Ministry of Natural Resources

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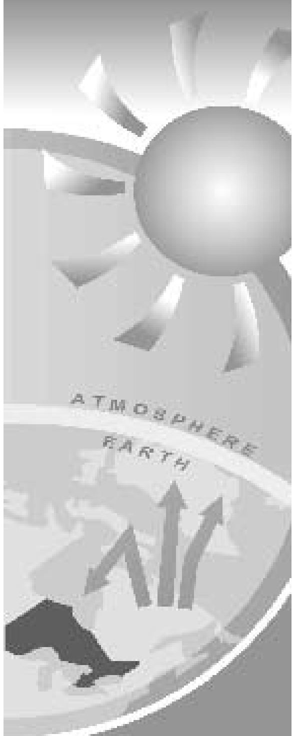
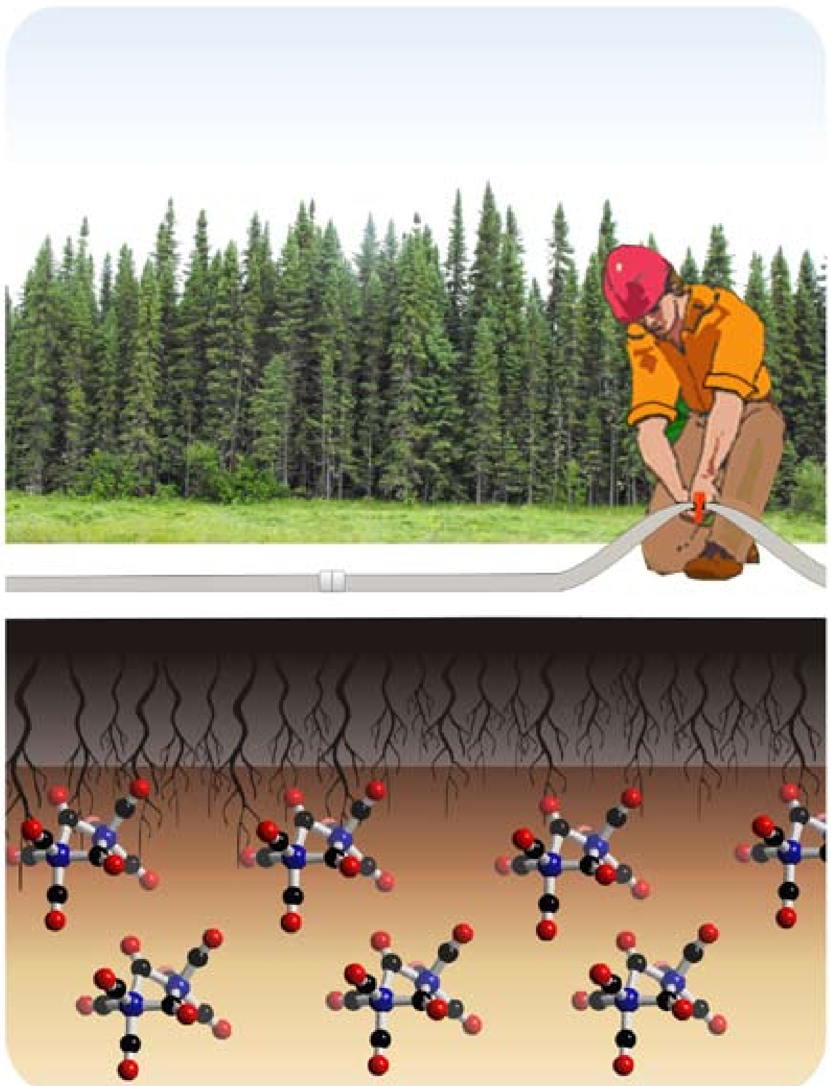
CLIMATE CHANGE RESEARCH REPORT

CCRR-20

Climate Change, Carbon Sequestration, and Forest Fire Protection in the Canadian Boreal Zone





Responding to Climate Change Through Partnership

Ontario

Sustainability in a Changing Climate: An Overview of MNR's Climate Change Strategy (2011-2014)

Climate change will affect all MNR programs and the natural resources for which it has responsibility. This strategy confirms MNR's commitment to the Ontario government's climate change initiatives such as the Go Green Action Plan on Climate Change and outlines research and management program priorities for the 2011-2014 period.

Theme 1: Understand Climate Change
MNR will gather, manage, and share information and knowledge about how ecosystem composition, structure and function – and the people who live and work in them – will be affected by a changing climate. Strategies:

- Communicate internally and externally to build awareness of the known and potential impacts of climate change and mitigation and adaptation options available to Ontarians.
- Monitor and assess ecosystem and resource conditions to manage for climate change in collaboration with other agencies and organizations.
- Undertake and support research designed to improve understanding of climate change, including improved temperature and precipitation projections, ecosystem vulnerability assessments, and improved models of the carbon budget and ecosystem processes in the managed forest, the settled landscapes of southern Ontario, and the forests and wetlands of the Far North.
- Transfer science and understanding to decision-makers to enhance comprehensive planning and management in a rapidly changing climate.

Theme 2: Mitigate Climate Change
MNR will reduce greenhouse gas emissions in support of Ontario's greenhouse gas emission reduction goals. Strategies:

- Continue to reduce emissions from MNR operations though vehicle fleet renewal, converting to other high fuel efficiency/low-emissions equipment, demonstrating leadership in energy-efficient facility development, promoting green building materials and fostering a green organizational culture.
- Facilitate the development of renewable energy by collaborating with other Ministries to promote the value of Ontario's resources as potential green energy sources, making Crown land available for renewable energy development, and working with proponents to ensure that renewable energy developments are consistent with approval requirements and that other Ministry priorities are considered.
- Provide leadership and support to resource users and industries to reduce carbon emissions and increase carbon storage by undertaking afforestation, protecting natural heritage areas, exploring opportunities for forest carbon management to increase carbon uptake, and promoting the increased use of wood products over energy-intensive, non-renewable alternatives.
- Help resource users and partners participate in a carbon offset market, by working with our partners to ensure that a robust trading system is in place based on rules established in Ontario (and potentially in other jurisdictions), continuing to examine the mitigation potential of forest carbon management in Ontario, and participating in the development of protocols and policies for forest and land-based carbon offset credits.

Theme 3: Help Ontarians Adapt
MNR will provide advice and tools and techniques to help Ontarians adapt to climate change. Strategies include:

- Maintain and enhance emergency management capability to protect life and property during extreme events such as flooding, drought, blowdown and wildfire.
- Use scenarios and vulnerability analyses to develop and employ adaptive solutions to known and emerging issues.
- Encourage and support industries, resource users and communities to adapt, by helping to develop understanding and capabilities of partners to adapt their practices and resource use in a changing climate.
- Evaluate and adjust policies and legislation to respond to climate change challenges.

Climate Change, Carbon Sequestration, and Forest Fire Protection in the Canadian Boreal Zone

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Summary

Boreal forests and peatlands in northern circumpolar areas, including Ontario, store globally significant amounts of carbon but are subject to forest fires and other natural disturbances that cycle carbon between terrestrial ecosystems and the atmosphere. Climate change projections for the 21st century suggest that wildland fire regimes will become more severe, with more fires, more extreme weather events, and the likelihood of increased area burned. Even if fire suppression resources are increased to cope with the changing fire conditions, suppression efforts will be challenged. Forest fires release significant amounts of greenhouse gases and under a more severe fire regime increased emissions are expected. Concerns over increasing greenhouse gas emissions, as well as the potential to achieve carbon offset credits through enhanced forest management practices, may lead resource management agencies to consider, as one of their options, increasing fire suppression efforts to reduce area burned and maintain carbon in storage. This policy option will be challenging in Ontario's fire-adapted forests, particularly in the Far North where most fires are not suppressed and a relatively natural fire regime is in place. Increasing fire suppression effectiveness in the boreal forest in response to a more severe fire regime will be expensive, operationally challenging, and may require tradeoffs between the goals of keeping carbon in storage and maintaining natural ecosystem functions. The effects of climate change on ecosystem processes and carbon storage in peatlands are not well understood, but the potential for more fire activity and resultant carbon losses, as well as irreversible ecosystem change, is high. As well, fire management strategies for peatland fuel types are not well developed. Fire management strategies in Ontario's forests and peatlands require review to balance future protection priorities, including carbon storage and fire management capabilities. Fire and forest managers will need to examine the role of fire in sustaining forest ecosystem health and resilience in a changing climate, and to better integrate forest and fire management principles, including the use of FireSmart forest management and other landscape design principles, to reduce the potential for large high-intensity fires. This literature review and policy discussion is intended to provide Ontario's forest and fire managers with current scientific and policy information to inform future decision-making.

Résumé

Le changement climatique, la séquestration de carbone et la protection contre les incendies de forêt dans la zone boréale canadienne

Les forêts boréales et les tourbières dans les régions circumpolaires Nord, y compris l'Ontario, accumulent des quantités considérables de carbone, mais elles sont sujettes aux incendies de forêt et à d'autres perturbations naturelles qui provoquent le déplacement du carbone entre les écosystèmes terrestres et l'atmosphère. Les projections à l'égard du changement climatique pour le 21e siècle suggèrent que le régime des feux de végétation deviendra plus intense, qu'il comportera plus d'incendies, plus de phénomènes météorologiques extrêmes et la probabilité d'une augmentation de la superficie brûlée. Même en augmentant les ressources pour faire face aux conditions changeantes des incendies, les efforts de suppression seront mis au défi. Les incendies de forêt dégagent des quantités importantes de gaz à effet de serre et on peut s'attendre à une augmentation des émissions en présence d'un régime des feux plus intense. Les préoccupations à l'égard de l'accroissement des émissions de gaz à effet de serre, ainsi que la possibilité d'obtenir des crédits d'émission de carbone par l'entremise de pratiques d'aménagement forestier, pourraient inciter les organismes de gestion des ressources à envisager, comme une de leurs options, l'augmentation des efforts de suppression afin de réduire la superficie brûlée et de conserver le carbone en stockage. Cette option de politique sera difficile pour les forêts ontariennes adaptées aux incendies, particulièrement dans le Grand Nord où la majorité des incendies ne sont pas éteints et où

il existe un régime des feux relativement naturel. L'augmentation de l'efficacité de la suppression des incendies dans la forêt boréale en réponse à un régime des feux plus intense sera coûteuse, difficile dans la pratique et elle pourrait nécessiter des compromis entre les objectifs de stockage du carbone et la conservation des fonctions de l'écosystème naturel. Les effets du changement climatique sur les processus de l'écosystème et le stockage de carbone dans les tourbières ne sont pas bien compris, mais le potentiel de connaître une augmentation de l'activité des incendies et les pertes de carbone qui en découlent, ainsi qu'un changement irréversible de l'écosystème, est élevé. De plus, des stratégies de gestion des incendies pour les types de combustibles des tourbières ne sont pas bien développées. Les stratégies en matière de la gestion des incendies des forêts et des tourbières de l'Ontario doivent être examinées afin d'équilibrer les priorités futures à l'égard de la protection, notamment le stockage de carbone et les capacités de gestion des incendies. Les gestionnaires des incendies et des forêts devront examiner le rôle des incendies à l'égard du maintien de la santé et de la résilience de l'écosystème forestier dans un climat changeant et afin de mieux intégrer les principes de gestion des forêts et des incendies, y compris l'utilisation des principes d'aménagement forestier Intelli-Feu et d'architecture paysagère, dans le but de réduire la possibilité d'incendies importants de forte intensité. La présente analyse documentaire et le débat des politiques visent à fournir aux gestionnaires des incendies et des forêts de l'Ontario des renseignements scientifiques actualisés ainsi que de l'information sur les politiques pour éclairer leurs futures décisions.

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Contents

Background and Context

Fire is the most important disturbance of global vegetation cover worldwide, affecting between 3 and 4 million square kilometres annually (UN ISDR, in press). In many ecosystems across the world, including the boreal zone, fire is a natural and essential force for maintaining ecosystem structure and productivity. In other regions, fire is an important land management tool embedded in the culture of many societies in the developing world (e.g., Africa). Fire is also uncommon and unnatural in many ecosystems (e.g., tropical rain forests) where its current application to clear land for agriculture is causing vegetation damage and site degradation. Many of the societal and economic issues driving the effects of wildland fire globally are just beginning to extend to the boreal zone, but it is important to view boreal fires in a global context to fully understand future adaptation and management options. The global boreal zone, stretching in two broad transcontinental bands across Eurasia and North America, covers approximately 12 million square kilometres, two-thirds in Russia and Scandinavia and the remainder in Canada and Alaska. Since the last Ice Age, some 10,000 years BP, forest fire has been the dominant disturbance in boreal forests, and is the primary process that organizes the physical and biological attributes of the boreal biome over most of its range, shaping landscape diversity and influencing energy flows and biogeochemical cycles, particularly the global carbon cycle (Weber and Stocks 1998). The physiognomy of the boreal forest is therefore highly dependent on the frequency, size, and severity of forest fires. The result is a classic example of a fire-dependent ecosystem, capable of sustaining the very large, high intensity wildfires that are responsible for its existence.

On average, boreal forest fires burn between 5 and 20 million hectares annually, almost exclusively in Canada, Alaska, and Russia. Over the past four decades annual area burned, while highly variable interannually, has averaged 2.2 million hectares for Canada (Martinez et al. 2006) and 400,000 hectares for Alaska (Kasischke and Stocks 2000). Close to 50% of the area burned in Canada occurs in the modified response zone in remote regions of northern Canada, where fires are essentially allowed to burn unsuppressed unless high value areas are threatened. Russian fire statistics were largely unreliable before the mid-1990s, but since that time area burned statistics have averaged 6 to 7 million hectares of forested land annually (Goldammer 2006). The development of sophisticated fire management programs aimed at protecting human and forest values from unwanted fire has been very successful in these jurisdictions over the past century. However, frequent periods of extreme fire danger, coupled with multiple ignition sources, often have overwhelmed suppression efforts resulting in extensive burned area. In addition, large areas in northern Canada and Alaska receive a modified level of fire protection, as values-at-risk do not warrant intensive suppression efforts. In these regions, fires are most often allowed to burn freely, fulfilling a natural role in maintaining boreal ecosystem integrity. Within the framework of the former Union of Soviet Socialist Republics (USSR), Russia maintained a very large and effective forest fire suppression capability, but this has been much reduced by economic difficulties following the collapse of the Soviet Union. While Russia has enormous natural resource-based wealth, very little of this is used to promote sustainability. As a result, wildland fires annually burn over huge areas, particularly in Siberia, where illegal logging and an underfunded fire management program lead to largely uncontrolled fires.

The average area burned each year in Canada is highly episodic, with large interannual variability. Annual area burned can vary by an order of magnitude, from as low as ~300,000 hectares to more than 7,500,000 hectares (Figure 1). While Canadian fire management agencies are among the most modern in the world, combinations of extreme weather and forest conditions can still lead to large fire events. The effectiveness of suppression efforts is reflected in the statistic that only 3% of Canadian fires grow larger than 200 hectares but these few large fires account for ~97% of the area burned across the combined full suppression and modified response zones of the country (Stocks et al. 2003).

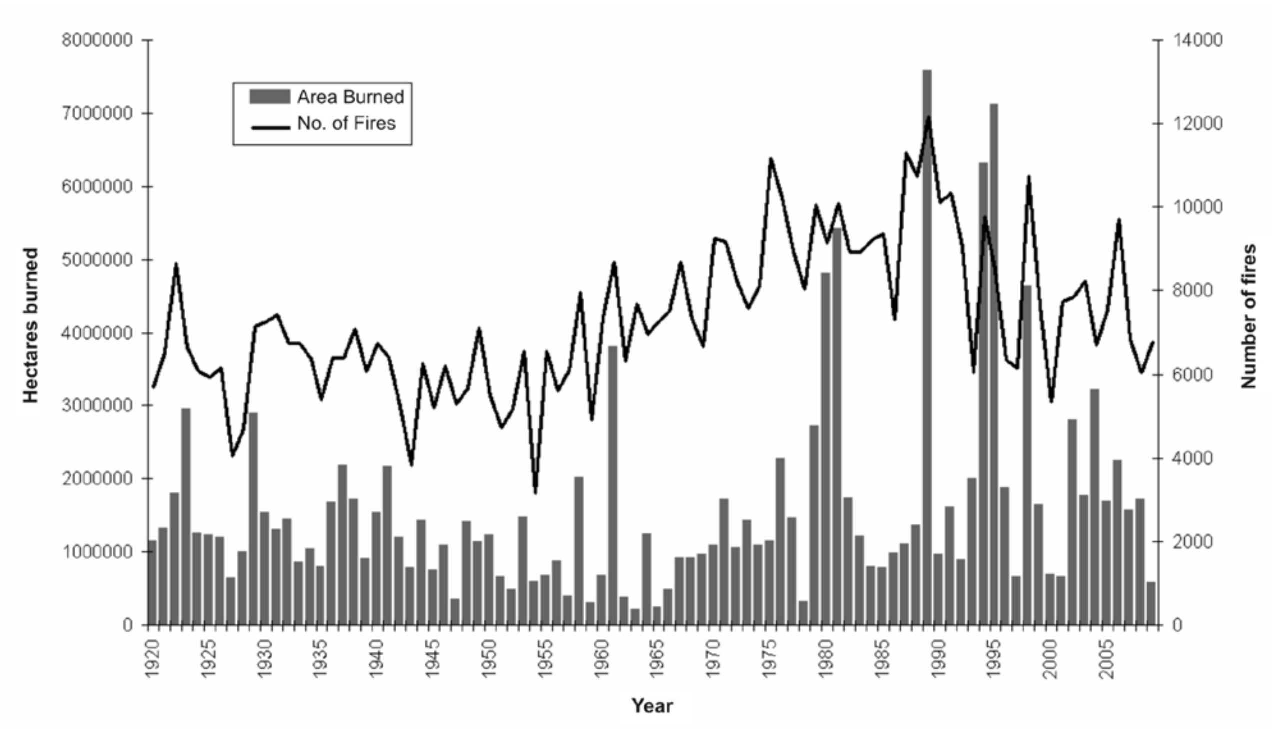

Figure 1. *Annual number of fires and area burned in Canada post-1920 (2008 and 2009 values are unofficial). Source: National Forestry Database Program, http://nfdp.ccfm.org*

The Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization in 1988 to create a forum in which scientists could work together to assess scientific evidence of climate change and provide policymakers with a consensus on the related science at regular intervals. From the first IPCC Report in 1990 (IPCC 1990), which weakly stated that "the world has been warming and future warming seems likely" to the fourth IPCC Report in 2007 (IPCC 2007), which indicated that "warming of the climate system is unequivocal, and most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations," the IPCC has more strongly endorsed the concept of climate change as a human-caused reality. This has raised political and public awareness around the world, and resulted in a general global commitment to develop means to mitigate and adapt to the effects of climate change.

In 1992, the United Nations Conference on Environment and Development (the Earth Summit) in Brazil attracted 172 countries in the first unified effort to address global warming. This meeting led to continued negotiations that resulted in the 1997 Kyoto Protocol (http://unfccc.int/kyoto_protocol/items/2830.php), which became legally binding in 2005, and committed industrialized countries to reduce emissions of six important greenhouse gases an average of 5% from 1990 levels between 2008 and 2012.

The development of General Circulation Models (GCMs), and more recently, higher-resolution Regional Climate Models (RCMs) allows projections of climates at coarse resolutions at a global scale, and research on potential effects to terrestrial, oceanic, and atmospheric biomes subsequently expanded. Since the establishment of the IPCC, several GCMs have been developed and revised. GCMs include three-dimensional representations of the atmosphere, oceans, and terrestrial biosphere, along with parameterizations of associated physical processes, and are used to generate climate scenarios based on the effects of various concentrations of greenhouse gases (GHGs) and other atmospheric pollutants on the earth-atmosphere system. Based on GCM projections, the earliest IPCC Assessment Report documented an expected global temperature increase of 0.8° to 3.5°C by 2100 AD. As GCM inputs and modelling capacity improved, the projected temperature increase reported in the Fourth IPCC Assessment Report rose to 1.4° to 5.8°C by 2100 AD.

As climate change science developed rapidly during the 1990s, concerns over global warming and the global carbon budget grew quickly, and early climate change scenarios projected the most significant warming at northern latitudes and over land. At this time, the broader scientific community studying terrestrial global change issues began to address boreal forests in a meaningful way. The Boreal Ecosystem-Atmosphere Study (BOREAS) (Sellers et al. 1997) conducted in northern Canada in the mid-1990s was an example of the increasing interdisciplinary and international interest of the global change scientific community in boreal forests. Global boreal forests were estimated to contain 703 petagrams (1 Pg=1 billion metric tons) of carbon (Apps et al. 1993), stored primarily in deep and slowly decomposing organic soil layers. With ~37% of the world's terrestrial carbon stores (Apps et al. 1993), and dominated by disturbance regimes forecast to react quickly to climate warming, the boreal zone became a major focus of climate change science.

In this report, we review the potential influence of climate change on fire regimes in boreal forests and associated peatlands and the implications for managing fires in those ecosystems. We also review the role of boreal forest and peatland fires in cycling carbon through both the release of carbon (in the form of GHGs) in combustion, and the subsequent uptake of carbon in post-fire vegetation renewal. Canada's boreal forests and peatlands store significant amounts of carbon, and maintaining or increasing that carbon storage may become an important future management objective as a means of mitigating climate change and addressing Canada's commitments to reducing or offsetting GHGs. The likelihood of increasing releases of carbon caused by climate change-induced increases in fire occurrence and intensity will pose challenges for fire managers and forest policy makers in Ontario. Increasing fire suppression efforts in boreal forests and peatlands may be proposed as a mechanism for maintaining carbon storage. Here we discuss these issues and suggest approaches to fire and forest management planning that will sustain forest health and reduce the potential for high-intensity fires in a more severe fire regime.

Climate Change and Boreal Forest Fires

Boreal fire is expected to be influenced quickly and significantly by climate warming, and extensive research has been undertaken in this area over the past two decades, particularly in North America. Canadian fire researchers have been involved since the late 1980s and early 1990s. Much of the Canadian research has concentrated on using outputs from various GCMs, in combination with recent fire and fire weather data to project boreal fire regimes under a changing climate, particularly in Canada, Alaska, and Russia. Early research investigated climate-related changes in fire weather and fire danger, with more recent studies focused on projecting fire occurrence and area burned, along with implications for fire management. This research was recently summarized within the context of global fire-climate change issues (Flannigan et al. 2009), and as part of a national summary of climate change effects on the Canadian forest sector (Lèmpriere et al. 2009).

Fire weather, fire danger, and fire severity

Initial research into climate change and fire regimes focused on developing future fire danger scenarios across the boreal zone. Street (1989) compared historical and GCM-derived monthly temperature and precipitation data for a 2x carbon dioxide (CO_2)[1] scenario and concluded that Ontario fire seasons would be longer and more severe. Flannigan and Van Wagner (1991) used results from three early GCMs to compare seasonal fire weather severity

[1]That is, a doubling of atmospheric CO_2 levels from the pre-industrial level of 280 ppm to 560 ppm, widely expected to lead to an increase in average global temperature of at least 3C, by mid-21st century. Current atmospheric CO_2 concentrations are about 385 ppm.

under a $2xCO_2$ (mid-2000s) climate with historical climate records. They determined that with climate warming fire danger levels would increase by nearly 50% across Canada. Fosberg et al. (1996) used a single GCM and Stocks et al. (1998) used four independently developed GCMs, along with recent weather data, to evaluate the relative occurrence of extreme fire danger conditions across Canada and Russia. Results indicated an earlier start to the fire season and a significant increase in the geographical expanse of severe fire danger conditions in both countries under a warming climate, particularly during the months of June and July. Stocks et al. (2000) described similar results for an analysis covering Alaska and Canada. However, this increase in severe fire danger conditions did not appear to be universal across Canada, as Flannigan et al. (1998) reported results using the Canadian GCM that indicated increased precipitation over eastern Canada could decrease fire activity in that region.

Wotton and Flannigan (1993) used the Canadian GCM to predict that fire season length across Canada would increase by 30 days in a $2xCO_2$ climate, with fire seasons beginning earlier. An increase in lightning frequency across the northern hemisphere is also expected under a doubled CO_2 scenario (Fosberg et al. 1990, 1996; Price and Rind 1994). Gillett et al. (2004) reported a positive relationship between increasing area burned and increasing temperatures in Canada over the past four decades; warmer temperatures are also expected to contribute to increased lightning activity (Price and Rind 1994).

Fire has been proposed as a major driver of vegetation shifts in response to climate change (Stocks 1993). Weber and Flannigan (1997) expanded on this assessment, concluding that “Fire regime as an ecosystem process is highly sensitive to climate change because fire behaviour responds immediately to fuel moisture...” and that “interaction between climate change and fire regime has the potential to overshadow the direct effects of global warming on species distribution, migration, substitution, and extinction”.

The intensity (energy release) and severity (fuel consumption levels) of boreal fires are also expected to increase substantially with climate change. Both de Groot et al. (2003) and Kafka et al. (2001) calculated an overall increase in fire intensity under a $2xCO_2$ scenario in western Canada. Similarly, Amiro et al. (2009) reported an increase in fire severity under a $2xCO_2$ climate, but that the increase in ground fuel consumed was small in comparison with the total increase in fuel consumption due to the increase in future area burned. Fire severity is strongly related to the amount of fuel available to burn, which can be expected to increase due to both drier conditions and stand degradation associated with vegetation shifts and forest health issues (de Groot et al. 2009).

Skinner et al. (1999, 2002) showed a strong correlation between the frequency and extent of mid-tropospheric ridging and the development of large forest fires. The persistence of upper atmosphere ridging is expected to increase in a $2xCO_2$ climate (Lupo et al. 1997), an additional factor that may contribute to increases in area burned in Canada.

Dendroclimatic studies have been used to show a statistically significant relationship between summer droughts and fire activity (fire occurrence and area burned) (Girardin et al. 2006), and to indicate that the post-1970 upward trend in Canadian fire activity reflects an early effect of a changing climate (Girardin 2007). In addition, most paleoecological studies of lake sediments in North America show fire frequency and intensity have increased in past warmer and drier climates (e.g. Clark 1988, 1990).

Area burned

While some researchers used forecast increases in fire danger conditions to speculate on how they might affect fire occurrence and area burned during the 1990s, it was not until the early 2000s that quantitative research was undertaken to link fire effects with a changing climate. Flannigan et al. (2005) used relationships between weather, fire danger, and area burned by large fires between 1959 and 1997 (Stocks et al. 2003) with two GCMs to estimate future area burned across Canada by ecozones, resulting in a forecast increase in area burned of 74 to 118% by 2100 AD when a $3xCO_2$ climate exists, with most increases in area burned occurring in the boreal and taiga regions. Bergeron et al. (2004) also projected increases in area burned for most, but not all, regions of Canada. Tymstra et al. (2007) showed increases of 13% and 29% in area burned in Alberta’s boreal forest region under a

$2xCO_2$ and $3xCO_2$ climate (late 2000s), respectively. Similarly, Balshi et al. (2008), using air temperature and fuel moisture data, predicted a 100% increase in decadal area burned in western North America by 2050, with a 350 to 500% increase by 2100. A doubling of current area burned in the Canadian boreal forest under a $3xCO_2$ scenario was also suggested by Amiro et al. (2009).

Fire occurrence

Predictions of changes in fire occurrence in response to climate change are made by developing relationships between lightning and human-caused fires and current weather and fire danger conditions, and applying these relationships with GCM climate data to forecast fire occurrence. Using this approach, Wotton et al. (2003) projected a 50% increase in human-caused fires in Ontario by 2100 AD. Similarly, Krawchuk et al. (2009) predicted an 80% increase in lightning-caused fires in northern Alberta by the end of the 21^{st} century. Most recently, Wotton et al. (2010), using two GCMs, investigated both human and lightning-caused fires across Canada under both a $2xCO_2$ and $3xCO_2$ (~2100 AD) scenario, and projected increases in fire activity by the end of the 21^{st} century of 75 to 140%, depending on the GCM used. While fire numbers were forecast to increase across all forested regions of Canada, the relative increase varied regionally. Lightning-based fire occurrence projections rely solely on changes in the receptivity of fuels to lightning ignitions, and do not account for increases in lightning activity associated with a warming and more active atmosphere, as described by Price and Rind (1994).

Fire management implications

The forecasts for dramatic increases in boreal forest fire occurrence and severity are resulting in questions about the ability of forest fire management programs to effectively mitigate the effects of future fire activity. Stocks (1993) suggested that, with Canadian fire management agencies currently operating within a very narrow margin between success and failure, under a warmer climate a disproportionate number of fires would escape initial attack resulting in an increase in area burned, which would proportionally be much greater than the corresponding increase in fire weather severity. Stocks also speculated that given competing fiscal demands, governments would be challenged to provide fire management agencies with the budget increases necessary to maintain current levels of effectiveness.

McAlpine (1998) suggested that increased frequency of drought years and extreme climatic events, in combination with longer fire seasons, would increase fire activity and area burned in Ontario. Minimizing the increases in area burned associated with climate change would require significant increases in fire management expenditures. McAlpine also stated that expanding intensive protection northward in Ontario to cover areas now only moderately protected would be extremely costly and likely not sustainable over time.

Simulation studies using the Ontario initial attack system (McAlpine and Hirsch 1998) showed that reducing the number of escaped fires from current levels would require a very large investment in additional resources, and that incremental increases in fire suppression resources result in diminishing gains in initial attack success. More recently, Wotton and Stocks (2006) used Ontario's initial attack simulation system in combination with scenarios of expected fire occurrence and fire weather to show that a doubling of current resource levels would be required to meet a modest increase of 15% in fire load (which is based on number of fires and difficulty to control).

The recent development of the Canadian Wildland Fire Strategy (CWFS), approved by federal, provincial, and territorial governments (CCFM 2005), is in direct response to the growing consensus that climate change-driven forest fire and forest health issues, along with diminishing fire management capacity and an expanding wildland-urban interface, will combine to create unprecedented fire effects across Canada in the near future. Under this scenario, maintaining current levels of fire protection success will be economically and physically impossible, as well as ecologically undesirable. A new accommodation with fire, in which fire assumes its natural role across more of the Canadian landscape, seems a likely outcome of this confluence of factors.

Carbon Emissions from Boreal Fires

During the late 1980s, the atmospheric chemistry science community began to focus on the effects of smoke from global-scale vegetation fires on human health and safety. Air- and ground-based sampling of forest fire smoke was initiated in the boreal zone, with measurements on experimental and prescribed fires in Ontario (Cofer et al. 1990, 1991). Along with the recognition that fires are a major driver of the boreal forest carbon balance (Harden et al. 2000; Bond-Lamberty et al. 2007), interest in emissions from boreal fires grew as concerns increased about health issues associated with smoke entering urban centres across North America (Wotawa and Trainor 2000; Lavoué et al. 2007).

Carbon is released from forest fires in two distinct phases: (1) through direct emissions resulting from flaming and smoldering combustion and (2) indirect or biogenic emissions resulting from post-fire decomposition, which occurs simultaneously with photosynthetic uptake of CO_2 from regenerating vegetation. Early research in this area focused on direct carbon loss during the fire event, using fuel consumption data from experimental fires and well-documented wildfires to estimate carbon losses. In recent years, indirect emissions have been analyzed using eddy-flux towers as part of broader research into carbon cycling in the boreal forest.

Direct emissions

Cofer et al. (1996) outlined several reasons why the importance of atmospheric emissions from boreal fires may be underestimated: the tremendous fluctuations in annual area burned in the boreal zone, the fact that boreal fires are located at climatically sensitive northern latitudes, the potential for positive feedback between climate warming and boreal fire activity, and the high energy level of boreal fires, which can produce smoke columns reaching into the upper troposphere.

Stocks (1991) used recent Canadian fire statistics, along with fuel consumption data from many Canadian experimental fires and wildfires used in the development of the Canadian Forest Fire Behaviour Prediction (FBP) System to estimate direct carbon loss during Canadian wildfires. Based on an average annual area burned in the 1980s of ~2.44 million hectares, and a constant fuel consumption value of 2.5 kg m^{-2} (25 tonnes per hectare), he estimated that Canadian fires consumed approximately 61 teragrams (Tg) of fuel, or approximately 30 Tg of carbon annually during this period. Based on the work of Cofer et al. (1990), 90% of the carbon is released as CO_2, 9% is released as carbon monoxide (CO), and the remaining 1% is released as methane and total nonmethane hydrocarbons.

Amiro et al. (2001) undertook a more detailed estimate of direct carbon emissions from Canadian fires. They used a database of large Canadian fires from 1959 to 1999, and estimated fuel consumption on each fire using the FPB System along with the ignition date and the primary fuel type in which the fire originated. Not surprisingly, they found that carbon emissions were highest from the boreal and taiga regions due to the very large areas burned in these regions. The mean area-weighted fuel consumption for all fires was 2.6 kg m^{-2}, which is very similar to the number proposed by Stocks (1991), but consumption varied among ecozones from 1.8 to 3.9 kg m^{-2}. The mean annual estimate of direct carbon emissions was 27 ± 6 Tg $year^{-1}$, ranging from 3 to 115 Tg $year^{-1}$.

In recent years, fuel consumption during fires has been further analyzed, with particular emphasis on forest floor fuel consumption. Typically, active boreal crown fires consume a relatively static amount of aerial and surface woody fuels, but forest floor moisture content levels and consumption can vary greatly, and contributes significantly to the overall intensity and severity of these fires. Moss and organic fuels on the forest floor are relatively compacted, with bulk density increasing with depth, and drying of these layers makes much more fuel (and carbon) available to the combustion process. Boreal fires typically consume up to 25% of aboveground biomass, but forest floor consumption can vary up to 100% (Kasischke et al. 2000), and is the greatest source of uncertainty in estimating total fire emissions. The most extreme forest floor carbon emission values were reported by Kasischke and Johnstone (2005) who measured levels between 0.56 and 5.67 kg m^{-2} on late season wildfires in Alaska. de Groot et al. (2009) used Canadian experimental fire and wildfire data to model forest floor consumption and carbon emissions in non-peatland standing-timber fuel types, determining a range in forest floor carbon emissions between 0.29 and 2.43 kg m^{-2}. These models are currently being used to estimate national wildland fire carbon emissions, with preburn fuel loads provided by the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz et al. 2008b).

New estimations of GHG emissions from Canadian forest fires have recently been calculated based on a new fuel consumption model that incorporates both the fire fuel load and the Drought Code of the FWI System (Amiro et al. 2009). This model was applied to climate scenarios to estimate future emission levels from Canadian fires. This application focused on forest floor consumption, on the assumption that these fuels would be much more affected by warmer and drier conditions than aerial fuels. Amiro et al. (2009) estimated that forest floor consumption would increase by 34% and 94% under a $2xCO_2$ and $3xCO_2$ scenario, respectively; however, most of this increase was due to the increase in area burned associated with these scenarios. Under a $1xCO_2$ climate (i.e., current conditions) they estimated total Canadian fire carbon emissions at 44.4 Tg $year^{-1}$, increasing to 85.3 Tg $year^{-1}$ under a $3xCO_2$ scenario.

A process-based Terrestrial Ecosystem Model has recently been used to investigate the role of historical fire disturbance on carbon dynamics in the pan-boreal region (Balshi et al. 2007). Emissions in the boreal region of North America were greatest across the western Canadian boreal zone and interior Alaska. The Canadian findings were similar to those calculated by Amiro et al. (2001) using an empirical approach. In addition, this study indicated that the 1960s and 1970s were periods of sink activity (that is, carbon sequestration exceeded carbon emissions), and that during the 1980s and 1990s, which had significantly more fire activity, sink activity continued due to a strong CO_2 fertilization effect (i.e., tree growth was enhanced by increased availability of CO_2 in the atmosphere). The authors identified four main challenges associated with improving emission estimates and carbon budgets: the lack of long-term historical fire records, need for better estimates of stand age distributions prior to the start of the historical fire record, methods to better represent burn severity and fuel consumption, and data to include peatland fires. They also mentioned the lack of a long-term fire record as a major impediment to circumboreal fire emission estimates.

The Terrestrial Ecosystem Model was also used to forecast the effects of fire on emissions and carbon storage in North American boreal forests in the 21st century (Balshi et al. 2009). The authors estimated that decadal total carbon emissions from fire will increase by 2.5 to 4.4 times by 2100 AD. Despite increases in fire emissions, their simulations indicated that the North American boreal zone would be a carbon sink over the 21st century due to CO_2 fertilization. If CO_2 fertilization were excluded, this region would be a carbon source.

Randerson et al. (2006), analyzing a boreal forest fire in Alaska, integrated the effects of GHG emissions, aerosols, black carbon deposition on snow and ice, and post-fire changes in surface albedo. They found that, while surface albedo (reflectivity to incoming solar radiation) initially decreased after fire, it actually increased (resulting in a decrease in radiative forcing) when averaged over an 80-year fire cycle, and they speculated that this result may indicate that increases in boreal fire activity may not provide a positive feedback to climate warming. Given the complexity of the Earth-atmosphere system, however, this tentative conclusion requires validation.

Although unknowns remain, the general consensus is that climate change-driven increases in forest fire activity would result in shorter fire return intervals, a shift in age-class distribution towards younger forests, and a decrease in biospheric carbon storage (Kasischke et al. 1995, Stocks et al. 1996). This would likely result in a positive feedback loop between fires in boreal ecosystems and climate change, with more carbon being released from boreal ecosystems than is being stored (Kurz et al. 1995).

Indirect (biogenic) emissions

Following the direct loss of carbon through the combustion process, vegetation killed by the fire decomposes over time and new growth occurs. Early modelling studies have suggested that post-fire carbon losses through decomposition roughly equal the direct loss of carbon through combustion (e.g. Kasischke et al. 1995, Kurz and Apps 1999). Following fire, respiration (which releases CO_2) and photosynthesis (which takes in CO_2) by new or remaining vegetation compete in the carbon budget. Vegetation eventually develops sufficiently so that gross ecosystem production (GEP) exceeds ecosystem respiration (ER) to result in a positive net ecosystem production (NEP) or carbon sink (Amiro et al. 2010). The time required for NEP to become positive may take decades in boreal forests. As new vegetation develops, GEP eventually exceeds ER and a long period of positive NEP follows until another fire or other disturbance affects the system.

Hicke et al. (2003), using satellite estimates of net primary production (NPP) following boreal forest fires, suggested a recovery period of approximately 9 years, after which NPP was estimated to be a net carbon sink. This finding is supported by CO_2 measurements from towers and aircraft (net ecosystem exchange by eddy covariance) and remote sensing (NPP) following fire that showed that regenerating boreal forest in western Canada had a low initial flux (the amount that flows through a unit area per unit time) that increased with time since fire (Amiro et al. 2003). Using a regression model, researchers estimated that the CO_2 flux would reach the rate of a mature site between 10 and 30 years following fire. Amiro et al. (2000), in a remote sensing-based analysis of NPP following fire, showed that NPP increased linearly for the first 15 years after fire in the boreal and taiga regions of Canada.

Litvak et al. (2003) investigated the role of recovery from fire in stand-level carbon dynamics, using five stand-replacing fires of various ages located in the BOREAS study area in northern Manitoba. They determined that stand age is critical to understanding regional-scale boreal forest carbon balances, and suggested that most of the net biomass accumulation occurs from 20 to 70 years after fire and that stands younger than 20 years appear to lack sufficient foliage area for rapid carbon accumulation. They also stated that the large spatial heterogeneity in CO_2 exchange that occurs with ecosystem recovery means that the results from a single eddy covariance tower are unlikely to be representative at a regional scale.

With carbon sequestration occurring at a faster rate as vegetation grows, fire affects the landscape carbon balance by modifying the forest age-class structure (Kurz et al. 2008b). As long as the fire regime remains unchanged, the large-scale forest carbon balance remains stable, but any shift in fire regime directly affects long-term forest carbon storage (Balshi et al. 2008).

Rising GHG concentrations linked to fossil fuel emissions have increased interest in finding ways to increase terrestrial sinks. With the realization that disturbances such as fire and insects drive much of the carbon balance in boreal forests, it has become increasingly important to employ a suite of techniques at a variety of scales to estimate post-disturbance carbon dynamics. A goal has been to use local measurements to provide data that can be scaled up to regional and global scales. The BOREAS experiment (Sellers et al. 1997) was a good first step, and a similar coordinated effort to evaluate global post-fire effects on carbon is needed. Unfortunately, in North America all fire chronosequence studies that included eddy covariance towers have been terminated.

Peatlands and fire

Over the past 10,000 years northern peatlands have functioned as a globally important sink of atmospheric CO_2, as the annual NPP of peatland vegetation generally exceeds the decomposition of litter and peat. At present, almost one-third of all the Earth's soil organic matter underlies northern peatlands as partially decomposed organic matter. Boreal peatland systems are estimated to occupy about 3.5 million km^2 globally and store from 250 to 455 Pg of carbon as peat (Vasander and Kettunen 2006). Within North America, peatlands cover about 1.14 million km^2 (Zoltai et al. 1998). Peatlands are distinguished from other northern wetlands by the thickness of the peat (Zoltai and Vitt 1995), with Canada defining peatlands as areas with organic layers 40 or more cm thick (Canada Soil

Survey Committee 1978). Common boreal peatland classes are fens, bogs, and swamps. In North America, fens account for about 46% of the area, followed by bogs underlain by permafrost (31%), permafrost-free bogs (15%), and forested swamps (8%) (Zoltai et al. 1998).

While northern boreal peatlands have functioned as net sinks for atmospheric CO_2 since the last deglaciation, concern is increasing that anthropogenic and natural disturbances, most notably wildfires, will threaten the stability of this huge, globally critical carbon sink. Projected changes in temperature and precipitation associated with climate change are forecast to significantly increase the release of gaseous carbon from northern peatlands (Morrissey et al. 2000). Any climatic changes that result in lower peatland water tables and reduced moisture content of near-surface peat would, in addition to making peatlands more susceptible to fire, affect the accumulation/decomposition balance in northern peatlands. Reduced surface moisture levels could also result in a shift from aerobic to anaerobic decomposition, greatly increasing decomposition rates and carbon loss (Morrissey et al. 2000).

Permafrost bogs and forested swamps, in which water tables are well below the surface throughout much of the growing season, are the peatland types most susceptible to fire. Zoltai et al. (1998) estimated that 85% of peat fire emissions are from remote subarctic bogs underlain by permafrost. They also suggested that on average about 0.5% of peatlands, or 6,420 km^2, burn annually. However, the surface peat layer burns in only a small portion (1,160 km^2) of this area. Zoltai et al. (1998) also determined that total estimated carbon release due to aboveground fuel combustion was 2.92 Tg $year^{-1}$, while underground peat combustion accounted for 6.72 Tg $year^{-1}$. These estimates suggest a relatively small source in comparison to carbon emissions from wildfires on upland sites, but climate change would likely result in more peatland fuels becoming available for combustion, resulting in more extensive and severe peatland fires. The result would be significant carbon losses from peatlands.

Wieder et al. (2009) characterized annual carbon accumulation following fire along a chronosequence of bog sites in central Alberta spanning 1 to 102 years since fire. These bogs burned with a fire return interval of 100 to 150 years. Results showed that immediately after fire bogs represented a net carbon source, but that they switched to a net sink at about 13 years after fire, mainly due to the recovery of moss and shrub layers. Black spruce biomass development (including roots) also contributed to the net carbon sink, peaking at 74 years after fire. After that time, biomass accumulation rates declined and net carbon sink strength declined accordingly. Based on these findings, Wieder et al. (2009) suggested that a decrease in the fire return interval to about 60 years would convert bogs in this region to a net carbon source, and that, under predicted climate change scenarios, these peatlands would become net carbon sources.

Turetsky et al. (2002) combined a detailed inventory of peat carbon across 1.7 million km^2 of Alberta, Saskatchewan, and Manitoba (Vitt et al. 2000) with fire data from the Canadian Large Fire Database (Stocks et al. 2003) to estimate peat carbon storage in the presence and absence of fire. They focused on dry, wooded peatlands, which burn much more readily than wet open or shrub-dominated peatlands. Their assessment suggested that peatlands accumulate 24.5 g C m^{-2} $year^{-1}$ without disturbance, but that a variety of natural and anthropogenic disturbances, mainly fire, reduce the accumulation rate to 3.6 g C m^{-2} $year^{-1}$, an 85% reduction in carbon uptake. They estimated that a 17% annual increase in area burned and fire severity in peatlands would convert them into a regional net carbon source, and argue that climate change effects will have major consequences for peatland carbon storage in continental boreal regions.

While generally drier than oceanic peatlands, continental peatlands were thought to experience less fire than uplands due to saturated surface fuels and sparse tree canopies. To address this issue, an investigation to determine whether uplands burn more preferentially during wildfires was carried out for a 1.2 million hectare area in central Alberta, using 50 years of fire perimeter maps (Turetsky et al. 2004). Results showed that burn areas and ignition points did not occur preferentially in uplands relative to bogs and fens, and that permafrost and peatland areas may be more vulnerable to fire than previously thought. Turetsky et al. (2004) also calculated area burned in peatlands for the 1980 to 2000 period, and used these estimates, along with an average combustion rate of 3.2 ± 0.4 kg C m^{-2} for peatland fires, to suggest that up to 5.9 Tg C is released annually through peatland fires across Saskatchewan, Alberta, British Columbia, and the Northwest Territories, in comparison to the 27 ±6 Tg C $year^{-1}$ average for all Canadian fires (Amiro et al. 2001). They further suggested that peatland fires show significant correlation with components of the Canadian Forest Fire Weather (FWI) System (Van Wagner 1987), especially the Duff Moisture Code and the Drought Code, and that more frequent and/or severe burning will lead to a landscape where terrestrial carbon stored in wetter fuels and soils is less “protected” from burning.

Tarnocai (2006) modelled peatland sensitivity to climate change and determined that the predicted increases in air temperature over northern Canada would result in degradation of frozen peatlands in the subarctic and northern boreal wetland regions and severe drying in the southern boreal wetland region. He also predicted flooding of coastal peatlands due to rising sea levels. These changes would result in much of the carbon in northern peatlands being released to the atmosphere.

With growing evidence that climate change is rapidly affecting northern forests and peatlands, concerns have been raised that mercury reserves once protected in cold, wet soils will be exposed to burning, resulting in large releases of mercury to the atmosphere. Turetsky et al. (2006) quantified organic soil mercury stocks and burn areas across western Canada, and estimated that circumboreal mercury emissions from wildfires are 15-fold greater when mercury stored in peatland and permafrost systems is considered. They also suggested that climate change-driven increases in fire activity at northern latitudes may mobilize relatively harmless mercury stored in saturated soils into potentially more mobile and toxic forms, exacerbating toxicities in northern food chains.

Permafrost is widespread across the Arctic and boreal regions of the Northern Hemisphere, occupying 22% of the exposed land surface. Total soil carbon in the northern circumpolar permafrost zone has been estimated at 1,672 Pg, with 277 Pg of that in peatlands (Schurr et al. 2008). Indications are that thawing permafrost at northern latitudes, and the resulting microbial decomposition of huge stores of previously frozen organic carbon, will be one of the most significant potential feedbacks from terrestrial ecosystems to the atmosphere in a changing climate (Zimov et al. 2006, Schurr et al. 2008).

Studies by Camill and Clark (2000) indicate that transient responses of permafrost and vegetation to climate change may be difficult to predict due to lags and positive feedbacks related to vegetation and disturbance. They suggest that boreal permafrost peatlands have strong local controls on microclimate that may preserve permafrost during the transient stages of climate warming, producing lagged responses. These lags and thresholds could lead to sudden and significant responses to climate change.

Research to date suggests that, while significant progress has been made in terms of understanding internal peatland and permafrost processes, much more research is required before climate change effects can be predicted in these ecosystems. Peatlands are currently not considered in Canada’s carbon budget modelling and GHG accounting system, nor in Ontario’s carbon modelling, a further indication of the uncertainties involved. Under MNR’s climate change research program, researchers are exploring the interactions of fire, permafrost, and peatlands and their effects on northern Ontario’s carbon balance. Related work is also underway at the national level.

Greenhouse Gas Emissions Accounting and the Forest Sector

Canada has international commitments to reducing GHG emissions and reporting on carbon emissions to and removals from the atmosphere. Carbon storage and sequestration in forests and peatlands are important in the Canadian context, but managing and accounting for forest and peatland carbon are complicated by the interaction between human influences (forest harvest, regeneration and potential efforts to enhance carbon storage) and effects of natural processes – the natural patterns of growth, decomposition, respiration, and mortality through fire, insects and disease, and other disturbances.

There is significant international focus on the effect of land-use, land-use change, and forestry (LULUCF) activities on GHG emissions and carbon accounting. Canada has a strong interest in managing LULUCF activities as a means of meeting its GHG emission targets.

The Kyoto Protocol and Canada's forests

The 1992 United Nations Framework Convention on Climate Change (UNFCCC) (http://unfccc.int/2860.php) called for the "protection and enhancement of sinks and reservoirs of greenhouse gases," requiring all countries to monitor and understand the major factors influencing the exchange of carbon between the biosphere and the atmosphere. Under the UNFCCC, 191 countries, including Canada, committed to "stabilizing greenhouse gas concentrations in the atmosphere that would prevent dangerous anthropogenic interference with the climate system."

The 1997 Kyoto Protocol was established with the goal of limiting the rate of carbon accumulation in the atmosphere through a two-pronged approach: reducing fossil fuel emissions while increasing the net carbon uptake ("removals" from the atmosphere) in terrestrial ecosystems. Under Article 3.3 of the protocol, the negotiating countries decided that net changes in GHG emissions by sources and removals by sinks through direct human-induced LULUCF activities, limited to afforestation, reforestation, and deforestation that occurred since 1990, could be used to meet a country's emission reduction commitments. Under Article 3.4 of the protocol, countries may elect to include additional human-induced activities related to LULUCF specifically, forest management, cropland management, grazing land management, and revegetation, in their accounting of anthropogenic GHG emissions and removals for the first commitment period.

During Kyoto Protocol negotiations, the large carbon sink in northern land surfaces inferred from global carbon cycle models were viewed as an option for northern countries to use to offset fossil fuel emissions by claiming large sinks in their managed forests. With the option to include or exclude Canadian forest management activities during the first Kyoto Protocol commitment period, Canada used the CBM-CFS (Kurz et al. 2008b) to evaluate the likelihood that Canada's managed forests would be a sink or source of carbon during this period. With the GHG balance of Canada's forests being strongly affected by periodic extensive insect outbreaks and naturally occurring wildfires with high interannual variability in area burned, it was not surprising that the CBM-CFS results projected that, considering these random disturbances, Canada's managed forests could be a source of between 20 and 245 Mt of CO_2 year^{-1} during the 2008 to 2012 period. These findings were fundamental to Canada's decision to exclude forest management activities in the first commitment period and raises the possibility that Canada's efforts to influence the carbon balance through forest management could be overwhelmed by natural disturbances.

Carbon budget models in Canada and Ontario

National and provincial commitments to reporting on GHG emissions requires the capability to measure or model the carbon budget in major economic sectors. In the late 1980s, Canadian Forest Service scientists began developing a sophisticated model of Canada's forest carbon budget in anticipation of the need to better understand and quantify the role of Canadian forests in the global carbon budget.

The CBM-CFS (Apps and Kurz 1991, Kurz et al. 1992) is a national-scale model of forest biomass, soil, and forest product sector carbon dynamics that has been used since the early 1990s to assess the net carbon budget of managed forests in Canada. The CBM-CFS tracks carbon in living trees (including roots), soil, and dead organic material. Changes (fluxes) in carbon due to growth, natural turnover, forest management, and large-scale natural disturbances (fire, insects, and windthrow) are also accounted for. The current version is CBM-CFS3.

The CBM-CFS has been critical to Canada's ability to satisfy the increasingly detailed requirements of forest carbon reporting required under the Kyoto Protocol, and it is used each year to provide estimates of Canadian forest emissions and retrievals reported in Canada's national GHG inventory report. Throughout its development the model has been used to address a variety of GHG and forest policy issues, including the carbon implications of changes in disturbance levels (e.g., mountain pine beetle, area burned by wildfire), changes in growth and decomposition rates under a changing climate, and the consequences of different forest management options.

Forest fire emissions within the CBM-CFS were initially calculated using static fuel consumption values derived from measurements on experimental burns and wildfires, along with area burned data provided through the Canadian Large Fire Database (Stocks et al. 2003). Revised fuel consumption numbers, which factored in fuel moisture and fire danger conditions at the time of each fire, were later provided by Amiro et al. (2001). It was recently recognized that annual UNFCCC and Kyoto Protocol reporting would require better estimates of carbon emissions from fire that would capture variations in emissions among years and fires, and even within large fires. A new approach (de Groot et al. 2007) was developed that incorporates satellite-derived daily area burned and fire behaviour data, spatially and temporally explicit fire danger information, and pre-fire fuel load information from the CBM-CFS3, and then uses the Canadian Fire Effects Model (CanFIRE) (de Groot et al. 2003) to calculate fuel consumption for various live biomass and dead organic matter pools by fuel type, fuel load, and fire behaviour within each fire. The CBM-CFS3 integrates these fire data at a national scale, along with fire management and insect damage data, for national reporting.

An early retrospective analysis by Kurz and Apps (1999), using the CBM-CFS2, estimated net ecosystem carbon fluxes in Canada's forests for the 1920 to 1989 period. Results indicated that forest ecosystems were a net sink of carbon during this period, but that this sink had decreased substantially during the 1970-1989 period. The observed sink was found to be due to a shift in forest age-class structure towards older forest. Forest disturbances, which largely determine Canadian forest dynamics on a time scale of decades, appeared to have been less frequent between 1920 and 1970 than in previous decades. They had, however, increased greatly in recent years (1970 to 1989) and contributed to a decrease in the carbon sink. This was the first strong evidence that natural disturbance regimes drive much of the net carbon balance in Canadian forests.

The possibility exists that increases in net primary productivity (NPP) resulting from climate change could offset anticipated carbon losses from increased disturbances. Kurz et al. (2007) used the CBM-CFS3 to address this issue by simulating rate changes in disturbance, growth, and decomposition on a hypothetical boreal forest landscape. Results of this study indicate that it would be extremely unlikely that enhanced growth could offset carbon losses resulting from increased disturbance. In fact, they show that carbon stocks in Canada's boreal forest are very likely to decline under a changing climate.

The CBM-CFS3 was also recently used to investigate the effect of the huge mountain pine beetle outbreak in British Columbia (Kurz et al. 2008a). Results showed that the cumulative effect of the beetle outbreak in the 2000 to 2020 period will be 270 Mt of carbon released over an average of 374,000 km^2 of forest. In the worst year, effects of the beetle outbreak were equivalent to approximately 75% of the average annual direct forest fire emissions for Canada during the 1959 to 1999 period, illustrating that insect outbreaks at a large scale can be an equally important mechanism through which climate change may undermine the capacity of northern forests to take up and store atmospheric carbon. Such effects should be accounted for in large-scale modelling analyses.

MNR researchers recently used an adaptation of FORCARB2 (Heath et al. 2010) the U.S. Forest Carbon Budget Model, to develop a carbon budget for Ontario's managed forests and harvested wood products for the 2001 to 2100 period (Chen et al. 2010). This study produced projections that carbon stocks in Ontario's managed forest would increase by more than 465 Mt in the 21st century, with 90% of this increase occurring in the harvested wood products sector. A fire disturbance model was incorporated in this analysis, but it did not include expected increases in fire activity as a result of climate change. The FORCARB-ON model is being further developed to include analysis of Ontario's Far North and to incorporate changing forest fire dynamics.

A study of implications of climate change and future disturbance regimes on the carbon balance of the Canadian managed forest for the 2010 to 2100 period was recently undertaken using CBM-CFS3 (Metsaranta et al. 2010). In this analysis, simulations were run with no increase in area burned relative to the last half of the 20th century and with linear increases in area burned by a factor of 2 or 4, depending on the region of Canada being analyzed. Results projected, for the post-2050 period, an annual probability of a sink near 70% with no increase in area burned, with this probability dropping to 35% with increasing area burned. All simulations projected that forests would be a cumulative carbon source from 2010 to 2100 even if annual area burned did not increase. Thus, the Ontario-based FORCARB-ON study, which included harvested wood products but no increased fire activity, suggested Ontario's managed forests would remain a carbon sink to 2100, while results from CBM-CFS3, which factored in an increase in fire activity but no removals for harvested wood products, suggested that on a national basis Canadian forests would likely be a carbon source in the latter half of this century. Different forest regions in Canada may be long-term sinks or sources, depending on regional variation in natural and anthropogenic influences. Development work continues on both models to enhance their capability to assess the effects of changing disturbance regimes and factor in the carbon stored in harvested wood products.

International climate change negotiations under the UNFCCC are continuing, and the international community will be required to develop new rules for the post-2012 period (i.e., to 2020). Consideration will be given to expanding these rules to cover emissions and removals from much larger areas within participating countries. For Canada, this may include the vast unmanaged forests in the north, where natural disturbances are ubiquitous, and that are unlikely to be subject to widespread management for the foreseeable future. Canada will likely be arguing strongly for rules that "factor out" the effects of natural disturbances in countries where natural disturbances have cycled carbon in forests for millennia (e.g. Canada, Russia), and where climate change is certain to exacerbate the effect of future disturbances. It is likely that, in order to exclude emissions from natural disturbances, countries will have to demonstrate that they continue standard practices and measures to manage or control natural disturbances. The Copenhagen Accord, agreed to in 2009, provides some high-level political guidance, and some progress has been made on a detailed, legally binding agreement.

Negotiations on LULUCF rules for forest carbon accounting in the post-2012 period have been slow, but progress has been made in terms of educating other countries about Canadian issues, particularly the need to focus accounting on human effects rather than the effects of natural disturbances, which are beyond human control. Countries are seeking agreement on:

- the use of reference levels for forest management, which means that what matters for accounting is the difference in the sink/source in the accounting period and the reference level assumed for that period
- improved rules for accounting for carbon in harvested wood products, in which emissions would be accounted for at the time they occur, rather than at the time of harvest
- a provision to allow emissions resulting from wildfire and insect infestations (and the subsequent removals as forests regenerate) to be excluded from accounting, subject to countries being able to show that they are making an active effort to control natural disturbances and promote subsequent forest recovery

This approach should provide strong incentives within Canada to consider how forest management affects carbon. It would reinforce the need to think of carbon as another "value" in forest management, thereby providing incentives to reduce emissions and increase removals.

In the case of expanded fire protection, for example, a reference level would include no natural disturbances as they would be removed from the accounting. Similarly, natural disturbance effects would be removed from estimates for the accounting period. Thus, expanded fire protection would not result in a "credit" for reduced emissions. This approach, while not perfect, seems best given the difficulties in predicting "business-as-usual" natural disturbance levels, and the risks that substantial emissions from natural disturbances could enter the accounting if the issue is not addressed, particularly under a changing climate.

Improving the science of the estimation of the "expected area burned" under climate change-driven fire danger conditions might help quantify the benefit of fire suppression and possibly support a carbon credit system. In that case, the rules could be adjusted for the post-2020 period to factor in natural disturbances in a way that provides incentives for prevention or suppression.

Managing Forested Areas to Promote Carbon Storage

Carbon offsets

The Kyoto Protocol resulted in an accounting framework that recognizes the important role of ecological carbon sinks in climate change mitigation, and permits countries to reduce emissions through LULUCF activities, including forestry. Canada's proposed Offset System for Greenhouse Gases (Government of Canada 2008), would, if implemented, allow the use of certain types of ecological carbon sinks to offset anthropogenic GHG emissions. Ontario and other provinces are also developing offset systems individually and as part of regional collaborative efforts such as the Western Climate Initiative. To date, fire-related projects have not been considered in the initial set of priority areas.

While ecological carbon sinks are already contributing to climate change mitigation, largely through the accumulation of biomass in forests, the capacity of terrestrial ecosystems to act as sinks may decline as climate change progresses (Canadell et al. 2007). Freedman et al. (2009) summarized much of the literature on ecological carbon offset programs and pointed out that, in addition to offsetting emissions, ecological projects that accumulate carbon credits may have a strong cross-linkage to the conservation of natural values such as biodiversity. While concerns about the veracity and security of carbon credits for ecological projects have been raised, Freedman et al. (2009) argued that issues related to, for example, certifiability, permanence, additionality, and leakage, can be satisfactorily mitigated. They further suggested that carbon offset projects can contribute to the conservation of natural areas and environmental stewardship, and that offset trading has the potential to leverage financial resources to meet these objectives. They speculated that such co-benefits of offset projects on non-carbon values, such as native biodiversity, will become more important as the emerging carbon offset marketplace grows.

Expanded fire protection and fuel treatment projects are unlikely to be eligible for consideration as offsets in domestic regulated carbon markets. One reason for this is that the basis of the market is issuance of credits for carbon emission reductions that have *already occurred* (e.g., tree growth in afforestation) and/or *demonstrably and clearly avoided* (e.g., avoided forest conversion where site-specific threat is demonstrated and activities are not simply shifted elsewhere). Domestic offset carbon markets are founded on the concept of *additionality* – that is, being above and beyond business as usual. Daigle and Dymond (2010) noted that in the case of fuel treatment projects, because regulated carbon markets do not pay on futures, a fire would have to occur in a fuel reduction treatment area before a carbon credit could be claimed (thus making it challenging to demonstrate additionality or develop a baseline). Fire suppression activities in Ontario are part of normal business practice.

Several recent studies have raised concerns about the viability of managing forests to ensure long-term carbon storage when the reality of climate change and increasing levels of natural disturbances is considered. Galik and Jackson (2009) argued that, while forest offsets may provide low-cost opportunities for GHG mitigation, a major concern has to be the risk of reversal, i.e., the intentional or unintentional release of carbon back to the atmosphere through disturbances such as fire, pests, storms, and land use decisions. They stated that the scale and magnitude of climate change-driven natural disturbance events will mean that management decisions at the project level will not adequately address reversal risk, and that this risk of reversal is a definite barrier to including forest offsets in climate policy. Programs in place (e.g., Climate Action Reserve, Regional Greenhouse Gas Initiative) and emerging across North America do, however, enable forest offsets and ensure permanence through a variety of mechanisms (e.g., program-level buffers, insurance).

Fire and forest carbon management

According to Breshears and Allen (2002), the potential for rapid, disturbance-induced losses of carbon will be a much greater problem than currently anticipated. They raised the issue of the complex and threshold-like nature of disturbances such as fire and drought and argued that the scientific community needs to develop the ability to predict such ecosystem dynamics to incorporate these processes into strategies and policies related to carbon management and sequestration.

According to Noss (2001), the issue of the effects of forest management activities to sequester carbon on biodiversity has been largely overlooked. He argued that today's fragmented and degraded forests are more vulnerable, and that maintaining forest biodiversity and ecological functions during climate change will require land use practices that represent forest types across environmental gradients in reserves, protect climatic refugia at multiple scales, protect primary forests, avoid fragmentation and promote connectivity (see Lemieux et al. 2010), involve low-intensity forestry and prevent natural forest conversion to plantations, maintain diverse gene pools, and maintain natural fire regimes.

Studies by Kashian et al. (2006), working in the Yellowstone Park area, showed that stand-replacing fires may shift the landscape from a carbon sink to a source for several decades following disturbance. They argued, however, that while increasing fire frequency will increase the amount of carbon released to the atmosphere in the short term, as long as forests continue to regenerate over the long term, equilibrium values of landscape carbon storage will be resistant to disturbance frequency. This is largely because stand-replacing fires remove relatively little biomass from the landscape. Long-term carbon storage would only be affected by drastically shortening fire return intervals.

Sohngen and Haynes (1997) used forest fire data in combination with an economic model of the U.S. forest sector to determine that a reduction in area burned by forest fires would increase the projected storage of carbon. They then compared the benefits of increased carbon storage (increased timber market welfare and reduced climate change damages) with the increased fire suppression costs required to produce an adequate reduction in area burned. Within the considerable ranges in potential costs and benefits that resulted, they found considerable overlap between costs and benefits. They suggested further research with improved data sets, but concluded that policy-makers should consider the cost-benefits of increased suppression within their broader portfolio of carbon mitigation strategies.

In the United States, several studies have been conducted to investigate the effect of forest fuel reduction treatments on carbon storage (Hurteau et al. 2008, North et al. 2009). In general, current fire-suppressed forests had substantially lower live tree carbon stocks than stands that developed under historic active-fire conditions, and those latter stands are thus likely to generate larger emissions if burned. Researchers also found that all fuel treatments (overstory thinning, understory thinning, prescribed fire), while reducing stand-level fire susceptibility, also reduced carbon stocks, either by producing milling waste or prescribed fire emissions. They concluded that understory thinning produced the most benefits, and suggested modifying current treatments to focus on surface fuels. However, they also pointed out that, under the Kyoto Protocol, emissions from stand-replacing wildfires are ignored, while emissions from thinning or prescribed fire operations to prevent uncontrolled wildfires (and greater emissions) are penalized.

Wiedinmyer and Hurteau (2010) used a regional fire emissions model to estimate the potential reduction in fire emissions using prescribed fire in dry, temperate ecosystems of the western United States. They found that wide-scale prescribed fire application could reduce CO_2 emissions by 18 to 25%, although they acknowledged the operational challenges associated with implementing wide-scale prescribed burning.

In a recent position paper, the Association for Fire Ecology in the United States stated quite clearly that full suppression of wildfires in fire-adapted ecosystems as a means of reducing GHG emissions may not yield long-term emissions reductions in comparison to landscapes where natural fire regimes are maintained. They also called on the U.S. Environmental Protection Agency to rectify its erroneous designation of wildfires as managed anthropogenic emission sources. They further stated that carbon emissions from prescribed fire are typically much lower than those from wildfires on the same landscape, and urged that these emissions, along with those from wildfires, be categorically excluded from legislation and regulation curbing annual GHG emissions.

The State of Alaska has recently conducted a review of its wildland fire policies and programs to address potential climate-induced increases in fire frequency and severity (www.climatechange.alaska.gov). Along with recommendations to expand and improve established community protection plans, two additional options are being considered:

- Review wildland fire management options for tundra lands that are at risk of more fire activity under a changing climate, including use of prescribed fire to pre-empt extreme tundra fire events.
- Allow fire to maintain healthy ecosystems in fire-dependent forests, while investigating opportunities to manage fires to break up high-risk forest fuels.

Daigle and Dymond (2010) summarized the relative effects of fire and fuel management on carbon dynamics, specifically for fire-prone ecosystems in British Columbia. They conclude that the net benefits to carbon storage across the landscape from fire suppression, fuel reduction, and modified fire response are unknown because all three approaches are affected by timing of future fires relative to management actions, fire behaviour, and the size of the fire relative to the area treated.

Fire in Ontario's Far North

Ontario's Far North is an area of increasing economic, political and scientific interest. In much of the Far North fires are largely unsuppressed unless they threaten communities, human health and safety, or economic infrastructure. However, several large economic development initiatives are underway that could increase the presence of people in the region, as well as creating more infrastructure and other values-at-risk. The Far North is also expected to see proportionately greater influences of climate change, which could significantly alter the existing fire regime. The stage is being set for a collision of significant issues: an increase in fire activity, demand for a greater level of protection, concern over fire and carbon storage, and the effects on what have been heretofore ecosystems little influenced by humans.

Portions of two broad ecozones make up the Far North Region (FNR) of Ontario: the Boreal Shield Ecozone and the Hudson Plains Ecozone (ESWG 1995). Although somewhat similar in climate, these ecozones differ in landforms, soils, vegetation, and fire activity.

The Boreal Shield Ecozone (BS) is dominated by a broadly rolling mosaic of uplands interspersed with numerous small to medium lakes and wetland areas. Precambrian granitic bedrock outcrops mixed with glacial materials are the characteristic surface materials. The area is over 80% forested and vegetation in this ecozone consists primarily of closed stands of conifers (black spruce and jack pine) mixed with some deciduous species such as birch, aspen, and alder.

The Hudson Plains Ecozone, usually referred to as the Hudson Bay Lowland (HBL), is a lowland plain underlain by flat sedimentary rocks that slope gently towards the Hudson and James Bays. The surface is composed of extensive wetlands with subdued glacial features and a belt of raised sandy beaches. The wetlands include extensive peatlands (largely bogs and fens). Permafrost ranges from continuous in the northwest to isolated patches in the southeast. The poorly drained areas support dense sedge-moss-lichen ground cover, while the less frequent better-drained sites support open woodlands of black spruce and tamarack.

Current fire regime

To manage forest fires to ensure maximum protection for human life and property while permitting fire to assume its natural role over much of the landscape, Ontario created three distinct fire management zones (OMNR 2004). The Intensive Zone (IZ) corresponds to those areas of central and northern Ontario containing major population centres, recreational areas, and regions where natural resource-extraction industries (including a large forest industry) dominate. Fires in this zone are actively detected and suppressed as quickly as possible. The Measured Zone (MZ) covers a broad east-west band immediately north of the IZ, and covers areas of moderate recreational use and potential wood supply. In this zone, most fires are actively detected and attacked, but if initial attack fails efforts are reassessed to determine the appropriate level of further suppression.

The Extensive Zone (EZ) represents almost all of the FNR of Ontario, where the vast majority of fires are allowed to burn freely unless specific values are at risk, in which case only defensive action is taken. The Extensive Zone (EZ) covers ~282,000 km^2, while the Measured Zone (MZ) covers ~38,000 km^2. In addition, parts of northern Ontario close to Hudson Bay are considered to be outside Ontario's protection zone (OPZ), but fires in this area (~122,000 km^2) have been documented in recent years.

(Note that this zoning was in effect from the mid-1980s to the mid-2000s. Since 2004, a new system of fire management zones was implemented under the *Forest Fire Management Strategy for Ontario*, but the zone boundaries and policy direction described here remain similar, with the Boreal and Great Lakes-St. Lawrence Zones being equivalent to the former Intensive Zone, the Northern Boreal Zone equivalent to the Measured Zone, and the Hudson Bay Zone equivalent to the Extensive Zone; see Figure 2.)

Figure 2. *Ontario's fire management zones (OMNR 2004).*

Ward et al. (2001) used fire history and recent fire disturbance records to show that Ontario's fire suppression policy had resulted in a lengthening of the fire return interval in the province's protected forest relative to pre-suppression times. For northwestern Ontario, they calculated a percent annual area burned (PAAB) of 1.11% in the EZ and 0.34% in the IZ, based on 1976 to 2000 fire data. A more detailed analysis by Martell and Sun (2008), using only lightning-caused fires, showed a statistically significant relationship between the PAAB in various regions of Ontario and vegetation, weather, and the level of fire protection.

The effectiveness of aggressive fire suppression in reducing area burned in Ontario was also illustrated by Colombo et al. (2005). Between 1990 and 2001, the PAAB in the IZ was 0.120% compared to PAAB values of 0.304% and 0.466 % for the MZ and EZ, respectively. Using these time-averaged PAAB values they suggested that practicing intensive fire management in the current extensive and measured zones could reduce area burned by 92,000 and 20,000 hectares annually, respectively, or 112,500 hectares per year for the entire 77.9 million hectares in which fires are currently managed in Ontario. Colombo et al. (2005) then used the CBM-CFS to determine the effects on carbon storage of expanding the IZ to include the MZ and found that it would result in the storage of an additional 4.1 Mt of carbon during the 2008 to 2012 commitment period.

Post-1970 (1970-2007) fire statistics (Stocks et al. 2003, Canadian Forest Service, *unpublished data)* indicate that 1,234 fires burned over 4,616,707 hectares in the BS portion of the FNR during this 38-year period, an average of 121,492 hectares annually. During the same period, 573 fires burned over 738,034 hectares in the HBL, an average of 19,422 hectares annually. The PAAB for the 1970 to 2007 period was 0.61% and 0.08% for the BS and HBL, respectively, although it is likely many fires in the HBL were not detected or mapped during the 1970s, so the HBL PAAB is likely a little higher. Fire data for EZ, MZ, and OPZ were used to compile these statistics, meaning that virtually all fires included in the data set were allowed to burn freely or received minimal suppression action.

Clearly, fire activity has differed significantly between the BS and HBL regions (Figure 3). Fire occurrence in the BS was more than twice that in the HBL, while the area burned was more than 6 times higher. The BS supports the typical high-intensity crown fires most identified with the broader boreal forest region, where stand-replacing fires are an ecological necessity. On the other hand, fires in the HBL are generally of a much lower intensity, and most often burn in areas where the water table is lower, some conifer tree cover exists, and root respiration dries surface mosses to the point where they will sustain fire. These fires are generally slower-spreading surface fires, with some torching (where fire moves up into tree crowns) in groups of trees. The fires appear much more fragmented than fires in the BS area, as they depend on the availability of sparse fuels in a predominantly wetland area. However, they can meander for weeks or months during the summer, often propagating through smoldering combustion, and growing quite large, as precipitation is much less effective in extinguishing deeper-burning peatland fires than those on the shallow-soiled boreal shield.

Carbon

Carbon stores on the BS within the FNR of Ontario are likely very similar to those in boreal forests across the Canadian Shield, averaging ~100 tonnes per hectare of carbon, excluding carbon stored in mineral soil (Stinson et al. 2011). In very general terms, high-intensity boreal shield crown fires likely consume 25 to 30% of this carbon. Estimates of fuel consumption are not currently available for HBL fires. However, since they are generally lower-intensity surface fires, it is likely that carbon consumption is somewhat lower than that for BS fires. This could change significantly if more frequent drought conditions lower the peatland water table making more fuel available for combustion.

Boreal peatlands worldwide account for 50 to 70% of the global carbon pool, and Canada contains ~30% of the boreal peatland carbon pool. These boreal pools are predicted to be a key element in the feedback mechanisms affecting climate change. They could contribute to reaching "tipping points", where carbon that has been stored since the last glaciation is released at greatly increased rates. Scientific understanding of peatland systems is limited, and a much better knowledge of internal peatland dynamics, hydrology, and the effect of human activity, is required to predict both their contribution to and response to climate change.

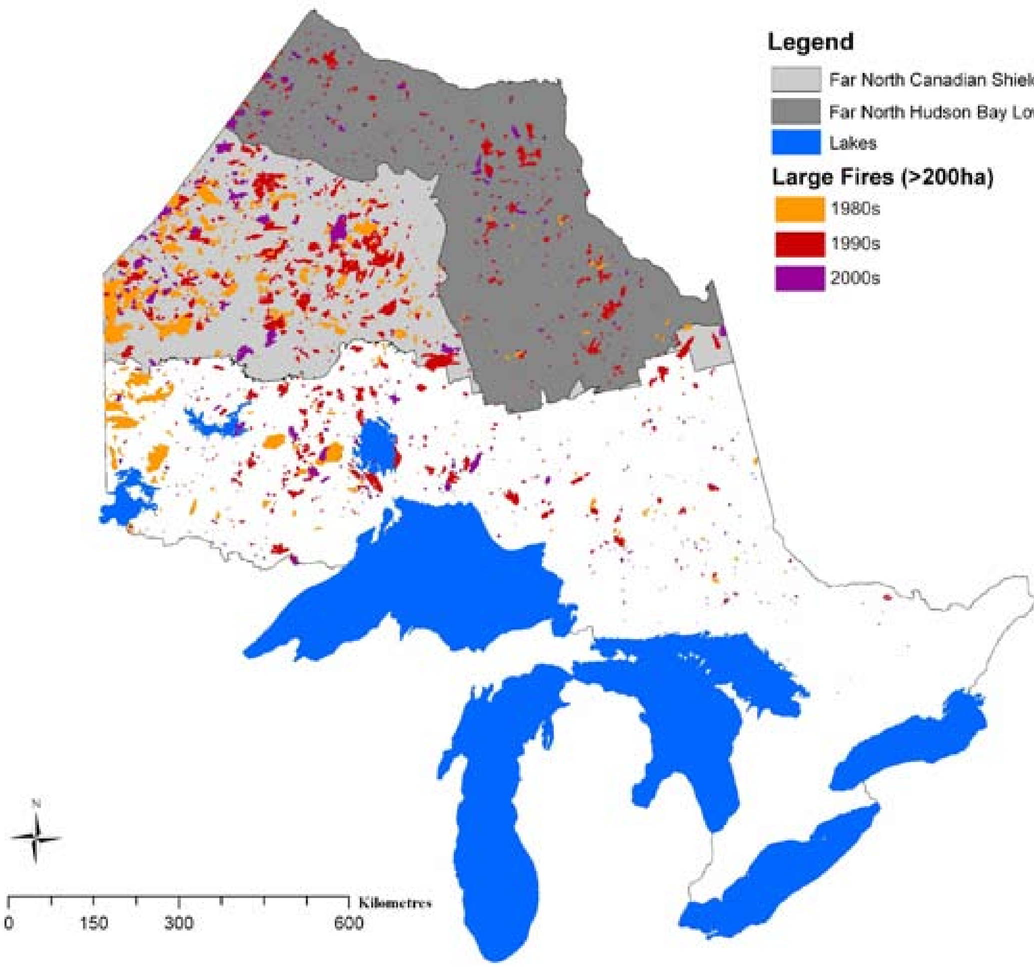

Figure 3. *Locations of fires larger than 200 ha in Ontario, 1980 to 2007 (The Far North Science Advisory Panel 2010).*

Within Canada, Ontario contains ~30% of Canadian peatland carbon, with a large majority of this residing in the HBL. Current estimates are that HBL peatlands contain 23.5 Gt (billion tonnes) of carbon, and the Ontario Ministry of Natural Resources (OMNR) is currently developing a science strategy to better understand how peatlands function and how they will respond to increased drought frequency, fire activity, and permafrost melting under a changing climate (Jim McLaughlin, Ontario Forest Research Institute, 2010, pers. comm.)

A recent United Nations report (Campbell et al. 2008) dealing with carbon storage in protected areas identified the HBL as a region where soil carbon storage levels are among the highest in the world (Figure 4). The authors of this report suggested that the large amount of carbon stored within protected areas, particularly in proportion to the land area covered, means that these areas could play a significant role in climate change mitigation. They further suggested that investing in protected areas could be a valuable component of a national strategy for reducing emissions in support of UNFCCC objectives.

Presently no obvious mechanism exists to obtain carbon credits for management of fires, and future accounting rules may exclude debits from fire emissions. As stewards of the land, governments may be responsible to ensure that fire suppression in peatlands occurs to meet climate change mitigation objectives, but accomplishing this in these remote areas would be very challenging. During the development of the 2009 Copenhagen Accord, many countries argued that peat stocks should be included in future accounting, so the trend will likely be towards more complete carbon accounting across the landbase. With this in mind, it seems likely that peatlands will be included in the next version of the CBM-CFS.

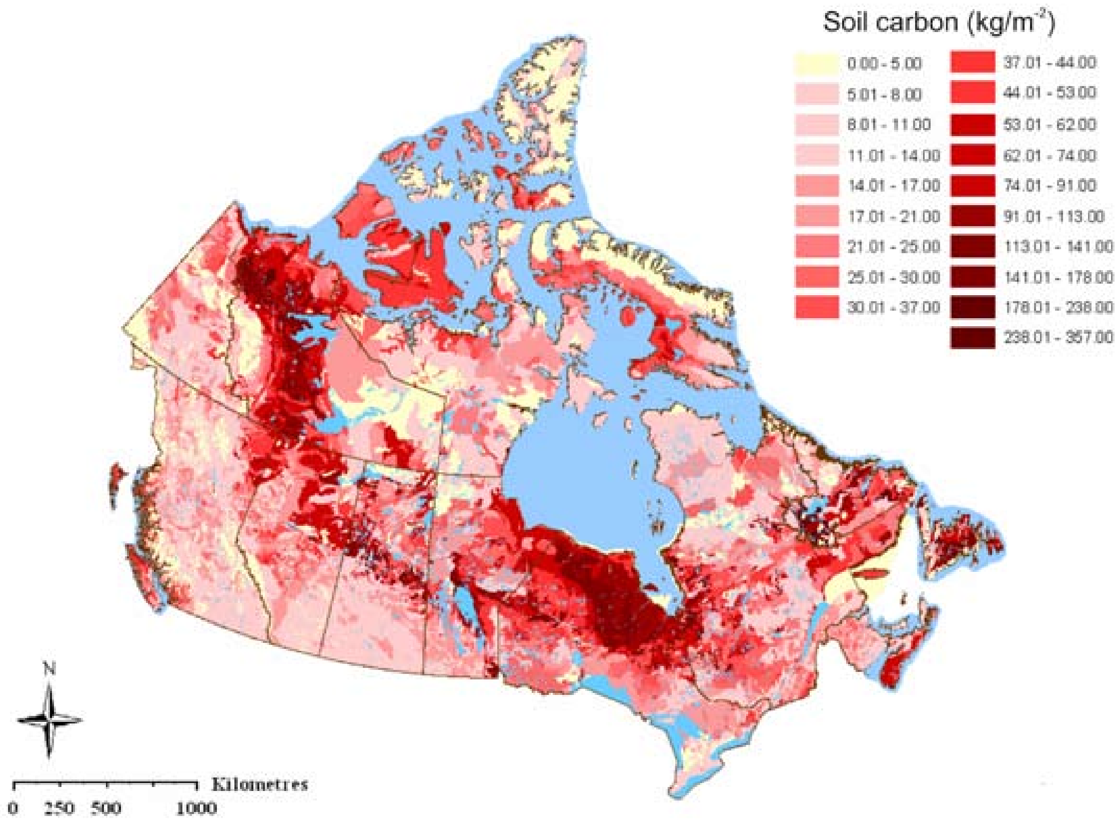

Figure 4. *Soil carbon estimates for Canada (Tarnocai et al. 2002).*

Future fire activity

Current climate change projections indicate significant warming (6 to 8°C) and a decrease in precipitation (~30%) across the FNR by the end of this century (Colombo et al. 2007). In response to warmer temperatures and changing precipitation across northern Ontario, the area burned by fire in the FNR is projected to double in that same period (Flannigan et al. 2005). In addition, both lightning and human-caused fire occurrence is expected to increase significantly (Wotton et al. 2010).

In the absence of increased fire protection in the FNR, fire activity in both the BS and HBL zones can be expected to increase significantly. The effect of this increase is somewhat easier to predict in the BS zone, where more frequent and severe fire activity would likely result in large regeneration failures as the forest age class distribution is steadily lowered by decreasing fire return intervals. Effects on carbon would be somewhat constrained by the lower levels of carbon on upland sites, but significant losses could occur from discontinuous lowland and peatland areas within the BS zone.

The effect of increasing fire activity combined with more frequent drought conditions is much more difficult to project in the HBL zone, as a lack of precipitation could result in differing degrees of dryness in bogs, fens, and swamps across the HBL. Increasing drought resulting from climate change will likely result in a general lowering of the water table across much of the HBL, although this will vary with peatland type. This would create an increase in the areal extent of fuels more receptive to lightning fires, which would result in more extensive and deeper-burning fires, and the release of significant amounts of long-stored carbon to the atmosphere. There is also concern that drought-induced lowering of the water table could upset the accumulation/decomposition balance in peatlands, within uncertain consequences.

Summary of Fire Management-Related Issues

Increasing global temperatures and related changes in long-term climate patterns will have significant effects on boreal ecosystems. Changing disturbance regimes may outpace the ability of ecosystems to adapt, disrupting long-term ecosystem processes. Forest managers will be faced with challenging policy issues: boreal forests and peatlands are being recognized as globally significant storehouses of carbon, but increasing disturbance regimes may increase carbon release to the point where those ecosystems become carbon sources instead. Management efforts to augment carbon storage may be countered by increasing disturbance rates. Increasing fire suppression efforts may be proposed as a means of dealing with increased fire activity and the related release of GHGs; this policy option will be operationally challenging and costly, particularly if these efforts are extended to Ontario's Far North. As well, conflicts will arise between a greater level of fire management effort and the desire to maintain ecosystem integrity and natural processes. Fire and forest managers will have to integrate fire management considerations into landscape-level planning to mitigate the potential for greater numbers of large, high-intensity fires driven by a more severe fire regime.

These issues will challenge forest and fire managers and policy-makers. While no simple solutions are provided here, we have attempted to summarize current scientific knowledge on these issues, and offer a summary of key points for further consideration.

Climate change effects on fire regimes in Ontario's forests and peatlands

- The fire regime in Ontario's forests is expected to become more severe in a warming climate – more variable weather, increased fire occurrence, more extreme fire events, and larger areas burned.
- A more severe fire regime in the managed forest will challenge the ability of the provincial forest fire management program to maintain the current level of protection provided to people and resource values. If fire management resources remain static, an increase in area burned and resource losses would be inevitable in a warmer climate.
- Although climate change effects in the Far North Region are somewhat uncertain, fire frequency and severity are expected to increase significantly, particularly in the fire-prone Boreal Shield region. Given the more complex ecosystems involved and uncertainties about how the internal mechanisms within peatlands will respond to increasing drought, fire effects in the Hudson Bay Lowlands are even less certain. However, given the huge amounts of legacy carbon in peatland and permafrost ecosystems, these may serve as a "tipping point" in terms of feedbacks to climate change if significant increases in fire-driven GHG emissions occur, further accelerating the warming process. Our understanding of the ecological effects of increased fire in peatlands is incomplete, which affects our ability to develop appropriate strategies to manage peatland fire events.

Fire and forest carbon storage

- Canada decided not to include forest management in its Kyoto Protocol accounting for the 2008 to 2012 commitment period, based primarily on uncertainty about both the extent and highly variable effects of natural disturbances on the sink-source strength of Canada's managed forest.
- Canada has argued strongly in international climate change negotiations that emissions from future natural disturbances should be "factored out", that is, not counted as credits or debits in carbon accounting procedures. Under this approach, no benefit (in terms of emission credits) would accrue from increased or more successful fire protection.
- A more severe fire regime may be problematic to the development of forest carbon offset credits as an economic opportunity in Ontario's fire-dependent forests. Increasing levels of fire disturbance would challenge the "permanence" of carbon stored in the forest through management actions to create forest carbon credits or offsets. Demonstrating additionality will also be challenging.
- Increasing the level of fire protection as a means of keeping carbon in storage might be seen as a desirable goal from a public good or environmental stewardship perspective, even if no direct carbon credits are gained.

Potential management responses

Significant issues are associated with the concept of increasing the level of fire suppression in both the managed forest and the Far North, whether in response to a more severe fire regime or a desire to maintain carbon in storage:

- Cost will be high and feasibility is uncertain.
- To date, fire in the Far North Region has generally been left to burn to promote natural ecosystem function, conserve biodiversity, and maintain wildlife habitat. Biodiversity in the boreal forest depends on fire, and fire exclusion alters the normal forest renewal process, negatively affecting ecosystem function. [Canada has signed international agreements related to maintaining biodiversity (Supply and Services Canada 1995)]. In addition to the logistical complexity of increasing fire suppression efforts in the Far North, intervening more intensely in the natural fire regime will likely result in a policy debate about the socio-economic need for fire protection and the role of fire in sustaining natural ecosystems in that region, as well as the contribution of fire to atmospheric carbon.
- The value of carbon, relative to other values that would be protected by fire management efforts, will need to be evaluated and ranked to provide fire managers with direction for suppression resource allocation decisions. For example, where does protecting carbon in the Far North rank among provincial fire protection priorities? Would protecting carbon there compromise protection levels elsewhere?
- There may be public policy pressure to increase fire suppression as a means to keep carbon in storage, even if there are no carbon credits to be gained. Despite modern and expensive fire management programs, fires still regularly burn large areas in Canada's managed forests. Expanding protection, even by increasing resources, is unlikely to eliminate this trend. Although fire management efforts may postpone fire losses, they will not eliminate them.
- There is a desire to maintain a "natural" ecosystem in the Far North and other areas across Ontario, which requires letting fires burn. A paradox will emerge as climate change begins to alter fire frequency and severity. The rate at which climate change alters the fire regime may exceed the rate of ecosystem adaptation, such that fire no longer represents a process in balance with the ecosystem; this in turn could precipitate changes in the ecosystem in terms of species assemblages and ecosystem function. Applying fire management to the ecosystem would also change the fire regime and alter the ecosystem, although perhaps very differently. In either situation, the current relationship between fire and ecosystem dynamics will change.
- In the long-term, Ontario's forests are carbon-balanced: fire and other disturbances cycle carbon between the atmosphere and the forest over long periods. Could the investment in fire protection necessary to delay the loss of carbon in forest fires be more effectively spent to reduce carbon emissions from other economic sectors?

Other fire and forest management policy issues

- If climate change leads to a more severe fire regime, the fire protection levels mandated in Ontario's Forest Fire Management Strategy will not be possible with current program resources. Current strategies and fire management zoning will need to be re-examined to determine where intensive fire protection should be maintained versus those areas where a greater level of fire disturbance would be acceptable.
- Enhanced forest management planning will need to include the use of FireSmart forest management and other landscape design principles to use natural barriers and create vegetation buffers that would reduce the spread potential of high intensity wildfires.
- Fire and forest managers will need to look more broadly at the role of fire in sustaining forest health and resilience, and in strategic-level forest management planning. Fire management planning and forest management planning will need greater integration, at both landscape and operational scales. The use of managed fire to promote forest regeneration, maintain and restore forest productivity, and promote forest health and resilience in a changing climate may need to be increased.
- Resource managers will require a better understanding of the costs, benefits, and implications of using fire as a tool to sustain forest health versus the on-going need to provide fire suppression for public safety and resource protection.

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