The adaptive capacity of forest management to changing fire regimes in the boreal forest of Quebec

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ABSTRACT

Climate influences natural processes at multiple spatial and temporal scales. Consequently, climate change raises many challenges for sustainable forest management; among them, the integration of fire and forest management is increasingly discussed. We propose here an evaluation of the adaptive capacity of forest management under changing forest fire regimes under climate change in the boreal forest of Quebec. Adaptation begins by reinterpreting current practices dealing with climatically driven variability. Among them, fire suppression, and regeneration enhancement can contribute to coping with some impacts of climate change. However, there is an increasing need to develop more integrative and spatially explicit management strategies to decrease the vulnerability of forest management to changing fire risk. Some developing management strategies, such as fuel management or the triad approach (zoning system for conservation, intensive, and extensive forest management), present an interesting potential for integrating the fire risk in management plans. While fuel management and fire suppression are indicated for particularly severe fire regimes, protection against insects, and maintaining a shorter disturbance cycle using forest management represent the preferred adaptation options where the fire cycle is lengthening under climate change.

Key words: forest fire, fire risk, climate change, vulnerability, impacts, adaptation strategy, adaptation options, sustainable forest management, fire management

RÉSUMÉ

Le changement climatique pose de nombreux défis pour l'aménagement forestier durable car le climat influence les processus naturels à de multiples échelles spatiales et temporelles. Parmi ces enjeux, l'intégration du risque de feu à l'aménagement forestier est de plus en plus discutée. Nous proposons ici une évaluation de la capacité adaptative de l'aménagement forestier aux changements de régimes de feu sous l'influence du changement climatique en forêt boréale au Québec. L'adaptation commence par une réinterprétation de certaines pratiques forestières courantes qui traitent déjà de la variabilité climatique. Parmi elles, la suppression des feux et l'amélioration de la régénération peuvent contribuer à atténuer certains impacts du changement climatique. Cependant, il y a une demande grandissante pour des approches plus intégratives et spatialement explicites afin de diminuer la vulnérabilité de l'aménagement forestier face aux changements du risque de feu. Certaines stratégies en développement, comme l'aménagement du combustible et l'approche et de la triade (système de zones de conservation, d'aménagement intensif et extensif) présentent un potentiel intéressant pour intégrer le risque de feu à la planification forestière. Alors que l'aménagement du combustible et la suppression des feux sont indiqués pour les régimes de feu particulièrement sévères, la protection des forêts contre les insectes et le maintient d'un cycle de perturbation plus court par l'aménagement forestier sont des options d'adaptation privilégiées lorsque le cycle de feu s'allonge sous l'influence du changement climatique.

Mots clés : incendies forestiers, changement climatique, vulnérabilité, impacts, stratégie d'adaptation, options d'adaptation, aménagement forestier durable, gestion des feux

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Introduction

Numerous assessments of climate change impacts (e.g. Saporta *et al.* 1997, Colombo *et al.* 1998, Forget *et al.* 2003) and sensitivity studies (e.g., Singh and Wheaton 1991, Lenihan and Neilson 1995, Johnston 2001) have been carried out all across the North American boreal forest; however, few adaptation options have been detailed and no comprehensive adaptation assessment has been proposed for the forestry sector. That said, reviews about adaptation for forest management typically recommend different options to reduce vulnerability of managed forests to climate change (see Dale *et al.* 2001, Wheaton 2001, Spittlehouse and Stewart 2003). Some adaptation options are current management practices that can be modified, while others involve practices that specifically address climate change consequences. An adaptation assessment is thus likely best initiated by a reinterpretation of current forest management practices with a focus on their climate change implications (Spittlehouse and Stewart 2003). In this paper, forest fires are the context in which we evaluate the adaptive capacity of forest management to a particular climate change vulnerability.

The adaptive capacity of a particular system to climate change is its potential or capability to adapt to climate change stimuli, effects or impacts (Smit and Pilifosova 2001). Here, the system of interest is the forest management of Quebec and its potential vulnerability to climate change related to forest fires. Boreal forests have disturbance-based dynamics, and post-disturbance recovery depends on the composition and age of managed forests, as well as on the severity and return rate of the disturbance. Altered disturbance and forest productivity are the main vulnerabilities to climate change that foresters will have to face (Johnston 2001). Adaptation refers to a variety of responses aimed at reducing adverse impacts or at taking advantage of opportunities created by novel conditions related to climate change (McCarthy *et al.* 2001). Fundamentally, adaptation depends on the vulnerability of a system to the climatic conditions. The vulnerability is the "degree at which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes." (McCarthy *et al.* 2001). It depends on the nature and magnitude of the climatic change (exposure), the susceptibility of the system to this climatic change (sensibility), the socio-economical characteristic of the system, and the ability of the system to adjust to climate change (adaptive capacity) (Füssel and Klein 2002). Therefore, the adaptive capacity of forest management to climate change hinges not only on the scientific and technical knowledge available, but also on the social, economical, and political components associated with the implementation of the different adaptation options (Yohe and Tol 2002).

The purpose of this paper is to review adaptation options and to evaluate the adaptive capacity of forest management to changing fire regimes in the boreal forest of Quebec . First, we briefly explain why forest fires constitute a vulnerability to climate change for forest management. Then, we propose an assessment of different adaptation options for forest management concerning forest fires. Finally, the adaptive capacity of forest management is evaluated for both an increase and a decrease in the fire activity under current and future climate change. This evaluation is a first step towards the evaluation of the global adaptive capacity that must integrate all the other vulnerabilities, including other natural disturbances and socio-economical components. This paper is limited to the forest fire issue and to the technical ability based on our current comprehension of how fire could affect forest management in the context of climate change.

Forest Fires as a Vulnerability of Forest Management to Climate Change

Climate change and forest fires

Climate change is typically presented as an increase in global mean temperature (0.6 ± 0.2°C worldwide) and precipitation (7–12% between latitudes 35° and 85°N) (Houghton *et al.* 2001). However, while natural and human systems are generally adapted to mean conditions, they are most sensitive and vulnerable to extremes or unusual variability in climatic conditions (Burton 1998, Parker *et al.* 2000). Climate change is now increasingly recognised as not only an increase in temperature and precipitation, but also as a change in variability and extremes. The relevance of this new perspective of climate change is of particular interest to the forest fire issue. In the Canadian boreal forest, only a small number of fires (3%) are responsible for most (97%) of the area burnt annually (Weber and Stocks 1998, Stocks *et al.* 2003). These few catastrophic fire events occur according to periods of drought, namely a few days with less than 1.5 mm of precipitation and relative humidity less than 60% (Flannigan and Harrington 1988). In the western boreal forest of Quebec, recent climate change has been associated with a reduction in drought frequency (Archambault and Bergeron 1993, Lefort *et al.* 2003). Dendrochronological studies suggest major changes in atmospheric circulation since the end of the Little Ice Age (LIA) (~1850) that are at the root of these changes over western Quebec: a shift involving less frequent upper level ridging likely contribute to the inclusion of more humid air masses (see Hofgaard *et al.* 1999; Girardin *et al.* 2004a, b). However, no trends in the drought conditions conducive to forest fires have been shown to date for the recent climate change in the different ecozones and ecoregions of the Canadian boreal forest (Amiro *et al.* 2004, Girardin *et al.* 2004b).

Concerning future climate change, General Circulation Model (GCM) simulations forecast an increase about 3–5°C and a slight decrease in precipitation (×0.9) under a 2×CO_2 scenario compared to the 1980–1989 time-period in Ontario and western Quebec (Parker *et al.* 2000). While a general increase in annual area burnt (Stocks *et al.* 1998, Flannigan *et al.* 2000) and an earlier start of the fire season (Wotton and Flannigan 1993) are anticipated across the Canadian boreal forest under future climate change, high variability at the regional scale characterises these trends. Under a 3×CO_2 climate change scenario, the annual area burned is anticipated to increase (by 1.7 to 2.2 depending on the GCM used) over the Boreal Shield ecoregion (Flannigan *et al.* in press). For Western Quebec, 2×CO_2 scenario anticipated a decrease or no change in the fire weather conditions (as calculated using the FWI, Flannigan *et al.* 1998, 2001), and a 3×CO_2 scenario predicted that the burn rate would decrease in the future (Bergeron *et al.* 2004a). These contrasting results highlight the importance of the spatial scale used for the projection in the future fire activity.

In the boreal forest, vegetation dynamics is primarily driven by fire regime (Flannigan and Wotton 2001), with second order factors being topography (Bessie and Johnson 1995) and fuel characteristics (Hély *et al.* 2000, Carcaillet *et al.* 2001). As a key process in the dynamics of boreal forests, fire notably influences biome boundaries (Payette *et al.* 1989, Bergeron *et al.* 2004b) and species range (Desponts and Payette 1992, 1993; Flannigan and Bergeron 1998; Asselin *et al.* 2003; Parisien and Sirois 2003). At a finer spatial scale, stand structure and composition are strongly influenced by fire interval (Larsen and McDonald 1998, Le Goff and Sirois 2004) and severity (Heinselman 1981). Conversely, fire activity across the Canadian boreal forest is characterized by important spatial variability, leading to several regional fire regimes. As fire activity depends mainly on climate, fire regimes may respond to current climate change as they did to past climate changes.

Vulnerability of forest management to changing fire regimes
Traditionally, forest management has taken place in forests with moderate fire regimes (fire cycle about 100 to 150 years). However, forestry operations are reaching northern forests, exposing forest management to new conditions of productivity and disturbance regimes, namely a shorter growing season and more severe fire regimes (MRNQ 2000, Bergeron *et al.* 2004a). To date, harvest scheduling takes into account existing fire regimes *a posteriori* by subtracting burnt timber volumes from the Allowable Annual Cut (AAC). However, the integration of fire risk (potential losses of timber supply related to forest fires) has been investigated since the 1980s (see Armstrong 2004 for a review). Forest fires have been found to have detrimental effects on wood supply (Martell 1994), and AAC targets are lower when forest fires are taken into account (Armstrong *et al.* 1999, Fortin *et al.* 2002, Armstrong 2004). Multi-scale influences of fire on forests under climate change are conducive to increasing probability of interference with industrial harvesting (MRNQ 2000, Wheaton 2001).

As we cannot alter the climatic and topographic control of fires, management actions are limited to the vegetation and ignition components. Basically, the few ways we can influence fire activity consist of preventive measures to avoid human-ignited fires, fire suppression, and management of forest structure and composition. More anticipative and integrative approaches must be developed to better prepare and adapt the forest industry to current and future climate change and variability. Natural disturbance-based management (NDBM) can contribute to the development of such an approach as it relies on an understanding of historical natural disturbance dynamics. The basic principle of NDBM assumes that management conducive to landscape compositions and stand structures that were historically created by natural disturbance regimes should also maintain biodiversity (Bergeron 2004).

The adaptive capacity of forest management strongly depends on the vulnerabilities to climate change of natural forests, managed forests, and forest industry (Leduc *et al.* 2004). In this respect, fires represent a major way by which climate change and variability affect forests, perhaps even more so than the direct effects of climate change on productivity and composition (Weber and Flannigan 1997). In Quebec, the northern limit of boreal forest has experienced several southward fluctuations because of the combined action of fires and climate variability (Payette and Gagnon 1985). The natural (unmanaged) forests of Quebec are situated above the northern limit of commercial forests and below the southern limit of the forest-tundra. Their northern location implies distinct vegetation types and environmental pressures: the northern climate imposes a shorter fire season, insects outbreaks are rare, and fire regimes are more severe (MRNQ 2000). Managed forests differ from coniferous natural forests to the north by their structure (more fragmented, more accessible) and composition (more deciduous, with a high proportion of mixedwood stands). All forests under management belong to the intensive fire management zone, where all fires are actively attacked. As post-harvest regenerating stands have increasing balsam fir (*Abies balsamea*) and trembling aspen (*Populus tremuloides*) components, they would be more vulnerable to insect outbreaks associated with these species. Managed forests are usually considered as having a better adaptive capacity to climate change because they are younger and planned adaptation can be implemented through forest management (Binkley and van Kooten 1994, Spittlehouse and Stewart 2003). However, younger forests will face specific vulnerabilities to climate change as they are more sensitive to late frosts and summer droughts, and an increased fire risk could lead to more frequent regeneration failures (Payette and Gagnon 1985, Lavoie and Sirois 1998). In turn, managed forests face the cumulative impacts of climate change experienced by natural forests as well as the impacts of structural and compositional modifications related to forest management (Leduc *et al.* 2004).

Forest management has the potential to increase the adaptive capacity of managed forests through planned adaptation, but also has the potential to delay adaptation if management plans do not take into account the changes, risks, and uncertainties implied by climate change (Stewart *et al.* 1998, Papadopol 2000, Spittlehouse and Stewart 2003). Climate change, as well as sustainable forest management, implies a long-term view potentially conflicting with the short-term obligations of forest management. Year-to-year variations in climate and fire activity represent strong environmental risks for forest industry at short- and long-term scales. If climate change impacts cannot be avoided, forest management may at least influence their location, timing and rate by planning interventions that consider vulnerabilities to climate change (Spittlehouse and Stewart 2003).

Adaptation Options Assessment

Adapting forest management to climate change and variability can be viewed as sustainable forest management focused on climate change (Spittlehouse and Stewart 2003). In forestry, like in other sectors, many existing practices can be used to meet adaptation objectives (Klein and MacIver 1999, Spittlehouse and Stewart 2003). First, we reinterpret some current management practices, then we review developing approaches that present an interesting potential for adaptation linked to the forest fire issue (Table 1).

Modifying current practices

Fire management
Fire management was traditionally separated from forest management. However, one goes with the other in boreal forestry when considering the key role of fire in this type of forest. The integration of forest and fire management is

Table 1. Adaptation potential of current forest and fire management practices

Practice	Adaptation potential	Recommendation	Limits
Fire weather monitoring	High		None
Restrain human activities in forest	High		None
Fire suppression	Medium	Fire management	Costs, logistics
Salvage logging	Low	Restrained use Case-by-case evaluation	Mitigates only economic losses Ecological impacts
Post-fire regeneration enhancement	Medium	In intensive forest management areas	Excluded from conservation areas and stands with good natural regeneration
Prescribed burn	Low	For fuel and biodiversity management	Costs, logistics, risk of fire escape
Intensive forest management	High	To rationalize forest protection efforts	Biodiversity constraints
Extensive forest management	Low	Restrained use	Forest protection

underway in all Canadian provinces at a more or less advanced state. The main rationales driving this process are i) when included in the AAC, fire risk decreases the availability of timber supply (Armstrong *et al.* 1999, Fortin *et al.* 2002), ii) climate change generally implies an increase in fire activity at the national scale, and iii) fires are also viewed as a source of greenhouse gas (GHG) (Amiro *et al.* 2001). This latter point leads first to consider fire suppression as a mitigation measure to reduce greenhouse gas emission related to forest fires (Dale *et al.* 2001, Spittlehouse and Stewart 2003); however, under high fire frequency, this option could not be economically feasible nor ecologically desirable (Amiro *et al.* 2002).

In Quebec, fire management policy can be essentially described as preventive and curative measures. Preventive measures consist of monitoring the fire weather conditions by calculating the Fire Weather Index (FWI) System across forested regions. The FWI is a daily rating of fire risk calculated using temperature, precipitation, windspeed, and relative humidity (Van Wagner 1987). When FWI values are extreme, activities such as forest recreation and harvesting are restrained to prevent human-caused fires. This measure has a high potential as an adaptation option regarding forest fire because it is preventive.

The fire suppression effort is determined according to intensive and restricted fire management zones. The intensive fire management zone covers essentially all managed and inhabited forests. In this zone, all fires must be controlled before they reach 3 ha. The restricted management zone covers all remaining remote forest territory. In this zone, fires are allowed to burn under monitoring, except when they threaten human settlements or infrastructure. Fire suppression is often recommended as an adaptation option to decrease the loss of timber due to forest fires (Krankina *et al.* 1997, Parker *et al.* 1998, Dale *et al.* 2001, McKinnon and Kaczanowski 2004). However, suppression has many logistical, economic, and ecological limitations (Hirsch *et al.* 2001, Chapin *et al.* 2003) that compromise its potential for adaptation (Wheaton 2001). Spatial variability in fire activity challenges the binary approach of letting fire burn or not. For example, the different fire regimes distributed across the intensive fire management zone (MRNQ 2000, Bergeron *et al.* 2001, Lefort *et al.* 2004) do not all imply equivalent suppression efforts. Even with high suppression efforts, about 3–4% of fires escape (McAlpine and Hirsh 1999), suggesting that suppression can reduce the number and size of fires under moderate climatic conditions, but cannot stop large fire events under extreme fire weather (Larsen 1997, Campbell 1999, Schneider 2000, Drolet 2002).

Another limitation concerns the ecological role of fire in the dynamics of boreal forests, because suppressing all fire implies the exclusion of their ecological benefits to forests. Fire rejuvenates stands and maintains fire-dependant species such as jack pine (*Pinus banksiana*). These limits suggest that "the challenge is not anymore to exclude fires, but rather to know when, where and how to limit socio-economical damage from wildfires" (Hirsch *et al.* 2001). The binary fire management approach must be replaced by a refined zoning system of intervention that depends on commercial, economic (stands currently harvested or scheduled for harvest), and social values, and on the accessibility of burning stands. In Ontario, an intermediate fire management response is planned in the measured management zone, situated at the northern limit of the current commercial forest and representing future timber reserves. In this management zone, fires that escape initial attack can be intensively attacked, limited, or let burn depending on the situation (Martell 2002a). This option leaves room for a compromise between economic priorities (future timber reserves, suppression costs) and the ecological benefits of fire. In remote or unscheduled forest areas, fires could be allowed to burn under surveillance to promote biodiversity associated with post-fire stands and ecosystem resilience to fire recurrence (Spittlehouse and

Stewart 2003). The change from fire suppression to fire management is under discussion in Quebec (Drolet 2002), and can feed the development of a global adaptation strategy for forest management.

Fire management typically operates before and during a forest fire. After a fire, forest managers face timber losses and regenerating stands. This necessitates interventions such as salvage logging and regeneration enhancement to mitigate negative impacts of fires on timber supply.

Salvage logging

Fires can decrease timber supply and increase the costs of timber harvest by modifying forest planning and harvest scheduling (Martell 2002b). Quebec's Forest Act prescribes a special plan specifying post-fire harvesting in cases of major losses due to fire (Quebec Government 2004). When fire is anticipated to increase under climate change, salvage logging is often recommended to mitigate loss of timber volumes due to fire (e.g., Papadopol 2000, Spittlehouse and Stewart 2003). While this practice is already used in forest management in Quebec, it raises many debates about tradeoffs between economic benefits and impacts on ecosystems and biodiversity (see Nappi *et al.* 2004).

At the operational level, salvage logging requires important road building and specific equipment use (Patry 2002) that makes its economic benefits questionable without government assistance. Salvage logging after fire acts as an additive disturbance (Kurulok and McDonald 2004, Lindenmayer *et al.* 2004) that occurs during a critical phase of ecosystem development. The decreased thickness of forest soil makes it particularly sensitive to additional disturbance by timber equipment (Brais *et al.* 2000). Several wildlife and biodiversity concerns are highlighted by recent research. Salvage logging decreases the availability of nesting sites for cavity and canopy nesting birds (Nappi *et al.* 2004), and probably the abundance of prey for insectivore birds (Morissette *et al.* 2002). Salvage logging simplifies biodiversity in ground vegetation (Kurulok and McDonald 2004, Purdon *et al.* 2004).

Salvage logging, which must take place in the few years following fire to ensure the commercial quality of wood fibre, contrasts starkly with the careful planning usually required for forest operations. Salvage logging is a post-fire management practice, but it could gain substantial efficiency if treated as a risk management approach that anticipates and elaborates salvage strategies before a fire occurs (Lindenmayer *et al.* 2004). From an adaptation perspective, salvage logging has restricted applicability since several limits are associated with its current implementation.

Regeneration enhancement

Regeneration enhancement has been proposed to improve forest recovery after disturbance (Parker *et al.* 2000, Dale *et al.* 2001, Wheaton 2001, Spittlehouse and Stewart 2003). Enhancement of regenerating stands consists essentially of modifying their structure and composition to accelerate stand recovery and succession by planting of carefully chosen species and thinning (Dale *et al.* 2001). Planting well-developed seedlings can reduce the regeneration phase by five to 10 years (Kurz and Apps 1995). As these practices accelerate stand development, they also accelerate fixation of atmospheric carbon and were thus first presented as mitigation options (Papadopol 2000, Parker *et al.* 2000). Regeneration enhancement involves a range of silvicultural practices that may be adapted to a diversity of ecological, social, and economic situations. These practices can further develop intensive forest management and form part of an adaptation strategy to cope with new fire risk.

Prescribed fires – managing fuel accumulation

Prescribed burning consists of fire "intentionally ignited for the purpose of achieving a clearly defined management objective" (Carter and Foster 2004). Management objectives include (a) reducing the risk of severe fires, (b) site preparation for regeneration enhancement, (c) restoring fire-dependant species or communities in areas where fire was systematically excluded (Weber and Taylor 1992, Hesseln 2000), and (d) maintaining seral stage vegetation for wildlife habitat.

Thus, prescribed fire may be used to alter the structure (fuel load, fuel continuity, or stand age distribution across a landscape) or composition as fire recurrence can influence the relative proportion of coniferous and deciduous species. The use of prescribed burns to reduce the risk of severe fire constitutes an adaptation option, as this can decrease the vulnerability of fire-prone forests to extreme climate variability. Mainly developed in western Canada and United States, prescribed fire is used only marginally in Quebec. Since 1990, Parks Canada sets prescribed fires to decrease understory competition and favour the regeneration of white pine (*Pinus strobus* L.) in the La Mauricie National Park (Queneville and Theriault 2002). The use of prescribed fire is restricted to conservation areas, as it is generally accepted that escaped fires present less serious consequences in conservation areas when compared to other land use designations. Because of the associated risk of fire escape and its difficult logistics, this practice is quite restricted across Canada. The first step in an adaptation context is evaluating the feasibility and relevance of prescribed fire to reduce the risk of severe fire in wilderness areas, as well as in areas where fuel build-up results from the fire suppression. Since fuel built-up does not likely represent an important issue in the boreal forest of Quebec (Hély *et al.* 2000), prescribed fire in Quebec is probably best restricted to conservation purposes as compared to other Canadian boreal forests. The adaptive capacity associated with prescribed burns greatly depends on a case-by-case evaluation.

Developing integrative approaches

Natural disturbance management

The natural disturbance-based management (NDBM) approach uses forest management to reproduce the structural and compositional variability resulting from natural disturbance regimes (Hunter 1993, Bergeron 2004). This coarse filter approach assumes that maintaining the natural diversity of habitats will maintain natural biodiversity (Adamowicz and Burton 2003). NDBM aims at the emulation of different attributes of natural disturbance regimes (severity, rate, spatial pattern, temporal pattern, etc.). For example, the rate of disturbance can be interpreted as the proportion of the area disturbed by fire or harvesting over a given period at the landscape scale, but can also be interpreted as the proportion of trees killed by fire or harvested at the stand scale. As fire reduces timber supply (Fortin *et al.* 2002), a sustainable AAC could be set as the difference between the average disturbed area with and without fire suppression (Armstrong *et al.* 1999, Bergeron 2004). These calculations are one way to integrate fire risk into forest management with respect to the natural resilience of forest ecosystems. Here, the natural resilience is defined as the capacity of the forest ecosystem to return to the structure and the composition prevailing before the disturbance. NDBM presents an interesting adaptation potential for forest management as it relies on the properties of the forest ecosystem. In the perspective of climate change, this approach could facilitate spontaneous adaptation of forest ecosystems to climate variability and change, and would be particularly indicated where forest management pressures are relatively low (extensive forest management areas).

Fuel management

Fuel management has been primarily developed in Alberta to control the landscape fire potential where mixedwood boreal forest is submitted to fairly severe fire regimes (fire cycles about 50 years) (Hirsch *et al.* 2001, Kafka *et al.* 2001). The alteration of fuels through forest operations can decrease their connectivity across a management area by the spatial repartition of cutblocks as well as decrease their flammability by replacing conifer stands with less flammable deciduous stands (Hély *et al.* 2000). Moreover, access roads for harvest operations may be designed as firebreaks and to increase accessibility for fire suppression. These practices, intended to decrease the fire potential of landscapes, are the principles behind the Fire-Smart landscape management (Hirsch *et al.* 2001, Kafka *et al.* 2001). However, this management approach is restrained to boreal mixedwood forests, and cannot be applied to cope with intensive fire regimes in managed northern coniferous forests. Additionally, an ecosystem management approach must be used to identify and mitigate fragmentation of wildlife habitat when modifying the fuel connectivity. Fire-smart management has good potential for adaptation as it already integrates several practices dealing with fire risk and post-fire management (Johnston 2001, McKinnon and Kaczanowski 2004). Its transferability from western boreal forest to eastern boreal forests must be evaluated, particularly with respect to the capacity of the deciduous component to support fire-smart management in the boreal forest of Quebec.

Spatially explicit forestry

In sustainable forest management, the spatial distribution of cutblocks should be a compromise among timber values, road building and habitat fragmentation. The triad approach was proposed to maintain timber values while maintaining non-timber values such as biodiversity. Basically, the triad approach distributes land in space and time according to a zoning strategy where extensive management is restrained to specific areas instead of being applied systematically across the managed area (Seymour and Hunter 1999, Andison 2003, D'Eon *et al.* 2004). Thus, three land uses are distributed across the managed forest: areas for conservation of biodiversity and wildlife habitat that exclude timber harvest, intensive management areas, and extensive management areas with multiple use objectives. With respect to fires, extensive forest management is more vulnerable to climate change than intensive forest management. A large territory with little or temporary road access is more difficult to protect from fire than a reduced area with many well-maintained roads. The triad approach proposes to focus a smaller part of the landbase on very intensive forestry, thereby maintaining high timber flow while increasing the amount of area under "ecosystem management" or extensive forestry. As the triad approach implies intensive and extensive forest management areas inside a management unit, protection efforts against fire must be determined by investment priorities. In this perspective, fire protection must be first aimed at intensive management areas and to future stocks in extensive management areas. The triad approach implies then a spatially explicit fire protection policy across the management unit. This highlights the importance of integrating fire risk to forest management at the local scale, principally through maps identifying stands that warrant first protection. The triad approach can then contribute to reduced vulnerability to fire and holds good potential for adapting our forest management under moderately severe fire regimes (100-year fire cycle).

The Adaptive Capacity of Forest Management to Changing Fire Risks

Even without considering climate change, forest planning implies management of many risks and uncertainties (Kangas and Kangas 2004). Integration of climate change in forestry is strongly amenable to an approach of risk management or at least as risk analysis by forest managers and planners (Hengelveld 2004, McKinnon and Kaczanowski 2004). Unfortunately, risk analysis is still rare in forest planning (von Gadow 2000). While adaptation must be designed for local scales, anticipated climate change has greater uncertainties at this scale than at larger scales regarding the timing, location, and rate of impacts (Burton 1998). Climate change will entail increases or decreases in fire activity in different parts of the Canadian boreal forest (Flannigan *et al.* 1998), and even inside the same ecozone (Bergeron *et al.* 2004a). Although the pattern of these responses cannot be anticipated with confidence at a regional scale, the adaptive capacity of forest management is evaluated below for both increases and decreases in fire activity.

Increased fire activity

Despite important regional variation, a general increase in the annual area burnt across Canada has been documented for the last decades (Van Wagner 1988; Skinner *et al.* 1999, 2002; Stocks *et al.* 2003, Gillett *et al.* 2004). Under higher fire frequency, forest management would contribute to moving even more forest-age distribution across younger age-classes by competing with forest fires for mature stands (Bergeron *et al.* 2004a). Biodiversity concerns already exist about old-growth forests, as they are principally targeted for harvest and support rare wildlife and biodiversity communities. Under this fire scenario, fire and industry compete for mature stands and this competition increases the probability of interference between these two disturbances. Repeated disturbances at the same location (i.e., salvage logging or fire in recently harvested stands) can result in regeneration failure or in lower AAC by burning stands scheduled in forest management plans. Under this scenario, interactions among management and other disturbances such as droughts, insect outbreaks and diseases must also be considered (Johnston 2001).

Under this scenario, the adaptation options most recommended in the literature are to increase suppression effort, salvage logging, and regeneration enhancement. Suppression

Table 2. Adaptation scenarios in the triad approach

Fire risk	Forest management areas		
	Intensive	Extensive	Conservation areas
Increase	Forest protection (fire) Regeneration enhancement Fire-smart management Integrate the fire risk in the annual allowable cut (AAC) calculations	Fire-smart management	Fire suppression to protect old-growth forests
Decrease	Sustainable forest management	Forest protection (insects)	Prescribed fire to maintain pyrophilous biodiversity

capacity would probably not cope with an intensified fire regime (Wheaton 2001). When considering the logistics and ecological limitations associated with these adaptation options, these efforts must be rationalized by a specific management strategy. Such a strategy could start from a map of timber reserves that must be first protected from fire. If fire risk is taken into account in the AAC *a priori,* unplanned losses of timber supply will become calculated risks. These anticipated losses could be compensated using intensive forest management approaches such as fast-growing plantations. Under this scenario, forest operations can be used to manage fuels in intensive and extensive management areas, and the triad approach may provide a spatial framework for an integrative forest and fire management strategy (Table 2).

The anticipated increase of fire activity under climate change concerns lightning-caused fires (Price and Rind 1994) as well as people-caused fires (Wotton *et al.* 2003). People-caused fire can be limited by preventive measures such as curtailing operations and other human activities during periods of extreme fire weather. This curtailment will obviously also affect forest management by delaying timber harvest during seasons of extreme fire weather or heavy fire years. This suggests the importance of integrating fire risk and its potential consequences on timber harvest. Under this scenario, preventive measures are a crucial part of forest and fire management. This approach presents a particularly interesting adaptation potential, as it could contribute to mitigating the limitations of fire suppression capacity.

Decreased fire activity

This scenario has been suggested by dendroclimatological studies in western Quebec (Archambault and Bergeron 1993) and some GCM projections suggest that this trend could persist under future climate change (Flannigan *et al.* 1998, 2000, 2001; Bergeron *et al.* 2004a). If fire activity is decreasing under climate change, the vulnerability of forest management concerning forest fire is lowered. In this situation, the opportunity for forest management to maintain a targeted age class distribution across the landscape must be considered (Bergeron 2004, Bergeron *et al.* 2004a). The targeted distribution can consist of a younger age class distribution than that resulting from fires alone. However, the evaluation of such an opportunity must take into account other natural disturbances also modified by climate, as well as biodiversity concerns regarding pyrophilous communities. If management does not maintain the historical disturbance cycle, the mean forest age could considerably increase and allow other disturbances such as insect outbreaks, diseases, and pathogens generally associated with older forest age class distributions. Insects, pathogens, and exotics are anticipated to expand northerly under climate change because of the northern migration of favourable conditions. In particular, outbreaks of insects such as spruce budworm (*Choristoneura fumiferana* (Clem.)) can gain in importance as the mean forest age increases (Fleming *et al.* 2002).

In the short term, this situation seems less difficult to manage; however, the long-term benefits are highly questionable. This impact scenario is not investigated in the adaptation literature, probably because it is perceived as less problematical for forest management. However, major long-term impacts are poorly known; thus, the sustainability of forest management under this scenario cannot be guaranteed. If fire decreases enough, other disturbances — like insect outbreaks — may drive forest dynamics. Also, in this case, the triad approach could provide a framework to better control insect outbreaks, since the outbreaks would be more easily manageable over restricted areas of concentrated forest management (Table 2). To conserve fire-dependent communities, fires must be allowed to burn in conservation areas where forest management is excluded and prescribed fire may be used to restore these communities.

Adapting forest management to climate change: the challenges

Even if both scenarios of future fire activity are still debatable in term of location and timing, the undeniable vulnerability that forest fires represents for boreal forest management encourage taking actions now. The most frequent and still recurrent reproach made about adaptation is that accurate strategies cannot be well designed before impacts are known with a certain (high) level of precision. This criticism is especially salient at the regional scale, which is the scale most relevant to designing adaptation strategies (Burton 1998) and, unfortunately, at which most projections of future climate suffer from a high level of uncertainty. That said, climate change is currently underway and has already modified boreal fire regimes (Flannigan and Van Wagner

1991, Flannigan *et al.* 1998). The precautionary principle advocates that adaptation has to be undertaken to limit damage to forest resources and to prepare forest management under future climate change by increasing its capacity to cope with potentially harmful change (Spittlehouse and Stewart 2003). By lowering its vulnerability to current climate variability and change, forest management would be better prepared to adapt to future climate change (Smit *et al.* 1999).

While human and natural systems will undoubtedly adapt spontaneously to gradual climate change, only human systems can have planned adaptation strategies (Smit and Pilifosova 2001). Planned adaptation is a structured process stretching from the definition of the system to be adapted and to what it must be adapted (Smit *et al.* 2000), to the analysis of the social adaptive capacity and the policy will for adaptation (Füssel and Klein 2002, Yohe and Tol 2002). Adaptation, like any other forest intervention, should be carefully planned; since planning adaptation requires lots of time, it should not be postponed until impacts occur (Klein and MacIver 1999, Dale *et al.* 2001, McKinnon and Kaczanowski 2004). This paper synthesizes the technical component of adapting forest management to changing fire risk, and raised many economical, social, and political questions associated with the implementation of the adaptation options presented here. In particular, there is still a lot of work remaining to inform the public and the decision-makers about this issue in order to prepare our society to the changes that will become more and more necessary. Forest policy will have to integrate the climate change issue and encourage adaptation (Parker *et al.* 2000, Burton *et al.* 2002, Spittlehouse and Stewart 2003). A substantial part of adaptation concerns the institutional and political barriers that should be rapidly identified and addressed to allow an effective adaptation strategy to step forward before climate change impacts become unmanageable.

Conclusions

Only areas under management can be submitted to an active adaptation strategy. Large forested areas will be impacted by climate change and will respond by autonomous adaptations. Boreal forests will be particularly affected by climate change and major anticipated changes highlight the ecological, social and economic limits of this resource. As most forested areas will adapt autonomously to climate change, society will have to adapt its demand, and a major social adaptation will be revising expectations of the forest resource (Spittlehouse 1997).

The key to adaptation to climate change in boreal forests with respect to fire lies in the integration of forest and fire management. Adaptation to climate change and sustainable forest management share some common concepts: both rely on natural forest dynamics and their development and implementation necessitate an adaptive approach. Climate change is currently ongoing without the impact and recovery processes being fully understood. Climate change may trigger increases as well as decreases in fire activity, and these impacts can vary widely (Chapin *et al.* 2004) even in the same ecoregion (Bergeron *et al.* 2004a, Lefort *et al.* 2004). Thus, forest management must be prepared for both situations. Given the considerable uncertainty about the impacts of climate change and efficacy of various adaptation actions, a useful adaptation strategy requires a learning framework such as adaptive management (Wheaton and MacIver 1999, Houghton *et al.* 2001, Burton *et al.* 2002). Integrative approaches such as the triad approach have high potential for the development of an adaptation strategy because they integrate the vulnerability of forest management and the vulnerability of other systems linked to forest such as conservation areas, which will play a key role in ecosystem management under climate change.

Adapting forest management to recent and current climate variability and change constitutes one of the best avenues to investigate adaptation to future climate change. This adaptation assessment constitutes a first step towards the evaluation of the global adaptive capacity of forest management to climate change in Quebec. However, the forest management community in Quebec will face many challenges to implement adaptation to current and future climate change.

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