffree CE, Rees WG (2003). Paludification and forest retreat in northern oceanic environments. *Annals of Botany* 91, 213-226.

272 Morishita T, Hatano R, Takahashi K, Kondrashov LG (2005) Effect of deforestation on CH_4 uptake in Khabarovsk, Far East, Russia. *Phyton-Annales Rei Botanicae,* 45, 267-274.

273 Crawford RMM, Jeffree CE, Rees WG (2003). Paludification and forest retreat in northern oceanic environments. *Annals of Botany* 91, 213-226.

274 Chapin FS, McGuire AD, Randerson J, Pielke R, Baldocchi D, Hobbie SE, Roulet N, Eugster W, Kasischke E, Rastetter EB, Zimov SA, Running SW (2000). Arctic and boreal ecosystems of western North America as components of the climate system. *Global Change Biology* 6, 211-223.

275 E.g., Malcolm JR,Campbell BD, Kuttner BG, Sugar A (2004). Potential indicators of the impacts of forest management on wildlife habitat in northeastern Ontario: A multivariate application of wildlife habitat suitability matrices. *Forestry Chronicle* 80, 91-106.

276 Bergeron Y, Harvey B, Leduc A, Gauthier S (1999). Forest management guidelines based on natural disturbance dynamics: Stand- and forest-level considerations. *Forestry Chronicle* 75, 49-54.

277 Hearnden KW, Millson SV, Wilson WC (1992). *A report on the status of forest regeneration*. Ontario Ministry of Natural Resources, Canada.

278 Friedman SK, Reich PB (2005). Regional legacies of logging: Departure from presettlement forest conditions in northern Minnesota. *Ecological applications,* 15, 726.

279 Hearnden KW, Millson SV, Wilson WC (1992). *A report on the status of forest regeneration*. Ontario Ministry of Natural Resources, Canada.

280 Carleton TJ (2000). Vegetation responses to the managed landscape of central and northern Ontario. In: Perera A, Euler D, and Thompson I (eds.) *Ecology of a managed terrestrial landscape*. UBC Press, Toronto, pp 179-197.

281 Jackson SM, Pinto F, Malcolm JR, Wilson ER (2000). A comparison of pre-European settlement (1857) and current (1981-1995) forest composition in central Ontario. *Canadian Journal of Forest Research* 30, 605-612.

282 Friedman SK, Reich PB (2005). Regional legacies of logging: Departure from presettlement forest conditions in northern Minnesota. *Ecological applications,* 15, 726.

283 Haeussler S, Bedford L, Boateng JO, MacKinnon A (1999). Plant community responses to mechanical site preparation in northern interior British Columbia. *Canadian Journal of Forest Research* 29, 1084-1100.

284 Bock MD, Van Rees KCJ (2002). Mechanical site preparation impacts on soil properties and vegetation communities in the Northwest Territories. *Canadian Journal of Forest Research* 32, 1381-1392.

285 Forman RTT, Alexander LE (1998). Roads and their major ecological effects. *Annual Review of Ecology and Systematics* 29, 207-231.

286 Trombulak CT, Frissell CA (2000). Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology* 14, 18-30.

287 Colombo CJ, Parker WC, Lukai N, Dang Q, Cai T (2003). *The effects of forest management on carbon storage in Ontario's forests*. Climate change research report (CCRR-03). Ontario Ministry of Natural Resources Applied Research and Development Branch. Queens Printer for Ontario. Ontario, Canada. 82.

288 ForestEthics (2007) *Canada's forest industry: Setting the record straight*. http://www.forestethics.org/downloads/FPACwhitepaper.pdf.

289 Lee P, Boutin S (2006). Persistence and developmental transition of wide seismic lines in the western Boreal Plains of Canada. *Journal of Environmental Management* 78, 240-250.

290 Hogg EH, Brandt, James P, Kochtubajda B (2002). Growth and dieback of aspen forests in northwestern Alberta, Canada, in relation to climate and insects. *Canadian Journal of Forest Research* 32, 823.

291 Fisher JT, Wilkinson L (2005). The response of mammals to forest fire and timber harvest in the North American boreal forest. *Mammal Review* 35, 51-81.

292 Brassard BW, Chen HYH (2006). Stand structural dynamics of North American boreal forests. *Critical Reviews in Plant Sciences* 25, 115-137.

293 Fahrig L, Merriam G (1994). Conservation of fragmented populations. *Conservation Biology* 8, 50-59.

294 Fahrig L (1997). Relative effects of habitat loss and fragmentation on population extinction. *Journal of Wildlife Management* 61, 603-610.

295 Bender DJ, Contreras TA, Fahrig L (1998). Habitat loss and population decline: A meta-analysis of the patch size effect. *Ecology* 79, 517-533.

296 Schmiegelow FKA, Monkkonen M (2002). Habitat loss and fragmentation in dynamic landscapes: Avian perspectives from the boreal forest. *Ecological Applications* 12, 375-389.

297 Shirley SM (2006). Movement of forest birds across river and clearcut edges of varying riparian buffer strip widths. *Forest Ecology and Management* 223, 190-199.

298 Fahrig L (1997). Relative effects of habitat loss and fragmentation on population extinction. *Journal of Wildlife Management* 61, 603-610.

299 Fahrig L, Merriam G (1994). Conservation of fragmented populations. *Conservation Biology* 8, 50-59.

300 Vors, LS, Schaeffer JA, Pond BA, Rodgers AR, Patterson BR (2007). Woodland caribou and anthropogenic landscape disturbance in Ontario. *Journal of Wildlife Management* 71, 1249-1256.

301 Committee on the Status of Endangered Wildlife in Canada (COSEWIC) (2002). *COSEWIC assessment and update status report on the woodland caribou* Rangifer tarandus *in Canada*. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xi + 98 pp.

302 Skog KE, Nicholson GA (1998). Carbon cycling through wood products: The role of wood and paper products in carbon sequestration. *Forest Products Journal* 48, 75-83

303 Colombo SJ, Chen J, Ter-Mikaelian MT. (2006). *Carbon storage in Ontario's forests, 2000–2100*. Ont. Min. Nat. Resour., Appl. Res. Devel. Br., Sault Ste. Marie, ON. Climate change Res. Note CCRN-06.

304 Natural Resources Canada (2007). Does harvesting in Canada's forests contribute to climate change? Canadian Forest Service science-policy notes. Her Majesty the Queen in Right of Canada, May 1, 2007.

305 E.g., Bayliss, M (2007). Countering the eco-claptrap. *Tissue World* October/November 2007, 3.

306 Natural Resources Canada (2007). Does harvesting in Canada's forests contribute to climate change? Canadian Forest Service science-policy notes. Her Majesty the Queen in Right of Canada, May 1, 2007.

307 Colombo SJ, Chen J, Ter-Mikaelian MT. (2006). *Carbon storage in Ontario's forests, 2000–2100*. Ont. Min. Nat. Resour., Appl. Res. Devel. Br., Sault Ste. Marie, ON. Climate change Res. Note CCRN-06.

308 Intergovernmental Panel on Climate Change (IPCC) (2003). *Good practice guidance for land-use, land-use change and forestry.* In: Institute for Global Environmental Strategies (IGES) for the Intergovernmental Panel on Climate Change, Kanagawa, Japan.

309 Buchanan AH, Levine AB (1999). Wood-based building materials and atmospheric carbon emissions. *Environmental Science and Policy*, 2:427–437.

310 Harmon ME, Ferrell WK, Franklin JF (1990). Effects on carbon storage of conversion of old-growth forests to young forests. *Science* 247, 699-702.

311 Houghton RA (2005). Tropical deforestation as a source of greenhouse gas emissions. In: *Tropical deforestation and climate change*. Moutinho P, Schwartzman S (eds.), IPAA, Belém, Brazil, & Environmental Defense, Washington DC, USA.

312 Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate change 2007*. IPCC third assessment report. IPCC Secretariat, Geneva.

313 Barlaz MA, Kaplan PO, Ranjithan SR, Rynk R (2003). *Evaluating environmental impacts of solid waste management alternatives.* BioCycle 44, 52-56.

314 Colombo CJ, Parker WC, Lukai N, Dang Q, Cai T (2003). *The effects of forest management on carbon storage in Ontario's forests*. Climate change research report (CCRR-03). Ontario Ministry of Natural Resources Applied Research and Development Branch. Queens Printer for Ontario. Ontario, Canada. 82.

315 ForestEthics (2007). *Canada's forest industry: Setting the record straight*. http://www.forestethics.org/downloads/FPACwhitepaper.pdf.

316 Schoene D, Killmann W, von Lupke H, Loyche Wilkie M (2007). *Forests and climate change working paper 5: Definitional issues related to reducing emissions from deforestation in developing countries*. Food and Agriculture Organization of the United Nations: Rome, 2007.

317 Ibid.

318 Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate Change 2007: Mitigation of climate change.* Contribution of Working Group III to the fourth assessment report of the Intergovernmental Panel on Climate Change. Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds), Cambridge University Press, Cambridge UK.

319 M.J. Apps, W.A. Kurz, R.J. Luxmoore, L.O. Nilsson, R.A. Sedjo, R. Schmidt, L.G. Simpson, and T.S. Vinson (1993). Boreal forests and tundra. *Water, Air, and Soil Pollution* 70, 39-53.

320 E.g., Bond-Lamberty B, Peckham SD, Ahl DE, Gower ST (2007). Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature*, 450, 89-93.

321 Page SE, Siegert F, Rieley JO, Boehm HDV, Jaya A, Limin S (2002). The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, 420, 61-65.

322 Greenpeace International, and European Renewable Energy Council (2007). *Energy revolution*: *A sustainable world energy outlook*. Greenpeace International and EREC, January 2007.

323 Analysis produced by Global Forest Watch Canada, 2008.

324 Analysis produced by Global Forest Watch Canada, 2008.

325 Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate change 20077: The physical science basis.* Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

326 Greenpeace International, and European Renewable Energy Council (2007). *Energy revolution*: A sustainable world energy outlook. Greenpeace International and EREC, January 2007.

327 Ibid.

328 Intergovernmental Panel on Climate Change (IPCC) (2007). *Climate change 2007: Synthesis report*. Summary for policymakers. IPCC fourth assessment report. http://www.ipcc.ch/ipccreports/ar4-syr.htm.