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Climate Change: Implications for the Boreal Forest

by

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CLIMATE CHANGE: IMPLICATIONS FOR THE BOREAL FOREST

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ABSTRACT

The finding of the recent IPPC Second Assessment Report [I] conclude that the boreal forest is more sensitive and will be more affected by climate change than either temperate and tropical forests. Results suggest that over the next century in response to projected changes in temperature and moisture patterns the boreal ecosystem will undergo major changes in ecosystem boundaries, growth and natural disturbances related to fire and insects. This paper outlines the key highlights of the IPCC and more recent literature in terms of the effects of climate change for the boreal forest over the next 100 years. As well, the boreal forest appears to be responding to environmental changes that have occurred over the last century and more particularly over the last 30 years. Changes in boreal ecosystems related to the permafrost zone, vegetation productivity, disturbances related to fire and the carbon cycle have been noted. This paper reviews some of the major highlights of the changes that have been noted.

Many of the changes projected for the boreal forest that forest managers will have to respond to in relation to climate change are not new. Subsequently, forest managers have many tools at their disposal that will enable them to assist the forest to both mitigate and adapt to climate change. The challenge for forest managers will be dealing with the rate and intensity of change that occurs. This paper outlines broadly some of the things forest managers can and are doing to respond to climate change. As well, additional actions forest managers need to take to better prepare for and respond to climate change are briefly discussed.

INTRODUCTION

There exists strong scientific consensus that the global climate will warm significantly within the next century, primarily in response to increased concentrations of greenhouse gases in the atmosphere [1]. The projected warming will be accompanied by changes in precipitation as well as greater variability in global weather patterns. Forests and woodland, which cover approximately 4 billion ha globally, will certainly be affected [2]. The manner in which we manage our forests will playa critical role in reducing impacts of climate change on forests, and adapting and responding to ongoing changes.

Current projections suggest that high latitude areas will undergo the greatest changes. Of concern are the potential implications of these changes on the boreal forests. The boreal represents one of the earth's largest biomes covering approximately 1.43 billion hectares (17% of the earth's land surface) in a circumpolar complex of northern Eurasia and North America [3]. In Canada, the boreal ecosystem occupies approximately 300 million hectares. Because of its size, the biome plays a major role in the global carbon cycle storing an estimated 714 billion tonnes of carbon (GtC) or 37% of the total carbon stored in the terrestrial biosphere [3]. It is characterized by a patchwork of small to very large areas dominated by about 15 evergreen and deciduous species, mixed with wetlands and peatlands. The boreal, depends extensively on fire and insect disturbance for renewal. The return interval for fire generally ranges from 50 to 100 years with well-established relationships between fire-cycle length, species composition, age-class distribution and carbon storage [4, 5, 3, 6, 7]. Net primary productivity in the boreal is low in comparison to temperate and tropical forests ranging from 1-8 t dry matter per year compared with 7-12 t ha yr^{-1} for northern hardwoods [8]. Low air temperature restricts growth and the production and germination of seed. Low soil temperature and permafrost limit growth and nutrient availability is generally low throughout the biome. Because of its northerly location, low temperature environment, and low productivity the boreal is sensitive to changes in climate.

Extensive reviews of the implications of climate change for global forests have been undertaken as part of the Intergovernmental Panel on Climate Change [2]. The implications for Canada's forest and forest management have been described and reviewed by Singh et al, [9], Duinker [10], Hall and Carlson [11], Pollard [12], Apps and Kurz [13], Harrington, et al. [14], Stewart [15], Spittlehouse [16, 17], and Cohen [18]. A detailed review of the implications for Canada's forests is currently underway as part of the Canada Country Study being led by the Atmospheric Environment Service of Environment Canada [19]. This paper summarizes the implications of climate change for boreal forests and forest management using the key findings and conclusions expressed in these analyses. The role of forest management in adapting and responding to the projected changes in climate is also reviewed.

HOW IMPORTANT ARE FORFSTS TO THE GLOBAL ECONOMY?

In any discussion of climate change it is important to consider the socio-economic implications. The following briefly outlines the importance of the forest to the global economy and then focuses on Canada.

Globally forests occupy an estimated 3.4-4.1 billion hectares, more than a quarter of the earth's land surface [20, 21]. The value of products produced was estimated at $418 billion in 1991, representing 4% of the GDP of developing countries and 1% of developed countries. World trade in forest products amounted to $68 billion.

Economically forestry is a major industry contributing significantly to the wealth and social structure of boreal nations - Canada, Russian, Finland, Sweden, Norway and Alaska in the United States. For example, in Canada forestry activities in 1996 contributed $53 billion to Canada' s economy and $32.1 billion to it's balance of trade [22]. Directly and indirectly, forest industries provided employment for 840,000 people, representing lout of every 16 jobs in Canada. Over 300 communities are economically dependent on forest industries for their existence. Forests also provide important recreational opportunities and a source of resources for indigenous groups. It is evident from these figures that any changes in the growth and productivity of the boreal forest as a consequence of climate change would likely have major socio-economic impacts on all boreal nations.

Climate Projections for the Boreal Zone

Significant global warming and other climatic changes are forecast to occur by the middle of the next century. The annual to decadal changes would include considerable variation, but the average rate of warming is expected to be greater than any seen in the last 10,000 years. Temperatures are projected to continue to increase beyond 2100, even if atmospheric concentrations of greenhouse gases were to be stabilised by that time [1].

Confidence in estimations of future possible climates at the regional scale remains much lower than at the global or continental scale. As well, estimates for temperature have higher confidence than estimates for other variables such as precipitation and soil moisture. However, large changes in the frequency of extreme events are known to occur with small changes in mean values of climatic elements. Projections for the year 2050 for the circumpolar boreal zone suggest [23, 5]:

- temperatures in the boreal increasing by an average 1-2°C during summer and 2-3°C in winter;
- night-time air temperatures increasing faster than day-time temperatures;
- increasing ground temperature;
- regional changes in precipitation of :t 20% ;
- precipitation increasing in winter and snow cover area and duration decreasing;
- soil moisture increasing in winter and decreasing in summer .

Projections imply longer, warmer and somewhat drier growing seasons, milder winters with potentially fewer extremes in minimum temperatures; and somewhat drier conditions. However, the timing, magnitude, spatial distribution and variability of the changes are very uncertain.

Implications of Climate Change for Boreal Forests

Over the next 50-100 years, what sort of change in climate might we expect, how will the changes effect global boreal forests?

Key points and conclusions for boreal forests derived from the IPCC second assessment report [5, 29] include:

- The impact on boreal forests is expected to be greater than on temperate and tropical forests;
- Changes in the frequency and patterns of disturbance may be more important agents of change than increased temperature and CO_2;
- Overall the boreal forest is likely to decrease in area, biomass, and carbon stocks, with a move to younger age-classes with major disruption and changes occurring along the southern boundaries;
- Over the next century the preferred geographic range of species may shift approximately 300-500 km to the north;
- Maximum potential migration rates may be too slow to keep up with the rate of climate change resulting in large areas of transitory forest decline. However, this may not happen if intraspecific genetic diversity buffers the change (i.e. species that are no longer in a favourable climate will simply grow and regenerate poorly and be overtaken by invading species either gradually or after disturbance.
- The role of elevated CO2 concentrations, through improved growth and water use efficiency on improving long term productivity is uncertain.

The results of the IPCC assessment indicate the effects of climate change on boreal ecosystems over the next 100 years could be quite severe with significant changes in ecosystem boundaries, plant growth and ecosystem productivity, disturbances related to fire and insects, and the carbon cycle. The following outlines the key findings related to each of these areas of change with particular emphasis on Canadian forests. As well, ecosystem responses to observed climate changes and variability over the last century are described.

Shifts in Forest-type Zones and Species Ranges

Implications of Climate Change Projections. A combination of climate and soil conditions control forest growth and distribution. As these change so will the range and zonation of the boreal ecosystem. Patch dynamic models cannot currently be used to simulate the transient behaviour of forests in a changing climate on a global scale [5] as they require large sets of species-specific information that is not available for many areas. In the absence of these models, vegetation-climate equilibrium type models have been used to assess the implications of climate change at the global level [24, 25, 26]). These models show good statistical agreement between simulated and observed distribution of vegetation classes, but Henderson-Sellers [27] notes that they give widely different responses to the same future climate. The results of Prentice et al. [24, 28] and Neilson et al. [30] show that the tropical forest will be the least affected by climate change and the boreal affected the most. For the boreal results suggest that the boreal forest ecosystem, even with a major shift into the current tundra zone, could be reduced by about 50% with large areas being replaced by either temperate forests or grasslands.

Wheaton et al. [9] and Rizzo and Wiken [31] indicate climate warming in Canada will create suitable climatic conditions for the boreal forests to grow farther north. However, this assumes that soil physical and moisture conditions will favour forest growth. At the same time the warmer conditions in the southern boreal will become detrimental to the existing tree species and many will begin to decline and retreat to areas more environmentally acceptable. Sargent [32] and Rizzo and Wiken [31] suggest that much of the existing Canadian boreal forest will be replaced by temperate deciduous forest similar to that located in southern Ontario and northern United States. Much of the central boreal would be replaced by climatic conditions more suitable to grasslands.

Although temperature affects the distribution of the boreal vegetation, moisture availability is likely the most important factor in drier regions, particularly in western Canada [33, 34] and Wheaton and Thorpe [35].

Hogg [33, 34] showed that the southern limit of the western boreal forest between the forest and grasslands corresponds most closely with climatic moisture regimes (annual precipitation minus potential evapotranspiration). Thermal characteristics of climate (e.g., growing degree-days) showed an inconsistent relationship with the southern limit [33]. One of the most likely explanations of this control by moisture is that conifer regeneration from seed is restricted in drier climates. Coniferous forests and peatland development are generally limited to areas where annual precipitation is greater than potential evapotranspiration. However, even in these regions moisture deficiency frequently reduces the germination rate, photosynthesis, and survival of conifer seedlings. In the eastern boreal where moisture is not generally a problem the limiting factor is one of competition with temperate species.

Migration Rates. Shifts in the distribution of forest zones in response to climate change take place with lag times of centuries to millennia [5]. Climate change projections for the next 100 years are of about the same magnitude as the changes that have taken place over the last 10,000 years. Consequently, there is major concern about the ability of our forests to adapt. Globally temperatures vary approximately 0.7°C per 100 km in latitude and 0.5-0.7°C per 100 m in altitude [5]. Global temperature changes of 0.1-0.35°C per decade projected for the next hundred years suggests that species would have to move toward the poles at a rate of 1.5-5.5 km yr^{-1} and increase their elevation at 1.5-5.5 m yr^{-1}. Natural rates of migration for most species range from 40-500 m per year -Scots pine 40-80 m yr^{-1} [36], white pine 1-2 km yr^{-1} [37]. Migration of a tree species involves movement of propagules to new locations, establishment of seedlings, growth of individuals to reproductive maturity. Many stages in this sequence could be disrupted by unsuitable climatic conditions [38]. As well, changes in the rate and timing of seed production could limit the rate of migration and cause substantial changes in species distribution. Consequently, it is unlikely that future species migration rates could match the projected rates of climate change in large areas [5].

Observed Changes in Ecosystem Boundaries Over the Last Century. There has been a temperature increase of 1-2 °C in the mid to northwestern boreal in Canada over the last century [39]. However, no appreciable changes have been detected at the southern fringes of the ecosystem boundaries. The reason for this can probably be attributed to the large lag time in terms of biophysical response to environmental change. Also fire, and pest protection practices, the proximity of agricultural lands and forest management to replanting and stand tending have likely mitigated or masked changes that might have occurred in the absence of human activity. No appreciable movement has been observed to date along the northern treeline. However, along a 1500 km section in the Northwest Territories and Yukon, Nichols [40] noted a widespread switch from infertility in the 19605 and 1970s to pollen and cone production in the 19905. Similar studies at 27 sites in western Siberia, northern Yakutia, and north-east Siberia, revealed that larch trees are now producing enough viable seed to allow seedling colonization of the tundra. Nichols notes that tree ring studies at various locations in Siberia also suggest a recent warming response.

Changes in the Permafrost Zone Over the Last Century. A major change appears to have taken place over the last century in the permafrost within the forest and tundra area of Canada and Alaska [41, 42]. Halsey et al. [42] concluded that permafrost underlying bogs along the southern discontinuous permafrost boundary has been disappearing in response to a 1-2°C warming over the last 200 years. The result has been a northward shift of the permafrost boundary by 140 km in Alberta, Saskatchewan and Manitoba. Similar findings have been reported in the southern fringes of the discontinuous permafrost zone of Alaska [43, 44]. As well, the insulating effects of the vegetation is allowing permafrost to exist in many areas where average annual temperatures are warmer than those required to initiate permafrost development and growth [41]. There are signs that changes are taking place in the permafrost, however, the response is lagging considerably behind the observed warming [41]. Displacement of the continuous permafrost in this area could take decades to centuries depending on the depth, thickness, and conductivity of the soil material. While the permafrost appears to be thinning and retreating in western Canada and Alaska in the eastern part of the Canada, particularly northern Quebec and Labrador, where cooling has been observed over the last century the permafrost layer appears to be thickening [45]. Regional cooling and accompanying changes is not inconsistent with global warming, especially during the early stages of change. The movement of the permafrost and thickening of the active layer in northern latitudes has obvious implications for improved biological activity and growth for forest management.

Changes in Growth Rates and Productivity

Implications of Climate Change Projections. Generally there is a positive correlation between net primary productivity and temperature and actual evapotranspiration. Longer growing seasons and warmer temperatures should increase growth rates in areas where temperatures are currently below optimum requirements, assuming adequate moisture is available. Productivity of the existing temperate and deciduous forest area in eastern Canada is expected to increase with the warming as the climatic conditions are currently below optimum levels. In areas where optimum temperatures are exceeded growth and productivity will likely decline, in conjunction with increased competition with new species more adapted to the warmer climate. Other factors, that may also limit the potential growth response to warming include moisture, extreme events, and changes in pests species and range and fire.

Observed Response in Growth and Productivity Over the Last Century. This is an extremely complex question to deal with given the myriad of other factors effecting biological growth, reproduction and survival in general. Also, we have no baseline information to assess whether global forests are growing faster today than in the past. The IPCC [5] basically concluded that no evidence of substantive change in growth and productivity in global forests over the last century had been detected. More recently, however, Myneni et al. [46] believe they have found a positive biological response between 45-70N to the observed warming over the period 1981-91. Plant growth increased by 10% during this period and the growing season start advanced by about 8 days, coincident with an early disappearance of winter snow cover. The greatest increases in vegetation took place inland from the oceans. Bands of increased growth were measured in Europe from Spain in a north-easterly direction across central Europe and southern Russia, and in North America from Alaska in a south-easterly direction to the Great Lakes and north-east again to Labrador. Little change was seen outside this band in the continental U .S. Whether, these changes are short term or long term is unknown.

Elevated CO_2 -Is This Affecting Forest Growth and Productivity?

Atmospheric CO_2 concentrations have increased from 280-36Oppmv since pre-industrial times [1]. Elevated CO_2 levels have been associated with increased photosynthetic rates and increased water-use efficiency of various forest species. This could potentially increase forest productivity and mitigate damaging climatic effects such as drought. Unfortunately, experimental results to date are inconclusive. Only a small number of short term open-air CO_2 enrichment experiments have been conducted with mature natural populations -and none have involved forests or forest stands [5].

To date no corresponding increase in forest growth under natural conditions has been observed that can be conclusively related to increased CO_2 concentration [5]. Observed increases in growth can be explained by other factors such as more favourable temperatures, improved water relations, successional age, or nitrogen fertilization by industrial pollution [47, 48, 5]. Even though the effects of CO_2 enrichment forest growth and productivity is unresolved, and will remain unresolved for some time to come, it is more likely to ameliorate, rather than exacerbate, the effect of climate change by widening the range of climatic tolerances in forests.

Changes in Fire Disturbances

Implications of Climate Change Projections. While climate warming may be the underlying cause of the potential shift of forest ecosystem boundaries, fire is the disturbance mechanism that is expected to bring about the changes. Warmer and drier conditions are expected to increase the frequency, duration and intensity of fires, and greater amounts of fuel associated with forested areas in decline may cause more and larger fires. For example, Flannigan and Wagner [49] project a 40-50% in area burned in the Canadian boreal for a doubled CO_2 climate, while Stocks [50 and Stocks and Lynham [51] predict more frequent fires of higher intensity and greater duration in both Canada and Russia. In Russia, projections suggest that an additional 7-12 million ha of forest per year will burn within the next 50 years, affecting 30-50% of the boreal forest area [52]. It is evident from these projections that changes in the boreal ecosystem in response to increased fire could occur much more rapidly than expected in relation to temperate and tropical ecosystems where disturbances associated with fire is not a problem.

Observed Changes in Fire Over the Last Century. Fire has been an ecologically important disturbance in global boreal forests for millennia. Statistics from Canada, Alaska, and Russia illustrate that, despite large fire protection efforts in their forests, fires still exert a significant influence on boreal ecosystem dynamics [53, 54, 55]. While intensive forest management has virtually eliminated large fires in Scandinavia, current estimates are that 5-10 million hectares burn annually in the circumpolar boreal zone [55]. Fire activity has been increasing over the past three decades in Canada, averaging 2.8 million hectares annually since 1980 [55], but a lack of complete data prior to satellite coverage in the early 1970s precludes direct comparison of this trend with fire statistics from earlier this century. Similar problems exist for data for the Russian boreal where fire statistics prior to the early 1990s are considered to have been vastly underestimated [55]. Recent work by Stocks et al. [54] in reviewing and correcting the historical data prior to 1970 in Canada suggest that the levels of area burned observed in the 80s and 90s is higher than at any point in the past 75 years.

Changes in Insect Disturbances

Implications of Climate Change Projections. Climate change will affect the distribution and degree of infestation of insect pests through both direct effects on the life cycle of insects and indirectly through climatic effects on host, predators, competitors, and insect pathogens. The risk of loss will also increase due to the expansion of insect ranges.

Climate and weather affect inset lifespan, fecundity, diapause, dispersal, mortality, and genetic adaptation. Temperature is probably the major variable limiting geographical ranges overwintering success, population growth rates, numbers of generations per annum, length of growing season, tree-pest synchronization) interspecific interactions, dispersal and migration. Many documented effects of climate on insects show the effects of unusual weather events) such as droughts and frosts, on the severity of insect outbreaks within their normal range. However, these variables are not well predicted by climate models.

Defoliating insects play an important role in boreal forests. The proportion of many forest species is directly related to the intensity of insect outbreaks [5]. They also affect forest productivity, e.g. 51.0 million m^3 per year are lost from tree mortality due to insect attack in Canada. These losses are 1.5 times those due to wildfire and are one third of the annual harvest volume [56].

Insect populations are normally maintained at relatively low levels by a combination of host resistance, natural enemies and weather conditions. Climate change could have a major effect on any of these and subsequently the damage patterns of insects may be drastically altered, especially for those limited by climatic factors [57]. The principal concern is whether species that can increase their population size by undergoing an extra generation each year will expand their geographic distributions [58]. A changing climate is expected to bring generally drier conditions with an increased likelihood of droughts and heat waves in the interior of large mid-latitude continents. The survival and fecundity of insect herbivores often improves on drought-stressed trees. Therefore, the boreal forest may suffer increasing insect pest problems with a warming climate. If an insect's geographic range is large, common genotypes from warmer areas may readily invade cooler areas as the climate warms. Change in insect disturbances, along with fire, is seen as a driving force to effect many of the expected forest ecosystem responses to climate change [59, 6].

The spruce budworm is responsible for more losses in Canada than any other insect. The spruce budworm range matches most of the range of the white spruce in the boreal forest. It can kill almost all the trees in dense, mature stands of fir during uncontrolled outbreaks. Periods of outbreaks (high population densities) usually last for 5-15 years, interspersing periods with low populations of 20 to 60 years. Per capita growth rate increases occur with warm, dry conditions. Under climate warming, higher temperatures should increase rates of foliage development and would reduce the time when the insect has access to immature foliage. This may reduce breeding success in some insects. But the budworm is so well synchronised with tree growth that weather may make little difference. Relationships with natural enemies may also change with climatic change. If the host develops much faster than the parasitoid, then the host may completely escape from its effect [57]. Then outbreaks could become more intense and widespread. Synergistic interactions between drought induced changes may in turn allow the budworm to improve its performance to the point that it can escape natural enemy regulation. Then outbreaks may become more frequent and severe [57].

Extreme weather events, especially late spring frosts and drought, shape budworm effects. Late spring frosts are associated with the end of outbreaks. As the climate warms, the frequency of late spring frosts will decline, and population densities of spruce budworm will remain high for longer periods in northern white spruce stands [57].

The white pine weevil reduces growth and timber quality in spruce and pine throughout North America. Sieben et al. [60] assessed the effects of climatic change on the weevil hazard in the Mackenzie River Drainage Basin. The weevil requires about 785 growing degree-day accumulations above 7.2°C to develop from eggs to adult emergence from the tree leader. A summer climate warming scenario of 3°C for the year 2050 increased the area of the high hazard class from 24 to 75% .The estimated weevil range shifted northward and upward in elevation [60]. Note that because the weevil is a pest of 5 to 40 year old stands, conversion to younger stands through harvesting, or climate change may create extensive reforestation problems, similar to problems a] ready occurring in the central interior of British Columbia.

Observed Changes In Insect Disturbances Over the Last Century. No major change in patterns or insect disturbances have as yet been detected in the boreal. However, a couple of items suggesting change may be occurring have been noted including the first significant outbreak of tent caterpillar in northwest Canada [61] and a change in phenological development of spruce budworm [62, 63]. The outbreak of forest tent caterpillar in the Fort Liard area in the Northwest Territories is the most northern recorded. Results of Fleming and Tatchell are the first conclusive evidence in Canada of accelerated phenological development in a major insect pest in response to observed warming. They found that flight periods of the spruce budworm have moved ahead by an average of 3- 7 days over the past 25 years.

Changes in the Carbon Cycle

Implications of Climate Change Projections. A significant amount of research has focused on determining the quantity of carbon contained in global forests since Tans et al. [64] suggested the existence of a large carbon sink in northern terrestrial ecosystems. Global forest ecosystems account for approximately 50% of the annual exchange (120 GtC) of CO2 with the atmosphere [1]. Forest ecosystems worldwide represent huge carbon pools in their soils and standing biomass, on the order of 1500 and 650 GtC, respectively. The Boreal forests are estimated to contain 30-50% of the global forest carbon [65,21,3, 1]. An estimated 714 GtC are stored within the boreal region [64, 3] of which 419 GtC is in peatlands within the forests, 231 GtC in the forest soils and 58 GtC in living biomass. The forests of Russia and Canada contain the bulk of the boreal carbon storage. Russia has 884 million ha of forest storing an estimated 42.1 billion tonnes of carbon in live standing biomass, 29.5 billion tonnes in soil detritus. In Canada, the amount of carbon stored in the boreal forest is estimated to be approximately 193.7 GtC of which 7.1 GtC is in standing vegetation biomass (trunks, branches, roots etc.), 51.6 GtC in forest soils and detritus, and 135 GtC in peatland soils [66, 65].

A vital question is how will future climate change affect carbon storage and cycling in the boreal forest? Under current climate change scenarios large amounts of carbon may be released into the atmosphere through forest decline and disturbances and before new forests replace the former vegetation. The resulting loss globally of aboveground carbon has been estimated to be 0.1-3.4 Gt yr^{-1} for a total of 10-240 Gt over the next 100 years. Kasischke et al. [3] suggest that the projected increase in area burned of 40-50% per year would have a significant impact on the carbon budget of the circumpolar boreal forest. For example, in Russia, an additional 7-12 million ha of forest will burn annually within the next 50 years, affecting 30-50% of the land area [67]. Kasischke et al. suggest that if this happens the amount of carbon stored in the ground layer would decrease and the amount of carbon in the living biomass would increase. Overall, they indicate the net loss of carbon in boreal forests between 27.1 and 51.9 GtC (3.8-7.3% of total carbon stored in boreal ecosystem). Because the carbon the ground layer is lost more quickly than carbon is accumulated in living biomass, this could lead to a release of carbon of 0.33-0.8 GtC yr^{-1} over the next 50-100 years. In Russia, the forest vegetation could change on 334-631 million ha (38- 71% of existing forest area) generating a direct carbon flux to the atmosphere of 6.1-10. 7 billion tonnes of carbon (a loss equivalent to 14-25% of current standing biomass estimate) [52]. The implications of these losses for accentuating climate change is unknown.

Current estimates are extremely crude because present models cannot adequately model the transient effects of climate change. Forest succession models suffer from our lack of understanding of the complexity of the processes involved. Of particular concern is the inability of current models to incorporate disturbances related to fire and insects which playa pivotal role in the current functioning of boreal ecosystems. Lohle and LeBlanc [68] argue that the succession models are programmed to make forests overly sensitive to climate change. Until we improve our understanding of forest succession dynamics the implications of climate change will remain very uncertain.

Observed Changes in the Carbon Budget Over the Last Century. Estimates of the carbon flux from forests indicate that since 1850,90-120 GtC have been released to the atmosphere [69, 21]. This flux is largely the result of increased population growth and the clearing of forests for agricultural purposes. However, we do not have a comprehensive picture of how the circumpolar carbon budget has changed over the last century. The only estimates are those developed by Kurz and Apps [6] for the Canadian boreal and subarctic forests covering 1920-90. Estimates for Russia cover the period 1980 to 1993 [(67]. Canada's boreal and subarctic forests for the period 1980-89 were a net source of 57 MtC yr^{-1} after having been a sink for atmospheric carbon for most of this century [6]. The major reason for this change is an apparent increase in fire and insect disturbances. " Apparent" is used to describe the change in fire disturbances because of the uncertainty in the accuracy of fire disturbance data prior to 1970. Harvesting appears to have played a minor role in this abrupt change from a sink to a source.

Results for Russia suggest forests have been a sink ranging from 0.1-0.5GtC [70, 71, 72, 73, 74, 21]. However, Krankina et al. [67] indicate for the period 1988-1993, Russian forests lost 500 MtC or 1.2% of their total standing biomass. The findings are similar, although covering a shorter period, to those reported above for boreal and subarctic forests in Canada [53]. Whether the overall carbon budget of the forest in Russia is positive or negative is unknown because of the inability to estimate fluxes from soil detritus. Krankina et al. [66] suggest qualitatively that the vast majority of the carbon loss from the standing biomass pool has been taken up by the soil carbon pool and the products pool with little lost to the atmosphere. However, this may be an optimistic view. Given the similarity of the standing biomass loss for Russia with those for Canada, where soil fluxes have been included and the forest is now a "net source" of atmospheric carbon, it is likely that the Russian boreal like the Canadian boreal, if not now, shortly will become a source of atmospheric carbon.

Investigations of the carbon budget of Canada's boreal and sub-arctic forest over the period 1920-89 have revealed a number of important findings in terms of improving our understanding of the role of boreal forests in the global carbon cycle. This include:

- The carbon budget of the boreal forest is not in equilibrium but changes from year-to-year and decade-to-decade depending on growth processes and disturbances, such as fire, insects, diseases and management practices, that affect their productivity;
- The amount of carbon contained in the forest is strongly influenced by the age distribution of the forests. Hence, timing and rates of disturbances are important factors in determining whether our forests are a sink or source for atmospheric carbon.
- Change in carbon uptake or release by the forest is primarily the result of fluctuation in natural disturbance regimes. The recent 20-year period of high disturbances in the boreal forest, even in the absence of climate change, will keep the forest a net source of carbon to the atmosphere for decades.
- Factoring in climate change over the next 100 years it is unlikely that boreal forests will be significant sinks for atmospheric carbon released by society's use of fossil fuel.

IMPLICATIONS FOR FOREST MANAGEMENT

Assuming the range of current climate change projections is correct, there are likely to be significant changes to the boreal forest ecosystems. This has major implications for management and use of these forests. What can forest management do to mitigate potential unwanted effects and take advantage of those that are desirable? Most of the projected problems related to fire, disease, insects and reforestation failure are ongoing problems in forest management and are presently being addressed in one form or another. It is the location and intensity of the problems that will change. Consequently, many of the forest research and management activities required to address climate change are already part of current actions. But surprises should be expected with climate change, and new management challenges should be anticipated, especially with our current level of understanding of climate-ecosystem dynamics and the long term effect of management activities.

Society and forest managers have two basic choices: let nature take its course, or plan to intervene and assist nature in making the changes. It is probable that the former will be by default the option chosen over a large part of the landscape. Management actions will be targeted to productive forest lands. The role of forest management in the future will be to develop and implement the necessary changes that will enable forest ecosystems and forest sector to adapt to ongoing changes, mitigate unwanted effects, and take advantage of desirable changes.

Forest management responses will be complicated by a number of factors [17]. First, climate change is not the only environmental issue forest managers have to deal with -others include land use change, biodiversity, atmospheric pollution, water quality, and increased UV-B radiation effects from the decline in stratospheric ozone. Second, and foremost is the differing and sometimes contradictory values placed on forests by society -timber, recreation, cultural and ethnic needs. Third, forest economics and decisions are often driven by short (< 10 years) time horizons, many controversial issues already fill the agenda, and climate change is seen to be just another one of the many unknowns that foresters must address. Fourth, there is likely to be increased pressure to manage forest for carbon, increasing carbon storage in forest and forest products, and as a source of energy to offset fossil fuel emissions. Fifth, there may be a requirement to manage forest to moderate the effects of climate change on non-timber resources such as wildlife habitat, biodiversity and domestic water supplies.

Forest managers have many tools at their disposal to assist forest ecosystems in mitigating and adapting to climate change. These include: species/provenance control in both artificial and natural regeneration; improved density control in both natural and artificial regeneration; programmes of multiple thinning before final harvest; breeding programmes that attempt to improve the desirable traits of species to be regenerated, and preserve diversity within the gene pool of trees; systems of protection from fire, insects and diseases; maintenance of wildlife corridors; and inventory and forecasting tools for planning and scheduling of forest interventions. Given this broad suite of tools some forest managers believe that the degree to which forest managers will be able to cope with adverse impacts of climate change on the forests will be directly related to the current and future intensities of management [10]. This may be true, however, these same tools if used unwisely or without a good knowledge of the biophysical implications and feedbacks could exacerbate the potential implications of climate change.

There are many things forest managers can do to mitigate potential unwanted effects of climate change on forests. For example, to counter prematurely reduced productivity and increased mortality associated with forests in decline, managers could develop and use more appropriate planting stock; carefully match species and sites in regeneration programmes; more closely control density through thinning; and, harvest declining stands first. Increased problems with insects, diseases and fire will require increased protection and forest redesign to reduce vulnerability to these agents. At the same time harsher environmental conditions for establishing new stands will call for more careful harvesting and regeneration silviculture. As well, forest planners will need to gauge carefully where forests are likely to have to give way to other natural plant communities or agricultural use, and where they are likely to gain new importance and suitability as land cover.

The critical factor in managing climate change is our ability to predict the future. To do this we often use models and with the use of models lies uncertainty resulting from the assumptions upon which they are based. Our current knowledge of climatic and biological process makes predicting the future very problematic for several reasons. First, climate change itself is fraught with uncertainty [1]. Important bioclimatic parameters such as extremes in maximum and minimum temperature and the frequency, duration and distribution of drought, and other extreme events are not included or are very imprecisely defined in the current suite of model predictions. In defining a biological response to climate it is these sorts of climatic events that are often most important [5, 16]. Second, we are deficient in our understanding of the environmental factors, processes and interactions that limit the distribution and range of various forest tree species [10, 75, 5, 68, 17]. Consequently, we cannot predict individual species or stand response with any certainty because we have not defined the important abiotic parameters and, in most cases we do not have the capability to sufficiently model these parameters. Third, disturbance regimes that play important roles in ecosystem dynamics and function including fire, insects and disease, severe storms and drought, and more recently human harvesting are poorly understood [65, 6]. How changes in frequency, duration or intensity of these disturbances will affect future forests in response to a changing climate is even more uncertain. Finally, little is known about the biophysical feedbacks of the forest on the climate system [1]. As the climate warms in the future and forest biomes begin to change will these changes further accelerate the warming, or slow it down? How will our management practices be affected or affect these changes? With our present state of knowledge we do not have the ability to answer these questions with any degree of confidence. As a consequence we cannot rule out major surprises which may mitigate or exacerbate potential changes.

Given the uncertainties associated with climate change, forest managers are largely planning for the unknown -they have an idea of what to expect but don't know precisely what changes are going to take place, where they will take place, or the rate at which the changes will occur. As a means of planning for climate change Spittlehouse [16, 17] suggests that policy makers and forest managers need to accept that change is probable and that responses can be developed. Incorporating responses into forest management planning requires they:

- Identify the issue of concern and the degree of change in forests that would be considered a serious problem.
- Determine the sensitivity of forests to changes in climate, and the impacts of potential future climate changes-
- Develop management responses that include actions to be taken in the future, and actions required now to facilitate future response. It is important to be able to simulate these responses and to include them in the assessment of climate impacts. This is a means to test and to improve these adaptive responses before they have to be tried in real life. This process would also provide more realistic impact assessments.
- Monitor forests to determine if changes are taking place, and if thresholds for intervention have been reached. This is perhaps the most important, but least likely to be adequately funded, activity.

Global climate model simulations can be used as a guide when defining the problem, e.g., what will happen if the future climate is warmer and drier. Given such a scenario, the management concern is what to do after disturbances such as harvesting, fire, disease, or a drastic productivity reduction have occurred. These disturbances provide an opportunity for adapting the forest to the new climate. Decisions must be made as to which changes can be managed and which must be left to nature to work out.

Current and future preparation must ensure that research provides information that will help in managing for climate change. Genetic variability of tree species needs to be evaluated in terms of the climate of the seed source and the climate of provenance trials [76, 77]. The ecological limits of species in managed (limited competition) and unmanaged situations needs to be determined. Process-based models should be used to assess ecosystem sensitivity to changes in climate, and they should be linked to ecological models that account for such factors as inter-species competition and tree death. The models should be based on short time steps because plants and animals respond to day-to-day weather conditions not average annual conditions. We should be assessing impacts of changes in intensity and frequency of extreme events, e.g., repeated years with summer drought [16].

CONCLUSIONS

The IPPC Second Assessment Report [2] concluded that the boreal forest will probably be more affected by climate change than temperate and tropical forests. Over the next century, conditions suitable for boreal ecosystems will migrate northward into areas currently suited to sub- arctic and tundra ecosystems. At the same time the climate at the southern edge of the boreal will change to conditions more suited to temperate forests and grasslands. In responding to current climate projections the boreal forest is expected to shrink considerably from its present size. Climate change is also expected to affect many of the features contributing to the functioning of boreal ecosystems. Growth and regeneration will be affected -in some areas it will increase while in others it will decrease. As well, natural disturbances related to fire and insects, which the boreal depends on for its health and survival, are expected to increase significantly and play a considerable role in ecosystem changes. However, the timing, location, and rate of projected changes remain very uncertain. As well, the potential benefits of elevated CO_2 in terms of increasing growth and productivity and mitigating potential undesirable effects remains inconclusive.

Boreal ecosystems appear to be responding to climate changes over the last century. A receding permafrost zone, and a noticeable warming in permafrost temperatures have been observed in forest and tundra regions. More recently an increase in vegetation productivity between 45 and 70 degrees north has been detected in conjunction with the improvement in seed production by boreal tree species along the northern boreal tree line. Disturbances related to fire also appear to have increased in the boreal although there is a fair degree of uncertainty with data prior to 1970. Accelerated phenological development in spruce budworm has also been detected. These responses to past climate changes are consistent with predictions of responses to future climate change due to global warming. Whether the observed climate changes in the boreal regions are the result of natural climate variability or anthropogenic climate change, are short or long term in nature, is unknown.

In determining and evaluating the implications of climate change on forests and the forest sector, it is not the doubled greenhouse gas or CO_2 equivalent scenario that is critical, but rather the climatic transition that will occur in getting to a that level. Forest managers have many tools at their disposal that will enable them to mitigate some of the unwanted impacts of climate change projected for the forest and forest sector and adapt to others that are more desirable. Many actions for responding to climate change are already part of ongoing forest management. Action required now in preparing for pending climate change is deciding the degree of change in the forest that constitutes a problem, determining and testing possible solutions, and initiating monitoring programs to determine when intervention is required. Our knowledge and understanding of forest ecosystem processes and how they interact with the physical climate system is crude. Improved knowledge is required to guard against unforeseen events or surprises. We must also be aware that our forest management practices have the potential to magnify and exacerbate potential unwanted effects of climate change if they are not carefully designed. Research is needed to identify species and forest areas at greatest risk, and to better quantify the eco-climatic limits and sensitivity of commercial and unmanaged species. Impact analysis should be done using physiologically based models with short time steps, and should determine the impact of changes in intensity and frequency of extreme events.

Ultimately, our ability to aid the boreal forest to adapt to climate change depends on improving our knowledge and understanding of the biological functioning of forests. This can then be used to develop well planned and timely action by forest managers. However, society will have to revise its expectations of and demands on the boreal forest.

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