UNIVERSITÉ DU QUÉBEC À MONTRÉAL

L'INFLUENCE DE LA VARIABILITÉ CLIMATIQUE RÉCENTE ET FUTURE SUR L'ACTIVITÉ DES FEUX DANS LA RÉGION DE WASWANIPI (QUÉBEC) ET SES IMPLICATIONS POUR L'AMÉNAGEMENT FORESTIER DURABLE

THÈSE
PRÉSENTÉE
COMME EXIGENCE PARTIELLE
DU DOCTORAT
EN SCIENCES DE L'ENVIRONNEMENT

PAR

HÉLOÏSE LE GOFF

Août 2009

REMERCIEMENTS

Je remercie Mike Flannigan et Yves Bergeron pour leur infinie patience et leur soutien continu tout au long de ce projet. Je remercie le Réseau de Gestion Durable des Forêts qui a contribué en grande majorité au financement de ces recherches.

Je remercie la myriade de personnes, croisées brièvement ou plus longuement, et qui ont eu le bon mot au bon moment: Marc Parisien, Luc Sirois, Patrick Béron, Adam Ali, Domique Berteaux, Venceslas Goudiaby, Jean-Claude Ruel, Carole Guérin, Jacques Tardif, Louis de Grandpré, France Conciatori, Sophie Gachet, Marilou Beaudet, Sylvie Gauthier... et tous ceux que qui m'ont aidée sans que je ne l'aie vraiment réalisé.

Merci à Danielle Charron et à Luc Lauzon pour tous les tracas administratifs et logistiques résolus avec bienveillance. Merci à Daniel Lesieur pour ses promptes réponses à mes innombrables questions. Merci à Ouranos pour les séminaires Impacts et Adaptation, auxquels j'ai assisté et présenté mes travaux de synthèse, mais aussi pour avoir fourni les données du Modèle Régional Canadien du Climat (un merci particulier à Daniel Houle et à Travis Logan). Fréquenter ce haut lieu d'innovation et de recherche a été particulièrement stimulant pour mon cheminement de doctorat. Je remercie Kim Logan, Alan Cantin et Lynn Gowan pour leur précieuse aide lors de l'analyse des données du Modèle Régional Canadien du Climat et des calculs de l'Indice Forêt-Météo. Je remercie également Rémi Saint-Amant pour avoir fourni les données météorologiques historiques.

Je remercie les nombreuses personnes qui m'ont aidée sur le terrain et en laboratoire pour la collecte et l'analyse des données dendrochronologiques: Daniel Lesieur, Benoît St-Vincent, Stéphane Valois, Steve McLaughlin et David Beauregard.

J'adresse un remerciement tout spécial à Sylvie Gauthier, qui m'a généreusement accueillie au Centre de Foresterie des Laurentides depuis 2005, ainsi qu'à ceux qui partageaient mon quotidien dans cet environnement de travail stimulant: Louis De Grandpré, Martin Girardin, Jacques Morissette, Dominique Boucher et Marie-Andrée Vaillancourt.

Je remercie mes compagnons de route Martin Girardin, Karelle Jayen, Dominic Cyr et Catherine Boudreault. Nous avons souvent échangé sur les difficultés et les victoires qui nous étaient communes, vous êtes donc particulièrement bien placés pour saisir tout ce que cet accomplissement signifie pour moi.

Merci à ma famille outre-mer, vous avez su rester proche de moi et me soutenir même si cette aventure pouvait vous paraître abstraite et éloignée de votre quotidien.

De Winnipeg à Montréal, pour terminer notre route à Québec, avec Maël et deux chats, je te remercie Martin pour ton soutien et ton amour aux cours de ces longues années de thèse.

AVANT-PROPOS

Cette thèse est composée de quatre chapitres qui correspondent à quatre articles scientifiques. Pour chaque article, j'étais la personne principalement responsable pour l'élaboration du plan expérimental, la récolte et la compilation de données, les analyses statistiques et la rédaction.

Le premier article s'intitule « Historical fire regime shifts related to climate teleconnections in the Waswanipi area, central Quebec, Canada ». Mes co-auteurs sont Mike Flannigan, Yves Bergeron et Martin Girardin. Cet article a été publié en 2007 dans International Journal of Wildland Fire (16: 607-618).

Le deuxième article s'intitule « Dendroclimatic inference of wildfire activity in Quebec over the 20th century and implications for natural disturbance-based forest management at the northern limit of the commercial forest ». Mes co-auteurs sont Martin Girardin, Mike Flannigan et Yves Bergeron. Cet article a été publié en 2008 dans International Journal of Wildland Fire (17: 348-362).

Le troisième article s'intitule « Potential changes in monthly fire risk in the eastern Canadian boreal forest under future climate change ». Mes co-auteurs sont Mike Flannigan et Yves Bergeron. Cet article a été accepté pour publication au Journal Canadien de la Recherche Forestière en juillet 2009.

Le quatrième chapitre s'intitule « Exploring links between adaptation to climate change and sustainable forest management: Integrating the fire risk into forest management planning ». Mes co-auteurs sont Yves Bergeron et Mike Flannigan. Cet article sera soumis pour publication à Forest Ecology and Management.

TABLES DES MATIÈRES

LISTES DES FIGURES

LISTE DES TABLEAUX

LISTE DES APPENDICES

RÉSUMÉ

Cette thèse analyse les opportunités de développer un aménagement forestier durable dans un contexte de changements climatiques et dans une région soumise à une fréquence de feu élevée lorsqu'on la compare à celle d'autres régions de la forêt commerciale du Québec.

Le premier chapitre examine la relation entre la distribution des classes d'âge, qui reflète l'activité régionale des feux, et les variations climatiques à grande échelle (circulation atmosphérique et océanique). Les variations interdécennales de l'activité des incendies forestiers de la région de Waswanipi, située dans le centre du Québec, ont été reconstituées pour la période 1920-2000 à l'aide d'analyses dendrochronologiques. Nous avons estimé le cycle de feu autour de 153 ans, avec un allongement de 99 ans avant 1940 à 282 ans après 1940. Cette reconstitution a été analysée à l'aide de différents indices climatiques tels que l'Oscillation Pacifique Décennale et l'Oscillations Nord-Atlantique, sur la période 1880-2000. Les corrélations entre la variabilité décennale des feux et les indices climatiques indiquent une influence positive de l'Oscillation Pacifique Décennale. Cette relation a été validée à l'échelle interannuelle pour les années de grands feux entre 1899 et 1996.

Le principal objectif du deuxième chapitre est de déterminer si un patron climatique particulier contrôle l'activité régionale des feux et se distingue de ceux contrôlant l'activité des feux dans d'autres parties de la forêt boréale québécoise. La carte de corrélation entre des hauteurs géopotentielles et l'aire brûlée annuellement dans la région d'étude a été produite et comparée avec celles produites pour l'aire brulée annuellement au Québec, et dans les zones de protection intensive (sud du Québec) et restreinte (nord du Québec). Ensuite, des analyses dendroclimatiques ont été réalisées afin d'obtenir des estimées de l'aire brûlée dans les différents territoires examinés de 1904 à 2001 afin d'évaluer la stabilité temporelle de l'influence climatique sur l'activité des feux. Le patron climatique qui contrôle l'activité des feux dans la région d'étude est intermédiaire entre ceux responsables de l'activité des feux dans les zones de protection intensive et restreinte. Ce patron serait relativement stable au moins depuis 1948.

Le troisième chapitre examine les taux de changement futurs de l'activité des feux sous l'influence des changements climatiques dans la région de Waswanipi, au centre du Québec. Tout d'abord, nous avons utilisé des régressions linéaires pour modéliser la relation historique (1972-2002) entre les conditions météorologiques et l'activité des feux. Ensuite, nous avons calculé les composantes du système de l'Indice Forêt-Météo à partir des simulations quotidiennes des conditions météorologiques du Modèle Régional Canadien du Climat (1961-2100). Nous avons testé les tendances linéaires de l'activité des feux sur la période 1961-2100, et calculé

les taux de changement entre les périodes 1975-2005, 2030-2060, et 2070-2100. Nos résultats suggèrent que le risque de feu du mois d'août pourrait doubler d'ici 2100, alors que celui du mois de mai pourrait diminuer. Ainsi, le pic saisonnier de l'activité des feux pourrait se réaliser et se prolonger plus tard dans la saison. Bien que nos résultats suggèrent une faible augmentation à long terme de l'activité des feux, la variabilité interannuelle qui y est associée reste un défi bien plus grand pour le développement d'un aménagement forestier durable.

Traditionnellement au Québec, le risque de feu est géré *a posteriori* en foresterie: quand un feu survient dans un territoire aménagé, une partie des pertes encourues est atténuée par des coupes de récupération. Dans le quatrième chapitre, nous explorons des approches davantage proactives pour inclure les risques et les incertitudes à la planification forestière. Nous présentons d'abord les concepts communs à l'adaptation aux changements climatiques et à l'aménagement forestier durable. Ensuite nous présentons différents indicateurs climatiques du risque de feu régional qui pourraient contribuer à mieux prévoir et intégrer le risque de feu dans la planification forestière stratégique et tactique. Enfin, nous discutons de différentes stratégies d'aménagement forestier qui permettent d'intégrer plus facilement le risque de feu à la planification forestière. Bien que nous ayons déjà de plusieurs outils pour intégrer les risques et les incertitudes dans la planification forestière, d'importants changements dans la perception de ces risques et incertitudes sont nécessaires pour les mettre en place.

En conclusion, il est techniquement possible de développer un aménagement forestier durable qui tienne mieux compte du risque de feu prévalant dans la région de Waswanipi. Cependant notre capacité technique et scientifique ne suffit pas à garantir qu'un tel aménagement sera effectivement réalisé puisque sa mise en place nécessiterait une véritable volonté politique et de profonds changements dans la perception des risques et incertitudes en aménagement forestier.

Mots-clés : feux de forêts, changements climatiques, aménagement forestier écosystémique, adaptation aux changements climatiques, dendroclimatologie, circulation atmosphérique, circulation océanique, indice forêt-météo, risque de feu.

INTRODUCTION GÉNÉRALE

Les variations et les changements climatiques ont des effets complexes sur les écosystèmes forestiers, sur leur dynamique et sur nos systèmes d'aménagement forestier. Les impacts des changements climatiques sur les ecosystèmes forestiers peuvent être regroupés en deux catégories : les impacts directs et les impacts indirects. Les impacts directs sont les effets des changements de température, de précipitation et d'autres paramètres climatiques sur la physiologie et l'écologie des organismes forestiers (e.g., croissance, reproduction, répartition, phénologie). À ces impacts directs se superposent des impacts indirects qui se manifestent par l'altération des régimes de perturbations naturelles telles que les feux, les épidémies d'insectes et les maladies. Les variations et les changements climatiques passés ont largement contribué aux variations passées de l'activité des feux dans diverses régions boréales (e.g. Girardin *et al.* sous presse, Marlon *et al.* 2008).

De façon générale, l'activité des feux dépend principalement des conditions climatiques et météorologiques, de la végétation (combustible), de la topographie (relief et disposition du réseau hydrographique) et des activités humaines qui contribuent à l'allumage et à la suppression des feux. Cependant, en forêt boréale, les paramètres météorologiques et climatiques semblent expliquer une plus grande part de la variabilité de l'activité des feux que les autres paramètres (Flannigan et Harrington 1988, Bessie et Johnson 1995, Lefort *et al.* 2003). Ainsi, les feux représentent des catalyseurs des effets des changements climatiques sur les écosystèmes forestiers et sur nos systèmes d'aménagement forestier (Weber et Flannigan 1997). Dans le cadre de cette thèse, les feux sont considérés comme une vulnérabilité majeure de l'aménagement forestier face aux changements climatiques puisque nous aménageons des forêts essentiellement boréales et que le feu y joue un rôle primordial (Le Goff *et al.* 2005).

Dans le contexte actuel d'une planification forestière basée sur le principe du rendement soutenu, les feux représentent une incertitude majeure et un risque de perte de volume de bois pour l'industrie forestière. Le feu représente une incertitude car il est difficile de prévoir où et quand un feu va survenir. Le feu représente également un risque de perte de volume de bois car il peut affecter des peuplements prévus plus tard pour la récolte, et la planification forestière stratégique et opérationnelle s'en trouve alors modifiée. Lorsqu'un feu survient sur un territoire aménagé, il fait d'abord l'objet d'efforts de suppression par l'organisme en charge de la gestion des feux de la province (la Société de Protection des Forêt contre le Feu, la SOPFEU, au Québec), puis les superficies brûlées peuvent faire l'objet de plans spéciaux de récupération des bois brûlés. Ces deux approches comportent des limites qui démontrent à quel point notre système d'aménagement forestier est mal adapté aux incendies. La suppression des feux coûte environ 500 millions de dollars en moyenne chaque année. L'étude de MacAlpine et Hirsh (1999) suggère que même si l'on disposait de moyens financiers illimités, nous ne pourrions pas supprimer tous les feux et que 3 à 4 % de feux échapperaient aux moyens de contrôle. Ces feux brûleraient de grandes superficies car ils seraient dus à des conditions météorologiques extrêmes de sécheresse et de vent. Par ailleurs, lorsque de nombreux feux sont déclenchés simultanément les agences de gestion du feu peuvent faire face à des situations de débordement qui nécessitent de sélectionner certains feux sur lesquels intervenir, alors que d'autres brûlent librement (Lemaire 2002). Notre système de suppression des feux s'est mis en place ces 50 dernières années (Blanchet 2003), alors que l'activité des feux au Canada et au Québec était relativement faible lorsqu'on examine les 200 dernières années. Depuis les années 1970, on observe une augmentation de l'aire brûlée annuellement au Canada (Skinner *et al.* 1999, 2002, Gillett *et al.* 2004, Podur *et al.* 2002), et les agences de suppression des feux font de plus en plus souvent face à des situations de débordement. L'exclusion totale des incendies en forêt aménagée semble impossible économiquement. De plus, elle n'est pas souhaitable écologiquement puisque les feux jouent un rôle écologique fondamental dans la dynamique de la forêt boréale, et que ce rôle est de plus en plus reconnu (Hirsh et Fuglem 2006). Les coupes de récupération quant à elles présentent plusieurs limites: les surfaces brûlées ne sont pas toujours accessibles et les peuplements brûlés ne sont pas toujours composés de tiges de diamètre commercial. Elles sont pratiquées selon les mêmes normes que celles en vigueur pour la récolte des peuplements non brûlés, ce qui suscite de nombreuses questions quant à leurs impacts sur les écosystèmes forestiers (Nappi *et al.* 2004, Lindenmayer *et al.* 2004, Schmiegelow *et al.* 2006, Donato *et al.* 2006) et à leur rentabilité pour les industriels (Patry 2002).

Au Québec, plusieurs études documentent la variabilité spatiale de l'activité des feux, et suggèrent qu'un territoire situé à l'ouest du lac Mistassini serait soumis à une fréquence de feu particulièrement élevée lorsqu'on la compare à d'autres territoires aménagés au Québec (Gauthier *et al.* 2001, MRNFQ 2000, Lefort *et al.* 2004). Ainsi, ce territoire, que l'on appellera la région de Waswanipi, est particulièrement indiqué pour étudier les interférences possibles entre l'aménagement forestier et le régime naturel des feux. Parmi les hypothèses explicatives de ce régime de feu, cette thèse explore l'hypothèse climatique en deux volets: i) ce régime de feu particulier est-il lié à un signal climatique particulier? Et ii) les changements climatiques risquent-il de mener à une augmentation de la fréquence de feu déjà élevée sur ce territoire?

Cette thèse s'intéresse à l'influence des variations et des changements climatiques sur l'activité récente (les 200 dernières années) et future (les 100 prochaines années) des feux dans la région de Waswanipi, située dans le centre du Québec. L'objectif principal est de vérifier s'il est possible de développer un aménagement forestier durable dans cette région, compte-tenu du régime de feu particulièrement sévère qui y prévaudrait. Pour aborder cette problématique, j'ai analysé la relation feux-climat passée dans ma region d'étude et je me suis appuiyée sur l'hypothèse que les feux vont répondre aux changements climatiques futures de la même façon qu'ils ont répondu aux variations climatiques passées afin d'anticiper la réponse possible du regime de feu regional aux conditions climatiques futures anticipées. Cette hypothèse determine l'interprétation de mes résultats et les limites dans lesquelles ils peuvent être interprétés puisqu'il est possible que les conditions climatiques futures conduisent à des dynamiques différentes qu'il n'est pas possible d'envisager à lartir de l'analyse des conditions passées. J'ai décomposé la question générale de la these en quatre questions spécifiques auxquelles répondent les quatre chapitres:

1. Le régime de feu est-il plus sévère dans la région de Waswanipi qu'ailleurs dans la forêt boréale commerciale du Québec et est-il en place depuis longtemps ou bien récemment?
2. Ce régime de feu est-il contrôlé par un patron climatique particulier?
3. Comment ce régime de feu va-t-il évoluer sous l'influence des changements climatiques futurs?
4. Comment mieux intégrer le risque de feu dans notre façon d'aménager les forêts de la région de Waswanipi?

Dans le premier chapitre, j'ai reconstitué la distribution des classes d'âge à l'aide d'analyses de photos aériennes, des données de feu provinciales et d'échantillons prélevés sur le terrain. J'ai également calculé le cycle de feu pour différentes périodes pour vérifier si les variations temporelles de l'activité des feux observées dans la région de Waswanipi concordaient avec celles observées dans d'autres régions forestières au Québec. Plusieurs études récentes suggèrent que la variabilité interdécennale de l'activité des feux dans différentes régions de la forêt boréale est influencée par les variations climatiques à grande échelle. J'ai donc calculé les corrélations entre la distribution des classes d'âges, qui reflète l'activité régionale des feux, et différents indices décennaux de circulation atmosphérique et océanique. Enfin, j'ai vérifié si cette corrélation pouvait également se traduire par une influence de la variabilité climatique interannuelle de certains de ces indices sur l'occurrence d'années de grands feux dans la région.

Dans le second chapitre, j'ai développé une reconstitution dendroclimatique de l'activité des feux pour différents territoires, dont le Triangle de Feu (comprenant la partie nord de la région de Waswanipi) à l'aide de huit chronologies de pin gris (*Pinus banksiana* Lamb.) et de huit chronologies d'épinette noire (*Picea mariana* (Mill.) B.S.P.). J'ai ensuite calculé les corrélations entre ces estimées de l'activité des feux et les hauteurs géopotentielles à 500 hPa, afin de déterminer les patrons de circulation atmosphérique associés à l'aire brûlée de ces territoires, et vérifier si le patron de circulation atmosphérique responsable de l'aire brûlée dans le Triangle de Feu diffère de ceux déterminant l'aire brûlée ailleurs dans la province.

Dans le troisième chapitre, j'ai utilisé les données météorologiques quotidiennes régionales simulées par le Modèle Régional Canadien du Climat pour la période 1961-2100 afin de calculer les composantes régionales de l'Indice Forêt-Météo pour un scénario de changements climatiques futurs. J'ai utilisé la relation historique (1972-2002) entre l'activité régionale des feux (aire brûlée annuellement et nombre annuel de feux) et les composantes de l'Indice Forêt-Météo comme fonction de transfert pour calculer les variations futures dans l'activité régional des feux sous l'influence des changements climatiques. J'ai ensuite calculé les taux de changements dans l'aire brûlée et le nombre de feux annuels entre trois périodes de référence: 1975-1995 (concentration actuelle de CO_2 atmosphérique, $1\times CO_2$), 2030-2060 ($2\times CO_2$) et 2070-2100 ($3\times CO_2$) afin de déterminer les tendances futures de l'activité des feux dans la région de Waswanipi sous l'influence des changements climatiques.

Dans le quatrième chapitre, j'ai analysé les concepts communs à l'adaptation aux changements climatiques et à l'aménagement forestier durable afin de vérifier comment la théorie et la pratique de l'adaptation aux changements climatiques pourraient contribuer à développer l'aménagement forestier durable. Dans ce chapitre, je présente les feux comme vulnérabilité particulière de notre système d'aménagement face aux changements climatiques. J'analyse également des stratégies d'aménagement encore peu utilisées (e.g., Triade, IntelliFeu) qui permettraient de concilier les objectifs d'aménagement durable des forêts et d'adaptation aux changements climatiques en facilitant l'intégration du risque de feu dans la planification forestière stratégique et tactique. L'objectif de ce chapitre est de livrer aux professionnels de la forêt des applications pratiques des connaissances développées dans les chapitres précédents.

CHAPITRE I

HISTORICAL FIRE REGIME SCHIFTS RELATED TO CLIMATE TELECONNECTIONS IN THE WASWANIPI AREA, CENTRAL QUEBEC, CANADA

1.1 Résumé

À travers la forêt boréale québécoise, des changements synchrones dans les régimes de feu régionaux ont été observés. Ce synchronisme suggère que les régimes de feu sont influencés par la variabilité climatique à grande échelle. La présente étude examine l'influence des variations climatique à grande échelle sur l'activité régional des feux, telle que reflétée par la distribution régionale des classes d'âge. Les variations interdécénnales de l'activité des incendies forestiers de la région de Waswanipi, dans le centre du Québec ont été reconstituées pour la période 1920-2000. Cette reconstitution a ensuite été analysée à l'aide de différents indices climatiques tels que l'Oscillation Pacifique Décénnale (OPD) et l'Oscillation Nord-Atlantique pour la période 1880-2000. Nous avons estimé le cycle de feu global à environ 153 ans, avec un allongement de 99 and avant 1940 à 282 ans après 1940. Les corrélations entre la variabilité décennale de l'activité des feux et les indices climatiques indiquent une influence positive de l'OPD. Cette relation a été validée à l'échelle interannuelle pour les années de grands feux entre 1899 et 1996.

1.2 Abstract

The synchrony of regional fire regime shifts across the Québec boreal forest, eastern Canada, suggests that regional fire regimes are influenced by large-scale climate variability. This study investigated the influence of large scale climate variations on the regional fire activity as it is reflected by the regional age-class distribution. The interdecadal variation in forest fire activity in the Waswanipi area, northeastern Canada, was reconstructed over AD 1720-2000. Next, the 1880-2000 reconstructed fire activity was analyzed using different proxies of the Pacific Decadal Oscillation (PDO) and the North-Atlantic Oscillation. We estimated the global fire cycle around 153 yr, with a major lengthening of the fire cycle from 99 yr before 1940, to 282 yr after 1940. Correlations between decadal fire activity and climate indices indicated a positive influence of the PDO. The positive influence of PDO on regional fire activity was also validated using t-tests between fire years and non-fire years between 1899 and 1996.

1.3 Introduction

Numerous studies have documented regional fire regimes throughout the boreal forest (Mann *et al.* 1995; Flannigan *et al.* 1998; Bridge 2001; Kasischke *et al.* 2002; Bergeron *et al.* 2004a, 2006; Parisien *et al.* 2004). These regional fire regimes result from the combination of local weather conditions, topography, forest fuels, and ignition agents (lightning and human activities). Given that volcanic activities, solar radiation and chemical composition of the atmosphere constantly influence the global climate dynamics (Bonan 2002), and that there is a strong linkage between climate and fire activity, variations in historical observations of fire activity due to changes in the climate are expected (Flannigan and Harrington 1988; Johnson 1992; Swetnam 1993). The fire regime integrates several variables describing the fire activity such as the mean fire size, the annual area burned, the fire severity, the fire frequency, and the mean fire return interval (or fire cycle) (Weber and Flannigan 1997). While regional fire regimes vary widely from one area to another, common temporal patterns in historical fire regime shifts have been reported. In the context of the past 300 years, many regional fire regimes of the Canadian boreal forest, as reconstructed from dendroecological analysis, experienced a decrease in fire frequency after 1850 (Bergeron and Archambault 1993; Larsen 1996) and a further decrease after 1940 (Bergeron *et al.* 2001, 2004a, 2004b, 2006). Conversely, analyses of fire statistics from provinces and Canadian agencies suggested that during the past three decades, area burned and fire frequency have increased throughout much of boreal Canada (Skinner *et al.* 1999, 2002; Stocks *et al.* 2003; Kasischke and Turetsky 2006). Whatever the temporal scale investigated, the synchrony of long-term temporal trends in fire activity across the Canadian territory suggests the persistence of a large-scale climatic control of fire activity (Bergeron *et al.* 2001, 2004, 2006).

Large-scale climatic variations in the Northern Hemisphere are typically described by recurrent oceanic and atmospheric circulation patterns, some of which are originating from the Pacific and Atlantic Oceans and acting at interannual to interdecadal timescales. In Canada, several modes were held responsible for temporal and spatial variations in the countrywide weather conditions conducive to fire activity. These include the global long-term trend in ocean temperatures (Skinner *et al.* 2006), the El Niño – Southern Oscillation (ENSO) and related Pacific Decadal Oscillation (PDO) (Girardin *et al.* 2006a; Skinner *et al.* 2006; Macias Fauria and Johnson 2006), the North Atlantic Oscillation (NAO) (Girardin *et al.* 2004), the Arctic Oscillation (AO) (Macias Fauria and Johnson 2006), and the Atlantic Multidecadal Oscillation (AMO) (Skinner *et al.* 2006). The influence of these modes on historical fire activity is heterogeneous across Canada and reflects the dynamics of the upper atmosphere longwave patterns (ridges and troughs) over oceans and lands (Bonsal *et al.* 1993; Bonsal and Lawford 1999; Skinner *et al.* 1999; Macias Fauria and Johnson 2006).

This study investigates the influence of large-scale climate variability on the regional fire activity as reflected by the age-class distribution, and on the occurrence of large fire years in the Waswanipi area, central Québec. First, we reconstructed the historical fire activity between 1720 and today over an area of 11 500 km^2 using dendroecological sampling along with forest inventories, aerial photographs, and ecoforest maps. The fire cycle in the Waswanipi area was estimated for different time periods to identify temporal trends in fire activity. Second, decadal fire departures obtained from the forest-age distribution were correlated to oceanic and atmospheric circulation indices. The regional fire activity was examined in light of climate index regime shifts at the interdecadal scale. Finally, fire years as documented by replicated fire scars and recent fire data were used to explore the influence of variations in oceanic and atmospheric circulation patterns on the occurrence of large fire years in the Waswanpipi area. Determination of the link between fire and climate is an essential step toward understanding the dominant forcing of landscape-scale disturbance of boreal forests. Additionally, such analysis yields valuable tools for planning fire management activities and to improve forecasts of climate change impacts on the boreal forest (Flannigan *et al.* 2005; Duffy *et al.* 2005; Skinner *et al.* 2006). Several studies have documented the temporal correlations (or teleconnections) between climate and ocean circulation indices and regional fire activity as documented by fire scars and tree-ring chronologies (Swetnam and Betancourt 1990; Sibold and Veblen 2006). Recently, Brown (2006) documented the influence of climate indices on the tree recruitment dynamics in ponderosa pine forests. However, our study is the first to our knowledge linking oceanic and atmospheric circulation indices to stand-age distribution in boreal Canada.

1.4 Methods

1.4.1 Study area

The study area (49.5-50.5° N; 75-76.5° W; Fig. 1.1) lies in the north-central commercial forest of Québec and covers more than 11 500 km² (Fig. 1.1). Situated in the western black spruce – feather moss bioclimatic domain (MRNFQ 2000), the forest consists principally of black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) stands. Situated on the Canadian Precambrian Shield, the landscape has a high density of lakes and is dominated by morainal till deposits with scattered rocky outcrops covering 10-30% of the landscape (Robitaille and Saucier 1998; Centre for Land and Biological Resources Research 1996). The relief is relatively rugged, consisting of a 10-30% slope going east that produces a well-drained landscape overall. The mean annual temperature is 0°C, with January and July being the coldest and the warmest months, respectively. The area receives an average 961 mm of total annual precipitation, about one-third of which falls as snow. The growing season is from April to October with 1235 growing degree-days above 5°C (data from Chapais weather station 1971-2000 climate normals, Environment Canada 2004).

Fire is the main disturbance of these forests. Using provincial fire data (1945-1998), Lefort *et al.* (2004) identified a gradient in the fire activity (increasing northward) across the broader region containing our study area. They estimated a fire cycle between 200 and 500 yr for the southern part and a fire cycle shorter than 200 yr for the northern part, where the Waswanipi area lies. This relatively high fire activity in our study area is corroborated by the high proportion of stands younger than 100 yr, and is one of the criteria underlying the current northern limit of the commercial forest in central Québec (MRNFQ 2000).

Colonization in the Waswanipi area began after 1940. It primarily hinged on mining and later on forest management, but no agricultural activities took place in the study area. Cree populations live around the Waswanipi Lake in the southwestern corner of the study area (Fig. 1.1) and on the shores of the Waswanipi River; a small fraction is scattered across the study area. The modern Waswanipi community was established in the 1970s. The nearby Chapais village developed in the 1950s to carry out mining activities. Thus, human influence had historically little effect on the natural fire regime when compared with the adjacent Abitibi and Lac-Saint-Jean areas where colonization started earlier, and converted forest territories to agricultural lands using slash and burn techniques (Lefort *et al.* 2004). Fire suppreesion over the study area started in 1958 (Langlois 1994).

1.4.2 Field sampling

The fire history (1720-2000) was reconstructed using forest inventories, aerial photographs, ecoforest maps, and field sampling to determine the cumulative time-since-last-fire (TSF) distribution for the study area (Johnson and Gutsell 1994). Two hundred sampling points were randomly located over the terrestrial area of the study area (when excluding rivers and lakes) using the Generate Randomly-Distributed Points script in ArcView GIS 3.2. Of these, 84 sampling points were located inside the burned areas compiled in the provincial fire database (Ministère des Ressources naturelles et de la Faune, MRNFQ) and were consequently dated using the most recent inventoried fire. Of the remaining 116 points, 67 were field sampled during the summers of 2002 and 2003. At each sampling point, 10 dominant trees of typically pioneer species (jack pine, or if not available, black spruce) were sampled by taking a cross section or two opposite increment cores from the trunk base *ca.* 30 cm above the ground. Forty-nine points, located outside the documented burned areas, were considered inaccessible (≥ 5 km from road access). These points were situated mostly in the northern part of the study area where the road network is sparse. For 15 of these points, permanent plots of the MRNFQ were sufficiently close (< 2 km) to provide a non-censored estimate of TSF from the oldest tree documented in each plot. For the 34 remaining points, stand ages from the ecoforest maps were used as a censored minimum TSF estimate, with

120 yr being the maximum age considered. As sampling was based on a random spatial distribution of sampling points, we assumed that each sampling point is representative of the same proportion of the study area (0.5%) and that the TSF distribution derived from the 200 random sampling points approximated the complete TSF distribution for the entire study area.

1.4.3 Dendrochronological analysis

Sampled cores (n = 792), and cross sections (n = 430) were dried, sanded, and aged by counting tree rings under a dissecting microscope, following standard procedures proposed by Yamaguchi (1991), Fritts (2001), and Stokes and Smiley (1968). Pith locators were used to estimate the number of missing rings to the pith on incomplete cores (Phipps 1985). Diagnostic rings allowed visual crossdating to confirm sample age. Among the sampled cross sections, 46 fire scarred trees allowed us to accurately estimate the fire date for 31 different sampling sites. Replicated fire scars (recorded on ≥ 2 trees, Brown 2006) were used to develop the regional fire-year chronology. Replicated fire scars were found in distant sampling points and were generally confirmed by cohort age originating from fire that fire-scarred trees survived. All fires reported are thus stand-replacing fires. To crossdate snags and living trees, we measured tree-ring width using a Velmex system coupled with the MEASUREJ2X 3.1 package for Windows (VoorTech 2001). Cross-dating of all samples was validated with COFECHA (Holmes 1999).

1.4.4 Fire history

The frequency of sampled sites was computed per decades to identify major fire decades. The global TSF distribution was computed to evaluate whether the fire frequency was constant over space and time (Johnson and Gutsell 1994). Assuming that the hazard of burning is independent of stand age, the TSF distributions should follow the negative exponential model and should appear as a straight line on a semilog scale (Van Wagner 1978; Johnson and Gutsell 1994). Fire cycles were computed using the LIFEREG procedure in SAS 9.1 (SAS Institute Inc. 2000), which is a standard maximum-likelihood procedure for analyzing survival data while taking into account censored data (Allison 1995). Our TSF estimates (survivorship) were considered censored when no accurate date could be attributed to the fire; in these cases, we used a minimum TSF estimate, i.e., the age of the oldest individual when no tree cohort could be clearly identified (Bergeron *et al.* 2004b). Thirty-one and a half percent of the data were censored. Finally, the LIFEREG procedure provides a Lagrange Multiplier Statistic based on a χ^2-test to evaluate whether the scale parameter of the exponential model was significantly different from one, thereby allowing us to determine if the data distribution followed a negative exponential model ($p > 0.05$) or not ($p < 0.05$). If this is the case, then the corresponding mean forest age provides a good estimate of the fire cycle.

TSF distributions were also computed for different parts of the study area and for different time periods to determine if the variations observed in the global fire activity (slope breaks on the TSF distribution) was related to spatial and/or temporal variations in the fire activity. Spatial patterns were investigated by a spatial sub-sampling. The dataset was divided into four equivalent sectors containing about 50 sampling points each (northeastern, northwestern, southeastern and southwestern sectors). Different periods were delimited according to documented period of changes in the fire activity in other parts of the boreal forest (end of the Little Ice Age *ca.*1850, and 1940) to verify if the Waswanipi area has similar temporal variations or not. The LIFEREG procedure was used to test these variations as this procedure allowed the evaluation of the effect of class covariables (sectors or time periods) using a χ^2 test, while taking into account censored data.

Reed (2006) underlined the limits of estimating the fire cycle using TSF distributions. We however chose to estimate this fire regime parameter to allow comparisons with other fire history studies using the same standard approach, and to provide a parameter useable for disturbance-based forest management. Also, the TSF distribution approach allowed us to take into account minimum TSF date when no accurate fire date could have been attributed to the sampling site. The fire cycle was also estimated using the LIFETEST procedure to estimate the hazard function (burn rate) associated with the life table survival estimates. This allowed us to provide an estimate of the fire cycle (1/burn rate) taking into account the censored data without constraining the survival function to follow the exponential negative distribution (which is required when using the LIFEREG procedure).

1.4.5 Climate indices

In this study, we used several climate indices to analyze the influence of large-scale climate variability on the Waswanipi fire history. The indices considered were the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO), and the Atlantic Multidecadal Oscillation (AMO).

The PDO corresponds to a long-lived El Niño-like pattern acting as a decadal mode of North Pacific sea surface temperature (SST) variability (Mantua *et al.* 1997; Zhang *et al.* 1997). Pacific SST anomalies have been linked with atmospheric circulation patterns consisting in ridging over western North America during warm coastal SSTs (Bonsal *et al.* 1993; Bonsal and Lawford 1999). The blocking highs typically persist for several days to several weeks and influence the fire weather conditions and the area burned across large Canadian regions (with greater area burned occurring downstream from the ridges; Johnson and Wowchuk 1993; Skinner *et al.* 1999; 2002; 2006; Girardin *et al.* 2006a). The PDO index of Mantua *et al.* (1997) is an instrumental series covering the period 1900 to the present (available at http://jisao.washington.edu/pdo) and is obtained from the leading principal component of North Pacific monthly SST poleward of 20°N. Smith and Reynolds (2003) extended this index back to 1854 using the most recently available SST data from the International Comprehensive Ocean-Atmosphere Data Sets (available at ftp://ftp.ncdc.noaa.gov/pub/data/ersst-v2/). The remaining three PDO datasets were paleoclimatological reconstructions derived from proxy data. The annual PDO reconstruction of D'Arrigo *et al.* (2001), extending from 1700 to 1979, is based on tree-ring chronologies from coastal Alaska and Pacific Northwest regions and accounts for up to 53% of the instrumental PDO variance. The annual PDO reconstruction of Biondi *et al.* (2001) is based on tree-ring data from

California and extends from 1661 to 1983. The annual Shen *et al.* (2006) record is based on proxy summer rainfall of eastern China and covers the 1470-2004 period.

The NAO index is based on the difference of normalized sea-level pressures (SLP) between the subtropical (Azores, Portugal) high and the subpolar (Stykkisholmur, Iceland) low pressure systems of the NAO (Hurrell 1995). The strongest and most climatologically effective expression of the NAO occurs during winter when the north-south pressure gradient is particularly stable between its two centres of action. Strong positive NAO phases are usually associated with above-normal temperatures in the northeastern United States and across northern Europe, and below-normal temperatures in Greenland and in Mediterranean regions (Visbeck *et al.* 2001). Instrumental monthly NAO series from Jones *et al.* (1997) and monthly NAO reconstructions from Luterbacher *et al.* (1999) were used. The Luterbacher monthly NAO index, covering the period 1659-2001, is based on early European instrumental SLP, temperature and precipitation. These two monthly databases were used to calculate seasonal NAO indices (December-January-February, March-April-May, June-July-August, and September-October-November). We also used the NAO series from Glueck and Stockton (2001), which is a tree-ring based winter reconstruction (1429-1983) calibrated against the Lisbon-Iceland NAO (from Hurrell 1995).

The PDO and the NAO reconstructions were extended to 1999 using the instrumental series (from Mantua *et al.* 1997 for the PDO, and from Jones *et al.* 1997 for the NAO) after adjusting the variance to that of the reconstructions.

The AMO corresponds to a basin-wide low-frequency (65-80 yr) component of SST variability (Kerr 2000). Enfield *et al.* (2001) have documented reduced summer rainfall and river flow regimes over the United States during warm AMO phases, while Skinner *et al.* (2006) have documented a negative influence of warm AMO phase on fire weather conditions across northern Ontario and Québec. We used the 1567-1990 annual North Atlantic sea surface temperature anomaly (SSTA) reconstruction of Gray *et al.* (2004). This annual reconstruction is based on the leading principal component of twelve tree-ring chronologies from southeastern North America, southern Europe, Scandinavia, western North Africa and the Middle East. The corresponding AMO index is a 10-yr running mean of the SSTA reconstruction. For the purpose of this study, we used the AMO variable for the decadal correlation with TSF distribution and the SSTA reconstruction for the analysis of fire years *versus* non-fire years to avoid the autocorrelation bias associated with the 10-yr smoothing.

1.4.6 Climate influence on the decadal fire activity

We were interested in characterizing the departures from the average area burned per decade. Because recent fires tend to eliminate information relevant to past fires, an exponential curve (as previously computed using the LIFEREG procedure) was fit to the stand-age distribution using survival analysis. The mean forest age for the whole period was estimated at 153 years with 95% confidence intervals [128; 183]. Decadal departures from the average area burned were calculated by subtracting the theoretical exponential curve from the stand-age distribution.

Next, annual values of atmospheric and oceanic circulation indices were averaged by decades and correlated with decadal fire departures. We restricted our analyses to the 1880-1990 time period as the previous fire decades were had a high proportion of censored data. Pearson correlations between decadal fire departures and decadal averages of the climate indices were computed using the PEARSONT program (Mudelsee 2003). This program uses a nonparametric stationary bootstrap to calculate the 95% confidence interval associated with the Pearson correlation coefficient and resamples blocks of data pairs to account for the presence of serial correlation in the time series. When the confidence interval contains zero, the hypothesis of 'no correlation' cannot be rejected at the 95% level. The normality of the data was verified prior to the correlation analyses using the Shapiro-Wilk normality test (Zar 1999). All variables satisfied the normality assumption ($p > 0.2$), except the decadal averages of the PDO series of Shen *et al.* (2006), the winter NAO of Glueck and Stockton (2001) and the winter NAO computed using the monthly NAO reconstruction from Luterbacher *et al.* (1999). For the two first variables, correlations were computed on ranked data as no transformation made it possible to reach normality. For the winter NAO from Luterbacher *et al.* (1999), an exponential transformation was used to reach normality (p = 0.65 after transformation). Scatterplots of the decadal fire departures and decadal climate indices (not shown) confirmed that relationships were linear and that Pearson correlations are an appropriate method for analyzing them.

1.4.7 Climate influence on the occurrence of fire years

The influence of interannual climate variavility on the occurrence of large fire years in the Waswanipi area was investigated by computing differences in mean climate indices (PDO, NAO, AMO) for fire years and non-fire years. Two-sample mean tests (Zar 1999) were computed using SYSTAT 11 (Systat Software Inc. 2004) on unlagged climate indices as well as on climate indices lagged by one and two years previous to the reported fire year. Critical t-values were adjusted to account for autocorrelation in data. All climate indices satisfied the normality assumption (according to the Shapiro-Wilk normality test, Zar 1999). Twelve fire years documented by replicated fire scars (1899, 1907, 1915, 1916, 1925, 1934, 1940, 1966, 1982, 1984, 1985, and 1994) were used to discriminate the fire years from the non-fire years. Also, three major fire years (1983, 1986 and 1996) that are not reported by our fire scar sampling and that accounted for more than 5% of the total area burned during the 1905-1998 period were added to the regional fire year chronology.

Regime shift analyses were computed on different responsive PDO and NAO indices using the program developed by Rodionov (2004). This analysis is based on a sequential t-test to detect regime shifts, where the time scale to be detected is controlled primarily by the cut-off length. Both cut-off length and probability level affect the statistically significant difference between regimes, and hence the magnitude of the shifts to be detected (Rodionov and Overland 2005). These analyses aimed to verify the synchrony of regime shifts from positive to negative phase and *vice versa*, with decadal fire departures and with the frequency of reported fire years. Results were highly sensitive to the cut-off length chosen, primarily in relation to the amplitude of interannual variations of the climate index considered. We used a cut-off length of 10 yr because we were primarily interested in the decadal influence of PDO on the TSF distribution, which also was gathered in 10-yr classes.

Finally, stepwise multiple regression analyses (SYSTAT 11, Systat Software Inc. 2004) were computed to prospect potential combination effects of teleconnections from the Atlantic and the Pacific oceans.

1.5 Results

1.5.1 The Waswanipi fire history

The early 20th century (1900-1940) was characterized by high fire activity, with 43.5% of the area burned recorded from 1720-2000 (Fig. 1.2). Three time periods of relatively high fire activity were observed: 1850-1860, 1910-1940, and 1980-1990. The 1870 peak of censored data corresponded to inaccessible sampling points that were documented by the oldest age-class reported on ecoforest maps (120 yr). The 1720-2000 mean forest age was estimated to be about 153 yr and the survival curve suggested changes in the fire frequency through time and/or space (Table 1, Fig. 1.3a).

The mean forest age varied according to the different sectors ($p = 0.0121$, Table 1.1), but was neither due to a latitudinal (North *versus* South), nor to a longitudinal (East *versus* West) effect ($p > 0.05$, Table 1.1). It was instead related to the combination of latitude and longitude as only the northeastern sector had the shorter mean forest age (85 yr) when compared with the three others (around 170 yr, Fig. 1.3b, Table 1.1). The TSF distributions for the sectors displayed mixed distributions with synchronous changes in the fire frequency around 1940 and 1840 (Fig. 1.3b, Table 1.1). The temporal changes of fire frequency for each sector were not tested because of insufficient sample size.

TSF distributions corresponded to relatively constant fire activity for the <1850 and the 1850-1930 periods. The 1940-2000 period had a weaker fit to the exponential model, likely due to the 1980-1990 higher fire activity (Fig. 1.3c, Table 1.1). The mean forest age was estimated to be about 164 yr before 1850, 99 yr for the 1850-1940 period, and 283 yr for the 1940-2000 period. Although striking, differences in the mean forest age over these intervals were not significant (Table 1.1).

An examination of the temporal evolution of the decadal burn rate through time (1820-2000) indicated a mean fire cycle of 132 yr with a 98-yr fire cycle before 1940 and a 232-yr fire cycle after 1940 (Fig. 1.4a). Moreover, the sequential computation of the fire cycle estimates during the 1820-2000 period confirmed that fire cycle varied significantly before and after the decades 1920, 1930, 1940, 1950, and 1960 (Fig. 1.4b). The fire cycle oscillated around 143-yr for the last 180 yr, with a constant increase from 1940 to 1980 (Fig. 1.4b). Hence, the temporal change in the regional fire activity around 1940 echoed synchronous change in neighbouring forested areas documented in the literature (Bergeron *et al.* 2001, 2004a, 2004b, 2006), suggesting a large-scale control of multidecadal trends in regional fire activity. Below, the reconstructed Waswanipi fire activity is analyzed with respect to large-scale climate variability.

1.5.2 Climate influence on recent fire activity

The visual inspection of the PDO series (Fig. 1.5a, 1.5b, 1.5c, 1.5d) and of the decadal fire departures (Fig. 1.5f) suggested a synchrony of phases of higher PDO (around 1860, before 1947, and after 1977) and periods of high fire activity in the Waswanipi area (1900-1940 and 1980-1990 fire decades). Conversely, a lower PDO phase is synchronous to the 1950-1970 low fire decades (Fig. 1.5f). The relationship is not as clear prior to 1880, perhaps because of the high amount of censored data in our fire departures prior to that period. All PDO time series tested were well correlated with the Waswanipi fire departures for the 1880-1990 period ($r > 0.58$, Table 1.2). The best predictors of the decadal fire departures were the instrumental PDO series of Mantua *et al.* (1997), and the 1790-1997 PDO reconstructions of D'Arrigo *et al.* (2001) ($r > 0.75$, Table 1.2). Significant positive correlation was also found with the winter NAO series of Luterbacher *et al.* (1999) and of Jones *et al.* (1997). Stepwise multiple regression (using an in-and-out probability of 0.1) suggested a combination effect of the PDO and the winter NAO according the following regression models:

$$y = 0.5655 + 8.5134PDO + 4.1304NAO_j \qquad \text{(Eq. 1.1)}$$

$$y = -3.2752 + 8.9911PDO + 5.5710EXP(NAO_{gs}) \qquad \text{(Eq. 1.2)}$$

where y are decadal fire departures, *PDO* is the 1790-1997 PDO reconstruction of D'Arrigo *et al.* (2001) (that alone explained about 58% of the variance in the 1880-1990 decadal fire departures, p = 0.004, not shown), NAO_j is the winter NAO series calculated using the Jones *et al.* (1997) dataset, and NAO_{gs} is the winter NAO reconstruction of Glueck and Stockton (2001). These models explained respectively about 71% (adjusted R^2 = 0.64, p = 0.004, NAO regression coefficient with t = 2.0085 and p = 0.0755), and 74% (adjusted R^2 = 0.68, p = 0.002, NAO regression coefficient with t = 2.3459 and p = 0.0436). The winter NAO index from Glueck and Stockton (2001) did not fully satisfy normality after an exponential transformation according to a Shapiro-Wilk normality test (p = 0.17). This index was used to confirm the results shown by Eq. 1.1. Both regression models suggested a reinforcing influence of the winter NAO on the positive relationship between PDO and the decadal fire departures.

As indicated by the correlation analysis on decadal averages of proxy climate indices, the distribution of fire years also followed well the long-term variations of the PDO. The t-tests indicated higher PDO values during reported fire years and for the two years previous to the reported fire years and higher NAO values for one and two years previous to the reported fire year (Table 1.3). Regime shift analysis confirmed coherent regime shift of the PDO indices around 1950 (from a positive to a negative phase) and around 1977 (from a negative to a positive phase). Only one fire year was reported for the negative PDO phase (1947-1966) while the other fire years were reported during higher PDO phases. The 1790-1997 PDO index of D'Arrigo *et al.* (2001) (Fig. 1.5c) also displays a higher regime before 1850, while no regime shift was detected on the other PDO indices before 1900 (PDO index of Smith and Reynolds (2002), Fig. 1.5b) or 1930 (PDO index of Shen *et al.* (2006), Fig. 1.5d). The different NAO indices gave no coherent regime shifts, so only the winter NAO reconstruction of Glueck and Stockton (2001) was used to compare visually the regime shifts detected with the decadal fire departures. The winter NAO had a higher regime around 1930 and changed from a negative to a positive phase around 1977 (Fig. 1.5e).

1.6 Discussion

1.6.1 The Waswanipi fire history

Conversely to other studies located south of our study area (Bergeron *et al.* 2001, 2004b), we did not detect any change at the end of the Little Ice Age *ca.*1850. The only significant change in the Waswanipi fire activity occurred around 1940. The fire cycle has lengthened from 99 yr (1850-1940) to 283 yr (1940-2000). This lengthening at *ca.* 1940 has been also reported from central to western Québec (Bergeron *et al.* 2001) and in southwestern Québec (Grenier *et al.* 2005; Drever *et al.* 2006). This may reflect the reported decrease in the incidence of extreme fire years at the scale of the Boreal Shield (Girardin *et al.* 2006b). In Québec, the early 20th century is usually associated with the onset of European settlement and the use of slash-and-burn techniques to clear forested lands for agriculture (Bergeron *et al.* 2001; Lefort *et al.* 2003; Grenier *et al.* 2005). As the Waswanipi area was settled later (after 1940) than the neighbouring regions of Abitibi and Lac-Saint-Jean (Lefort *et al.* 2004), and given that no agricultural activities took place in this area, the higher fire activity of the early 20th century cannot be explained by settlement and was mainly prompted by climate. Girardin *et al.* (2006b) suggested this climate effect prevailed over the Boreal Shield. Their reconstructions of annual area burned using tree-ring data suggested that greater fire activity occurred in the first half of the 20th century than after 1950.

It should however be noted that the 1980-1990 decades were also marked by a high fire activity in the Waswanipi area. These decades were also reported as being major fire decades in Eastern Abitibi and in Central Québec (Bergeron *et al.* 2001), two locations close to the Waswanipi area. These higher fire decades were also reported in other parts of the Canadian boreal forest (Gillett *et al.* 2004; Skinner *et al.* 1999, 2002; Macias Fauria and Johnson 2006). Moreover, the years 2002 and 2005, two major fire years in the Waswanipi area, are not included in our fire cycle estimates. Also, the fire cycle estimates computed using the survival analyses with the negative exponential model is very sensitive to the distribution of high fire years: while we presented a 283-yr fire cycle estimate for the 1940-2000 period, the fire cycle estimate for the 1920-2000 period is about 173 yr (not shown). This suggests that numerical estimates of fire cycle varied greatly depending on the inclusion or the exclusion of the 1920-1930 high fire decades. Given the sensitivity of the fire year distribution and the fact that we did not include the recent high fire years in our analyses, our estimates probably overestimate the recent fire cycle. However, the global 1820-2000 mean fire cycle estimates (132 and 143 yr) are close to the 153-yr mean forest age calculated for the 1720-2000 period using the negative exponential model.

1.6.2 Climate influence on recent fire activity

Our results reported a positive influence of the PDO on the fire activity in the Waswanipi area at least for the 1880-1990 period. Skinner *et al.* (2006) also reported that warm winter El Niño – PDO events lead to fire-conducive droughts in northern Ontario and Québec. However, large spatial variability was found and some regions, such as the Great Lakes regions of southern Ontario and central Québec, are showing an inverse relationship to these Pacific processes. Their analyses of the relationship between fire-weather conditions across Canada during the 1953-1999 period and the Pacific SSTs could reconcile our results with those of Girardin *et al.* (2006a) who suggested a negative influence of PDO on fire-conducive drought conditions over eastern boreal Canada (i.e., cool PDO phase associated with greater fire activity) as our study area is situated north of that of Girardin *et al.* (2006a). Finally, Macias Fauria and Johnson (2006) also reported a positive influence of the PDO variability on interdecadal variation of area burned in several areas east of the Canadian Rocky Mountains, including our study area. The positive influence of PDO on decadal fire departures could have prevailed earlier as suggested by the regime shift analysis computed on the D'Arrigo *et al.* (2001) PDO index. This index displayed a stronger PDO before 1860, while the positive 1870 decadal fire departure is related to a high proportion of censored data (suggesting that the fire activity of previous decades was more important than our data showed, see Fig. 1.2). The lag observed between the 1870 decadal fire departure and the higher PDO regime highlights the declining reliability of TSF dendrochronological estimates when going further back in the past. We may assume that the higher PDO regime prevailing before 1860 could also have triggered higher fire activity for periods previous to 1870.

Dendroclimatic analyses by Hofgaard *et al.* (1999) suggested that the south-north climate gradient of western Québec between 48°N and 50°N was disrupted around 1875. The authors attributed this disruption to the northern displacement of the influence of dry cold Arctic air masses from 48°N to higher latitudes. Their findings were recently corroborated by a spatio-temporal analysis of 90 multicentury chronologies distributed across the eastern half of Canada (Girardin *et al.* 2006a). While fire activity in southwestern Québec decreased since *ca.* 1850 with the increasing incursion of humid air masses from the subtropical North Atlantic (Bergeron and Archambault 1993; Hofgaard *et al.* 1999; Girardin *et al.* 2006b), our study area (located north of 49°N) could still be under the influence of the dry cold arctic air masses. This climate disruption would explain why we did not detect any change in the fire frequency *ca.* 1850, conversely to other study areas situated south of ours (Bergeron *et al.* 2006). Similar dipolar structures have been reported in the U.S. Negative PDO phases were found to be associated with periods of high fire activity in Colorado (Sibold and Veblen 2006), while forest fires in Washington tended to occur during positive PDO phases (Hessl *et al.* 2004). The fire-climate relationship is however not linear. Periods of relatively high and low fire activity at the regional scale would instead be controlled by the combination of different climate indices. Brown (2006), Sibold and Veblen (2006), Collins *et al.* (2006), Trouet *et al.* (2006) and Kitzberger *et al.* (2007) reported combination effects of teleconnections that modulate regional fire activity. Our stepwise regression models did identify a combination effect of PDO (positive) and NAO (positive) on the 1880-

2000 decadal fire departures in our study area. Macias Fauria and Johnson (2006) also reported that the AO (Arctic Oscillation) would modulate the interannual variability of the PDO-area burned relationship. Their results suggested that the strong positive AO phase would have contributed to further influence positively the increase in the area burned noted since 1977. As the NAO and the AO are highly correlated (Ambaum *et al.* 2001), the agreement of our results with those of Macias Fauria and Johnson (2006) is not surprising. Our results obtained using regional dendrochronological data confirmed the results of Skinner *et al.* (2006) and Macias Fauria and Johnson (2006) that were obtained using the 1959-1999 Large Fire Database (Stocks *et al.* 2003).

Correlations and t-tests suggested a positive influence of the PDO on the fire activity in the Waswanipi area without providing any insight on the physical mechanisms underlying such a relationship. Antecedent works linking atmospheric and oceanic circulation indices to fire activity of different parts of North America (Bonsal *et al.* 1993; Bonsal and Lawford 1999; Skinner *et al.* 1999, 2002; Duffy *et al.* 2005) suggested that the statistical relation between monthly weather and teleconnections would provide a plausible mechanism underlying large-scale climate influence on fire activity. Further analyses investigating this regional fire-climate relationship at the interannual scale are needed to help us better understand how large-scale climate variability could influence long-term trends in regional fire activity.

Synchronous shifts in regional fire activity and in large-scale climate regimes imply that the fire activity criteria underlying the northern limit of the commercial forest in central Québec (MRNFQ 2000) must be viewed as a dynamic component rather than a static criterion. Moreover decadal-scale climate variability, and regime shifts in particular, can be anticipated (Enfield and Cid-Cerrano 2006; Rodó and Rodríguez-Arias 2006). The anticipation of future climate regime shifts may contribute to the development of adaptation strategies of forest management to future fire regimes driven by climate variability and change.

1.7 Acknowledgements

We gratefully thank D. Lesieur, B. Saint-Vincent, S. Valois, S. McLaughlin, D. Beauregard for their contributions to the field and laboratory work. We also thank D. Cyr for his guidance throughout the survival analyses. The comments and suggestions of S. Gauthier, Pamela Cheers, the associate editor and two anonymous reviewers contributed to improving the manuscript. This research was supported by the Action Concertée Fonds Forestiers-FQRNT and the Sustainable Forest Management Network.

1.8 References

Allison, P.D. 1995. Survival analysis using SAS: a practical guide. SAS Institute Inc. Cary, NC.

Ambaum, M.H.P., Hoskins, B.J., and D.B. Stepheson. 2001. Arctic Oscillation or North Atlantic Oscillation? Journal of Climate 14: 3495-3507.

Bergeron, Y. and S. Archambault S. 1993. Decreasing frequency of forest fires in the southern boreal zone of Québec and its relation to global warming since the end of the "Little Ice Age". The Holocene 3: 255-259.

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., and D. Lesieur. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. Canadian Journal of Forest Research 31(3): 384-391.

Bergeron, Y., Flannigan, M., Gauthier, S., Leduc, A., and P. Lefort. 2004a. Past, current and future fire frequency in the Canadian boreal forest: implications for sustainable forest management. Ambio 33(6): 356-360.

Bergeron, Y., Gauthier, S., Flannigan, M., and V. Kafka. 2004b. Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Quebec. Ecology 85(7): 1916-1932.

Bergeron, Y., Cyr, D., Drever, C.R., Flannigan, M., Gauthier, S., Kneeshaw, D., Lauzon, È., Leduc, A., Le Goff, H., Lesieur, D., and K. Logan. 2006. Past, current, and future fire frequencies in Quebec's commercial forests: implications for the cumulative effects of harvesting and fire on age-class structure and natural disturbance-based management. Canadian Journal of Forest Research 36(11): 2737-2744.

Biondi, F., Gershunov, A., and C.R. Cayan. 2001. North Pacific decadal climate variability since 1661. Journal of Climate 14(1): 5-10.

Bonan, G.B. 2002. Ecological climatology: concepts and applications. Cambridge University Press: New York, NY.

Bonsal, B.R., Chakravarti, A.K., and R.G. Lawford. 1993. Teleconnections between North Pacific SST anomalies and growing season extended dry spells on the Canadian Prairies. International Journal of Climatology 13: 865–878.

Bonsal, B.R. and R.G. Lawford. 1999. Teleconnections between El Niño and La Niña events and summer extended dry spells on the Canadian Prairies. International Journal of Climatology 19: 1445-1458.

Bridge, S.R.J. 2001. Spatial and temporal variations in the fire cycle across Ontario. Northeast Science and Technology. NEST Tech. Rep. TR-043. Ontario Ministry of Natural Resources. South Porcupine, ON.

Brown, P.M. 2006. Climate effects on fire regimes and tree recruitment in Black Hill ponderosa pine forests. Ecology 87(10): 2500-2510.

Centre for Land and Biological Resources Research. 1996. Soil Landscapes of Canada, v.2.2, Research Branch, Agriculture and Agri-Food Canada. Ottawa, ON. Available at: http://nlwis-snite1.agr.gc.ca/slc-ppc22/index.phtml [access on 8 November 2006].

Collins, B.M., Omi, P.N., and P.L. Chapman. 2006. Regional relationships between climate and wildfire-burned area in the Interior West, USA. Canadian Journal of Forest Research 36: 699-709.

D'Arrigo, R., Villalba, R., and G. Wiles. 2001. Tree-ring estimates of Pacific decadal climate variability. Climate Dynamics 18(3-4): 219-224.

Drever, C.R., Messier, C., Bergeron, Y., and F. Doyon. 2006. Fire and canopy species composition in the Great Lakes-St. Lawrence forest of Témiscamingue, Québec. Forest Ecology and Management 231(1-3): 27-37.

Duffy, P.A., Walsh, J.E., Graham, J.M., Mann, D.H., and T.S. Rupp. 2005. Impacts of large-scale atmospheric-ocean variability on Alaskan fire season severity. Ecological Applications 15(4): 1317-1330.

Enfield, D.B. and L. Cid-Serrano. 2006. Projecting the risk of future climate shifts. International Journal of Climatology 26: 885-895.

Enfield, D.B., Mestas-Nuñez, A.M., and P.J. Trimble. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. Geophysical Research Letters 28(10): 2077-2080.

Environment Canada. 2004. Canadian climate normals or averages 1971–2000. Environment Canada, Ottawa, Ont. Available from http://climate.weatheroffice.ec.gc.ca/climate_normals/ [access on 5 July 2006].

Flannigan, M.D. and J.B. Harrington. 1988. A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada (1953–80). Journal of Applied Meteorology 27(4): 441–452.

Flannigan, M.D., Bergeron, Y., Engelmark, O., and B.M. Wotton. 1998. Future wildfire in circumboreal forests in relation to global warming. Journal of Vegetation Science 9: 469-476.

Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., and B.J. Stocks. 2005. Future area burned in Canada. Climatic Change 72: 1-16.

Fritts, H.C. 2001. Tree rings and climate. Blackburn Press: Caldwell, NJ.

Gillett, N.P., Weaver, A.J., Zwiers, F.W., and M.D. Flannigan. 2004. Detecting the effect of climate change on Canadian forest fires. Journal of Geophysical Research 31: L18211.

Girardin, M.P., Tardif, J.C., Flannigan, M.D., and Y. Bergeron. 2004. Multicentury reconstruction of the Canadian Drought Code from eastern Canada and its relationship with paleoclimatic indices of atmospheric circulation. Climate Dynamics 23: 99-115.

Girardin, M.P., Tardif, J.C., Flannigan, M.D., and Y. Bergeron. 2006a. Synoptic-scale atmospheric circulation and boreal Canada summer drought variability of the past three centuries. Journal of Climate 19(10): 1922-1944.

Girardin, M.P., Bergeron, Y., Tardif, J.C., Gauthier, S., Flannigan, M.D., and M. Mudelsee. 2006b. A 229-year dendroclimatic-inferred record of forest fire activity for the Boreal Shield of Canada. International Journal of Wildland Fire 15: 375-388.

Glueck, M.F. and C.W. Stockton. 2001. Reconstruction of the North Atlantic Oscillation, 1429-1983. International Journal of Climatology 21: 1453-1465.

Gray, S.T., Graumlich, L.J., Betancourt, J.L., and G.T. Pederson. 2004. A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D. Geophysical Research Letters 31: L12205.

Grenier, D.J., Bergeron, Y., Kneeshaw, D., and S. Gauthier. 2005. Fire frequency for the transitional mixedwood forest of Timiskaming, Quebec, Canada. Canadian Journal Forest Research 35: 656-666.

Hessl, A.E., McKenzie, D., and R. Schellhaas. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. Ecological Applications 14: 425-442.

Hofgaard, A., Tardif, J., and Y. Bergeron. 1999. Dendroclimatic response of Picea mariana and Pinus banksiana along a latitudinal gradient in the eastern Canadian boreal forest. Canadian Journal Forest Research 29: 1333-1346.

Holmes, R.L. 1999. Dendrochronology program library. Laboratory of Tree-Ring Research, University of Arizona. Tucson, AZ.

Hurrell, J.W. 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science 269: 676-679.

Johnson, E.A. 1992. Fire and vegetation dynamics: studies from the North American boreal forest. Cambridge Studies in Ecology. Cambridge University Press: New York, NY.

Johnson, E.A. and D.R. Wowchuk. 1993. Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. Canadian Journal of Forest Research 23: 1213-1222.

Johnson, E.A. and S.L. Gutsell. 1994. Fire frequency models, methods and interpretations. Advances in Ecological Research 25: 239-287.

Jones, P.D., Jónsson, T., and D. Wheeler. 1997. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland. International Journal of Climatology 17: 1433-1450.

Kasischke, E.S., Williams, D., and D. Barry. 2002. Analysis of the patterns of large fires in the boreal forest region of Alaska. International Journal of Wildland Fire 11: 131-144.

Kasischke, E.S. and M.R. Turetsky. 2006. Recent changes in the fire regime across the North American boreal region – Spatial and temporal patterns of burning across Canada and Alaska. Geophysical Research Letters 39(3): L09703.

Kerr, R.A. 2000. A North Atlantic climate pacemaker for the centuries. Science 288: 1984-1985.

Kitzberger, T., Brown, P.M., Heyerdahl, E.K., Swetnam, T.W., and T.T. Veblen. 2007. Contingent Pacific-Atlantic Ocean influence on multicentury wildfire synchrony over western North America. Proceedings of the National Academy of Science of the United States of America 104(2): 543-548.

Langlois, M. 1994. Receuil d'information sur les incendies forestiers au Québec de 1922 à 1993. Ministère des Ressources Naturelles du Québec, Direction de la conservation des forêts. Québec, QC.

Larsen, C.P.S. 1996. Fire and climate dynamics in the boreal forest of northern Alberta, Canada, from AD 1850 to 1985. The Holocene 6(4): 449-456.

Lefort, P., Gauthier, S., and Y. Bergeron. 2003. The influence of fire weather and land use on the fire activity of the Lake Abitibi area, Eastern Canada. Forest Science 49(4): 509-521.

Lefort, P., Leduc, A., Gauthier, S., and Y. Bergeron. 2004. Recent fire regime (1945-1998) in the boreal forest of western Quebec. Ecoscience 11(4): 433-445.

Luterbacher, J., Schmutz, C., Gyalistras, D., Xoplaki, E., and H. Wanner. 1999. Reconstruction of monthly NAO and EU indices back to AD 1675. Geophysical Research Letters 26: 2745-2748.

Macias Fauria, M. and E.A. Johnson. 2006. Large-scale climatic patterns control large lightning fire occurrence in Canada and Alaska forest regions. Journal of Geophysical Research 111: G04008.

Mann, D.H., Fastie, C.L., Rowland, E.L., and N.H. Bigelow. 1995. Spruce succession, disturbance, and geomorphology on the Tanana River floodplain, Alaska. Ecoscience 2(2): 184-199.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and R.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78: 1069-1079.

Ministère des Ressournces naturelles et de la Faune (MRNFQ). 2000. La limite nordique des forêts attribuables. Rapport final du comité, ministère des Ressources naturelles du Québec. Québec, QC.

Mudelsee, M. 2003. Estimating Pearson's correlation coefficient with bootstrap confidence interval from serially dependent time series. Mathematical Geology 35: 651-665.

Parisien, M.A., Hirsch, K., Lavoie, S., Todd, B., and V. Kafka. 2004. Saskatchewan fire regime analysis. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre. Edmonton, AB.

Phipps, R.L. 1985 Collecting, preparing, crossdating and measuring tree increment cores. USGS Water Resources Investigations Report 85-4148. Denver, CO. pp 5-35.

Reed, W.J. 2006. A note on fire frequency concepts and definitions. Canadian Journal of Forest Research 36(7): 1884-1888.

Robitaille, A. and J.-P. Saucier. 1998. Paysages régionaux du Québec méridional. Les Publications du Québec, Sainte-Foy, QC.

Rodionov, S. and J.E. Overland. 2005. Application of a sequential regime shift detection method to the Bering Sea ecosystem. ICES Journal of Marine Science 62: 328-332.

Rodionov, S.N. 2006. Use of prewhitening in climate regime shift detection. Geophysical Research Letters 31: L12707, doi:101029/2006GL025904.

Rodó, X. and M.À. Rodríguez-Arias. 2006. A new method to detect transitory signatures and local time/space variability structures in the climate system: the scale-dependent correlation analysis. Climate Dynamics 27: 441-458.

SAS Institute Inc. 2000. SAS OnlineDoc, Version 8. SAS Institute Inc., Cary, NC.

Shen, C., Wang, W.C., Gong, W., and Z. Hao. 2006. A Pacific Decadal Oscillation record since 1470 AD reconstructed from proxy data of summer rainfall over eastern China. Geophysical Research Letters 33: L03702.

Sibold, J.S. and T.T. Veblen. 2006. Relationships of subalpine forest fires in the Colorado Front Range with interannual and multidecadal-scale climatic variation. Journal of Biogeography 33: 833-842.

Skinner, W.R., Stocks, B.J., Martell, D.L., Bonsal, B., and A. Shabbar. 1999. The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada. Theoretical and Applied Climatology 63: 89-105.

Skinner, W.R., Flannigan, M.D., Stocks, B.J., Martell, D.L., Wotton, B.M., Todd, J.B., Mason, J.A., Logan, K.A., and E.M. Bosch. 2002. A 500 hPa synoptic wildland fire climatology for large Canadian forest fires, 1959-1996. Theoretical and Applied Climatology 71: 157-169.

Skinner, W.R., Shabbar, A., Flannigan, M.D., and K. Logan. 2006. Large forest fires in Canada and the relationship to global sea surface temperatures. Journal of Geophysical Research 111: D14106.

Smith, T.M. and R.W. Reynolds. 2002. Extended reconstruction of global sea surface temperatures based on COADS data (1854-1997). Journal of Climate 16: 1495-1510.

Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D., Hirsch, K.G., Logan, K.A., Martell, D.L., and W.R. Skinner. 2003. Large forest fires in Canada, 1959-1997. Journal of Geophysical Research 108: D18149.

Stokes, M.A. and T.L. Smiley. 1968. An introduction to tree-ring dating. University of Chicago Press, Chicago, IL.

Swetnam, T.W. 1993. Fire history and climate change in giant sequoia groves. Science 262(5):
885-889.

Swetnam, T.W. and J.L. Betancourt. 1990. Fire-Southern Oscillation relations in the southwestern United States. Science 249: 1017-1020.

Systat Software Inc. 2004. SYSTAT 11. Systat Software, Richmond, CA.

Trouet, V., Taylor, A.H., Carleton, A.M., and C.N. Skinner. 2006. Fire-climate interactions in forests of the American Pacific coast. Geophysical Research Letters 33: L18704.

Van Wagner, C.E. 1978. Age-class distribution and the forest fire cycle. Canadian Journal of Forest Research 8: 220-227.

Visbeck, M.H., Hurrell, J.W., Polvani, L., and H.M. Cullen. 2001. The North Atlantic Oscillation: Past, present, and future. Proceedings of the National Academy of Sciences of the United States of America 98(23): 12876-12877.

VoorTech Consulting. 2001. MeasureJ2X V3.1. VoorTech Consulting. Holderness, NH.

Weber, M.G. and M.D. Flannigan. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. Environmental Reviews 5: 145-166.

Yamaguchi, D.K. 1991. A simple method for cross-dating increment cores from living trees. Canadian Journal of Forest Research 21: 414-416.

Zhang, Y., Wallace, J.M., and D.S. Battisti. 1997. ENSO-like interdecadal variability: 1900-93. Journal of Climate 10: 1004-1020.

Zar, J.H. 1999. Biostatistical analysis, 4th edition. Prentice Hall, Upper Saddle River, NJ.

Table 1.1 Fire cycle estimates (yr) for the entire dataset and for spatial and temporal sub-samplings. The associated 95% confidence interval is indicated in parentheses. The dataset (n=200) was sub-sampled in 4 sectors (northeast, northwest, southeast, and southwest) with about 50 sampling points each; pLMS: probability associated with the Lagrange Multiplier Statistics; when pLMS is > 0.05, the stand-age distribution follows the negative exponential model and the mean forest age provides a good estimate of the fire cycle; $p\chi^2$: χ^2-probability for testing the effect of the factor, significant when < 0.05.

Data	Fire cycle estimate	p_{LMS}	Factor	p_{χ^2}
All data	153 (128-183)	0.0390		
NE	85 (59-122)	0.9930	Sectors	0.0121
NW	188 (126-310)	0.1644		
SE	166 (120-230)	<0.0001		
SW	170 (124-234)	<0.0001		
NE+NW	129 (97-171)	0.1801	N *vs.* S	0.1553
SE+SW	168 (134-211)	<0.0001		
NE+SE	130 (102-166)	0.0430	E *vs.* W	0.0748
NW+SW	179 (138-232)	0.2674		
<1850	164 (85-315)	0.3526	Periods	0.3258
1850-1940	99 (80-122)	0.3449		
>1940	283 (204-392)	0.0305		

Table 1.2 1880-1990 correlation analyses between decadal fire departures and decadal values of different climate indices (n=12, except for the PDO series from Mantua *et al.*1997, and the AMO series from Gray *et al.* 2004). Correlations were calculated using PEARSONT (Mudelsee 2003) which calculated Pearson coefficient (r) on detrended time series and the associated 95% confidence interval (95% CI) using bootstrap. Pearson coefficients are significant at p = 0.05 when the associated 95% CI does not contain the 0 value. Note that Pearson correlation for PDO of Shen *et al.* (2006) and winter NAO from Glueck and Stockton (2001) were calculated on ranked data.

Climate indices	r	(95% CI)
PDO instrumental Mantua *et al.* 1997	0.75	0.30;0.92
PDO Smith and Reynolds 2003	0.58	0.02;0.84
PDO 1790 D'Arrigo *et al.* 2001	0.79	0.55;0.90
PDO 1700 D'Arrigo *et al.* 2001	0.65	0.20;0.83
PDO Biondi *et al.* 2001	0.69	0.33;0.87
PDO Shen *et al.* 2006	0.61	0.08;0.87
Winter NAO instrumental Jones *et al.* 1997	0.68	0.25;0.91
Winter NAO Luterbacher *et al.* 1999	0.49	0.03;0.82
Winter NAO Glueck and Stockton 2001	0.80	0.48;0.94
AMO Gray *et al.* 2004	-0.07	-0.47;0.65

Table 1.3 T-values for different climate indices between reported fire years (n=15) and non-fire years between 1899 and 1996. Significant t-values ($p < 0.10$) are indicated in bold. Significance of the t-values was adjusted by calculating the effective sample size (n') to account for the autocorrelation (AR(1)) estimated using the IP4 method described in Rodionov 2006). Fire years were documented by replicated fire scars (n=12) and provincial fire data (n=3). Climate indices were tested without time lag (same year as the reported fire year), and one and two years before the reported fire year.

	PDO indices*					NAO indices	
	Instrumental Mantua	Smith Reynolds	D'Arrigo 1790	D'Arrigo 1700	Shen	Instrumental Jones	Glueck Stockton
AR(1)	0.37	0.32	0.04	0.00	0.26	0.07	0.43
n'	45	50	90	98	73	85	37
0	**-1.97**	-1.61	-0.73	-0.42	**-2.40**	0.00	0.63
1	-1.63	**-3.48**	**-1.96**	**-1.68**	-1.49	**-1.22**	**-2.00**
2	**-1.83**	**-1.87**	-0.92	-1.04	**-1.68**	**-1.71**	**-1.84**

* The Biondi *et al.* (2001) PDO index was not tested due to a high AR(1) parameter.

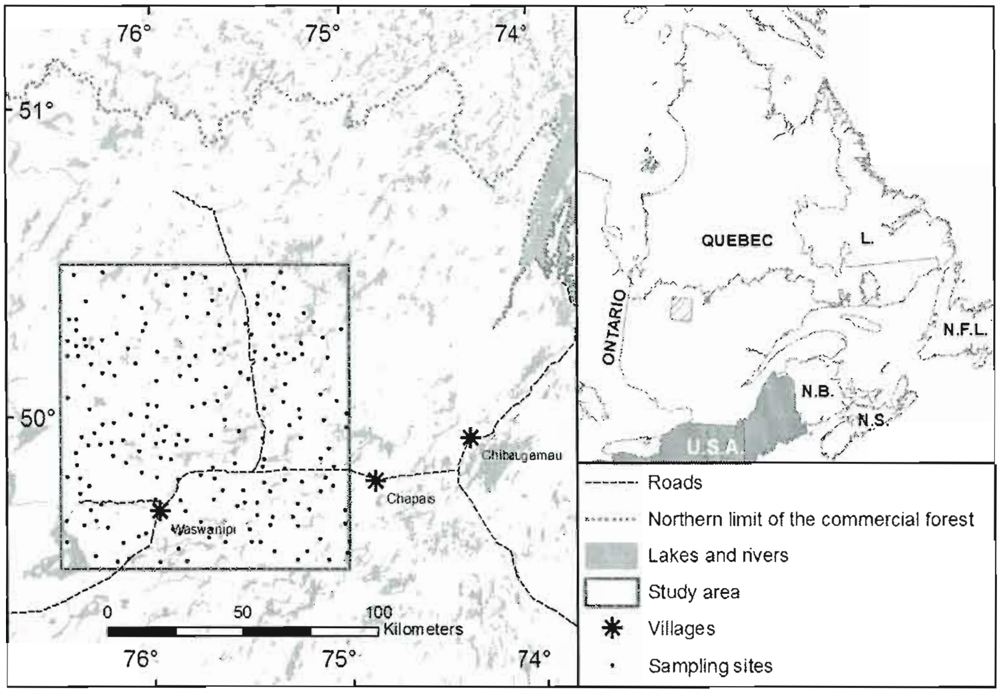

Figure 1.1 Location of the study area relative to the northern limit of the commercial forest in Quebéc.

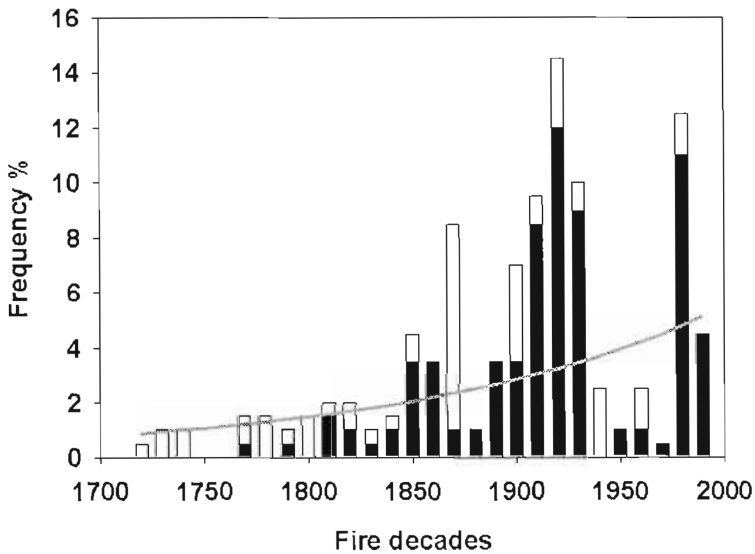

Figure 1.2 Forest age distribution (% of sampling points) per decade for the entire study area; open bars indicate censored data (minimum time-since-fire) and black bars indicate non-censored data (accurate estimate of the last fire date). The solid grey line represents the theoretical stand-age distribution expected under a constant fire frequency given by the negative exponential model (corresponding to a 153-yr fire cycle, see Table 1.1).

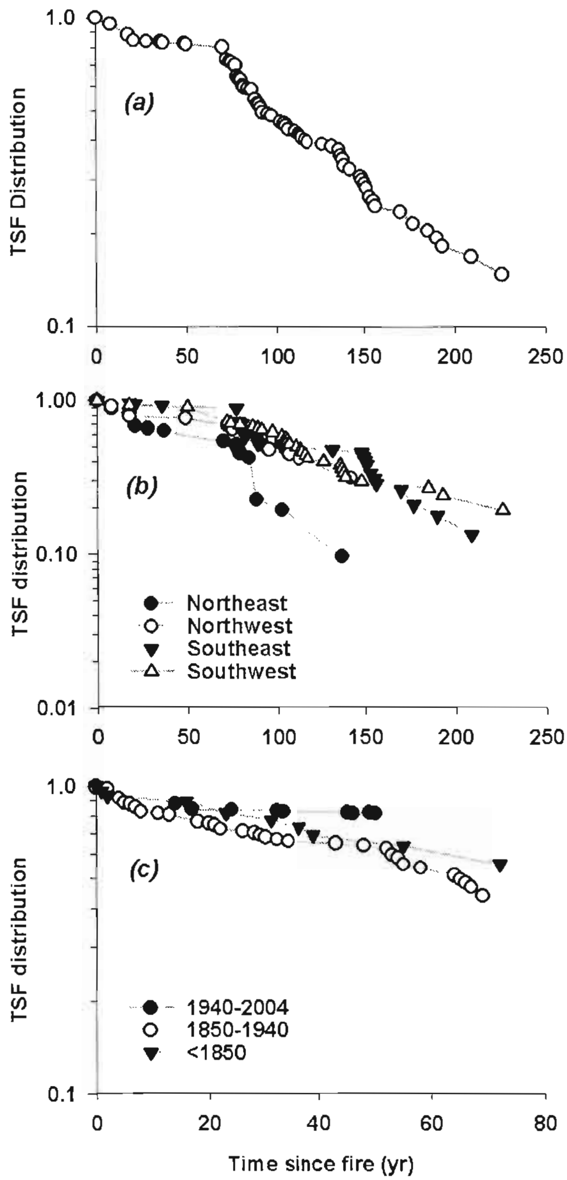

Figure 1.3 Time-since-fire distributions for the entire study area (a), for sectors of the study area (northeast, northwest, southeast, southwest) (b), and for time periods (<1850, 1850-1940, and 1940-2004) (c); see Table 1.1 for associated statistics.

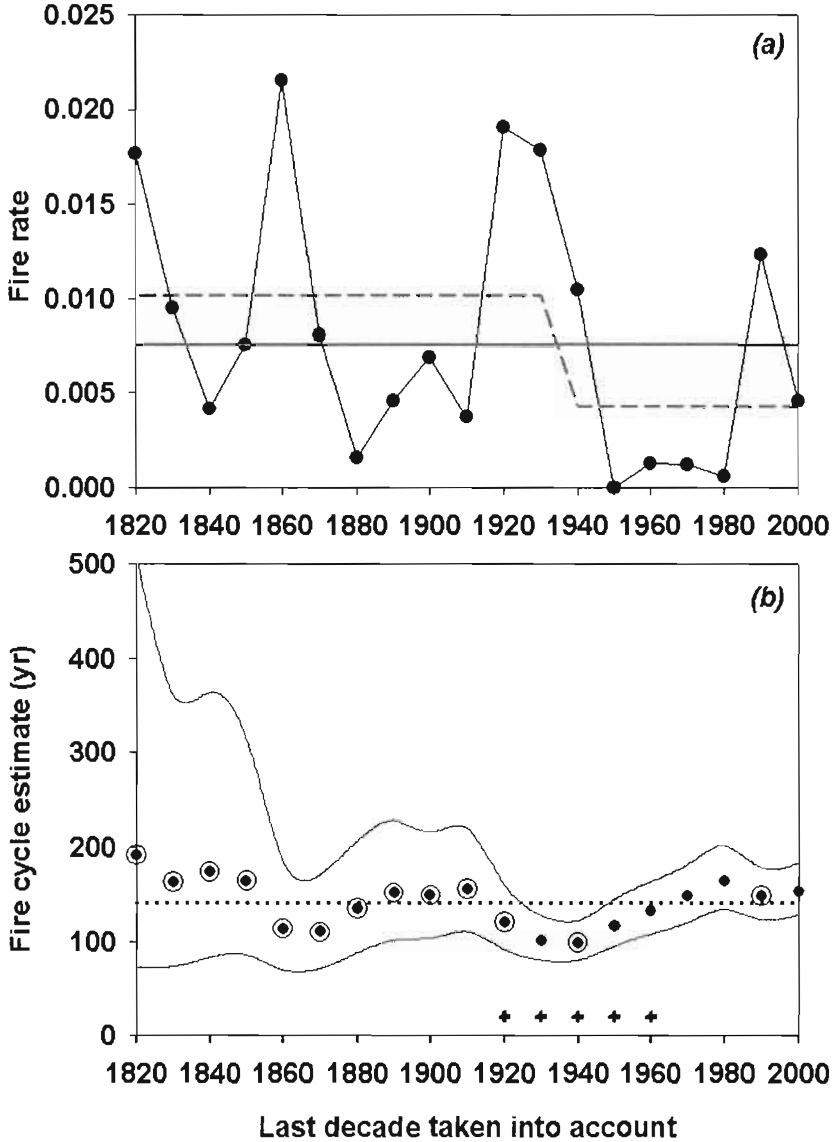

Figure 1.4 a) 1820-2000 variations in the decadal burn rate associated with the survival analysis of the time-since-fire data. The solid grey line indicates the 1820-2000 mean burn rate (1/mean fire cycle) corresponding to a 132-yr fire cycle. The dashed line indicates the mean burn rate before and after 1940, corresponding to a 98-yr and a 232-yr fire cycle, respectively. b) Fire cycle estimated through time. Computations were done sequentially by eliminating the most recent decade at each run. Upper and lower limits of the 95% confidence interval limits of the fire cycle estimates are indicated by the grey curves. Crosses indicate significant changes in the fire frequency before and after the corresponding decade using the χ^2-test at $p<0.05$. Circled dots indicate fire estimates associated with distribution well fitted ($p_{LMS}>0.05$) to the negative exponential model. The dotted line indicates the mean fire cycle for the entire time period investigated (141 yr).

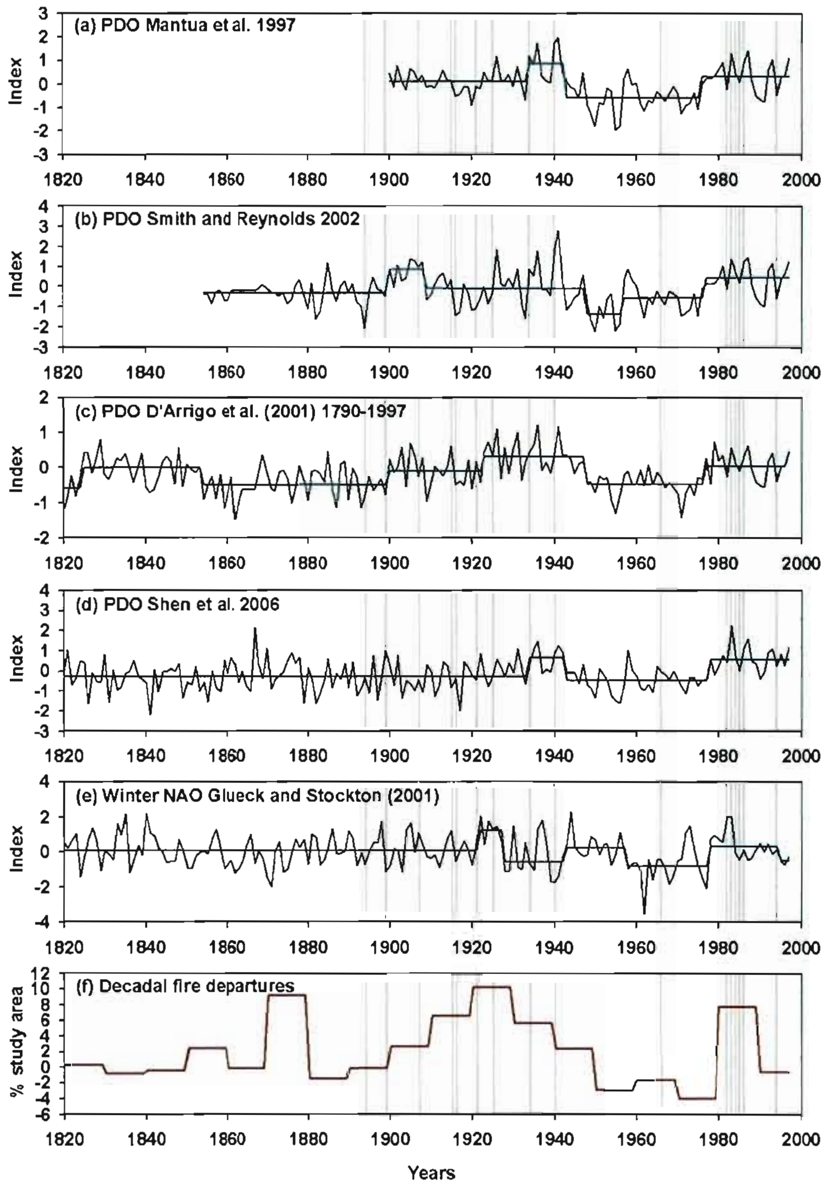

Figure 1.5 Climate indices (thin line) and decadal fire departures. Vertical grey bars indicate the fire years reported by replicated fire scars and major recent fire years. Thick line on (a), (b), (c), (d), and (e) is regime shift detection of the corresponding climate index with correction for autocorrelation (AR(1)). Regime shift detection makes it possible to verify that changes in the mean from one period to another are not just a manifestation of a red noise process (probability $\sigma = 0.10$, cut-off length = 10 years; parameters for AR(1) were estimated using the IP4 method; see Rodionov 2006). (f) Decadal fire departures as calculated by subtracting the theoretical (negative exponential) decadal time-since-fire (TSF) distribution to the sampled TSF distribution presented on Figure 2. See Table 1.3 for t-test results between fire and non-fire years.

CHAPITRE II

DENDROCLIMATIC INFERENCE OF WILDFIRE ACTIVITY IN QUÉBEC OVER THE 20TH CENTURY AND IMPLICATIONS FOR NATURAL DISTURBANCE-BASED FOREST MANAGEMENT AT THE NORTHERN LIMIT OF THE COMMERCIAL FOREST

2.1 Résumé

Cette étude examine l'influence du climat sur l'activité des feux à la limite nord de la forêt commerciale québécoise, dans une région où l'aménagement forestier entre en compétition avec l'activité des feux pour les peuplements matures. Le principal objectif est de déterminer si un signal climatique particulier contrôle l'activité régionale des feux, lorsqu'on la compare à l'activité des feux observée dans d'autres parties de la forêt boréale québécoise. La carte de corrélation entre des hauteurs géopotentielles à 500 hPa et l'aire brûlée annuellement (ABA) dans la région d'étude a été produite et comparée avec celles produites pour toute l'aire brulée annuellement au Québec, dans les zones de protection intensive (sud du Québec) et restreinte (nord du Québec). Ensuite, des analyses dencroclimatiques ont été réalisées afin d'obtenir des estimées de ABA dans les différents territoires examinés de 1904 à 2001 afin de vérifier la stabilité temporelle de l'influence climatique sur l'activité des feux. Le patron climatique qui contrôle l'ABA dans la région d'étude est intermédiaire entre ceux responsables de l'ABA dans les zones de protection intensive et restreinte. Les patrons de corrélation entre l'ABA et la circulation atmosphérique à 500 hPa entre les périodes 1948-1971 et 1972-2001 sont relativement similaires pour l'aire d'étude et pour la zone de protection restreinte. Nos résultats fournissent un mécanisme plausible expliquant le lien entre les variations des températures océaniques et l'activité des feux établie par de précédentes études. Ils fournissent également une information complémentaire à celle issue du système de l'Indice Forêt-Météo utilisé quotidiennement au Canada pour prévoir le risque de feu.

2.2 Abstract

We examined the influence of climate on the fire activity at the northern limit of commercial forest in western Québec, a region where forest management is currently competing with fires for mature stands. The main objective was to determine if a particular climate signal would control the fire activity in this region when compared with other parts of the Québec boreal forest. 500-hPa spatial correlation maps were created to compare the atmospheric patterns associated with the annual area burned (AAB) of the study area with those of the entire province of Québec, the intensive (southern Québec) and the restricted (northern Québec) fire management zones. Next, dendroclimatic analyses were used to obtain tree-ring

estimates of the AAB back to 1904 and to investigate the temporal stability of the climate influence on the regional fire activity. The climate controls associated with the AAB of the study area are intermediate between those associated with the AAB of the intensive and restricted fire management zones. The 500-hPa correlation patterns for the 1948-1971 and 1972-2001 periods were relatively stable through time for the study area and for the restricted fire management zone. Our results provide a plausible mechanism explaining the link between sea surface temperature and fire activity established by previous studies. They also provide information complementary to the Fire-Weather Index system that uses daily weather data.

2.3 Introduction

Forest fire is a major disturbance agent across the boreal forest, creating a mosaic of stands with different compositions and structures. The spatial variability of fire activity is a main challenge for boreal forest management, as laws and guidelines are generally formulated for large territories with heterogeneous fire regimes. When forest fires occur in managed forests, they can delay timber harvests by burning stands scheduled for harvest. They force the rapid development of salvage logging activities that modify management plans and annual allowable cut calculations *a posteriori* (Martell 1994; Armstrong 2004; Didion *et al.* 2007). At the landscape scale, natural disturbance-based forest management aims a stand-age distribution similar to that produced under a natural fire regime (Harvey *et al.* 2002). The spatial variations of the fire activity correspond to different opportunities to implement such management options (Bergeron *et al.* 2006). Lefort *et al.* (2004) described the spatial variations of the fire cycle for the recent period (1945-1998) across the commercial boreal forest in Québec using the provincial fire data. In particular, they identified a shorter fire cycle in the northwestern commercial forest. Dendroecological reconstruction of the historical fire activity at its southern margin indeed unveiled a short fire cycle compared with other parts of the Québec commercial forest (estimated at 280 years over the period 1940-2001; Le Goff *et al.* 2007). In this part of the Québec boreal forest, the northern limit of the commercial forest was set partly because of the high fire frequency prevailing in the James Bay territory (south to the Hudson Bay), situated north of this limit (MRNFQ 2000).

In Québec, fire suppression efforts are allocated according to two fire management zones approximately located south and north of 51°N since 1966 (Langlois 1994, Fig. 2.1). The intensive fire management zone (south of 51°N) covers inhabited and managed forests where all fires are actively fought to be controlled before they reach 3 ha in size. In the restricted fire management zone (north of 51°N), fires are allowed to burn under surveillance and are fought only if they threaten human lives or infrastructures, or if there is a risk that they will penetrate the intensive forest management zone. The territory identified as having a particularly high fire regime when compared with other parts of the commercial forest (Lefort *et al.* 2004; Le Goff *et al.* 2007) is crossed by the limit separating the two fire management zones (Fig. 2.1), which is also the northern limit of the commercial forest. This area of high fire activity is popularly known as the Fire Triangle Area.

Fire activity is controlled by a number of factors, namely weather and climate (Flannigan and Wotton 2001), vegetation composition and structure (Nash and Johnson 1996; Hély *et al.* 2000), anthropogenic activities (Lefort *et al.* 2003; Wotton *et al.* 2003; DeWilde and Chapin 2006), and topographic features (Kasischke *et al.* 2002; Cyr *et al.* 2007). Dry forest fuels and winds are major contributors to large-stand destroying fires (Flannigan and Wotton 2001; Westerling *et al.* 2006). The drying of forest fuels results from droughts of 3 days or more with less than 1.5 mm of total precipitation (Flannigan and Harrington 1988). These droughts have been associated with blocking high-pressure systems in the upper atmosphere, typically at the 500 hPa pressure level, over or upstream from the affected region (Nash and Johnson 1996; Skinner *et al.* 1999, 2002; Macias Fauria and Johnson 2006). The lightning activity associated with increased convective activity (creating thunderstorms) during the breakdown of these positive tropospheric anomalies (Nash and Johnson 1996) results in lightning fires. Skinner *et al.* (2006) further documented the influence of previous winter sea surface temperatures of the Atlantic and Pacific Oceans on the summer fire weather in the different forested regions across Canada. In particular, they highlighted the role of the Pacific Decadal Oscillation (PDO, Mantua *et al.* 1997) in creating a dipolar climatic control over the Québec forest: the PDO would negatively influence the fire activity in southern Québec and positively affect that in northern Québec (see Fig. 9c in Skinner *et al.* 2006). Moreover, Le Goff *et al.* (2007) found a positive correlation between changes in the decadal stand-age distribution in the Fire Triangle Area and changes in the PDO phases. Macias Fauria and Johnson (2006) also confirmed that the PDO would be a major control of the fire activity over northeastern Canada. A better comprehension of climatic patterns controlling the regional fire activity, and annual area burned in particular, would allow forest managers to better anticipate the fire risk for forthcoming years.

While the progress in characterizing the spatial and temporal variability of fire, fire-weather, and climate in Canada is significant (e.g. Skinner *et al.* 1999, 2002, 2006; Macias Fauria and Johnson 2006), the information is based upon observational data and is limited to periods not exceeding a few decades. To address this temporal constraint, tree-ring data have been used to reconstruct past fire activities in different regions (Westerling and Swetnam 2003; Drobyshev and Niklasson 2004; Girardin *et al.* 2006a, 2006b, 2007). The rationale behind this approach is that in temperate regions, trees produce annual radial increments, where changes in ring width from one year to the next reflect changes in precipitation and temperature, as well as other environmental factors (Hofgaard *et al.* 1999; Fritts 2001; Tardif *et al.* 2003; Girardin and Tardif 2005). Tree-growth is also sensitive to climate variations that promote fire activity, such as droughts and fluctuations in the strength of atmospheric oscillations (Larsen 1996; Girardin *et al.* 2006c). Spatial and temporal patterns of annual tree radial increments can be used to infer area burned variability and additionally extend area burned records at times during which there was no fire recording (Girardin 2007). Here we evaluate if such an approach is applicable to modelling past fire activity in Québec.

The aim of the present study was to characterize the Fire Triangle Area fire regime and to contrast its interannual variability against that prevailing elsewhere in the Québec forest. First, we have compared the 1972-2002 annual area burned (AAB) of the Fire Triangle Area with that of the province of Québec, the intensive forest management zone and the extensive fire management zone. Next, 500-hPa geopotential height spatial correlation maps were created for each area considered (spatial domain) to verify whether a particular climate signal would be associated with the Fire Triangle Area AAB. Finally, we have evaluated the potential of tree-ring chronologies for extending the AAB variability further back in the past as a means for assessing the temporal stability of the influence of climate variability on fire activity.

2.4 Study area

The study area, called the Fire Triangle area is located in the western feather moss-black spruce bioclimatic domain (Robitaille and Saucier 1998) (49°30'-52° N; 73-78°30' W; Fig. 2.1). Its forest consists principally of black spruce (*Picea mariana* (Mill.) B.S.P.) and jack pine (*Pinus banksiana* Lamb.) stands. The territory belongs to the Canadian Precambrian Shield, where the landscape has a high density of lakes and is dominated by morainal till deposits with scattered rocky outcrops covering 10-30% of the landscape (Robitaille and Saucier 1998, Centre for Land and Biological Resources Research 1996). It stretches over three ecoregions: the James Bay lowlands, the Rivière Rupert Plateau, and the Abitibi Plains (Ecological Stratification Working Group 1996). Eastman, Nemiscau, Waskaganish, Waswanipi and Mistissini are the main native communities established in the study area. The part belonging to the intensive fire management zone (commercial forest) is entirely allocated to forest management.

The mean annual temperature ranges from -2°C to 1°C with summer temperatures about 11.5°C to 14°C and winter temperatures from -16°C to -12°C. Annual precipitation ranges from 700 to 900 mm. Altitude, relief and lake density gently increase towards the west, while the frequency of bogs and poorly-drained sites decreases moving away from the James Bay Lowlands (Ecological Stratification Working Group 1996). In the eastern part of the study area, the altitude is about 350 m, with summits about 1065 m around Lac Mistassini (located at the far eastern end of the study area). Most of the area is underlain by Precambrian granites and gneisses, and has an undulating drift-covered surface. It consists largely of flat, poorly drained plains with subdued fluvial and marine features near James Bay while its southwestern part is dominated by fine-textured, level to undulating lacustrine deposits. Intermixed within these deposits are bedrock outcrops and organic deposits (Ecological Stratification Working Group 1996).

2.5 Data and methods

This section is divided as follows. First, we describe the fire data and 500-hPa geopotential height data under use, along with the relevant statistical analyses linking these datasets. Second, we describe the development of the site tree-ring width chronologies and the analyses of climate response functions. Here we define site tree-ring width chronologies as averages of annual ring-width measurements for one to several cores per tree and from a sample of trees (typically 30) growing on similar ecological sites. Third, the statistical procedure employed to develop tree-ring estimates of past annual area burned is described. Essentially, this procedure consists in calibrating fire statistics against the tree-ring width chronologies and applying the statistical model to the chronologies at times for which there are no fire recordings available.

2.5.1 Fire data

We used the provincial fire data provided by the Ministère des Ressources naturelles et de la Faune du Québec (MRNFQ) for the 1972-2002 period to calibrate our annual area burned (AAB) models. The period covered by these data encompasses that during which systematic fire detection in the restricted fire management zone was made by detection planes, which only began in the late 1960s (Blanchet 2003). AAB variability was examined at the scale of four spatial domains, namely the Fire Triangle Area, the entire province of Québec, the intensive (southern Québec) and the restricted (northern Québec) fire management zones as set in 2005 (Fig. 2.1). Additionally, the large fire database (LFDB), consisting of all forest fires of size greater than 200 ha that occurred in Canada from 1959 to 1999 (Stocks *et al.* 2003), was also used to look at systematic differences in the timing of the season of large forest fires among the four domains. The period for this analysis was restricted to 1972-1999. The LFDB was also used to test the fidelity of our tree-ring estimates of AAB against independent data (procedure described further below). Although incomplete, the LFDB still contains information about extreme fire years prior to 1972 that may be used as independent information for validation of our AAB models.

Shapiro-Wilk normality tests indicated right-skewness in the MRNFQ AAB frequency distributions (P = 0.000). The logarithmic transformation (LOG) was found to provide an adequate data transformation to meet the normality requirement (P > 0.05). Next, a positive trend in the AAB data was removed using a linear least squares fitting.

2.5.2 *Fire-climate relationships*

The statistical relationship between year-to-year area burned and climate variability was analyzed using correlation maps with 500-hPa geopotential height (NCEP/NCAR reanalysis data from Kalnay *et al.* 1996). The NCEP/NCAR reanalysis grid has a temporal coverage from 1948 to the present and a spatial coverage of 2.5° latitude by 2.5° longitude. Geopotential height approximates the actual height of the air column above sea level (in meters) of a given constant pressure surface (here 500 hPa). As a warm layer of air is less dense and thicker than a cool one, a region of warm air appears as a region with higher atmospheric pressure. Large forest fires in Canada (> 200 ha) are generally associated with blocking high-pressure systems in the upper atmosphere that cause obstruction, on a large scale, of the normal west-to-east progress of migratory storms (Skinner *et al.* 1999). Spatial correlation maps were created using the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer (http://climexp.knmi.nl/).

2.5.3 *Tree-ring analyses*

Sampling for tree-ring width data from jack pine and black spruce was conducted in the summers of 2002 and 2003 in stands located in the southernmost part of the Fire Triangle Area (Fig. 2.1). Site selection was mainly constrained by accessibility. A total of 16 sites were sampled along the two main road axes crossing the study area, drawing a latitudinal transect and a longitudinal transect about 160 km each (Fig. 2.1). Dendrochronological samples were collected after scanning each 40-km road section for old-looking stands. For each sampling site, two diametrically opposite cores or one transversal section was taken from 30 trees of each species. Cores and cross-sections were dried, sanded, and dated by counting annual tree rings. Dendrochronological samples were then measured using a Velmex system with the MEDIR packaging for windows (available at http://web.utk.edu/~grissino/software.htm). Crossdating was validated using the program COFECHA from the Dendrochronology Program Library (Holmes 1999). All cores with potential errors were rechecked and corrected if possible; otherwise, they were omitted from further analyses. Series having low correlation with the mean site chronology ($r < 0.3$) were excluded.

The raw tree-ring width measurements were processed to remove age/size-related trends using a cubic smoothing spline of 60 years with 50% frequency response (Cook and Peters 1981). It preserves about 99% of the variance within individual series at a wavelength of 19 years. This means that common trends (1–20 years) between trees are conserved (Hofgaard *et al.* 1999). These chronologies were then averaged by site to further remove endogenous stand disturbance effects on ring width and to enhance the common signal. Autoregressive modelling was used to remove serial persistence. All these transformations were done using the ARSTAN program (Cook and Holmes 1999) to obtain these 16 site tree-ring width residual chronologies. Chronologies and their associate statistics are described in Appendix A1.

The common variance within the site tree-ring width residual chronologies was extracted and analyzed using a non-rotated Principal Component Analysis (PCA) performed on a correlation matrix (Legendre and Legendre 1998). In this procedure, the 16 tree-ring chronologies were transformed into new sets of orthogonal variables. The first principal component (PC) accounted for the maximum possible proportion of the variance in tree growth, and succeeding PCs accounted for as much of the remaining variance as possible. Eigenvectors, or the loading of each tree-ring chronology on each component, gave the spatial representation of the PCs.

The effects of climate fluctuations (temperature and precipitation) on radial growth were analyzed using correlation and bootstrap response function analyses (Guiot 1991; Briffa and Cook 1990) for the period 1916-2002 to describe the climate signal recorded by tree-growth, and to evaluate the potential of dendroclimatology to extend further in the past variability in fire activity. The bootstrap response function analysis provides a test of significance of the stability of the regression coefficients between tree-growth and weather variables within a specific period by repeated, random sampling of the data. A weight was associated with each monthly variable, expressing the separate relative effects of several climate factors on ring width. This method has the advantage of avoiding errors caused by collinearity among variables and providing a more realistic estimate of tree response to climate. Bootstrap response functions (processed through 500 iterations) and correlations were performed using PRECON 5.17 (Fritts *et al.* 1991). Monthly mean temperature from Chapais-Chibougamau and total monthly precipitation data from the Roberval Airport were obtained from the Adjusted Historical Canadian Climate Database (Environment Canada 2004). This database provides rehabilitated precipitation and homogenized temperature datasets where data have been adjusted to account for changes in the instrumental equipment or for station relocation (Vincent and Gullett 1999; Mekis and Hogg 1999). The selected stations were the closest to our area covering a relatively long common interval (1916-2002). For the correlations and response functions, a sequence of 16 months was used, from May of the year prior to ring formation (t – 1) to August of the year current to ring formation (t). Correlation and response functions were computed for the 1916-2001 period. This timeperiod was limited by the availability of temperature and precipitation records. While the AAB are available until 2002, the timeperiod used for the analysis end in 2001 because of the forward lag used for the PCs.

2.5.4 Tree-ring estimates of the annual area burned

As a means of evaluating the potential of the site tree-ring width chronologies for reconstruction of past annual variations in fire activity, a stepwise multiple regression using a backward selection was computed using SYSTAT 11 (Systat

Software Inc. 2004) to fit a linear model relating the detrended LOG-transformed AAB records (period 1972-2001) to the PCs (including their forward lag). Once the regression coefficients were estimated for the calibration period, they were applied to the PCs for as far back as possible to produce a series of AAB estimates (Girardin *et al.* 2006b; Girardin 2007). The short length of the instrumental AAB series (31 years) prevented us from conducting a split-sample calibration scheme commonly employed in tree-ring based climate reconstructions (Cook and Kairiukstis 1990).

We used the LFDB fire data for the 1959-1971 period to verify the ability of the tree-ring estimates to detect high fire years out of the calibration timeperiod (1972-2001). The difference in mean of estimated fire activity at the time of the four highest and remaining nine fire years between 1959 and 1971 from the large fire database was tested using the non-parametric Mann–Whitney U test statistic (Zar 1999). A significant test result indicates a tendency for the statistical fire estimates to reproduce with confidence years of high fire activity (Girardin *et al.* 2006a). In addition, we created 500-hPa geopotential height correlation maps of AAB estimates for the pre-calibration period (1948-1971) and for the calibration period (1972-2001), and compared these with those obtained from the instrumental AAB data (1972-2002). We postulated that for an effective reconstruction, when applied to the period 1948-1971, the spatial correlation patterns should resemble that of the period 1972-2001. We also repeated the procedure on temperature and precipitation data from the Climate Research Unit TS 2.1 database (Mitchell and Jones 2005) for two sub-periods: 1904-1950 and 1951-2001. All correlation maps were computed using the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer (http://climexp.knmi.nl/).

2.6 Results

2.6.1 Description of the annual area burned series

All of the domains under study had high AAB in 1976, 1983, 1996, 1997, and 2002 (Fig. 2.2). Conversely, 1989 was a highest fire year for the Québec province between 1972 and 2002, the 1989 fire activity being located in the restricted fire management zone. 1991 was the highest fire year in the intensive fire management zone only, but this fire year did not appear as majot at the scale of the Québec province. Between 1972 and 2002, about 72% of the AAB in the entire province of Québec (Fig. 2.2b) occurred in the restricted fire management zone (Fig. 2.2d). In spite of these few years during which the fire activity seems asynchrounous between the restricted and the intensive fire management zones, both AAB series are correlated (Pearson correlation coeficient r = 0.3933, significant at P = 0.05).

June was the month with the highest area burned by large forest fires for all spatial domains (between 60 and 80% of the total area burned, Fig. 2.3). July was the second month with the highest area burned for the Fire Triangle Area and for the restricted fire management zone (Fig. 2.3a, 2.3d), while it was May for the intensive fire management zone (Fig. 2.3c).

2.6.2 Atmospheric controls of the annual area burned in Québec

All AAB series correlated with similar atmospheric patterns, consisting of three centres-of-action (Fig. 2.4). High fire years are associated with 1) blocking highs south of the Hudson Bay area, 2) a trough on the Pacific Coast, and 3) another trough on the Atlantic Coast. For the intensive fire management zone (Fig. 2.4c), the Ontario High and the Pacific Low are however located south relative to the position they occupied for the other spatial domains examined. In the following section, we used dendroclimatology to obtain tree-ring estimates of AAB further back in time and verify whether these atmospheric patterns associated with fire activity had also prevailed earlier.

2.6.3 Tree radial growth and climate relationships

The first three principal components of the 16 residual chronologies accounted for 80% of the variance in tree growth (Fig. 2.5). The first principal component (PC1) captured the environmental signal held in common by the chronologies and explained 57% of the variance, PC2 accounted for 16% of the variance and separated species (Fig. 2.5a), and PC3 discriminated northern and southern sites (7% variance, Fig. 2.5b). According to the correlation and response functions, tree growth (PC1) was negatively influenced by previous July temperatures, and positively correlated with previous October and current January to June temperatures (Fig. 2.6). Winter and spring precipitation (mostly in the form of snow, Environment Canada 2004) negatively influenced tree growth. PC2 is negatively correlated with previous October temperatures, meaning that jack pine growth would be positively influenced by a prolonged autumn. PC3 (latitudinal gradient) would also be negatively influenced by previous summer temperatures (like PC1) (Fig. 2.6).

2.6.4 Tree growth and fire activity

Tree-ring chronologies and AAB are negatively correlated, excepted for two spruce chronologies (N2E and N3E) that displayed a significant positive correlation with the Fire Triangle Area AAB (Table 2.1). Eight of the nine chronologies that correlated with the restricted fire management zone AAB were also correlated with the Québec AAB. The tree-growth of the next year ($PC1_{t+1}$) and the latitudinal gradient in tree growth for the current year ($PC3_t$) were correlated with the AAB for the Fire Triangle Area, for the province of Québec and for the restricted fire management zone. The tree-growth variability associated with species growth for the next year ($PC2_{t+1}$) was also correlated with the AAB for the restricted fire management zone and for the province. The negative correlation between AAB of the current year and tree growth of the next year ($PC1_{t+1}$) is confirmed by the high negative correlation (and response function) between tree-growth (current year, PC1) and the July temperature of the previous year (Fig. 2.6). Recall that June-July are the months accounting for the highest fire activity in the fire season for all spatial domains examined except the intensive fire management zone (Fig. 2.3). No chronologies and no PCc were correlated to the AAB of the intensive fire management zone.

Results of the stepwise multiple regressions relating AAB to tree-ring components are presented in Table 2.2. The most parsimonious model corresponded to the Fire Triangle Area, where tree-growth of the next year ($PC1_{t+1}$) alone accounted for about 20% of the variance in the AAB estimates in the equation:

$$LOG(FTA)_t = 4.1718 - 0.1341PC1_{t+1} \quad \text{(Eq. 2.1)}$$

where $LOG(FTA)_t$ is the estimate of LOG-transformed and detrended AAB of the Fire Triangle Area for the current year. No solution was found for the intensive fire management zone. The models for the Québec AAB and for the restricted fire management zone AAB also selected the PC3 (latitudinal gradient) and are very similar (corresponding reconstructed AAB series were highly correlated: r = 0.999 over 1972-2001). As the model for the restricted fire management zone AAB presented slightly better statistics (Table 2), we chose to represent only the best of both models in Fig. 2.7. A total of 48.3% of the variance in the AAB of the restricted fire management zone over the period 1972-2001 was accounted for by estimates obtained from the equation:

$$LOG(RES)_t = 4.8063 - 0.1071PC1_t - 0.2034PC3_t - 0.1081PC1_{t+1} \quad \text{(Eq. 2.2)}$$

where $LOG(RES)_t$ is the estimate of LOG-transformed and detrended AAB of the restricted fire management zone. Mann–Whitney U test statistics indicated that tree-ring fire estimates have some skills for reconstructing high fire years (as established by the LFDB over 1959-1971), with t values ranging from −3.0782 (P = 0.0105) for the Fire Triangle Area, and −10.7194 (P = 0.0001) for the restricted fire management zone.

Over the calibration period 1972-2001, spatial correlation maps indicated similar patterns between the Fire Triangle Area AAB observations (Fig. 2.4a), AAB estimates (Fig. 2.8b), and 500-hPa heights. Specifically, year-to-year AAB changes, for both the observations and estimates, were positively correlated with heights over the Hudson Bay area and negatively to heights over the Pacific and Atlantic coasts. When applied to the period 1948-1971 (Fig. 2.8a), the spatial correlation pattern for the Fire Triangle Area AAB estimates resembles that of the interval 1972-2001, albeit weaker, and with a slight eastern displacement of the centres-of-action between both sub-periods (Fig. 2.8b). For the restricted fire management zone, the correlation patterns between AAB estimates and 500 hPa geopotential heights were also weaker for the earlier period (Fig. 2.8c) than for the later (Fig. 2.8d). AAB estimates were associated with the same three centres-of-action as AAB observations (Fig. 2.4d), although slightly different positions and weaker correlations were found for the earlier period.

The weakening of the AAB-climate relationships between both sub-periods examined is elucidated with spatial correlation maps between AAB estimates and temperatures and precipitation (Fig. 2.9). For the later interval (1951-2001), AAB estimates displayed positive correlations with temperature (Fig. 2.9b) and negative correlations with precipitation (Fig. 2.9d). For the earlier period, correlation pattern with temperature is weaker than for the recent period for the Fire Triangle Area (Fig. 2.9a), and almost disappeared for the restricted fire management zone (Fig. 2.9e). Correlation patterns with precipitation for both areas examined are weaker for the pre-calibration period than for the calibration period, but stayed negative. Hence, while the estimates are tracking seemingly well the AAB-climate relationships during the second half of the 20th century, weaker correlation patterns obtained during the pre-calibration period highlight some temporal instability in the AAB estimates. The correlation between AAB estimates and the $PC1_{t+1}$ was constant over 1904-2001, but they also showed that the $PC3_t$ (latitudinal gradient, unlagged) has been correlated to AAB estimates only since 1951 (Table 2.3).

2.7 Discussion

2.7.1 The Fire Triangle Area fire regime

1989 and 1991 AAB illustrate the importance of the spatial location of fire across the province: while major conflagrations occurred in 1989 in the north of the boreal forest at the James Bay latitudes (in the restricted fire management zone, Couturier and Saint-Martin 1990), the 1991 fires occurred in the North Shore area (in the intensive fire management zone, Lavoie *et al.* 1997). These particular fire events illustrated how extreme fire years may be determined by a few large fire events located in a specific geographic area. Based on the AAB, the monthly distribution of AAB and the associated atmospheric patterns, we identified the fire regime of the

Fire Triangle Area as intermediate between those of the intensive and the extensive fire management zones.

The intensive fire management zone was the only spatial domain for which no residual chronology was correlated with its AAB time series. This suggests that the climate pattern controlling the fire activity in the Fire Triangle Area and the restricted fire management zone was different from the one controlling the fire activity in the intensive fire management zone. The fire suppression history, the easier fire detection, the better accessibility to fire suppression means, the composition and the distribution of forest fuels in the southern part of the intensive fire management zone are other factors that could have altered the fire-climate relationship in this zone. In the Fire Triangle Area, while the fire cycle followed the historical trends observed in other parts of the commercial forest in Québec (i.e., lengthening of the fire cycle since 1850, 1910-1940 higher fire period), it was generally shorter (Le Goff *et al.* 2007) than in other parts of the intensive fire management zone (commercial forest).

2.7.2 Tree-ring analyses

The dendroclimatic response of black spruce and jack pine that we obtained was consistent with those obtained by Hofgaard *et al.* (1999) and by Girardin *et al.* (2006c). In particular, spring temperatures have a strong positive influence on tree growth by determining the start of the growing season. Late previous summer temperatures had conversely a negative effect on tree growth by slowing or preventing trees from building reserves necessary for the next growing season. The response of trees to precipitation seems more variable from one study to another, probably due to the higher spatial variability in precipitation data (while the spatial variability in temperature acts over larger areas). Tree growth in our study area responded negatively to winter and spring precipitation. In the Fire Triangle Area, precipitation falls as snow from September to May (Environment Canada 2004). Winter and spring precipitation is thus associated with a thicker snow depth that takes more time to melt, and that can delay the start of the growing season and the fire season.

Tree growth and AAB are generally negatively correlated as drought may slow tree growth and favour the occurrence of large fires. However, two spruce chronologies were positively correlated with the Fire Triangle Area AAB. Both chronologies were sampled on the northern part of the latitudinal transect. At these latitudes, the transect crossed several recent burns (1986, 1983) inside the Fire Triangle Area (Fig. 2.1). Alive old black spruce stands were only located in topographic depressions that had escaped these recent fires, probably because of their poor drainage, creating fire breaks (all other chronologies were typically sampled on well-drained sites). Their positive correlation with the AAB may be explained by the positive effects on spruce growth of a lowering of the water table. Fire prone (dry) years would allow spruce to grow better in these sites where usually nutrient uptake in coniferous species is showered by the oxygen deficiency in roots when compared with stands growing in well-drained sites (Zinkan *et al.* 1974). In dendroclimatology, it is generally recognized that chronologies should be sampled in well-drained sites to extract a regional drought signal, but our results suggested that chronologies from poorly-drained sites can also provide a local climate signal suited for calibration against fire activity observations.

Our tree-ring AAB estimates showed good correlations with the instrumental AAB series. The 500-hPa correlation patterns for the pre-calibration and calibration periods were relatively stable through time for the Fire Triangle Area and for the restricted fire management zone. The weaker correlation patterns obtained with the analyses of temperatures and precipitation prior to 1950 however brings us to question the reliability of our estimates to adequately model past AAB. The higher correlation of temperature, precipitation, and PC3 for the recent period could be a confounding consequence of tree age rather than an actual shift in climate responses of trees. Indeed, most chronologies started in 1840, and tree-age can alter tree-growth response to climate (Carrer and Urbinati 2004). The correlation between AAB estimates and 500 hPa geopotential height indicated however a relatively stable fire-climate relationship for both sub-periods. The suitability of our AAB estimates for inference of multidecadal variability in mean is also questionable due to the detrending and prewhitening procedures applied to the tree-ring width measurement series (Cook *et al.* 1995). They however provide good estimates of the frequency of high (or low) fire years (interannual variations in AAB; Girardin *et al.* 2006a). Moreover, the correlations obtained with the geopotential heights and with tree-growth (PC1) are constant enough to consider the potential of tree rings is this region to reconstruct past fire activity. A larger tree-ring chronology sampling design would increase the likelihood of extracting the seasonal drought signal that most strongly relates to the fire activity. A sampling design that would encompass a large corridor across the boreal forest could also more efficiently track the upper atmosphere oscillation responsible for much of the AAB (Girardin 2007).

2.7.3 The fire-climate relationship in the Fire Triangle Area

The atmospheric circulation pattern related to AAB was similar for the Fire Triangle Area and for the restricted fire management zone, but differed from the pattern controlling the intensive fire management zone AAB. The Ontario High co-occurring with a Pacific Low would have controlled the AAB in Québec since at least 1948 (the period examined was limited by the availability of geopotential height data). The Atlantic Low correlated with AAB since about 1972, and would have been a more recent climate feature than the two previous centres-of-action of the climate pattern associated with AAB. Interestingly the position of the Atlantic Low identified here is close to another well-documented Low over Iceland that corresponds to the positive phase of the North Atlantic Oscillation reported since 1970 (Hurrell and Van Loon 1997). Le Goff *et al.* (2007) reported that the recent positive phase of NAO would have contributed to the increase in area burned observed in the Fire Triangle Area for the last 30 years. These results were in relatively good agreement with those of Macias Fauria and Johnson (2006) who reported that the Arctic Oscillation (a teleconnection highly correlated with the NAO, see Ambaum *et al.* 2001) would partly explain the recent increase in area burned observed over northern Québec. We might speculate that the Atlantic Low reported here could be related to the recent positive NAO phase as both phenomena seem synchronous.

The 500 hPa correlation maps presented here provided a plausible step for the mechanism underlying the influence of changes in the Pacific sea surface temperatures (SST) on the fire activity of the Fire Triangle Area (Le Goff *et al.* 2007; Macias Fauria and Johnson 2006), as well as on the fire activity of the other spatial domains examined. Recent studies demonstrated how SST anomalies of the North Atlantic and the North Pacific Oceans may influence global atmospheric circulation in the Northern Hemisphere (Lau 1997; Czaja and Frankignoul 1999, 2002; Frankignoul and Sennéchael 2007). The survey of the frequency, intensity, and length of these climate patterns can provide complementary information to the daily monitoring of the fire risk using the Fire Weather Index system (Van Wagner 1987). Tracking changes in SST patterns would allow us to forecast high and low fire seasons about six months before the beginning of the fire season (Skinner *et al.* 2006; Macias Fauria and Johnson 2006), while the monitoring of 500 hPa anomalies over the Hudson-Bay/Ontario, the Pacific and the Atlantic coasts could provide complementary information allowing us to anticipate fire risk in the different sectors of forested Québec a few weeks in advance. This information could contribute to the planning and strategic deployment of fire management efforts throughout the territory.

2.7.4 Fire and forest management in the Fire Triangle Area

Le Goff *et al.* (2007) and Macias Fauria and Johnson (2006) documented that fire activity in the Fire Triangle Area has been increasing since 1970 in spite of the development of fire suppression efforts over the same period. Our results suggested that fire suppression did not alter the fire–climate relationship (which has been stable since at least 1948) and would not contribute to significantly decreasing the AAB in this part of the boreal forest. Conversely, the fact that we did not obtain AAB tree-ring estimates for the intensive fire management zone suggested either that suppression could have interfered in the fire-climate relationship earlier than the 1970s (as fire suppression in this zone started earlier than in the Fire Triangle Area), or that the fire activity is controlled by a climate signal different than the one for the other spatial domains. The fire suppression system was developed during a period (1950-1970) when forest fire activity was relatively low compared with the 1910-

1940 period and with the global increase in the fire activity observed over the last 30 years (Skinner *et al.* 1999, 2002; Gillett *et al.* 2004). This situation triggers more and more situations where the fire suppression capacity is overwhelmed.

In the Fire Triangle Area, forest management faces timber losses due to forest fires. Given that the fire activity is high in the Fire Triangle Area when compared with other parts of the Québec commercial forest (Le Goff *et al.* 2007), and that this fire risk will remain high in the future (Bergeron *et al.* 2006), forest fires will remain a significant constraint to the development of sustainable forest management strategies in this part of the boreal forest. While the influence of climate on the regional fire activity seems to have been stable since at least 1948, the interannual variability of fire activity challenges the fire regime criterion to set the northern limit of the commercial forest in Québec. Due to its climate controls, and in the context of climate variability and change, this criterion is highly dynamic, and should thus be re-evaluated to analyze the additive effects of fire and harvesting on the forest dynamics in this area. This evaluation could be done using modelling (see Fall *et al.* 2004; Didion *et al.* 2007) to compare different management scenarios and to determine which one is the best compromise between the minimum additive impacts of both disturbances on forested ecosystems and our socio-economic expectations relative to the forest.

2.8 Acknowledgements

Julie Fortin (Ministère des Ressources naturelles du Québec) provided the provincial fire data. We gratefully thank Jacques Tardif and France Conciatori from the Centre for Forest Interdisciplinary Research, University of Winnipeg, for the lab facilities and for their expertise in dendrochronology. This research was funded by the Sustainable Forest Management Network.

2.9 References

Armstrong, G.W. 2004. Sustainability of timber supply considering the risk of wildfire. Forest Science 50: 626-639.

Ambaum, M.H.P., Hoskins, B.J., and D.B. Stephenson. 2001. Arctic oscillation or North Atlantic oscillation? Journal of Climate 14: 3495-3507.

Bergeron, Y., Cyr, D., Drever, C.R., Flannigan, M., Gauthier, S., Kneeshaw, D., Lauzon, È., Leduc, A., Le Goff, H., Lesieur, D., and K. Logan. 2006. Past, current, and future fire frequencies in Quebec's commercial forests: implications for the cumulative effects of harvesting and fire on age-class structure and natural disturbance-based management. Canadian Journal of Forest Research 36(11): 2737-2744.

Blanchet, P. 2003. Forest Fires: The Story of a War. Cantos International Publishing, Montreal, QC.

Briffa, K. and E.R. Cook. 1990. Methods of response function analysis. In 'Methods of Dendrochronology', Cook, E.R. and L.A. Kairiukstis (eds) pp. 240-247. Kluwer Academic Publishers, Boston, MA.

Brown, P.M. 2006. Climate effects on fire regimes and tree recruitment in Black Hill ponderosa pine forests. Ecology 87(10): 2500-2510.

Carrer, M. and C. Urbinati. 2004. Age-dependent tree ring growth responses to climate in Larix decidua and Pinus cembra. Ecology 85: 730-740.

Centre for Land and Biological Resources Research. 1996. Soil Landscapes of Canada, v.2.2, Research Branch, Agriculture and Agri-Food Canada, Ottawa, ON. Available at: http://nlwis-snite1.agr.gc.ca/slc-ppc22/index.phtml [accessed 12 June 2007].

Cook, E.R. and K. Peters. 1981. The smoothing spline: A new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. Tree-Ring Bulletin 41: 45–53.

Cook, E.R. and L.A. Kairiukstis. 1990. 'Methods of Dendrochronology.' Kluwer Academic Publishers: Boston, MA.

Cook, E.R., Briffa, K.R., Meko, D.M., Graybill, D.A., and G. Funkhouser. 1995. The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies. The Holocene 5: 229–237.

Cook, E.R. and R.L. Holmes. 1999. User manual for ARSTAN program. Laboratory of Tree-Ring Research, University of Arizona. Tucson, AZ.

Couturier, S. and G. Saint-Martin. 1990. Effets des feux de forêts sur les caribous migrateurs. Ministère des Loisirs, de la Chasse et de la Pêche du Québec, Direction Générale de Nouveau-Québec. Québec, QC.

Cyr, D., Gauthier, S., and Y. Bergeron. 2007. Scale-dependent determinants of heterogeneity in fire frequency in a coniferous boreal forest of Eastern Canada. Landscape Ecology 22: 1325–1339.

Czaja, A. and C. Frankignoul. 1999. Influence of the North Atlantic SST on the atmospheric circulation. Geophysical Research Letters 26: 2969-2972.

Czaja, A. and C. Frankignoul. 2002. Observed impact of Atlantic SST anomalies on the North Atlantic oscillation. Journal of Climate 15: 606-623.

DeWilde, L. and F.S. Chapin III. 2006. Human impacts on the fire regime of interior Alaska: interactions among fuels, ignition sources, and fire suppression. Ecosystems 9: 1342–1353.

Didion, M., Fortin, M.-J., and A. Fall. 2007. Forest age structure as indicator of boreal forest sustainability under alternative management and fire regimes: A landscape level sensitivity analysis. Ecological Modelling 20: 45-58.

Drobyshev, I. and M. Niklasson. 2004. Linking tree rings, summer aridity, and regional fire data: an example from the boreal forests of the Komi Republic, East European Russia. Canadian Journal of Forest Research 34: 2327-2339.

Ecological Stratification Working Group. 1996. A National Ecological Framework for Canada. Agriculture and Agri-Food Canada. Ottawa, ON.

Environment Canada. 2004. Canadian climate normals or averages 1971–2000. Environment Canada. Ottawa, ON. [Online] URL: http://climate.weatheroffice.ec.gc.ca/climate_normals/index_f.html [accessed 12 June 2007].

Fall, A., Fortin, M.-J., Kneeshaw, D.D., Yamasaki, S.H., Messier, C., Bouthillier, L., and C. Smyth.
2004. Consequences of various landscape-scale ecosystem mangement strategies and fire cycles on age-class structure and harvest in boreal forests. Canadian Journal of Forest Research 34: 310-322.

Flannigan, M.D. and J.B. Harrington. 1988. A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada (1953-80). Journal of Applied Meteorology 27: 441-452.

Flannigan, M.D. and B.M. Wotton. 2001. Climate, weather, and area burned. In 'Forest Fires', Johnson, E.A. and K. Miyanishi (Eds). pp. 351-373. Academic Press, New York, NY.

Frankignoul, C. and N. Sennéchael. 2007. Observed influence of North Pacific SST anomalies on the atmospheric circulation. Journal of Climate 20: 592-606.

Fritts, H. 2001. Tree ring and climate. Blackburn Press, Caldwell, NJ.

Fritts, H.C., Vaganov, E.A., Sviderskaya, I.V., and A.V. Shashkin. 1991. Climatic variation and tree-ring structure in conifers: empirical and mechanistic models of tree-ring width, number of cells, cell size, cell-wall thickness and wood density. Climate Research 1: 97–116.

Gillett, N.P., Weaver, A.J., Zwiers, F.W., and M.D. Flannigan. 2004. Detecting the effect of climate change on Canadian forest fires. Geophysical Research Letters 31(18): L18211.

Girardin, M.P. and J. Tardif. 2005. Sensitivity of tree growth to the atmospheric vertical profile in the Boreal Plains of Manitoba, Canada. Canadian Journal of Forest Research 35(1): 48-64.

Girardin, M.P., Bergeron, Y., Tardif, J.C., Gauthier, S., Flannigan, M.D., and M. Mudelsee. 2006a. A 229-year dendroclimatic-inferred record of forest fire activity for the Boreal Shield of Canada. International Journal of Wildland Fire 15(3): 375-388.

Girardin, M.P., Tardif, J., and M.D. Flannigan. 2006b. Temporal variability in area burned for the province of Ontario, Canada, during the past 200 years inferred from tree rings. Journal of Geophysical Research – Atmosphere 111(D17): D17108.

Girardin, M.P., Tardif, J.C., Flannigan, M.D., and Y. Bergeron. 2006c. Synoptic-scale atmospheric circulation and boreal Canada summer drought variability of the past three centuries. Journal of Climate 19(10): 1922-1947.

Girardin, M.P. 2007. Interannual to decadal changes in area burned in Canada from 1781 to 1982 and the relationship to Northern Hemisphere land temperatures. Global Ecology and Biogeography 16 (10): 557-566.

Guiot, J. 1991. The bootstrapped response function. Tree-Ring Bulletin 51: 39–41.

Harvey, B.D., Leduc, A., Gauthier, S., and Y. Bergeron. 2002. Stand-landscape integration in natural disturbance-based management of the southern boreal forest. Forest Ecology and Management 155(1-3): 369-385.

Hély, C., Bergeron, Y., and M.D. Flannigan. 2000. Effects of stand composition on fire hazard in mixed-wood Canadian boreal forest. Journal of Vegetation Science 11: 813–824.

Hofgaard, A., Tardif, J., and Y. Bergeron. 1999. Dendroclimatic response of Picea mariana and Pinus banksiana along a latitudinal gradient in the eastern Canadian boreal forest. Canadian Journal of Forest Research 29: 1333-1346.

Holmes, R.L. 1999. Dendrochronology program library. Laboratory of Tree-Ring Research, University of Arizona. Tucson, AZ.

Hurrell, J.W. and H. van Loon. 1997. Decadal variations in climate associated with the North Atlantic Oscillation. Climatic Change 36: 301-326.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and D. Joseph. 1996. The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society 77: 437-471.

Kasischke, E.S., Williams, D., and D. Barry. 2002. Analysis of the patterns of large fires in the boreal forest region of Alaska. International Journal of Wildland Fire 11: 131-144.

Langlois, M. 1994. Recueil d'information sur les incendies forestiers au Québec de 1922 à 1993. Ministère des Ressources naturelles du Québec, Direction de la conservation des forêts. Québec, QC.

Larsen, C.P.S. 1996. Fire and climate dynamics in the boreal forest of northern Alberta, Canada, from AD 1850 to 1989. The Holocene 6(4): 449-456.

Lavoie, L., Sirois, L., and M.-J. Fortin. 1997. Évaluation de l'efficacité de l'ensemencement de graines d'essences forestières dans des sites présentant des difficultés de régénération dans le feu de 1991 sur la Côte-Nord. Ministère des Ressources naturelles du Québec. Québec, QC.

Lau, N.-C. 1997. Interactions between global SST anomalies and the midlatitude atmospheric circulation. Bulletin of the American Meteorological Society 78(1): 21-33.

Lefort, P., Gauthier, S., and Y. Bergeron. 2003. The influence of fire weather and land use on the fire activity of the Lake Abitibi area, eastern Canada. Forest Science 49(4): 509-521.

Lefort, P., Leduc, A., Gauthier, S., and Y. Bergeron. 2004. Recent fire regime (1945-1998) in the boreal forest of western Québec. Ecoscience 11(4): 433-445.

Legendre, P. and L. Legendre. 1998. Numerical ecology. 2nd English edition. Elsevier Science BV, Amsterdam, Netherlands.

Le Goff, H., Flannigan, M.D., Bergeron, Y., and M.P. Girardin. 2007. Historical fire regime shifts related to climate teleconnections in the Waswanipi area, central Quebec, Canada. International Journal of Wildland Fire 16(5): 607-618.

Macias Fauria, M. and E.A. Johnson. 2006. Large-scale climatic patterns control large lightning fire occurrence in Canada and Alaska forest regions. Journal of Geophysical Research 111: G04008.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and R.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78: 1069-1079.

Martell, D.L. 1994. The impact of fire on timber supply in Ontario. The Forestry Chronicle 72(2): 164-173.

Mekis, E. and W.D. Hogg. 1999. Rehabilitation and analysis of Canadian daily precipitation time series. Atmosphere-Ocean 37(1): 53-85.

Mitchell, T.D. and P.D. Jones. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25(6): 693-712.

Ministère des Ressources naturelles et de la Faune du Québec (MRNFQ). 2000. La limite nordique des forêts attribuables. Ministère des Ressources naturelles du Québec. Québec, QC.

Nash, C.H. and E.A. Johnson. 1996. Synoptic climatology of lightning-caused forest fires in subalpine and boreal forests. Canadian Journal of Forest Research 26(10): 1859–1874.

Robitaille, A. and J.-P. Saucier. 1998. Paysages régionaux du Québec méridional. Les Publications du Québec. Sainte-Foy, QC.

Skinner, W.R., Stocks, B.J., Martell, D.L., Bonsal, B., and A. Shabbar. 1999. The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada. Theoretical and Applied Climatology 63: 89-105.

Skinner, W.R., Flannigan, M.D., Stocks, B.J., Martell, D.L., Wotton, B.M., Todd, J.B., Mason, J.A., Logan, K.A., and E.M. Bosch. 2002. A 500 hPa synoptic wildland fire climatology for large Canadian forest fires, 1959-1996. Theoretical and Applied Climatology 71: 157-169.

Skinner, W.R., Shabbar, A., Flannigan, M.D., and K. Logan. 2006. Large forest fires in Canada and the relationship to global sea surface temperatures. Journal of Geophysical Research 111: D14106.

Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D., Hirsch, K.G., Logan, K.A., Martell, D.L., and W.R. Skinner. 2003. Large forest fires in Canada, 1959-1997. Journal of Geophysical Research–Atmospheres 108(D1): 8149.

Systat Software Inc. 2004. SYSTAT 11. Systat Software, Richmond, CA.

Tardif, J., Camarero, J.J., Ribas, M., and E. Gutiérrez. 2003. Spatiotemporal variability in tree growth in the central Pyrénées: climatic and site influences. Ecological Monographs 73(2): 241-257.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Petawawa National Forestry Institute, Forestry Technical Report 35. Chalk River, ON.

Vincent, L.A. and D.W. Gullett. 1999. Canadian historical and homogeneous temperature datasets for climate change analyses. International Journal of Climatology 19: 1375-1388.

Westerling, A.L. and T.W. Swetnam. 2003. Interannual to decadal drought and wildfire in the western United States. Eos, Transactions of the American Geophysical Union 84(49): 545-560.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., and T.W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313(5789): 940-943.

Wigley, T.M.L., Briffa, K.R., and P.D. Jones. 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. Journal of Climate and Applied Meteorology 23: 201-213.

Wotton, B.M., Martell, D.L., and K.A. Logan. 2003. Climate change and people-caused forest fire occurrence in Ontario. Climatic Change 60(3): 275-295.

Zar, J.H. 1999. Biostatistical analysis. 4th edn. Prentice Hall, NJ.

Zinkan, C.G., Jeglum, J.K., and D.E. Harvey. 1974. Oxygen in water culture influences growth and nutrient uptake of jack pine, black spruce, and white spruce seedlings. Canadian Journal of Plant Science 54: 553-558.

Table 2.1 Pearson correlations between tree-ring width residual chronologies and their principal components and annual area burned records (log-transformed and detrended) from the Fire Triangle Area (FTA), the province of Quebec (QC), and the restricted fire management zone (RES). Only significant correlation coefficients ($P < 0.10$) are indicated. Coefficient above the critical value for $P = 0.05$ are indicated in bold. Site chronology idents: first letter indicates the transect (E for the longitudinal transect, N for the latitudinal transect), number indicates the position on the transect (increasing eastern or northern), and last letter indicates the species (E for black spruce and P for jack pine). Period analyzed is 1972-2002. Unlagged principal components are indicated by t (current year) while lagged principal components are indicated by t+1 (next year). No correlations were found for the intensive fire management zone annual area burned.

Tree-growth index	FTA	QC	RES
E1E		-0.313	-0.308
E2E		**-0.384**	**-0.414**
E3E			
E4E			
N1E			
N2E	0.305		
N3E	0.322		
N4E			
E1P		**-0.398**	**-0.414**
E2P		**-0.365**	**-0.369**
E3P		-0.319	-0.330
E4P		**-0.396**	**-0.415**
N1P			-0.316
N2P			
N3P			
N4P		-0.315	-0.343
$PC1_t$			
$PC2_t$			
$PC3_t$	0.305	**0.457**	**0.455**
$PC1_{t+1}$	**-0.453**	-0.333	-0.356
$PC2_{t+1}$		-0.321	-0.315
$PC3_{t+1}$			

Table 2.2 Forward stepwise regressions of the annual area burned (log-transformed and detrended) of the Fire Triangle Area (FTA), the province of Quebec (QC), and the restricted fire management zone (RES) using the principal components of the residual chronologies (t unlagged, t+1 lagged one year forward). No regression was found for the intensive fire management zone. In-and-out thresholds were set at P < 0.05. The period investigated is 1972-2001.

Variable	R^2	adj R^2	SE	*P*	F-ratio	D stat	AR1	Selected
FTA	0.2054	0.1770	0.7977	0.0119	7.2374	2.0291	-0.0346	$PC1_{t+1}$
QC	0.4391	0.3743	0.5121	0.0016	6.7834	2.5634	-0.3070	$PC1_t$ $PC3_t$ $PC1_{t+1}$
RES	0.4829	0.4232	0.5560	0.0006	8.0935	2.6302	-0.3271	$PC1_t$ $PC3_t$ $PC1_{t+1}$

Table 2.3 Pearson correlations between estimates of the annual area burned (log-transformed and detrended) of the Fire Triangle Area (FTA), the province of Quebec (QC), and the restricted fire management zone (RES) and principal components (unlagged t and lagged t+1) of the residual chronologies for the 1904-2001 period and for two sub-periods (1904-1950, 1951-2001). Only significant correlations at P = 0.05 are indicated. No correlations were found significant for PC2t, PC2t+1, and PC3t+1.

	$PC1_t$	$PC3_t$	$PC1_{t+1}$
		1904-2001	
FTA			-1.000
QC	-0.568	-0.491	-0.594
RES	-0.588	-0.454	-0.600
		1904-1950	
FTA		0.312	-1.000
QC	-0.690		-0.665
RES	-0.701		-0.669
		1950-2001	
FTA			-1.000
QC	-0.499	-0.654	-0.555
RES	-0.522	-0.621	-0.558

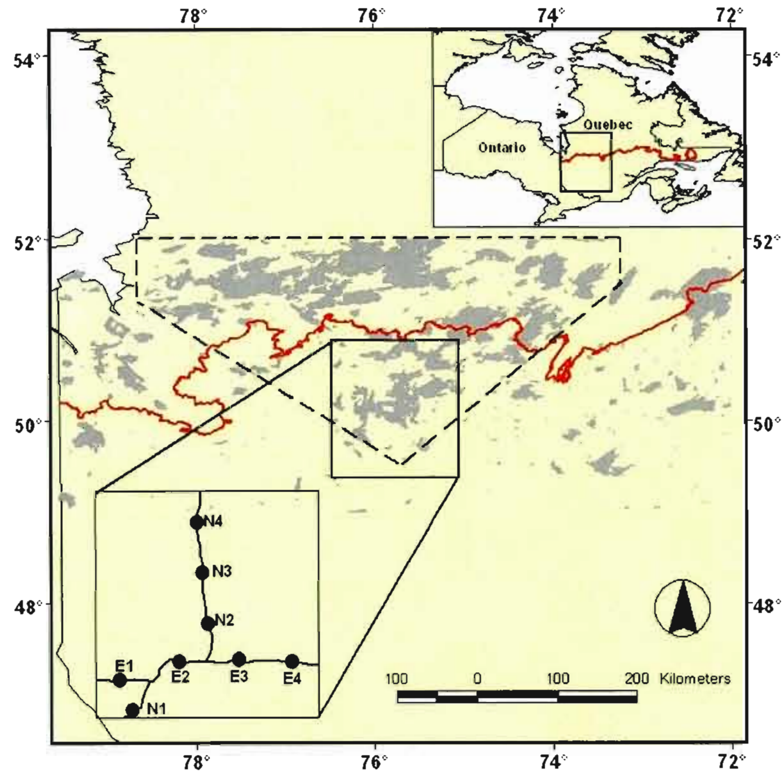

Figure 2.1 Location of the study area and map of the dendrochronological sampling sites. The study area is delineated by a dashed line and lies over the 2005 limit between the intensive and restricted fire management zones (top chart). Area burned polygons (grey) highlight the prevailingly high area burned in the study area (1972-2002). Tree-ring chronologies were sampled at 40 km intervals along the two main road axes crossing the squared area. Site chronology idents: the first letter indicates the transect (E for the longitudinal transect, N for the latitudinal transect) and the number indicates the position on the transect (increasing eastern or northern).

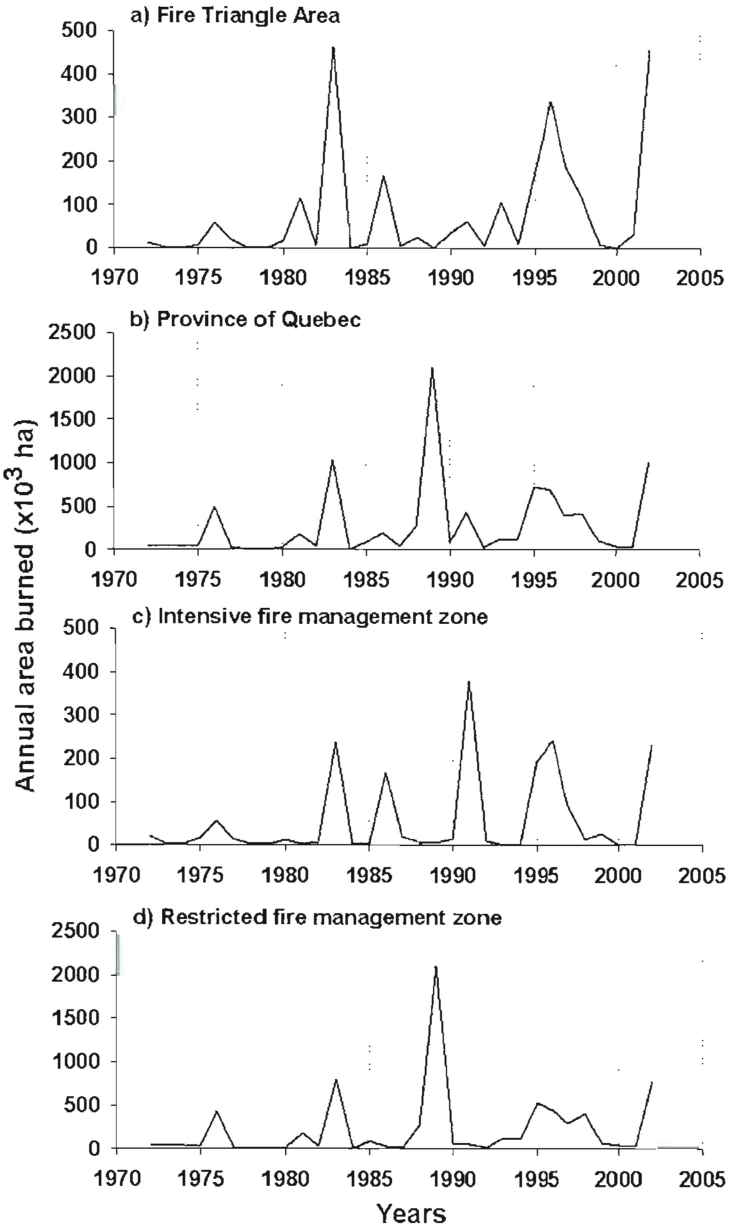

Figure 2.2 1972-2002 annual area burned in the Fire Triangle Area (a), in the province of Québec (b), and in the intensive (c) and extensive (d) fire management zones.

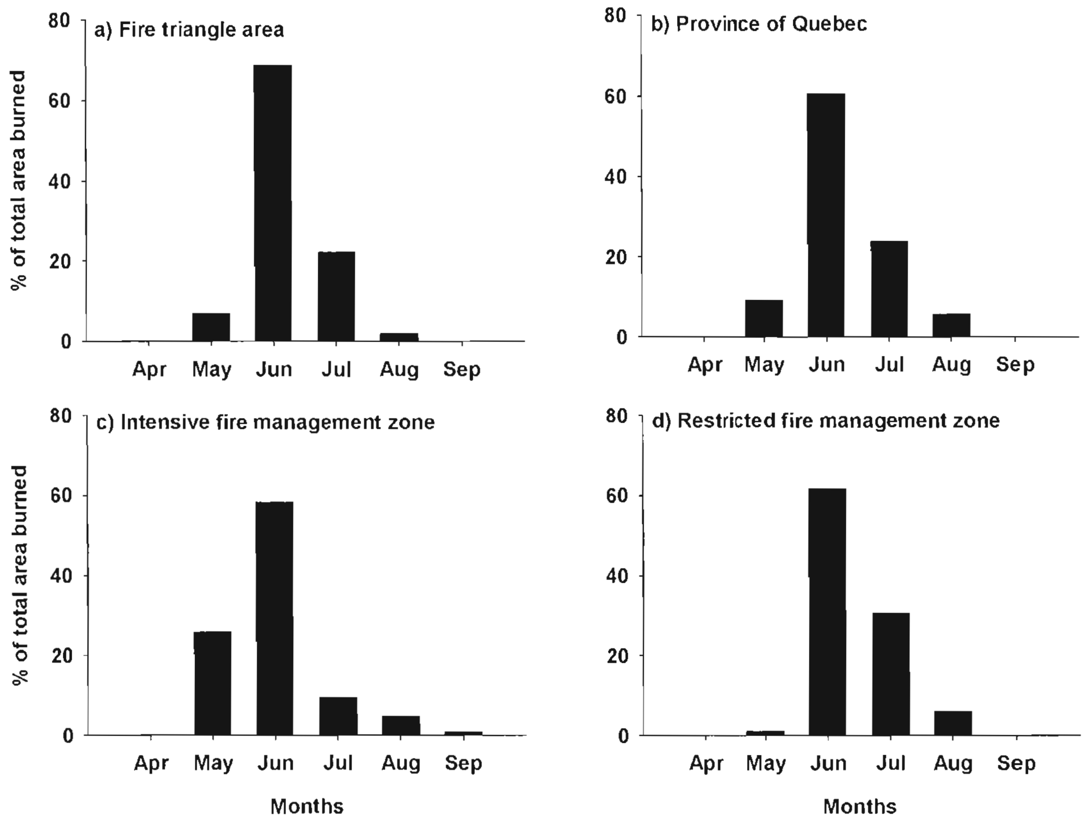

Figure 2.3 1972-1999 monthly distribution of the area burned across the fire season for the four spatial domains investivated. Area burned data from the Large Fire Database (Stocks *et al.* 2003).

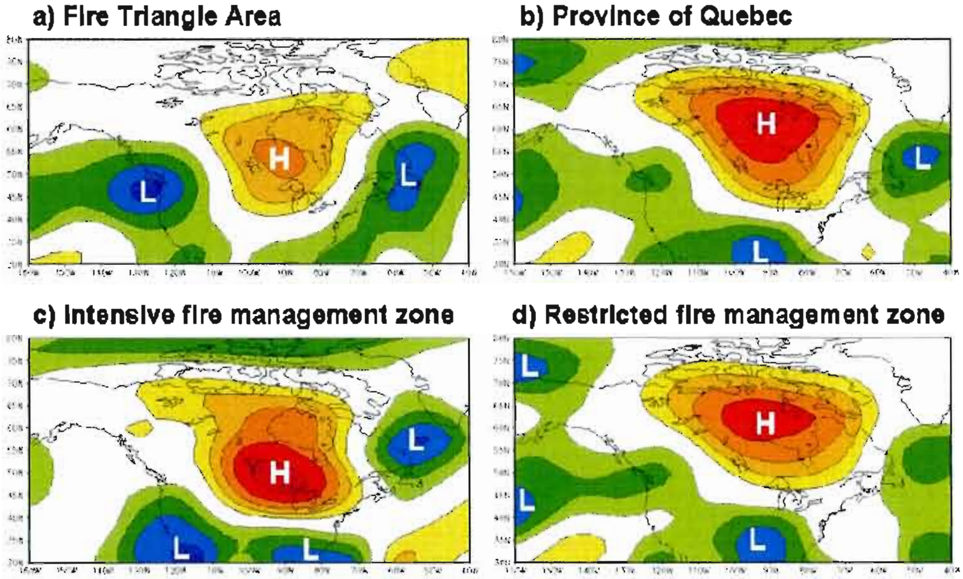

Figure 2.4 Correlation maps of the instrumental (1972-2002) annual area burned (log-transformed and detrended) and June 500 hPa geopotential heights for the four domains investigated. Correlation scale ranges from -0.5 (dark violet) to 0.5 (dark pink). H identifies positive 500 hPa anomalies and L identifies negative 500 hPa anomalies (anomalies correspond to correlations significant at $P < 0.10$).

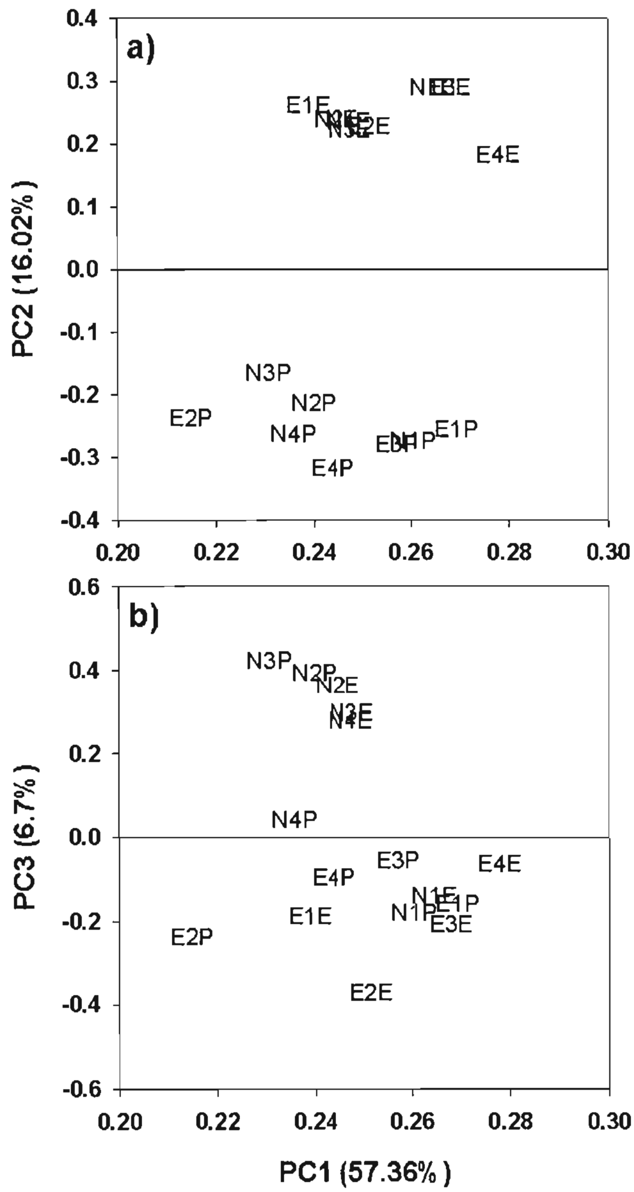

Figure 2.5 Residual chronology eigenvectors along the first three axes of the principal component analysis (period 1904-2002). Percentage of variance explained is indicated for each principal component. Site chronology idents: first letter indicates the transect (E for the longitudinal transect, N for the latitudinal transect), number indicates the position on the transect (increasing eastern or northern), and last letter indicates the species (E for black spruce and P for jack pine).

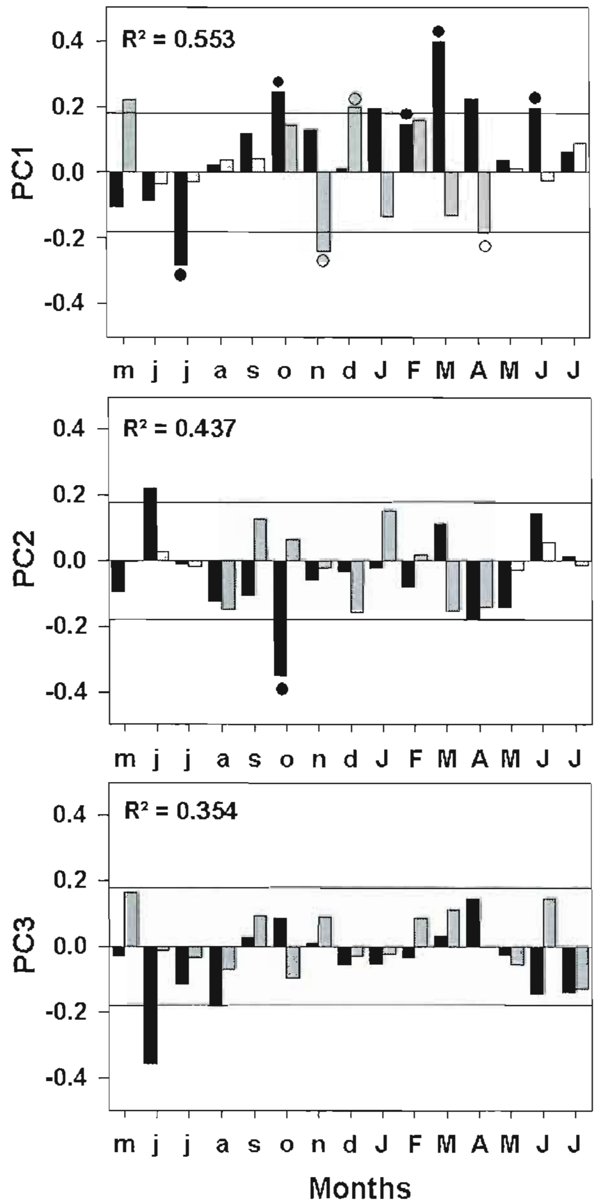

Figure 2.6 Correlations and response functions of the first three principal components of the residual chronologies with monthly temperature (black bars) and precipitation (grey bars) from May of the year previous to ring formation (lower case) to September of the year current to ring formation (upper case). Dots indicate the monthly variables with significant response functions. For each principal component, the R^2 obtained with monthly temperature and precipitation taken together is indicated. Critical threshold for the correlations (at $p < 0.10$) is indicated by the dotted lines. The period investigated is 1916-2001.

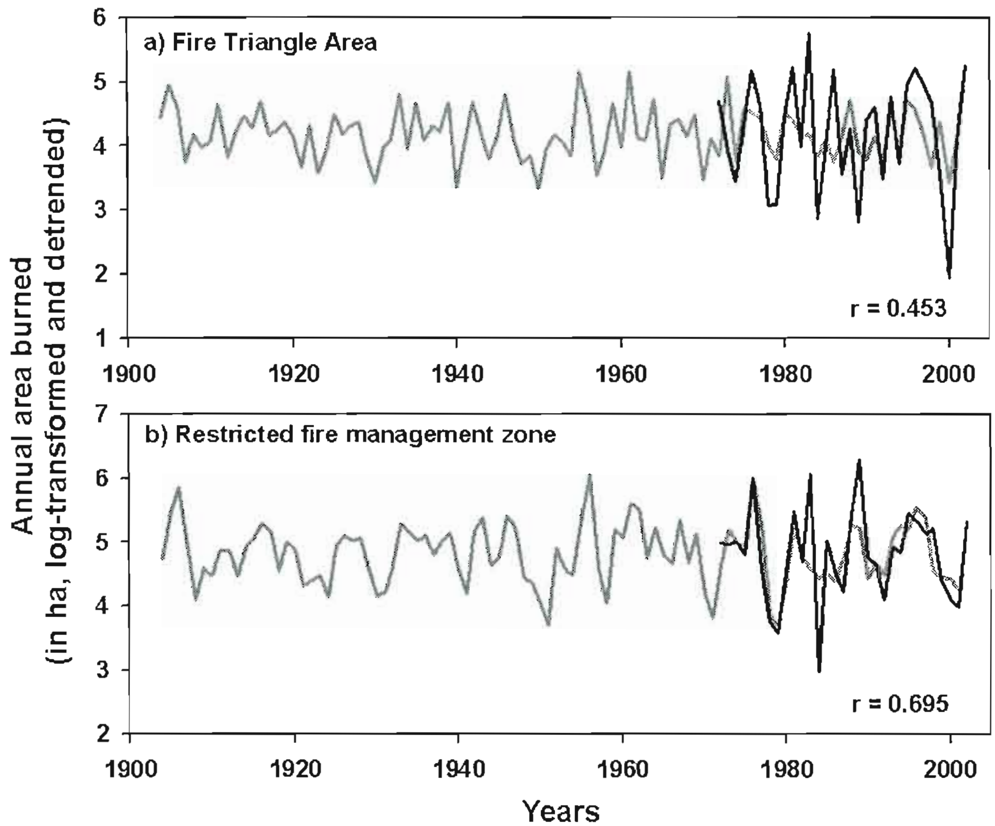

Figure 2.7 Tree-ring estimates of the log-transformed and detrended annual area burned at different spatial domains for the 1904-2001 period (grey) against the instrumental fire records (black). The Pearson correlation coefficient for the common period (1972-2001) is indicated on each graph (n=30, critical r at $P < 0.05$ is 0.361). The model for the log-transformed and detrended annual area burned for the province of Quebec (not represented) was similar to the model for the restricted fire management zone (see Table 2.5), and had a similar correlation to the instrumental data ($r = 0.663$). See Table 2.4 for statistics on the tree-ring estimate models.

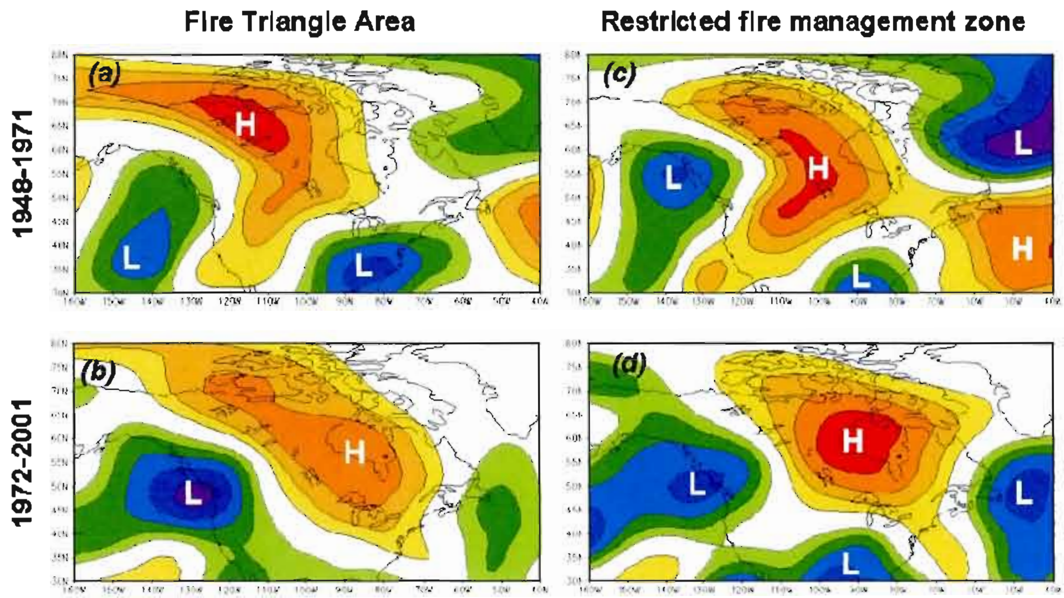

Figure 2.8 Correlation maps between annual area burned tree-ring estimates with June 500 hPa geoptential heights for the Fire Triangle Area (left), and for the restricted fire management zone (right). Correlation maps were computed for two different periods to verify the stationariness of the models: 1948-1971, and 1972-2001. Correlation scale ranges from -0.5 (dark violet) to 0.5 (dark pink). H identifies positive 500 hPa anomalies and L identifies negative 500 hPa anomalies (anomalies correspond to correlations significant at $P < 0.10$).

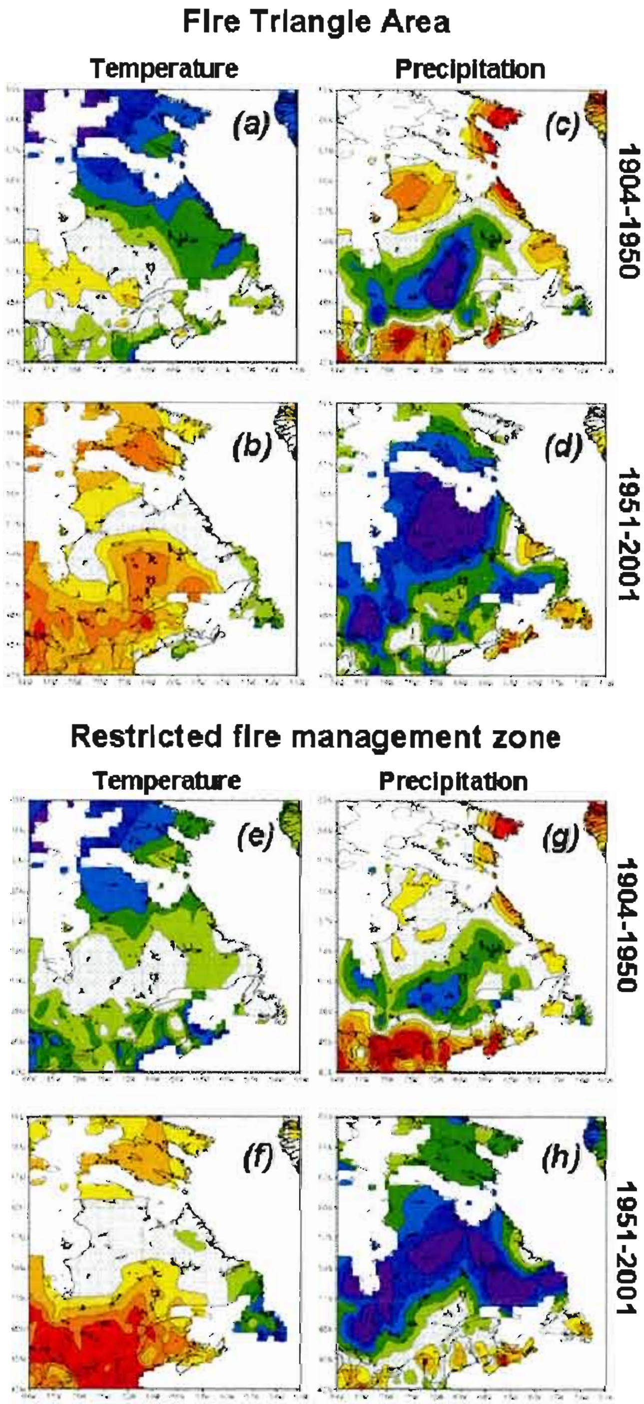

Figure 2.9 Correlation maps for the tree-ring annual area burned estimates of the Fire Triangle Area, and the restricted fire management zone with June to August temperatures and precipitation from the CRU TS 2.1 database (Mitchell and Jones 2005), for 1904-1950, and 1951-2001. Correlation scale ranges from -0.3 (dark violet) to 0.3 (dark pink).

CHAPITRE III

POTENTIAL CHANGES IN MONTHLY FIRE RISK IN THE EASTERN CANADIAN BOREAL FOREST UNDER FUTURE CLIMATE CHANGE

3.1 Abstract

The main objective of this paper is to evaluate if future climate change would trigger to an increase in the fire activity of the Waswanipi area, central Québec. First, we used regression analyses to model the historical (1973-2002) link between weather conditions and fire activity. Then, we calculated Fire-Weather Index System components using 1961-2100 daily weather variables from the Canadian Regional Climate Model for the A2 climate change scenario. We tested linear trends in 1961-2100 fire activity and we calculated rates of change in fire activity between 1975-2005, 2030-2060, and 2070-2100. Our results suggest that the August fire risk would double (+110%) for 2100 while the May fire risk would slightly decrease (-20%), creating a moving of the fire season peak, later in the season. Future climate change would trigger weather conditions more favourable to forest fires and to a slight increase in regional fire activity (+7%). While considering these long-term increases, interannual variations of fire activity remain a major challenge for the development of sustainable forest management.

3.2 Résumé

Le principal objectif de cet article est d'évaluer si des changements climatiques futurs vont conduire à une augmentation de l'activité des feux dans la région de Waswanipi, au centre du Québec. Tout d'abord, nous avons utilisé des régressions linéaires pour modéliser la relation historique (1973-2002) entre les conditions météorologiques et l'activité des feux. Ensuite, nous avons calculé les composantes du système de l'indice forêt-météo à partir des simulations quotidiennes des conditions météorologiques du Modèle Canadien Régional du Climat pour le scénario A2 de changements climatiques (1961-2100). Nous avons testé les tendances linéaires de l'activité des feux sur la période 1961-2100, et calculé les taux de changement entre 1975-2005, 2030-2060, et 2070-2100. Nos résultats suggèrent que le risque de feu pourrait doubler (+110%) en août d'ici 2100 alors que le risque de feu pourrait diminuer en mai (-20%). Ainsi, le pic saisonnier de l'activité des feux pourrait se réaliser plus tard dans la saison. Les changements climatiques futurs pourraient également créer des conditions davantage favorables aux incendies forestiers, et donc à une légère augmentation de l'activité des feux régionale (+7%). Bien que nos résultats suggèrent des augmentations à long terme dans l'activité des feux, la variabilité interannuelle des feux reste un défi important pour le développement d'un aménagement forestier durable.

3.3 Introduction

In boreal forests, fire is one of the main ecological processes shaping the forest mosaic. In return, regional fire regimes are influenced by forest structure and composition, topography, human activity (land use and ignition) and climate and weather (mainly drought, lightning, and wind). In Canada, climate and weather are the dominant controls of fire activity in boreal forest (Bessie and Johnson 1995; Carcaillet *et al.* 2001; Drever *et al.* 2008, 2009; Balshi *et al.* 2009). Climate change has direct and indirect effects on forest ecosystems. Direct effects include the alteration of species growth, reproduction and migration. Indirect effects correspond to modifications of disturbance regimes such as forest fires, insect outbreaks and diseases (Dale *et al.* 2001). Indirect effects, such as changes in fire regimes, may in fact have more dramatic effects than direct effects (Weber and Flannigan 1997). While the impacts of climate change on forest ecosystems are extensively documented, climate change issues are generally not taken into account in the forest management planning process, because they are considered by forest managers too complex and uncertain to be included in deterministic timber calculations (Brumelle *et al.* 1990; Borchers 2005; Hoogstra and Schanz 2008). In fact, science often failed to give information at time and spatial scales relevant and compatible with forest management planning (Burton 1998; Johnston *et al.* 2006; Le Goff *et al.* 2009).

Because of their connection with climate, forest fires may be viewed as a major vulnerability of forest management to climate change (Le Goff *et al.* 2005, 2009). This study contributes to the research effort made to provide information about potential impacts of climate change at a spatial scale closer to the management scale, by using a study area covering few management units. While available only for the A2 climate change scenario, the Canadian Regional Climate Model (CRCM) provides continuous daily climate outputs from 1961 to 2100 to examine future climate conditions with a resolution of few tens kilometres, while preceding research used General Circulation Models (GCMs) outputs with a spatial resolution of few hundreds kilometres (Flannigan *et al.* 2005; Nitschke and Innes 2008a;

Drever *et al.* 2009). We used CRCM daily weather outputs to calculate future fire conditions and future fire activity using regression modelling.

The aim of this paper is to evaluate if future climate change would trigger an increase in the regional fire activity for the Waswanipi area, central Quebec. The specific objectives are i) to model 1961-2100 fire activity (area burned and annual number of fires) using CRCM-predicted FWI components for the western black spruce – feather moss subdomain and for the Waswanipi area using a regression approach, and ii) to evaluate if temporal trend can be detected in the predicted regional fire activity. First, we used multiple linear regressions to estimate the 1973-2002 fire activity (annual area burned and annual number of fires) using weather variables and fire-weather indexes. We also used logistic regression to estimate the monthly fire risk, defined here as the monthly probability to have more than 500 ha and more than 2000 ha of area burned. Then we used daily 1961-2100 outputs from the Canadian Regional Climate Model to estimate future fire activity using previously calculated models. We tested linear trends in estimated fire activity for the 1961-2100 period and we calculated rates of change in fire activity parameters between three reference periods: 1975-2005, corresponding to the current level in atmospheric CO_2 ($1\times CO_2$), 2030-2060 ($2\times CO_2$), and 2070-2100 ($3\times CO_2$). Finally, we examined future changes in monthly fire risk distribution across the fire season for the three reference periods.

3.4 Data and methods

3.4.1 Study area

We examined the fire-climate relationship in the Waswanipi area, central Quebec. It is about 15 000 km^2 and it is situated in the western black spruce – feather moss bioclimatic subdomain, (Robitaille and Saucier 1998) (Fig. 1). It is composed of continuous boreal forest where stands are dominated by of black spruce (*Picea mariana* (Mill.) B.S.P.) growing on thick glacio-lacustrine tills originating from Ojibway proglacial lake (Robitaille and Saucier 1998). Jack pine (*Pinus banksiana* Lamb.) is abundant on coarse textured soils; while mixed stands of aspen (*Populus tremuloides* Michx), white birch (*Betula papyrifera* Marsh.), white spruce (*Picea *glauca* (Moench) Voss) and balsam fir (*Abies balsamea* (L.) Mill.) can be found on upland till soils (Rowe 1972). To model the fire-climate relationship we will calculate regression analyses for two territories: the Waswanipi area (15 000 km^2) and the western black spruce-feather moss bioclimatic subdomain (that enclose the Waswanipi area). We used two different territories as the regression approach used to establish the historical fire-climate relation usually raises better results for larger territories owing a smaller number of years with no fire activity.

According to the 1971-2000 climate normals from the Chapais weather station (49°47'N, 74°51'W, altitude: 396.20 m), the area has 1235 degree-day above 5°C per year, and around 961 mm of precipitation, with a third falling as snow. February and July are the coldest and the warmest months, with a daily mean temperature of -16.6 and 16.3°C, respectively (Environment Canada 2004).

3.4.2 Fire data

We used the provincial fire data provided by the Ministère des Ressources naturelles et de la Faune du Québec for 1973-2007. This database reports all fires from all origins (from lightning as well as from human activities). We selected all fires >10 ha for our analyses to eliminate very small fires that were not contributing to the area burned. The period covered by these data encompasses that during which systematic fire detection in the restricted fire management zone was made by detection planes, which only began in the late 1960s (Blanchet 2003).

We summarized the total area burned and the total number of fires for each day of the fire season considered. For the fire-climate analyses, we set the fire season from May 1st to August 31st, since this period accounted for more than 99% of the 1973-2007 annual area burned in the Waswanipi area.

No transformation allowed normality to be achieved at the monthly step because of the frequent occurrence of months with no fire. Because of these numerous non-fire months, the monthly area burned variable behaves rather like a binomial variable. This property oriented our analyses to logistic regressions to model the monthly fire risk rather than to use linear multiple regressions to model the quantity of area burned occurring in a month (see Flannigan *et al.* 2005). The fire risk is defined here as the probability to have large fire months (with area burned over 500 ha), or very large fire months (with area burned over 2000 ha).

3.4.3 Historical meteorological data

Fire-Weather Index (FWI) system (Van Wagner 1987) is the tool that is used across Canada to evaluate the daily fire risk using local daily weather data. It consists of moisture codes and fire behaviour indices calculated from the daily temperature, 24-h accumulated precipitation, relative humidity and wind speed (Fig. 2; Wotton 2008; Van Wagner 1987). The three moistures codes track moisture in different levels of the forest floor. The Fine Fuel Moisture Code (FFMC) evaluates the moisture content in small readily consumed fuels on the surface of the forest floor. The FFMC indicates the ease of ignition and flammability of fine fuels. The Duff Moisture Code (DMC) measures the moisture content of the moderate organic layers of the forest floor where litter begins to decay. It provides an estimate of consumption of these duff layers and of medium-size woody debris. The Drought Code (DC) is an indicator of the moisture content of deep layers of the forest floor and of large down and dead woody debris on the forest floor. The Buildup Index (BUI) is a combination of the DMC and DC. It evaluates the potential fuel available for surface fuel consumption by the passing fire front. The ISI is a combination of FFMC and wind speed and evaluates the potential rate of spread of a fire. Here, we will evaluate if one or several of these FWI components could provide good estimates of the regional fire activity in central Quebec, Canada.

Daily temperature, precipitation, wind speed and relative humidity from May 1st to August 31st for 1960-2007 were extracted using BioSim 9 for the centre of the Waswanipi area (Régnière and Saint-Amant 2008). For each weather variable, BioSim 9 provided the mean daily value of the three nearest weather stations. Values were adjusted for distance and elevation. We calculated annual and monthly mean, minimum and maximum values for each weather variable and FWI component from the daily 1960-2007 dataset. We entered these potential predictors

(Table 1) in the linear regression analysis to model the LOG-transformed annual area burned and of the LOG-transformed annual number of fires, and in logistic regression to model the monthly fire risk.

3.4.4 Historical fire-weather relation: annual step

The historical link between the annual fire activity (LOG-transformed area burned and number of fires), weather variables and FWI components was calculated using multiple linear regressions (Flannigan *et al.* 2005; Bergeron *et al.* 2006) in SAS 9.1 (SAS Institute Inc. 2000). The structure of the linear models is:

$$Y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i + \varepsilon_j \qquad \text{(Eq. 1)}$$

Where Y is the LOG-transformed annual area burned (or the LOG-transformed annual number of fires) in the territory investigated (Waswanipi area and western black spruce-feather moss subdomain), α is a constant, β_i is the regression coefficient estimate of the variable selected x_i among the candidate explanatory variables (Table 1), and ε_j is the standard error associated to the model.

Multiple regression models were compared and evaluated using different statistics in addition to the adjusted coefficient of determination and the standard error of the estimates. The F-ratio was used to evaluate the predictive capability of the model, considering the number of variables selected. The F-ratio is obtained by dividing the explained variance by the unexplained variance. We used the Akaike information criterion corrected for small sample sizes (AICc, see Mazerolle 2006) to select the best model among three sets of candidate explanatory variables: weather variables only, FWI components only, and weather variables and FWI components taken together. We also reported the Bayesian information criterion (BIC). The BIC is another information criterion for model selection that we used to compare with result obtained with the AICc. As underlined by Girardin *et al.* (2008) the empirical modelling provides evidence of statistical association between forest fire activity and climate, but only suggests possible biological relations (Arbaugh and Peterson, 1989). Using a threshold of $p<0.05$, there is typically a 5% of chance that some of the 24 potential predictor variables may be retained in spite of weak biological justification or because of spurious relationships. Selected variables that had illogical ecological relationships to the model (e.g. positive influence of relative humidity on fire activity, or negative influence of FWI on fire activity) were thus manually removed from the candidate explanatory variables, and models were re-calculated again until all variables taken by the model were ecologically sound.

The stability of the regression model was tested using a split sample calibration-verification scheme. Regressions were calculated for the entire time period 1973-2007. Variables selected were then entered in a complete regression over two subperiods: 1973–1990 and 1991-2007. The regression coefficients estimated for one subperiod (calibration period) were then applied to the selected variables over the other subperiod (verification period) (see Girardin 2007). The strength of the relationship between the regression models and observations was measured using Pearson correlation coefficients.

3.4.5 Historical fire-weather relation: monthly step

When examined at the monthly time step, the area burned produced many months without fire, so this variable was treated as a binomial variable. We used logistic regression analyses to model the monthly fire risk, using monthly weather variables and FWI components as potential explanatory variables. Monthly fire risk is defined here as the probability to have a month with area burned over 500 ha or 2000 ha. The structure of the logistic model is:

$$P_{FIRE}= 1/(1\text{-}e(\alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i)) \qquad \text{(Eq. 2)}$$

where P_{FIRE} is the monthly fire risk, α is a constant, β_i is the regression coefficient, x_i is the variable selected among the candidate explanatory variables. We reported the same information criterions as for the previous regression analyses. Logistic regressions were calculated using the SAS 9.1 (SAS Institute Inc. 2000) with a stepwise forward selection procedure. As for the linear regressions, we manually deleted aberrant variables. The candidate explanatory variables are presented in Table 1.

To verify the stability of the regression coefficients, we calculated the logistic regression with the variables selected for the 1973-2007 period for two subperiods:

from May 1973 to June 1990, and from July 1990 to August 2007. We evaluated submodels using the percentage of concordance, the proportion of event and non-event correctly predicted by the submodels.

3.4.6 CRCM data

To anticipate climate conditions under climate change, we used daily 1961-2100 outputs from the Canadian Regional Climate Model. The CRCM is a high-resolution limited-area model, nested at its lateral boundaries with the Canadian Global Circulation Model (Plummer *et al.* 2006; Laprise 2008). While the IPCC recommends using multi-model and multi-scenario approach to determine an envelope of possible future impacts resulting from climate change (Bernstein *et al.* 2007), only one regional climate model and one climate change scenario (A2) with two realizations (runs with different boundary conditions) were available for this study. The A2 scenario corresponds to a *status quo* situation (Nakicenovic *et al.* 2007): greenhouse gas emissions are continuing to rise at the current rate in a very heterogeneous world with a rapid population growth and a regional-oriented economic development. It is generally considered as the most pessimistic climate change scenario (Bernstein *et al.* 2007). Moreover, the examination of recent climate observations suggested that even the most pessimistic scenarios used by the IPCC tend to underestimate changes in atmospheric CO2 concentration and temperature (Rahmstorf *et al.* 2007), so the A2 scenario may actually provide conservative estimates of future climate conditions. We have chosen to use the CRCM rather than several GCMs with several scenarios (see Drever *et al.* 2009) as we were interested in a relatively small territory and that we wanted to have a more accurate estimates of future climate conditions at the regional scale (more appropriate for forest management).

Continuous 1961-2100 daily weather data were obtained for the two available A2 realizations for the 21 CRCM cells covering the Waswanipi area (Fig. 1). Daily minimum and maximum temperatures were also extracted to calculate daily relative humidity at noon using the Goff-Gratch equation (Goff and Gratch 1946). We calculated the mean values of each meteorological variable for the 21 CRCM cells of each realization. Then we calculated the mean value of these two runs. Monthly and annual mean and maximum were calculated on these mean daily values. The 1961-2007 median of temperature, wind speed and relative humidity were adjusted according to the median of the corresponding historical series (by subtracting the difference between both medians). The rain series did not necessitate adjustments (both medians were close from each other). Then we used the adjusted daily meteorological variables to calculate the daily values of FWI components.

When compared to other months of the fire season, June accounted for the highest proportion of the annual area burned between 1973 and 2002 (42% for the Waswanipi area, and 55% for the western black spruce-feather moss bioclimatic subdomain). For this reason, we examined the CRCM derived meteorological variables and FWI components for this month in particular. Annual area burned and annual number of fires (for forest fires > 10 ha) were LOG-transformed to achieve normality according to a Kolmogorov-Smirnov one sample test. Potential temporal trends were tested using a linear regression with time as predictor. To examine future trends in weather variables and FWI components, we extracted the mean and maximum June values, as this month accounted for the largest part of the annual area burned. We tested linear temporal trends in meteorological variables and FWI components using a simple linear regression with time as predictor in Sigmaplot 11 (Systat software 2006). Normality of mean and maximum series was tested using a one sample Kolmogorov-Smirnov test. Maximum rain and mean DSR failed this normality test.

3.4.7 Future fire activity and risk

We substituted historical weather variables and FWI components by those from CRCM in the best regression models previously identified to estimate 1961-2100 fire activity. We tested linear temporal trends in 1961-2100 LOG-transformed annual area burned and annual number of fires using linear regression with time as predictor. Then we calculated mean values for 1975-2005 ($1\times CO_2$), 2030-2060 ($2\times CO_2$), and 2070-2100 ($3\times CO_2$) to calculate the rates of change in the fire activity ($2\times CO_2/1\times CO_2$, and $3\times CO_2/1\times CO_2$). We calculated rates of change in the monthly fire risk between the three reference periods for all months taken together, as well as each month taken separately to verify if future monthly distribution of fire risk will change under climate change.

3.5 Results

3.5.1 Historical fire-climate relation

Linear regression models of LOG-transformed annual area burned and number for fires displayed adjusted R^2 from 0.20 to 0.45. They were generally higher for the number of fires than for the area burned (Table 2). They were equivalent for the two territories considered. According to the lowest AICc, best models always corresponded to the combination of weather variables and FWI components (Table 2). Verification analyses indicated good correlations between observed data and submodels (Pearson coefficients >0.5, Table 3).

Monthly fire risk for the western black spruce-feather moss subdomain was best predicted by a combination of temperature and a FWI component (BUI or FFMC) (Table 4). Conversely the fire risk in the Waswanipi area was best explained by BUI only. For all models the percentage of concordance between modeled and observed data was around 80. The verification displayed percentages of concordance >71% for all submodels and were more stable for the Waswanipi area (Table 5).

3.5.2 Climate change and future fire conditions

A positive linear trend was identified for the maximum and mean temperature ($p=0.000$) and for maximum and mean relative humidity ($p=0.000$, both) (Fig. 3). These trends were however less evident in the FWI components as only maximum FWI and maximum DSR displayed a positive linear trend with time ($p=0.030$ and $p=0.017$, respectively) (Fig. 4).

3.5.3 Future fire activity in the Waswanipi area

A linear trend was detected for the 1961-2100 LOG-transformed annual area burned ($R^2=0.13$, $p=0.000$), while no trend was detected in the annual number of fires ($p=0.47$) (Fig. 5). The increasing trend in 1961-2100 LOG-transformed annual area burned was observable on the 10-yr moving average, but the standard error associated to the model indicated a high interannual variation. When examining the rates of change between future and current periods, we observed a general increase in the Waswanipi fire activity. This increase is more pronounced for the 3xCO_2 period (2070-2100), than for the 2xCO_2 period (2030-2060). By 2100, the annual area burned could increase by 1.07 times, and the monthly fire risk could increase by 1.3 times with the highest increases observed in July (-31%) and August (100%) (Table 6 and Fig. 6). However, the annual number of fires did not exhibit changes, and the May fire risk displayed a decrease (-20%) (Table 6).

3.6 Discussion

3.6.1 Change in the fire season and fire management in Quebec

The monthly fire risk increased for June, July and august, while the May fire risk slightly decrease between the current and future time periods. These results suggest that spring fire may be less frequent in the future, while the fire risk would increase considerably in July and August in the future. This contrasts with the study of Wotton and Flannigan (1993) that suggested an earlier start of the fire season under climate change. Our study did not consider April, September and October, and these months because the area burned and the number of fire events during these months were too low to allow statistical analysis. However these months may play an important role in the future fire season (Wotton and Flannigan 1993; Nitschke and Innes 2008b). The change in the fire risk distribution across the fire season represents a major challenge for the fire management strategy in Quebec. While June is currently the main fire month, the future fire season would present a prolonged high fire risk from June to August. This suggests a prolonged effort of fire management means implying an increasing investment in fire control efforts. The fire management agency may face more often situations where its fire suppression capacity may be overwhelmed. The decrease observed in May could be linked to the increase in winter precipitation associated to climate change (Christensen *et al.* 2007). The longer snow melt could delay the drying of forest fuels in spring.

3.6.2 Future fire activity under climate change

According to our results, the increase in fire-weather conditions (maximum FWI) as well as in fire activity (area burned) is relatively modest when compared to other studies that used GCM data over the same territory (Flannigan *et al.* 2005; Bergeron *et al.* 2006). Future climate change would trigger fire-weather conditions more favourable to forest fires, and annual area burned will continue to increase when compared to the 1975-2005 reference period. Using the same linear regression approach, Flannigan *et al.* (2005) anticipated an increase about 50-100% times the area burned observed in the reference period 1975-1995 for the 2080-2100 period in the eastern part of the Boreal Shield ecozone. Bergeron *et al.* (2006) estimated that fire rate (annual proportion of area burned) would increase by 30% for 2080-2100 when compared to 1940-2003 in the Waswanipi area. The standard error associated with the fire activity estimates along with the use of a single climate change scenario (A2) constitute the main limitations of the interpretation of an increase in the fire activity under climate change in the Waswanipi area. The main challenge to develop a ecosystem forest management is less this slight increase in the fire activity than the interannual variation of fire activity estimates. Our results yet suggested that fire will remain a key-constrain for forest management in the context of climate change.

Wind is a key-variable controlling the fire activity (notably area burned) and behaviour. This is confirmed by the selection of the maximum wind speed in the annual area burned models for the western black spruce – feather moss subdomain and for the Waswanipi area. However, no linear trend was detected in the 1961-2100 RCM wind speed. Interestingly, the clear increase observed in temperature data over the 1961-2100 period, is less perceptible in the FWI components, as only maximum FWI displayed a positive linear trend with time. Maximal DSR also displayed the same positive linear trend as this index is basically a log-transformed FWI. As speculated by previous work (Bergeron and Flannigan 1995), our results suggested that the increase in temperature alone is not the sufficient condition to lead to weather conditions favourable to forest fires. We postulate that in a certain measure, the increase in temperature would be compensated by the increase in relative humidity. While this could appear contradictory with the increasing linear trend observed in maximum FWI, this could be reconciled by considering the seasonality aspect. The variance explained by our linear models (R^2) is comparable to those of Flannigan *et al.* (2005).

3.6.3 Conclusions

To face current and future fire activity, several strategies may be developed. First, a diversified pool of management practices should be developed to enhance ecosystem resilience and resistance to environmental change in some cases, and to assist forest ecosystems to adapt to ongoing environmental change in other cases (Millar *et al.* 2007). This avenue consists in improving our fire management system, by mapping intervention priorities, and planning salvage logging modalities that satisfy sustainable forest management principles (Le Goff *et al.* 2005).

Second, as forest fire will remain a continuous constraint to forest operations and annual allowable cut calculations, current fire risk should be better integrated in annual harvesting calculations. As these calculations are implemented over time horizons where climate change impacts are expected, anticipated change in future fire risk should also be taken into account.

Third, scientific tools to anticipate future fire regimes at time and spatial scales relevant for forest management should be continuously developed. Here, the 21 CRCM cells available for this study were insufficient to produce spatial analyses of future fire condition and activity. Next steps should include the spatial mapping of these parameters across the Quebec province, to plainly beneficiate the spatial resolution provided by the CRCM. We used a single model- single scenario approach as a first step to the use of the best available data, as our study is one of few using CRCM data (Flannigan *et al.* 2001; Amiro *et al.* 2001; Tymstra *et al.* 2007). However, future work will include other scenarios and other models to determine an envelope of possible future conditions under climate change. Statistical tools used to model fire activity using weather condition are also developing with, for example, the advent of multivariate adaptive regression spline approach (Balshi *et al.* 2009). Here, we favoured simple regression model including a small number of predictors to encourage potential applications as predictive tools for forest and fire management planning. Finally, study combining climate parameters to lightning data and vegetation inputs would provide a more complete picture of fire regime controls (Krawchuck *et al.* 2006) and better reflect our current comprehension of regional fire regime dynamics.

3.7 Acknowledgements

Julie Fortin (Ministère des Ressources naturelles et de la Faune du Québec) provided the provincial fire data. Rémi Saint-Amant extracted the historical meteorological data from BioSim. We gratefully thank Travis Logan (Consortium Ouranos) for providing the data from the Canadian Regional Climate Model. We thank Alan Cantin and Lynn Gowman (Canadian Forest Service) for their help to compute FWI calculations. We also thank Lynn Gowman for the edition of the manuscript. Financial support was provided by the Sustainable Forest Management Network.

3.8 References

Amiro, B.D., Stocks, B.J., Alexander, M.E., Flannigan, M.D., and Wotton, B.M. 2001. Fire, climate change, carbon and fuel management in the Canadian boreal forest. Int. J. Wild. Fire, 10(3-4): 405-413.

Arbaugh, M.J., and Peterson, D.L. 1989. Variable selection in dendroclimatology: an example using simulated tree-ring series. For. Sci. 35: 294–302.

Balshi, M.S., McGuire, A.D., Duffy, P., Flannigan, M., Walsh, J., and Melillo, J. 2009. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. Glob. Change Biol. 15(3): 578-600

Bergeron, Y., and Flannigan, M.D. 1995. Predicting the effects of climate change on fire frequency in the southeastern Canadian boreal forest. Water, Air, Soil Pollution, 82: 437–444.

Bergeron, Y., Cyr, D., Drever, R.C., Flannigan, M., Gauthier, S., Kneeshaw, D., Grondin, P., Lauzon, E., Leduc, A., Le Goff, H., Lesieur, D., and Logan, K. 2006. Past, current and future fire frequency in Quebec commercial forests: implications for sustainable forest management. Can. J. For. Res. 36(11): 2737-2744.

Bernstein, L., Bosch, P., Canziani, O., Chen, Z., Christ, R., Davidson, O., Hare, W., Huq, S. Karoly, D., Kattsov, V., Kundzewicz, Z., Liu, J., Lohmann, U., Manning, M., Matsuno, T., Menne, B., Metz, B., Mirza, M., Nicholls, N., Nurse, L., Pachauri, R., Palutikof, J., Parry, M., Qin, D., Ravindranath, N., Reisinger, A., Ren, J., Riahi, K., Rosenzweig, C., Rusticucci, M., Schneider, S., Sokona, Y., Solomon, S., Stott, P., Stouffer, R., Sugiyama, T., Swart, R., Tirpak, D., Vogel, C., and Yohe, G. 2007. Climate Change 2007: Synthesis Report.

Intergovernmental Panel on Climate Change. Available online at http://www.ipcc.ch/ipccreports/ar4-syr.htm (last accessed on August 2008).

Bessie, W.C., and Johnson, E.A. 1995. The relative importance of fuels and weather on fire behaviour in subalpine forests. Ecology, 76(3): 747-762.

Blanchet, P. 2003. Forest fires: the story of a war. Cantos International Publishing, Montreal, Canada.

Borsher, J.G. 2005. Accepting uncertainty, assessing risk: decision quality in managing wildfire, forest resource values, and new technology. For. Ecol. Manage. 211: 36-46.

Brumelle, S, Stanbury, W.T., Thompson, W.A., Vertinsky, I., and Wehrung, G. 1990. Framework for the analysis of risks in forest management and silvicultural investments. For. Ecol. Manage. 35: 279-299.

Carcaillet, C., Bergeron, Y., Richard, P.J.H., Frechette, B., Gauthier, S., and Prairie, Y.T., 2001. Change in fire frequency in eastern Canadian boreal forests during Holocen: does vegetation composition or climate trigger fire regime? J. Ecol. 89: 930-946.

Drever, R.C., Drever, M.C., Messier, C., Bergeron, Y., and Flannigan, M. 2008. Fire and the relative role of weather, climate and landscape characrteristics in the Great lakes-St. Lawrence forest of Canada. J. Vege. Sci. 19: 57-66.

Drever, R.C., Drever, M.C, Flannigan, M., Logan, T., Messier, C. 2009. Effects of climate on occurrence and size of large fires in a northern hardwood landscape: historical trends, future predictions, and implications for climate change in Témiscamingue. Appl. Vege. Sci. 12(3): 261-272. DOI:10.1111/j.1654-109X.2009.01035.x.

Environment Canada. 2004. Canadian Climate Normals. Available online at http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html?& (last access on August 2008).

Flannigan, M.D., Campbell, I., Wotton, M., Carcaillet, C., Richard, P., and Bergeron, Y. 2001. Future fire in Canada's boreal forest: Paleoecology results and general circulation model - Regional climate model simulations. Can. J. For. Res. 31(5): 854-864.

Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., Stocks, B.J., 2005. Future area burned in Canada. Clim. Change, 72: 1-16.

Girardin, M.P. 2007. Interannual to decadal changes in area burned in Canada from 1781 to 1982 and the relationship to Northern Hemisphere land temperatures. Glob. Ecol. Biogeo. 16(5): 557-566, doi: 10.1111/j.1466-8238.2007.00321.x.

Girardin, M.P., Raulier, F., Bernier, P.Y, and Tardif, J.C. 2008. Response of tree growth to a changing climate in boreal central Canada: A comparison of empirical, process-based, and hybrid modelling approaches. Ecol. Model. 213: 209–228

Goff, J.A., and Gratch, S. 1946. Low-pressure properties of water from -160 to 212 °F, in Transactions of the American Society of Heating and Ventilating Engineers, pp 95-122, presented at the 52nd annual meeting of the American Society of Heating and Ventilating Engineers, New York.

Hély, C., Flannigan, M., Bergeron, Y., and McRae, D. 2001. Role of vegetation and weather on fire behavior in the Canadian mixedwood boreal forest using two fire behavior prediction systems. Can. J. For. Res. 31: 430–441.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr A., and Whetton, P. 2007. Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor M., and Miller H.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jayen, K., Leduc, A., and Bergeron, Y. 2006. Effect of fire severity on regeneration success in the boreal forest of north-west Quebec, Canada. Ecoscience, 13(2): 143-151.

Johnston, M., Williamson, T., Price, D., Spittlehouse, D., Wellstead, A., Gray, P., Scott, D., Askew, S., and Webber, S. 2006. Adapting Forest Management to the Impacts of Climate Change in Canada. BIOCAP synthesis paper. Available online http://www.biocap.ca/ (last accessed on August 2008).

Krawchuk, M.A., Cumming, S.G., Flannigan, M.D., and Wein, R.W. 2006. Biotic and abiotic regulation of lightning fire initiation in the mixedwood boreal forest. Ecology, 87: 458-468.

Laprise, R. 2008. Regional climate Modelling. J. Comput. Physics, 227: 3641-3666.

Le Goff, H., Flannigan, M.D., Bergeron, Y., and Girardin, M.P. 2007. Historical fire regime shifts related to climate teleconnections in the Waswanipi area, central Quebec, Canada. Int. J. Wild. Fire, 16(5): 607-618.

Le Goff, H., Flannigan, M., Bergeron, Y., Leduc, A., Gauthier, S., and Logan, K. 2009. Management solutions to face climate change: the example of forest fires. In Gauthier, S. Vaillancourt, M.-A. Leduc, A. De Grandpré, L. Kneeshaw, D. Morin, H. Drapeau, P., and Bergeron, Y. « Ecosystem Management in the Boreal Forest » Presses de l'Université du Québec, Québec, Québec.

Mazerolle, M.J. 2006. Improving data analysis in herpetology: using Akaike's Information Criterion (AIC) to assess the strength of biological hypotheses. Amphibia-Reptilia, 27: 169-180.

Millar, C.I., Stephenson, N.L., and Stephens, S.L. 2007. Climate change and forest of the future: managing in the face of uncertainty. Ecol. Appl. 17(8): 2145–2151.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Tae Yong Jung, A., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., and Zhou, D. 2000. Emission scenarios. Intergovernmental Panel on Climate Change. Available on line http://www.ipcc.ch/ipccreports/special-reports.htm (last accessed on August 2008)

Nitschke, C.R., and Innes, J.L. 2008a. Integrating climate change into forest management in South-Central British Columbia: an assessment of landscape vulnerability and development of a climate-smart framework. For. Ecol. Manage. 256(3): 313-327.

Nitschke, C.R., and Innes, J.L. 2008b. Climatic change and fire potential in South-Central British Columbia, Canada. Glob. Change Biol. 14: 841-855.

Plummer, D.A., Caya, D., Frigon, A., Côté, H., Giguère, M., Paquin, D., Biner, S., Harvey, R., and De Elia, R. 2006. Climate and climate change over North America as simulated by the Canadian RCM. J. Climate 19: 3112-3132.

Podur, J., Martell, D.L., and Knight, K. 2002. Statistical quality control analysis of forest fire activity in Canada. Can. J. For. Res. 32: 195–205.

Rahmstorf, S., Cazenave, A., Church, J.A., Hansen, J.E., Keeling, R.F., Parker, D.E., and Somerville, R.C.J. 2007. Recent climate observations compared to projections. Science, 316: 709.

Régnière, J., and Saint-Amant, R. 2008. BioSIM 9 - User's Manual. 2008. Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, Quebec, QC. Inf. Rep. LAU-X-134E.

Robitaille, A., and Saucier, J.P. 1998. Paysages régionaux du Québec méridional. Les publications du Québec, Sainte-Foy, Canada.

Rowe, J.S. 1972. Forest Regions of Canada. Environment Canada, Ottawa.

SAS Institute Inc. 2000. SAS OnlineDoc, Version 8. SAS Institute Inc. Cary, NC.

Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D., Hirsch, K.G., Logan, K.A., Martell, D.L., and Skinner, W.R. 2002. Large forest fires in Canada, 1959-1997. J. Geophys. Res. 108(D1): 8149, doi:10.1029/2001JD000484.

Systat software, Inc. 2006. SIGMAPLOT 10. San Jose, CA, USA.

Tymstra, C., Flannigan, M.D., Armitage, O.B., and Logan, K. 2007. Impact of climate change on area burned in Alberta's boreal forest. Int. J. Wild. Fire, 16(2): 153-160.

Van Wagner, C.E. 1987. The development and structure of the Canadian Forest Fire weather index system, For. Tech. Rep. 35, Can. For. Serv. Ottawa, Ont. Canada.

Van Wagner, C.E. 1988. The historical pattern of annual burned area in Canada. For. Chron. 64: 182-185.

Weber, M.G., and Flannigan, M.D. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. Environmental Reviews, 5: 145–166. doi:10.1139/ER-5-3-4-145.

Wotton, B.M. 2008. Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research. Environmental and Ecological Statistics. DOI 10.1007/s10651-007-0084-2.

Wotton, B.M., and Flannigan, M.D. 1993. Length of the fire season in a changing climate. For. Chron. 69: 187-192.

Table 3.1 Description of the candidate explanatory variables for the linear (annual) and for the logistic (monthly) regression analyses.

Name	Description
TEMPme	Mean temperature
TEMPma	Maximum temperature
RAINme	Mean precipitation
RAINma	Maximum precipitation
RAINtot	Total precipitation
RHme	Mean relative humidity
RHma	Maximum relative humidity
RHmi	Minimum relative humidity
WSme	Mean wind speed
WSma	Maximum wind speed
FFMCme	Mean fine fuel moisture code
FFMCma	Maximum fine fuel moisture code
DMCme	Mean duff moisture code
DMCma	Maximum duff moisture code
DCme	Mean drought code
DCPma	Maximum drought code
ISIme	Mean initial spread index
ISIma	Maximum initial spread index
BUIme	Mean buildup index
BUIma	Maximum buildup index
FWIme	Mean fire-weather index
FWIma	Maximum fire-weather index
DSRme	Mean daily severity index
DSRma	Maximum daily severity index

Table 3.2 Multiple linear regression models for LOG-transformed annual area burned (AREA) and number of fires (NB) for the western black spruce-feather moss bioclimatic subdomain (b), and the Waswanipi area (w) for the 1973-2002 period. The model type corresponds to the set of potential explanatory variables used: "Weather" corresponds to the weather variables only (temperature, precipitation, wind speed and relative humidity), "FWI" corresponds to the FWI components only, and "all" corresponds to weather variables and FWI components taken together. Candidate explanatory variables are presented in Table 1. aR^2 is the adjusted coefficient of determination; SE is the standard error of the estimate; F is the ratio of the model mean square to the error mean square. AICc is the Akaike information criterion corrected for small sample sizes, and BIC is the Schwartz criterion. For each model type, the model with the lower AICc is presented. Among the model types, the model with the lowest AICc is selected for the following analyses. Best values for aR^2, standard-error, F-ratio, AICc and BIC are indicated in bold.

Model	Type	Coefficients	Variables	aR^2	SE	F	P	AICc	BIC
AREAb	Weather	-.674	RAINme	.27	.84	5	.005	-7	-5
		-.057	RHmi						
		.096	WSma						
	FWI	.160	BUIme	.25	.85	**12**	.001	-9	-6
	All	.103	WSma	**.36**	**.78**	10	.000	**-13**	**-11**
		.200	BUIme						
NBb	Weather	-.106	RAINma	.40	.22	12	.000	-103	-100
		-.001	RAINtot						
	FWI	.005	DCme	.37	.22	**20**	.000	-102	-100
	All	-.011	RAINma	**.45**	**.21**	14	.000	**-105**	**-103**
		.004	DCme						
AREAw	Weather	-.009	RAINtot	.28	1.08	7	.002	8	10
		.137	WSma						
	FWI	.172	FFMCme	.20	1.14	**9**	.004	11	13
	All	-.033	RAINma	**.38**	**1.00**	8	.000	**4**	**6**
		.153	WSma						
		.198	BUIme						
NBw	Weather	-.014	RAINma	.39	.25	11	.000	-93	-91
		-.001	RAINtot						
	FWI	.005	DCme	.34	.26	**18**	.000	-91	-89
	All	-.014	RAINma	**.45**	**.24**	14	.000	**-96**	**-94**
		.004	DCme						

Table 3.3 Split sample calibration-verification results for the linear regression models of LOG-transformed annual area burned and number of fires. p is the probability for the regression on the calibration period. r is the Pearson correlation coefficient for the verification period between modeled and observed data series (all coefficients are significant at $p<0.05$). See table 3.2 for the description of regression models.

Model	Calibration period	p	Verification period	r
AREAb	1973-1990	.0496	1991-2007	.57
	1991-2007	.0188	1973-1990	.58
NBb	1973-1990	.0345	1991-2007	.67
	1991-2007	.0014	1973-1990	.43
AREAw	1973-1990	.0378	1991-2007	.62
	1991-2007	.0124	1973-1990	.51
NBw	1973-1990	.1512	1991-2007	.75
	1991-2007	.0006	1973-1990	.41

Table 3.4 Logistic stepwise regressions of monthly fire probability for the western black spruce-feather moss subdomain (b) and for the Waswanipi area (w). Candidate explanatory variables are presented in Table 3.1. n is the number of months with large area burned over the area burned threshold (500 or 2000 ha) for a total of 140 months (May to August, 1973-2007). The percentage of concordance (% concord) indicates the proportion of events and non-events correctly predicted by the model when compared to observed data. AICc is the Akaike information criterion corrected for small sample sizes. The BIC is the Schwartz criterion. The lowest AICc value (corresponding to the best model) is indicated in bold. See table 3.1 for the description of explanatory variables.

Model	Type	Coefficients	Variables	% concord	AICc	BIC
P_{500b}	Weather	.349	TEMPme	76	163	172
		-.117	RHmi			
	FWI	.186	BUIme	73	166	172
	All	.193	TEMPma	**79**	**161**	**169**
		.148	FFMCma			
P_{2000b}	Weather	.393	TEMPme	79	145	153
		-.139	RHmi			
	FWI	.253	BUIme	80	137	**142**
	All	.197	TEMPma	**82**	**134**	**142**
		.221	BUIme			
P_{500w}	Weather	.327	TEMPma	**83**	123	134
		-.165	RHme			
	FWI	.245	BUIme	**83**	**121**	**117**
	All	.245	BUIme	**83**	**121**	**117**
P_{2000w}	Weather	.416	TEMPme	**82**	113	121
		-.161	RHmi			
	FWI	.218	BUIme	**82**	**112**	**118**
	All	.218	BUIme	**82**	**112**	**118**

Table 3.5 Verification results for logistic regression models of the monthly fire probability for the black spruce-feather moss domain (b) and for the Waswanipi area (w). the monthly fire probability is defined as the probability to have a month with area burned over 500 ha (P_{500}) or 2000 ha (P_{2000}).We calculated the complete regression with variables selected for the 1973-2007 period for two sub-periods: period A corresponds to the period from May 1973 to June 1990 and period B corresponds to the period from July 1990 to August 2007. The percentage of concordance (% concord) indicates the proportion of events and non-events correctly predicted by the model when compared to observed data.

Model	Calibration period	%concord
P_{500b}	A	71.6
	B	86.5
P_{2000b}	A	78.3
	B	87.5
P_{500w}	A	82.7
	B	83.9
P_{2000w}	A	83.7
	B	81.8

Table 3.6 Rates of change (%) for the fire activity (annual area burned : AREA, and annual number of fires : NB) in the Waswanipi area between future (2× or 3×CO2) and current (1×CO2, corresponding to the 1975-2005 period) mean values.

Variable	$2\times CO_2$ 2030-2060	$3\times CO_2$ 2070-2100
LOG-AREA	4	7
LOG-NB	0	2
P500	5	33
P500 May	-22	-20
P500 June	04	10
P500 July	18	68
P500 August	25	109
P2000	7	34
P2000 May	-21	-19
P2000 June	6	9
P2000 July	18	70
P2000 August	29	110

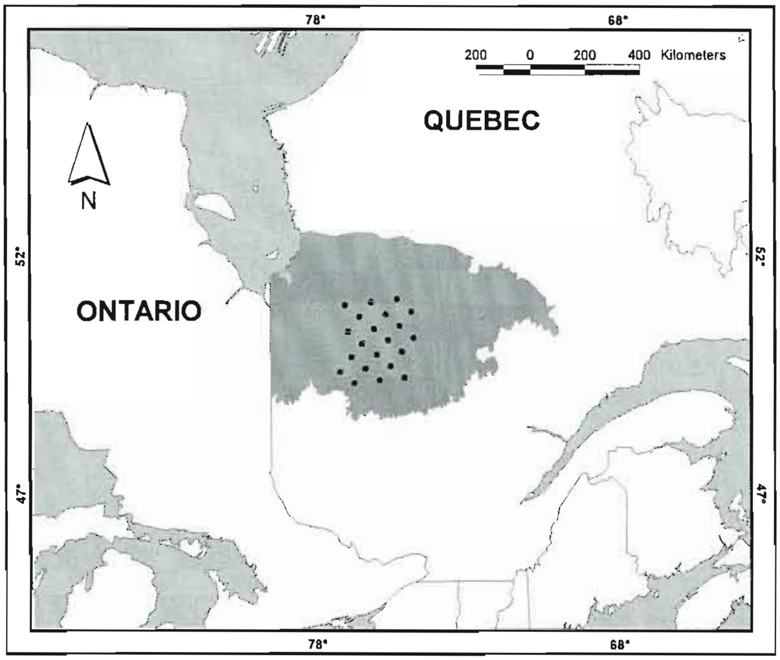

Figure 3.1 Location of the study area. The grey area corresponds to the western black spruce – feather moss bioclimatic subdomain. The points indicate the Canadian Regional Climate Model cells covering the Waswanipi area.

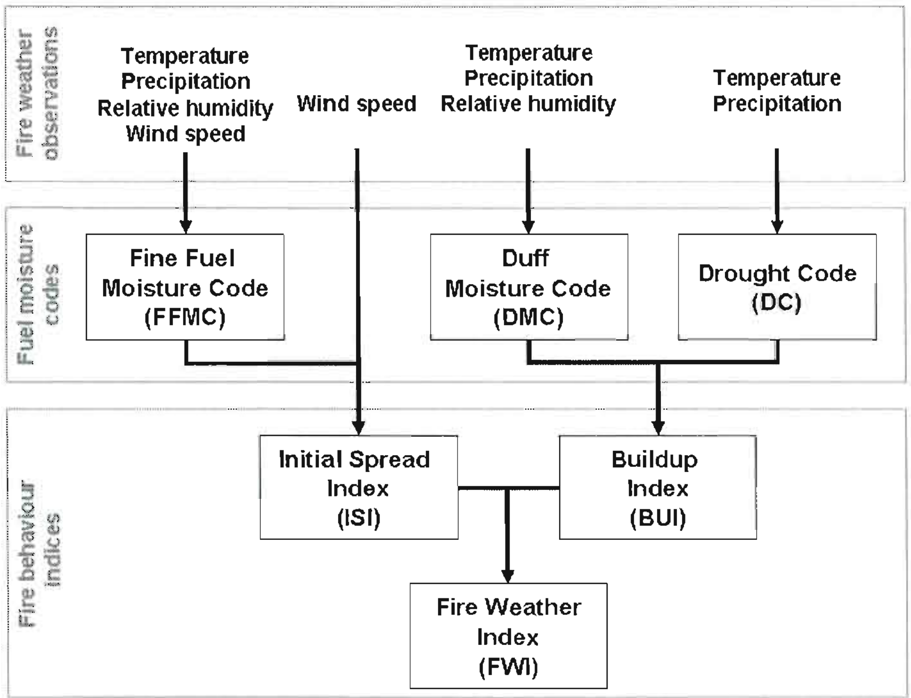

Figure 3.2 Structure of the Fire-Weather Index system (Van Wagner 1987).

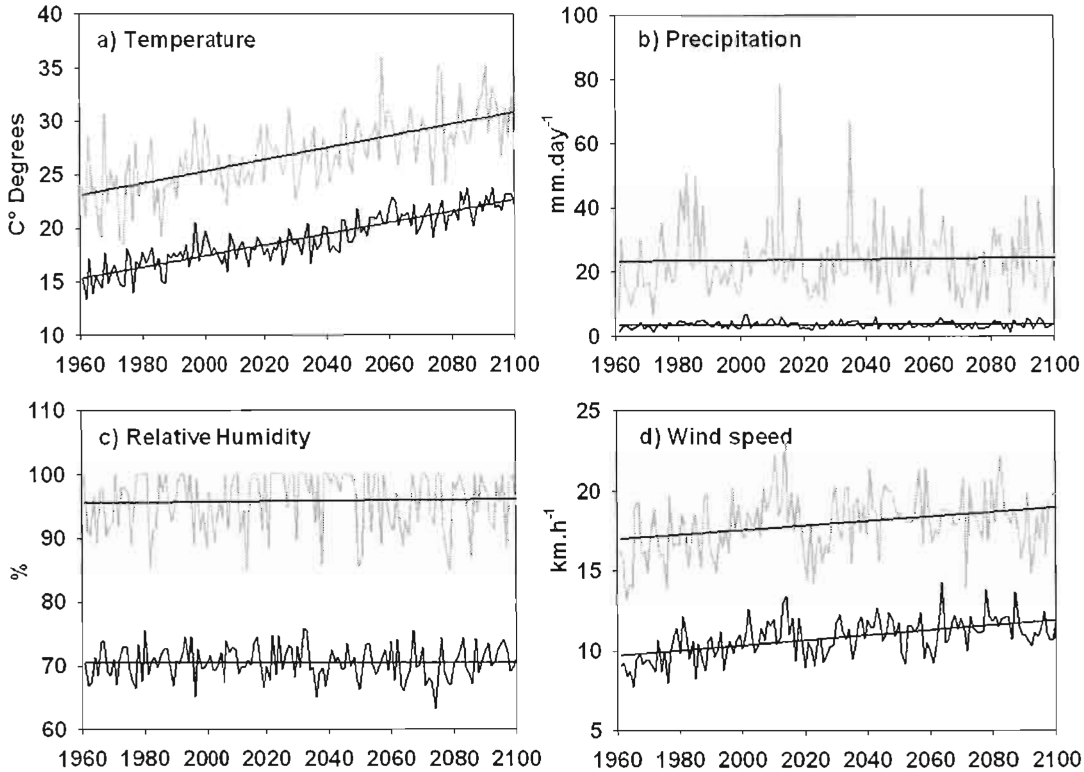

Figure 3.3 1961-2100 June mean (black) and maximal (gray) values for temperature (a), precipitation (b), relative humidity (c), and wind speed (d) as calculated from the Canadian Regional Climate Model outputs for the A2 climate change scenario. Variables were adjusted in function of the median of the historical data (1961-2007), except for rain.

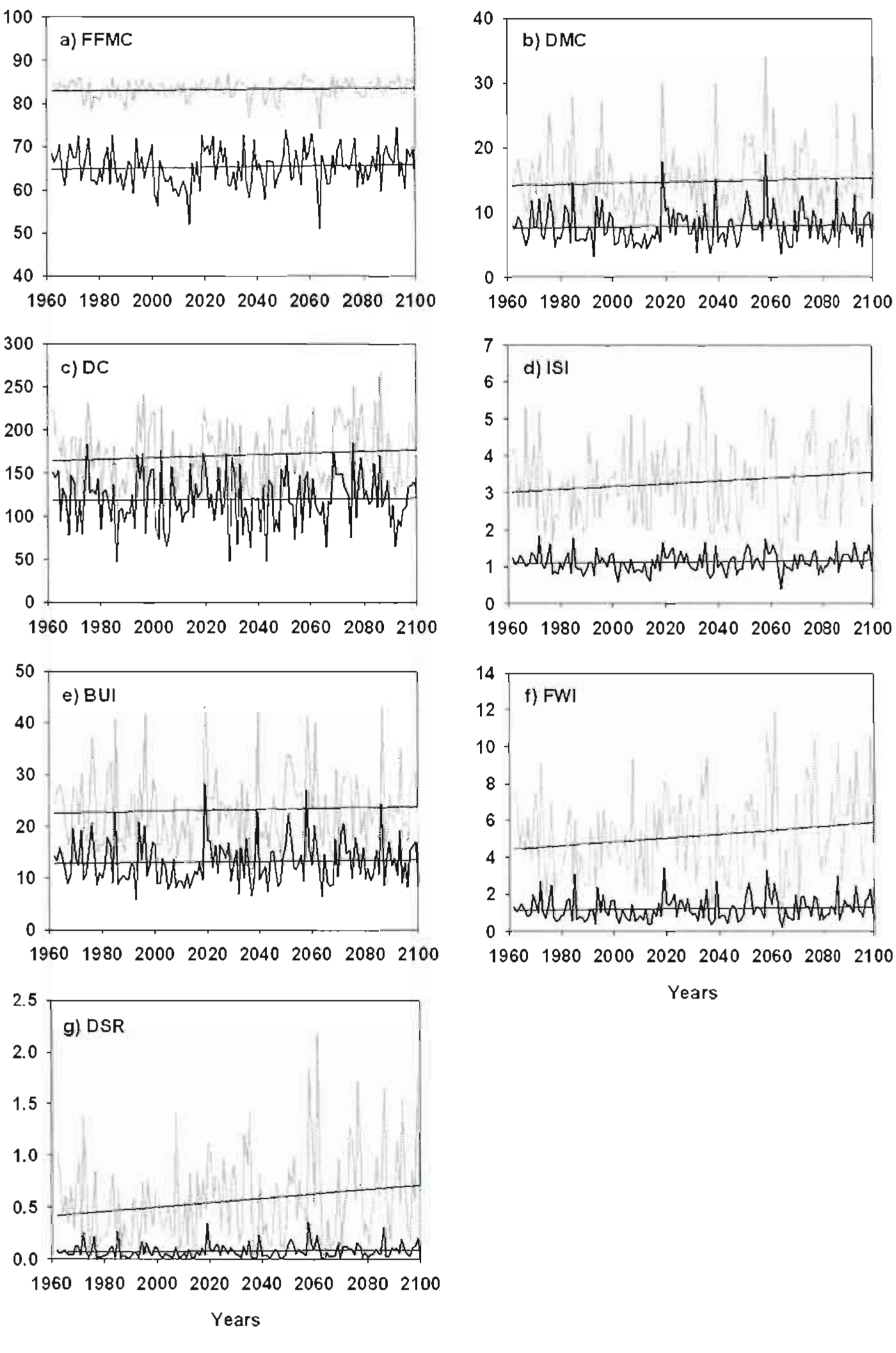

Figure 3.4 1961-2100 June mean (black) and maximal (grey) values for the Fire-Weather Index (FWI) system components as calculated from the Canadian Regional Climate Model outputs for the A2 climate change scenario. FFMC: Fine Fuel Moisture Code, DMC: Duff Moisture Code, DC: Drought Code, ISI: Initial Spread Index, BUI: Buidup Index, FWI: Fire-Weather Index, and DSR: Daily Severity Rating. See Fig. 3.1 for the FWI system structure.

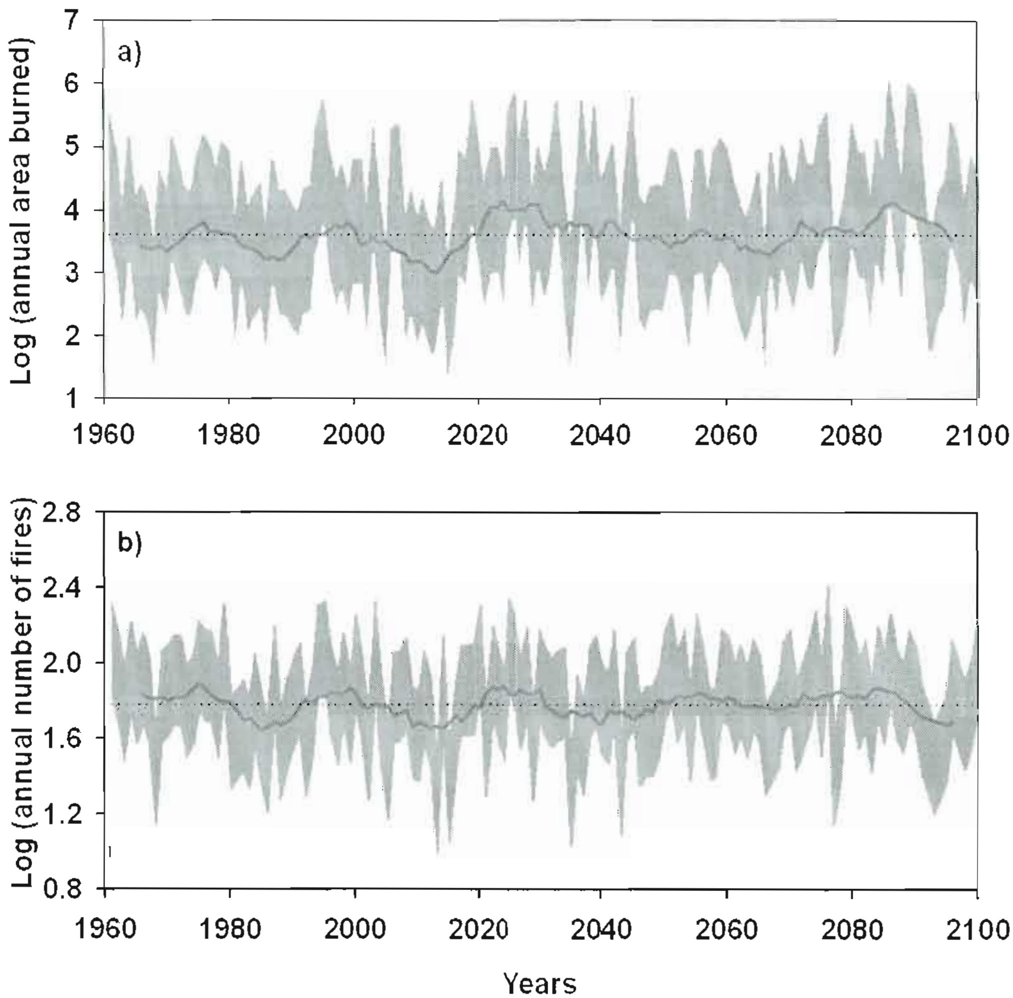

Figure 3.5 LOG-transformed annual area burned (a) and annual number of fires (b) for 1961-2100 in the Waswanipi area. Gray area indicates 95% lower and upper limits of the error of the estimates. Thick dark grey line indicates the moving mean (10 years) of the interannual estimates. Dotted lines indicate the 1961-2100 mean values of the estimates. See table 3.4 for the description of regression models and table 3.5 for the rates of change between reference periods.

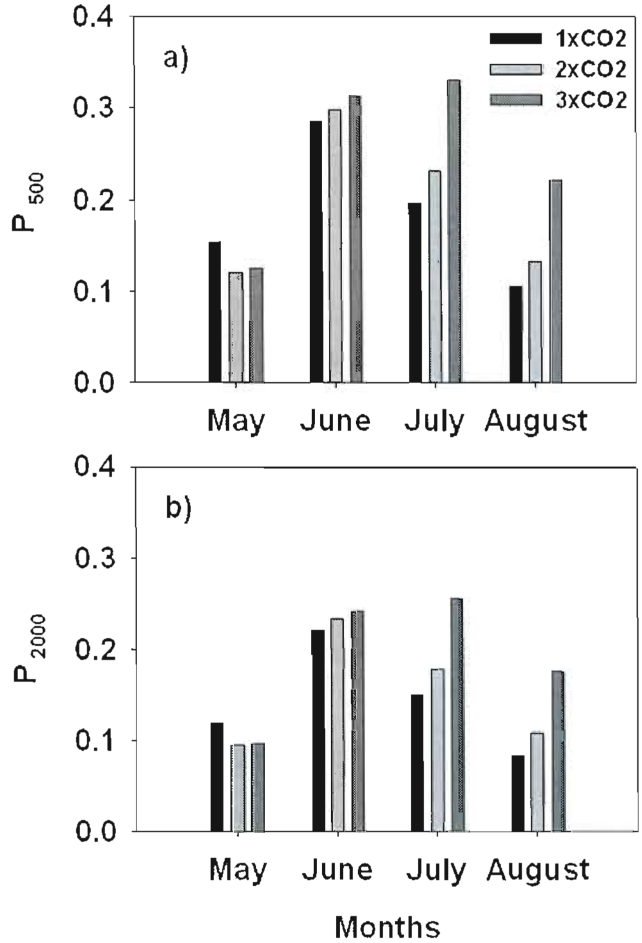

Figure 3.6 Anticipated changes in monthly fire risk under climate change in the western in the Waswanipi area. The fire risk is defined here as the probability to have large fire months (with area burned over 500 ha, P_{500}, (a)) or very large fire months (with area burned over 2000 ha, P_{2000} (b)). Changes in the fire risk were evaluated between three reference periods corresponding to increasing atmospheric concentration of CO_2: 1975-2005 (1×CO_2), 2030-2060 (2×CO_2), 2070-2100 (3×CO_2). Logistic regression models used to calculate fire risk are described in table 3.4. See table 3.7 for global rates of change.

CHAPITRE IV

EXPLORING LINKS BETWEEN ADAPTATION TO CLIMATE CHANGE AND SUSTAINABLE FOREST MANAGEMENT: INTEGRATING THE FIRE RISK INTO FOREST MANAGEMENT PLANNING

4.1 Résumé

L'aménagement forestier se caractérise par de longs horizons temporels pendant lesquels les conditions économiques, environnementales et sociales changent. En particulier, les changements climatiques vont amener de nouvelles contraintes climatiques sur les écosystèmes forestiers. Ces nouvelles conditions sont difficiles à prévoir en termes de nature et de magnitude à une échelle pertinente pour la planification forestière. Nos efforts pour atteindre des objectifs d'aménagement forestier durables pourraient être compromis si nous ne prenons pas en compte les vulnérabilités impliquées par les changements climatiques. En forêt boréale, le feu est un element clé de la dynamique forestière et dépend étroitement de la variabilité et des changements climatiques. Les feux de forêt représentent des incertitudes et des risques de pertes de volume de bois marchand. Cependant le risque de feu est géré après que le feu soit survenu par la réalisation de coupes de récupération. Dans cette étude, nous explorons des moyens davantage proactifs pour intégrer les risques et les incertitudes dans la planification forestière en utilisant les feux de forêt comme exemple de vulnérabilité de notre aménagement forestier face à la variabilité et aux changements climatiques. Tout d'abord, nous présentons les concepts communs à l'adaptation aux changements climatiques et à l'aménagement forestier durable. Ensuite, nous présentons des indicateurs climatiques qui influencent le risque de feu régional et qui pourraient contribuer à mieux l'anticiper et à mieux l'intégrer dans la planification forestière stratégique (indicateurs climatiques décennaux) et tactique (indicateurs climatiques mensuels et annuels). Enfin, nous présentons des stratégies d'aménagement forestier qui facilitent l'intégration des risques et des incertitudes dans la planification forestière. Alors que nous disposons déjà d'outils et de connaissances de base pour mieux intégrer les risques et les incertitudes dans la planification forestière, leur mise en place exigera d'importants changements dans la perception traditionnelle que nous avons des risques et des incertitudes en foresterie.

4.2 Abstract

Forest management typically implies long time horizons during which economic, environmental and social conditions change. In particular, climate change will create new climate constraints on forest ecosystems that are difficult to predict in terms of nature and magnitude at a spatial scale useful for forest management planning. Our efforts to achieve sustainable forest management objectives may fail if we do not integrate the evaluation of vulnerabilities associated with climate change. In boreal forest, fire is a key element of the forest dynamics and strongly depends on climate variability and change. Forest fires represent highly variable and uncertain losses of timber supply. The fire risk is however traditionally managed after the fire has occured using a salvage logging plan. In this paper, we explore more proactive ways to include risks and uncertainties in forest management planning using forest fire as an example of vulnerability of forest management to climate variability and change. First, we present concepts common to adaptation to climate change and to sustainable forest management that could facilitate their implementation. Then, we present different climate indicators influencing the regional fire risk that may contribute to better estimates of these risks and to integrate them into strategic (decadal climate indicators) and tactical (monthly to yearly climate indicators) forest management planning. Finally, we present forest management strategies facilitating the integration of risks and uncertainty into forest management planning. While we already have the technical tools to better integrate risks and uncertainties into forest management planning, important changes in the traditional perception of risks and uncertainties in forestry will be necessary to implement these new tools.

4.3 Introduction

Forest management typically implies long time horizons during which economic, environmental and social conditions change. In particular, climate change will create new climate constraints on forest ecosystems (Chapin *et al.* 2007) that are difficult to predict in terms of magnitude at a spatial scale useful for forest management planning (Burton 1988, Pilkey and Pilkey-Jarvis 2007). Our efforts to achieve sustainable forest management objectives (e.g., maintaining forest health and vitality) may fail if we do not integrate the evaluation of risks and uncertainties associated with climate change (Yohe *et al.* 2007, Ogden and Innes 2007, Nitschke and Innes 2008). If we engage in the development of sustainable forest management, we should address these risks and uncertainties, and integrate them into the forest management planning process. The management of risks and uncertainties linked to climate variation and change in the perspective of decrease the vulnerability of natural and human systems to climate change is the object of adaptation to climate change.

Fortunately, efforts made to cope with impacts of climate change and efforts devoted to promote sustainable management share common concepts and approaches including decision-support mechanisms to cope with uncertainty (Yohe *et al.* 2007). Sustainable forest management is a management framework that aims to restore natural forest degraded by forest management and to maintain healthy and resilient forest ecosystems by focusing on a reduction of differences between natural and managed landscapes to ensure long-term maintenance of ecosystem functions. It thereby retains the social and economic benefits they provide to society (Gauthier *et al.* 2009). In 2003, Spittlehouse and Stewart stated that « Climate change adaptation strategies can be viewed as a risk management component of sustainable forest management plans. ». Since them, a large body of scientific and technical papers explored the relations between adaptation to climate change and sustainable forest management, but few of them provided insights about the practical means to implement an adaptation strategy for the forest sector (Le Goff *et al.* 2005, 2009, Ogden and Innes 2007, Nitschke and Innes 2008). Sustainable forest management could thus benefit from of several management tools developed to address adaptation to climate change such as adaptive management frameworks and tools helping the anticipation and the integration of climate risk and uncertainties.

In this paper, we present forest fires as a major vulnerability of forest management to climate change to illustrate how adaptation to climate change concepts may helps to develop more sustainable forest management approaches. The objectives of this paper are to present concepts common to adaptation to climate change and sustainable forest management in terms of planning consideration and approaches, and to illustrate practical contributions of adaptation to climate change to the development of sustainable forest management.

4.4 Forest fire as a major vulnerability of foret management to climate change

Climate change impacts are generally described as direct and indirect. Direct impacts include impacts of change in temperature, precipitation, seasonality on the physiology and ecology of organisms (e.g., phenology, distribution range, extinctions, and migration). Indirect effects superimpose direct impacts through the alteration of natural disturbance regimes (forest fires, insect outbreaks, pathogens, windthrow, soil and nutrient cycling). Adaptation to climate change refers to adjustment in natural or human systems in response to actual or expected climate change or their effects. These adjustments moderate harm or exploit beneficial opportunities. Adaptation may be autonomous, when no specific management actions are undertaken and that natural or human systems respond spontaneously to climate change impacts. Adaptation may also be planned, when it results of a deliberate decision, based on awareness that conditions have changed (or are about to change) and that action is required to restore, maintain or achieve a desirable state. Planned adaptation involves changes in social and environmental processes, perceptions of climate risk, practices and functions to reduce potential damages or to realise new opportunities (IPCC 2007a). Adaptation to climate change is a strategy complementary to the mitigation of climate change impacts. Adaptation aims to address climate change impacts at the short term, while mitigation strategies aims the reduction of greenhouse gas emissions of the development of greenhouse gas sinks, and necessarily implies long time horizons, and international commitments.

Given that our comprehension of climate change impacts is constantly evolving, adaptation strategies include a feedback loop allowing the periodic revision of management objectives and approaches to take into account the best knowledge available (Fig. 1; Smit *et al.* 1999 2000). While unmanaged systems will respond to climate change using autonomous adaptation, managed ecosystems will benefit both autonomous and planned adaptation to climate change. Autonomous adaptation of forest ecosystems mainly relies on natural resilience, resistance and stability under climate change. These characteristics are also at the root of the development of sustainable forest management (Drever *et al.* 2006, Bodin and Winam 2007, Le Goff *et al.* 2005). When speaking about adaptation to climate change for the forest sector, we refer here to planned adaptations that can be undertaken through forest management strategies and practices to address climate-related risks. As only forests under management will benefit of planned adaptation, large parts of forest will respond autonomously to climate change. We will have to adjust our expectations from the forest resource to face this new forest (Spittehouse 1997).

Fire activity is controlled by several factors, namely weather and climate, vegetation, human activities, and topography. Dry forest fuels and winds are major contributors to large stand-destroying fires (Flannigan and Wotton, 2001; Westerling et al. 2006). The strong linkage between historical forest fire activity and climate suggests that future climate change will continue to influence forest fire activity. However, the forest fire risk is still poorly taken into account in allowable cut (AAC) calculations and management planning (Martell 1994, Lindenmayer *et al.* 2004, Armstrong 2004, Le Goff *et al.* 2005, 2009, Didion *et al.* 2007). When forest fires occur in areas under management, they generally trigger unpredicted changes in management plans (salvage logging) and specific equipment use (roads and machinery). Forest fires have been found to lower wood supply (Martell 1994), and AAC targets when forest fires are taken into account (Armstrong *et al.* 1999, Armstrong 2004, Didion *et al.* 2007), but also stabilize them (Boychuck and Martell 1996). Multi-scale influences of fire on forests under climate change are conducive to increasing probability of interference with industrial harvesting. Many authors suggest that forest fire risk should be evaluated and integrated in forest management planning in a more proactive way than currently (Le Goff *et al.* 2005, 2009; Lindenmayer *et al.* 2004, Armstrong 2004, Didion *et al.* 2007).

Developing tools that anticipate and manage fire risk are crucial elements of sustainable forest management in boreal forests submitted to high fire activity. Many approaches could contribute to better take into account forest fire risk in forest management strategies, including the use of climatic indicators of the regional fire risk and the implementation of spatially-explicit forest management such as Triad zoning and Fire-Smart forest management. Following, we present and discuss climate indicators of the regional forest fire risk, and forest management strategies facilitating the integration of the fire risk.

4.5 Planning considerations

4.5.1 Long temporal scales

On the one hand, climate change impacts as well as forest management are typically considered over time horizons about few hundreds of years, during which economic, environmental and social condition will change (Chapin *et al.* 2007, Nitschke and Innes 2008). On the other hand, spatial scales implied by these two issues are relatively different. Climate models (GCMs and RCMs) can estimate with confidence the direction and magnitude envelope of climate change impacts over large territories (e.g., increase in atmospheric temperature). Their predictions for climatic changes at regional and local scales are however associated with a high uncertainty (e.g., change in regional precipitation). This means that climate models can not predict future climate conditions with the accuracy and at a spatial scale usually required by forest management planning (Pilkey and Pilkey-Jarvis 2007, Burton 1998). While imprecise, climate change impacts projections are essential to determine current trend in fire activity and risk, and variability in possible future fire condition. Climatic conditions are only a part of uncertainties implied in long term management planning. Social and economic conditions are major uncertainties that are much more difficult to anticipate.

4.5.2 Uncertainties

Sustainable forest management is implicitly challenging because of the large magnitude and uncertain nature of ecological, economic and social changes occurring between regenerating and harvesting trees (Chapin *et al.* 2007), especially for northern regions where the time from planting to harvesting is much longer than in other parts of the world. Particularly, public expectations of forest management are a major uncertainty over long-time horizons, as it is constantly evolving (Gough *et al.* 2008). Similar to adaptation to climate change, sustainable forest management should be implemented under poorly known social and economic contexts and uncertain future climatic conditions. Sustainable forest management implies long term planning and implies the management of economic, social and ecological risks. This means that risk management is an important part of sustainable forest management. While forest management planning is particularly exposed to uncertainties, forestry traditionally ignores uncertainties and surprises because of the range of uncontrollable and unpredictable factors operating in the future. The acknowledgement and the integration of risk and uncertainties as information (Bradshaw and Borchers 2000) in forest management planning will thus necessitate a real cultural break from the traditional perception of these risks and uncertainties (Hoogstra and Schanz 2008, Borchers 2005).

4.5.3 Risk management

The development of risk management has modified our interpretation of the precautionary principle by treating uncertainty as "Information about information" (Bradshaw and Borchers 2000). For a long time, the precautionary principle has led to favour inaction rather than acting under uncertain conditions. Even if we do not fully understand how to manage forests sustainably and even if we can not anticipate with accuracy local impacts of future climate change, our current comprehension of sustainable forest management principles and issues, as well as our knowledge about future climate change impacts allow us to take actions now. For example, we could use approaches sufficiently flexible (allowing adjustments of management objectives) to respond quickly to changing environmental conditions and knowledge. Another approach was proposed by Lempert and Collins (2007) to promote management scenario performing under a variety of climate conditions (robust decision making). Many other approaches exist to address risks and uncertainties in management planning and decision analyses (see Kangas and Kangas 2004). The first step towards the integration of risks and uncertainties in forest management is to identify their nature and order of importance. These components rely strongly on the specific perception of the different people implied into the forest management planning process, particularly how they perceive and accept the different risks and uncertainties (Borchers 2005, Hoogstra and Schanz 2008).

4.5.4 Participative management

In climate change adaptation as well as in sustainable forest management, many stakeholders are involved, each having their own perceptions of risks, uncertainties, and priorities. The selection of vulnerabilities to climate change generally reflects the perceptions and values of stakeholders, including public in the case of public lands (Nitschke and Innes 2008). For example, as local impacts of climate change are highly uncertain at the scale of the forest management unit, many forest managers doubt about the relevance and the ways to change their practice. Conversely, governments are committed in adaptation strategies that include the forest sector (MDDEP 2008, Ministry of the Environment 2008).

The perception of climate change and its associated risks for natural resource management and public health determines the political and social efforts invested in climate change adaptation to decrease risks and to reduce uncertainties. The public perception of the risks associated with the natural resource management determines the social acceptability of current management policies and practices. Social acceptability of forest management is thus fed by information. To increase the social acceptability of sustainable forest management as well as of adaptation to climate change, information about ecological, economic and social rationales must be efficiently communicated (Fisher 2000). Moreover, it is crucial to give to stakeholders the opportunity to use the new information they learned in the decision process. This means that the information communicated to stakeholders should make them skilled to enhance the process (Bouthillier and Roberge 2007). The social acceptability of management practices highly depends on the collaborative aspect of the decision process: people involved in early stages of the decision process generally better understand and accept the decision taken. Sarr and Puettman (2008) underline that sustainable forest management can be achieved only if it fully considers environmental, economic and social needs associated with forest landscapes. They present collaborative sustainable forest management portfolios. This approach is based on the active involvement of people living and working in the forest landscape to improve the social acceptability and the transparency of forest management.

Participative management is a criterion of many sustainable forest management guidelines and environmental certification for forest products, particularly public involvement and first nation involvement (Chambers and Beckley 2005, Stevenson and Webb 2005, CSA 2003, FSC 2000). Participative management is also a key-element of adaptation to climate change as adaptation strategies should integrate responses to decrease the ensemble of identified vulnerabilities to climate change. An adaptation strategy is composed of a set of adaptation options, each aiming the reduction of a particular vulnerability to climate change. It is crucial to evaluate in an integrated process the vulnerabilities and adaptation of a particular system to avoid situations where a particular adaptation options trigger the aggravation of a non-targeted vulnerability to climate change (Wheaton 2001).

4.6 Planning approaches

4.6.1 Portfolio approach

Environmental sciences have adapted financial terminology, like portfolio strategy (Millar *et al.* 2007, Lempert and Collins 2004, Sarr and Puettmann 2008) and insurance strategy (Bodin and Winam, 2007) to describe decision support framework that allows the management of multiple risks and uncertainties. The portfolio approach is widely used for landscape conservation planning (Groves 2003, Davis *et al.* 2003, Jongman *et al.* 2003), and has only recently been applied in resource management (Costanza *et al.* 2000, Machado *et al.* 2006). Firstly used in management forest planting, portfolio strategies consisted in selecting groups of seed sources that perform well under a range of climatic conditions corresponding to plausible future conditions (Crowe and Parker 2008). However, the interest of portfolio strategies for the development of sustainable forest management and for adaptation to climate change is not limited to this application.

There is an increasing interest towards portfolio approaches because of the spreading recognition that no single approach will fit all changing climates (Stewart and Spittlehouse 2003, Hobbs *et al.* 2006, Millar *et al.* 2007). This change in adaptation to climate change perception is motivated by the recognition that 1) climate change impacts vary across regions (e.g., Flannigan *et al.* 1998, 2001, 2005, Bergeron *et al.* 2006), and 2) there is many uncertainties implied by climate change. We should thus favour diversified strategies to distribute the risk to use approaches failing under new climate conditions. Portfolio approaches were suggested by the range of variation associated with future climate conditions anticipated by models according to different climate change scenarios (Meehl *et al.* 2007). It includes management strategies promoting resistance, resilience, or response of forest ecosystems to climate change (Millar *et al.* 2007). Sarr and Puettman (2008) pointed out the necessity of take into account the multiple values of the different stakeholders by using collaborative sustainable forestry portfolios. Such an approach aims the resolution of the economic and ecological interests often opposed in forest management process, but also potential conflicts between local community, national guidelines, and policy issues. Lempert and Collins (2004) proposed robust portfolio approaches that include diversified management strategies performing under a wide range of possible future conditions. Portfolio approaches also would necessitate a break-up with the prevailing principle of sustained yield based on optimization strategy, and that lead to the implementation of the best scenario anticipated.

4.6.2 Adaptive management

Adaptive management was developed to face uncertainty and evolving comprehension of different managed systems. Adaptive management is an approach complementary to portfolio strategies to face risks and uncertainties. While the portfolio strategy consist in the implementation of many alternative management strategies to get better chances to have successful management strategies under future climate conditions, adaptive strategy consist in the implementation of one management strategy in a framework planning the periodic adjustments of approach and objectives. It provides a systematic and rigorous process to improving management practices according to the periodic adjustment of management goals by incorporating updated knowledge. It is also a learning philosophy (Nichols and Williams 2006) by providing a conceptual framework including planning, choosing and implementing management scenarios, examining if management objectives are met, and deliberately planning a step to revise the management objectives and scenarios.

Adaptive management is recommended for the development of sustainable forest management as well as for adaptation to climate change because it allows us to take actions now using our incomplete comprehension, and because it facilitates the improvement of management scenario by easily including new information into the process.

4.7 Management strategies facilitating the integration of the fire risk into forest management planning

If we take actions now to decrease the vulnerability of forest management to current climate conditions, we will better be prepared to respond to future climate conditions. Because of its climate determinism, fire is a major vulnerability of forest management to climate change. Tools allowing the decrease of this particular vulnerability will thus contribute to better adapt forest management to climate variability and change and will also contribute to the development of a more sustainable forest management.

4.7.1 Integrating climate indicators of the regional fire risk

Large forest fires in boreal Canada are associated with prolonged high-pressure systems in the upper atmosphere over or upstream from the affected region (Nash and Johnson 1996, Skinner *et al.* 1999, 2002, Macias Fauria and Johnson 2006). These systems are defined as "anomalous" circulation patterns. They typically remain nearly stationary or move slowly, and persist for a week or more (American Meteorological Society 2000, Macias Fauria and Johnson 2006), slowing the normal west-to-east progress of migratory storms by deflecting the low pressure systems away from the ridge location. As drought is a main factor determining the fire risk, drought indicators contribute to anticipate the fire risk. Here we present a few indicators recently developed to anticipate regional fire risk in the Waswanipi area, central Québec, Canada. They are based on the analysis of historical fire activity and diverse climate data such as atmospheric and oceanic circulation indexes, geopotential heights and weather variables.

4.7.1.1 Decadal scale

Interdecadal climate variability contributes to explain decadal variation in forest fire activity. Large scale climate variations are characterized by recurrent atmospheric and oceanic circulation patterns such as El Niño in the Pacific Ocean. Atmospheric and oceanic circulation indexes measure the alternation and strength of these recurrent patterns, and may be used to anticipate periods with high and low fire activity in different parts of the boreal forest. Girardin *et al.* (2009) developed a drought indicator based on atmospheric circulation indexes that determines a bipolar circulation pattern between central (Manitoba) and eastern (Québec) Canada. According to this indicator, wet periods over central Canada are concomitant with droughts over eastern Canada and *vice versa*. Composites and decadal coherency analyses indicated that the North Atlantic and the North Pacific circulation patterns demonstrate the strongest relationship with the drought variance over the Manitoba-Quebec corridor (Girardin et al. 2004). Other studies also reported that regional fire activity in different parts of the North-American forest is related to oceanic and atmospheric circulation indexes (e.g., Trouet *et al.* 2006, Skinner *et al.* 2006, Kitzberger *et al.* 2007). These studies stress that this relation is not linear but rather that it is the combination of phase of different circulation indexes that determines the alternation of high and low fire activity at the regional scale. Le Goff *et al.* (2007) reported that a positive (negative) phase of Pacific Decadal Oscillation (PDO) associated with a positive (negative) phase of the Northern Atlantic Oscillation (NAO) would contribute to the occurrence of high (low) fire activity periods at the decadal scale in central Québec. When PDO and NAO are in opposed phases, the PDO influence prevails, but the relation is weaker than when both NAO and PDO are in phase. These indicators however are not quantitative, and do not allow us to evaluate a mean fire activity for a particular period, that would be integrated in AAC calculations for example.

4.7.1.2 Monthly to yearly scales

Fire behaviour and activity are influenced by day-to-day variations in weather conditions at a specific location. The Fire-Weather Index (FWI) system (Van Wagner 1978) tracks weather condition determining the forest fire potential. This system is used daily across Canada during the fire season to determine the potential forest fire behaviour and to allocate adequate suppression means and strategy. The FWI allows anticipating fire conditions for the current and the following day. However, fire protection agencies would benefit from additional time for planning their resources if tools are developed to anticipate regional fire activity weeks or months in advance. Many studies reported the influence of atmospheric and oceanic circulation indexes of the regional fire activity few months or years in advance (Skinner *et al.* 2006, Macias Fauria and Johnson 2007, Le Goff *et al.* 2008). These are good tools to anticipate potential fire risk few months in advance. For example, the PDO and the NAO would influence the occurrence of high and low fire years in central Québec (Le Goff *et al.* 2007; Fig. 2). Values of PDO and NAO of the year preceding a high fire year are generally higher than values observed in the year preceding a low fire year in this part of the boreal forest.

The long-term trends in the winter oceanic temperature play prominent roles in affecting summer fire severity conditions. Summer seasonal severity rating values in eastern and central Canada were correlated with the winter Atlantic Multidecadal Oscillation index. The warm phase of El Niño-Southern Oscillation and positive phase of PDO leads to dry conditions and higher fire severity in western and north-western Canada as well as north-eastern Canada (Skinner et al. 2006). Le Goff *et al.* (2008b) examined the influence of the June 500 hPa atmospheric circulation on the fire activity over different forest zones in Québec. The atmospheric circulation patterns associated with the fire activity in these territories are composed of one main positive anomaly located over the province of Ontario and the Hudson Bay and negative anomalies located on the eastern and western coasts (Fig. 3). The location of these anomalies (positive and negative) varies depending on the territory considered. The pattern of June 500 hPa circulation may be used as an indicator of the fire season severity. Moreover, the location of the anomalies observed may indicate the location of territories with a higher fire risk. These atmospheric indicators of fire risk could contribute to anticipate periods of high fire risk at the regional scale few days in advance.

Tracking changes in oceanic circulation (surface temperatures) contribute to forecast high and low fire season about six months in advance before the beginning of the fire season while the monitoring of 500 hPa circulation anomalies over the Hudson Bay and Ontario provides information complementary to the FWI system. These indicators could contribute to decrease the vulnerability of forest management to climate change by evaluating the potential severity of the fire season. For example, the anticipated mean forest fire activity could be used to adjust AAC targets on a yearly basis. They also contribute to a better estimation of fire risk in managed landscapes. By contributing to the evaluation of fire risk, these indicators are a first step toward a more sustainable forest timber calculation, but also to calculated risk related to climate variability and change. However, an important complementary adaptation would be to better prepare salvage logging plans into tactical management planning and to ensure the availability of qualified forest manager to develop and implement efficiently salvage logging plans.

4.7.2 Distributing the fire risk across the forest management unit

4.7.2.1 Functional zoning

To translate sustainable forest management principles into forest management planning, Seymour and Hunter (1992) propose the "Triad Approach". Essentially, this is a portfolio strategy allocating the territory under management according to three different zones. Each zone corresponds to a particular management priority: wood fibre production in the intensive forest management zone, multi-objective forest management (recreation, timber production, development of other non-timber values) in the extensive forest management zone, and biodiversity conservation in the protected zone. Functional zoning is a portfolio approach as it is composed of several management strategies (typically three), distributed across the forest management unit depending on the site conditions.

The Triad strategy was first formulated to minimize conflict at specific location between wood fibre and conservation objectives by explicitly assigning specific management objectives in different parts of a forested landscape (Sarr and Puettman 2008). This approach presents also a good interest to manage the forest fire risk across a forest management unit. For example, intensive forest management may be located in area of the forest management unit where the lowest fire activity has been documented to decrease the risks and costs associated with fire and fire protection (Cyr *et al.* 2007). Where no human lives or infrastructures are located, fire protection objectives are prioritized according to investments. Under a Triad zoning, forest fires may be suppressed actively in the intensive forest management zone while some fires may be allowed to burn in the protected zone. There are important operational difficulties to this approach that currently inhibit the change from the current systematic exclusion of fire to a fire management strategy allowing some fires to burn in the areas submitted to forest management. First, it supposes that the conservation zone is bigger than the median fire size to reduce the probability to have forest fire affecting intensive and extensive forest management zones. It also implies that the intensive management zone is accessible to suppression means, to facilitate detection and suppression activities. Finally, forest fire managers do not have operational tools allowing fire behaviour prediction more than one day in advance, that restraints the choice of letting a fire burn freely in managed areas (Gaétan Lemaire, personal communication, 2009). However in western Canada, some fire management agencies use Prometheus (http://www.firegrowthmodel.com/index.cfm) and weather forecasts to predict fire behaviour for the next day or two (Kerry Anderson, personal communication, 2009). Ultimately, fire management in the Triad strategy would integrate the conservation management objectives by allowing a certain proportion of the territory to burn, to maintain post fire habitats and thereby, the ecological role of forest fire in the forest dynamics. In the extensive forest management zone, forest fire could be also actively suppressed and salvage logging operation would be submitted to ecosystem management criteria.

Functional zoning strategies could facilitate the management of forest fire risk across the territory by allocating different fire suppression efforts depending on the zone considered. Zoning strategies thus may contribute to decrease the vulnerability of forest management to climate change, and also to develop a forest management that is closer to sustainable forest management principles.

4.7.2.2 Fire-Smart forest management

The Fire-Smart forest management is strategy that aims the reduction of fire behaviour potential at the landscape scale. It uses of forest management strategy and operations (e.g., site preparation, regeneration, stand tending, harvest scheduling, and road construction) in a proactive and planned manner to reduce both the area burned by undesirable wildfires and the risk associated with the use of prescribed fire (Hirsch *et al.* 2001). Based on the Fire-Smart principles, Martell *et al.* (2004) and Palma *et al.* (2007) developed a burn probability model that predicts when and where fires might occur, the performance of the initial attack system and the growth of fires that escape initial attack to predict the probability that any point on the landscape will burn given the fuel, weather, topography and level of fire protection. By contributing to reduce the vulnerability of forest management to changing (increasing) fire risk under climate change, the Fire-Smart forest management approach may integrate an adaptation strategy. However, this approach does not integrate explicitly sustainable forest management approaches, because it was not design to meet biodiversity objectives at first. Martell *et al.* (2004) provided a first evaluation on the effect of Fire-Smart management strategy on habitat availability of different animal species. They suggested that the subsequent forest fragmentation would not affect negatively the species examined.

Currently, the sustained yield principle underlying the AAC calculations makes forest planning particularly vulnerable to risks of losses related to forest fire. The sustained yield is based on the lowest age-class anticipated in the forest management unit in the next decades, and if forest fire affects this particular age-class, departures from the pre-established sustained yield could be important. A Fire-Smart forest management could be implemented to protect in priority this age-class.

4.7.2.3 Wood timber reserves to cope with the fire risk

Forest fire represents highly variable and uncertain losses of timber supply. They often lead to unpredicted departures of the targeted sustained yield (Boychuk and

Martell 1996). While traditionally managed a posteriori using salvage logging plans, timber losses related to forest fire would gain to be considered and managed a priori (before they occur) according to several authors (Armstrong 2004, Boychuk and Martell 1996, Lindenmayer *et al.* 2004). When taken into account *a priori* in AAC calculations, forest fires lead to decreases in timber supply (Armstrong 2004, Didion *et al.* 2007), but would also stabilize the timber supply (Boychuk and Martell 1996). Particularly, wood timber reserves could contribute to decrease the departures from the targeted sustained yield. However, as underlined by Hoogstra and Schanz (2008), this kind of adaptation strategy would require an important change in the cultural perception of forest fire risk in forest management planning.

4.7.2.3 Prescribed burning

Among the multiple objectives that prescribed burning may address, few are linked to adaptation to climate change and others to sustainable forest management. For example, In British Columbia, prescribed burnings are used to decrease the forest fire risk in periurban areas and help to decrease the vulnerability of managed landscaped to climate variability and change. In Ontario, and national parks managed by Canada Parks, prescribed burnings are used to maintain the ecological integrity of fire-dependant forest ecosystems such as white pine (*Pinus strobus*) forests or to restore wildlife habitat (Queneville and Thériault 1994, Beverly and Martell 2003, OMNRN 2008). Ecosystem and species biodiversity objectives addressed by prescribed burnings meet the sustainable forest management objectives and principles aiming the maintenance of ecological processes essential to fire-dependent species. Depending on their objectives prescribed burnings may address adaptation or sustainable forest management.

4.8 Conclusion

Adaptation to climate change may contribute to develop more sustainable forest management strategies through the management of climate-related risks, such as forest fires. In boreal forest, fire is a key-element of the forest dynamics and strongly depends on climate variability and change. If we pretend to step forward a real commitment towards sustainable forest management, the identification of risks and uncertainties, their relative ordering, and their inclusion into forest management planning should be recognized as a priority. Here, we have presented a few tools that could contribute to reduce the vulnerability of forest management to changing forest fire activity, and thus contributing to the development of a more sustainable forest management in boreal forests. First, different climate indicators influencing the regional fire risk may contribute to better estimate these risks to integrate them into strategic (decadal climate indicators) and tactical (monthly to yearly climate indicators) forest management planning. Second, we have presented management frameworks allowing the integration risks and uncertainty into forest management planning. While there is an increasing body of literature suggesting that we already have the technical tools allowing a better integration of risks and uncertainties into forest management planning, important changes in the traditional perception of risk and uncertainty in forestry will be necessary to implement these new tools.

4.9 Acknowledgments

The Sustainable Forest Management Network provided the financial support for this research. We gratefully thank two anonymous reviewers whose comments contributed to streghten the manuscript.

4.10 References

American Meteorological Society. 2000. Glossary of meteorology. 2nd ed. Allen Press, Boston, MA.

Armstrong, G.W., Cumming, S.G., Adamowicz, W.L. 1999. Timber supply implications of natural disturbance management. The Forestry Chronicle 75, 497–504.

Armstrong, G.W. 2004. Sustainability of timber supply considering the risk of wildfire. Forest Science 50, 626–639.

Bergeron, Y., Cyr, D., Drever, C.R., Flannigan, M., Gauthier, S., Kneeshaw, D., Lauzon, È., Leduc, A., Le Goff, H., Lesieur, D., Logan, K. 2006. Past, current, and future fire frequencies in Quebec's commercial forests: implications for the cumulative effects of harvesting and fire on age–class structure and natural disturbance-based management. Canadian Journal of Forest Research 36, 2737–2744. doi:10.1139/X06-177

Bodin, P., Winam, B.L.B. 2007. The usefulness of stability concepts in forest management when coping with increasing climate uncertainties. Forest Ecology and Management 242, 541-552.

Borchers, J.G. 2005. Accepting uncertainty, assessing risk: decision quality in managing wildfire, forest resource values, and new technology. Forest Ecology and Management 211, 36-46.

Bouthillier, L., Roberge, A. 2007. Intentions of the public participation programs to be implemented in the forest industry: Condition in Quebec. The Forestry Chronicle 83, 810-817.

Bradshaw, G.A., Borchers, J.G. 2000. Uncertainty as information: narrowing the science-policy gap. Conservation Ecology 4, 7. [online] URL: http://www.ecologyandsociety.org/vol4/iss1/art7/ (last access March 2009).

Burton, I. 1998. Climate adaptation policies for Canada? Policy Options May 1998, 6–10.

Canadian Standart Association (CSA). 2003. CAN/CSA-Z809-02 Sustainable Forest Management: Requirements and Guidance. A National Standard of Canada. Canadian Standart Association. [online] URL: http://www.csa-international.org/product_areas/forest_products_marking/program_documents/CAN_CSA_Z809-02O_English.pdf (last access on April 2009, 8).

Chapin, F.S, III, Danell, K., Elmqvist, T., Folke, C., Fresco, N. 2007. Managing climate change impacts to enhance the resilience and sustainability of Fennoscandian forests. Ambio 36, 528-533.

Costanza, R., Daly, H., Folke, C., Hawken, P., Holling, C.S., McMichael, A.J., Pimentel, D., Rapport, D. 2000. Managing our environmental portfolio. BioSience 50, 149-155.

Crowe, K.A., Parker, W.H. 2008. Using portfolio theory to guide reforestation and restoration under climate change scenarios. Climatic Change 89, 355-370.

Cyr, D., Gauthier, S, and Y. Bergeron. 2007. Scale-dependent determinants of heterogeneity in fire frequency in a coniferous boreal forest of eastern Canada. Landscape Ecology 22(9): 1325-1339. doi 10.1007/s10980-007-9109-3.

Davis, F.W., Stoms, D. M., Costello, C., Machado, E., Metz, J., Gerrard, R., Andelman, S., Regan, H., Church, R. 2003. A Framework for Setting Land Conservation Priorities Using Multi-Criteria Scoring and an Optimal Fund Allocation Strategy. National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara, California. [Online] URL: http://www.nceas.ucsb.edu/nceas-web/projects/4040/TerrBiod_framework-report.pdf (accessed 3 March 2009).

Didion, M., Fortin, M.-J., Fall, A. 2007. Forest age structure as indicator of boreal forest sustainability under alternative management and fire regimes: A landscape level sensitivity analysis. Ecological Modelling 200, 45-58.

Drever, C.R., Peterson, G., Messier, C., Bergeron, Y., Flannigan, M. 2006. Can forest management based on natural distrurbances maintain ecological resilience? Canadian Journal of Forest Research 36, 2285-2299.

Flannigan, M.D., Bergeron, Y., Engelmark O., Wotton, B.M. 1998. Future wildfire in circumboreal forests in relation to global warming. Journal of Vegetation Science 9, 469–476.

Flannigan, M.D., Campbell, I., Wotton, B.M., Carcaillet, C., Richard, P.J.H., Bergeron, Y. 2001. Future fire in Canada's boreal forest: paleoecology results and general circulation model – regional climate model simulations. Canadian Journal of Forest Research 31, 854–864.

Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner W.R., Stocks, B.J. 2005. Future area burned in Canada. Climatic Change 72, 1–16.

Flannigan, M.D., Wotton, B.M. 2001. Climate, weather, and area burned. In E.A. Johnson and K. Miyanishi (eds.). Forest fires. pp. 351–373. Academic Press Inc., New York.

Forest Stewardship Council (FSC). 2004. FSC Principles and Criteria for Forest Stewardship. FSC-STD-01-001. Forest Stewardship Council. [Online] URL: http://www.fsccanada.org/principlesandcriteria.htm?RD=1 (last access on April 2009, 8).

Gauthier, S., Vaillancourt, M.-A., Kneeshaw, D., Drapeau, P., De Grandpré, L., Claveau, Y., Paré, D. 2009. Ecosystem-based forest management: origins and foundations. In Gauthier, S., Vaillancourt, M.-A., Leduc, A., De Grandpré, L., Kneeshaw, D., Morin, H., Drapeau, P., Bergeron, Y. (eds) "Ecosystem Management in the Boreal Forest" Presses de l'Université du Québec, Québec, QC. pp 13-37.

Girardin, M.P., Tardif, J., Flannigan, M.D., Wotton, B.M., Bergeron,Y. 2004. Trends and periodicities in the Canadian Drought Code and their relationships with atmospheric circulation for the southern Canadian boreal forest. Canadian Journal of Forest Research 34, 103–119.

Girardin, M.P., Flannigan, M.D., Tardif, J.C., Bergeron, Y. 2009. Climate, Weather and Forest Fire. In Gauthier, S., Vaillancourt, M.-A., Leduc, A., De Grandpré, L., Kneeshaw, D., Morin, H., Drapeau, P., Bergeron, Y. (eds) "Aménagement Écosystémique en Forêt Boréale" Presses de l'Université du Québec, Québec, QC. pp 79-102.

Gough, A.D., Innes, J.L., Allen, S.D. 2008. Development of common indicators of sustainable forest management. Ecological Indicators 8, 425–780.

Groves, C.R. 2003. Drafting a Conservation Blueprint: A Practitioner's Guide to Planning for Biodiversity. Island Press, Covelo, California.

Hirsch, K., Kafka, V., Tymstra, C., McAlpine, R., Hawkes, B., Stegehuis, H., Quitilio, S., Gauthier, S., Peck, K. 2001. Fire-smart forest management: A pragmatic approach to sustainable forest management in fire-dominated ecosystems. The Forestry Chronicle 77, 357–363.

Hobbs, R.J., Arico, S., Aronson, J., Baron, J.S., Bridgewater, P., Cramer, V.A. , Epstein, P.R., Ewel, J.J., Klink, C.A., Lugo, A.E., Norton, D., Ojima, D., Richardson, D.M., Sanderson, E.W., Valladares, F., Vilà, M., Zamora, R., Zobel, M. 2006. Novel ecosystems: Theoretical and management aspects of the new ecological world order. Global Ecology and Biogeography 15, 1-7.

Hoogstra, M.A., Schanz, H. 2008. How (un)certain is the future in forestry? A Comparative assessment of uncertainty in the forest and agricultural sector. Forest Science 54, 316-327.

Hulme, P.E. 2005. Adapting to climate change: is there scope for ecological management in the face of a global threat? Journal of Applied Ecology 42, 784-794.

International Panel on Climate Change (IPCC), 2007a. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change, Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson C.E. (Eds.) Cambridge University Press, Cambridge, UK, 976pp. [Online] URL: http://www.ipcc.ch/ipccreports/assessments-reports.htm (Accessed 3 March 2009).

International Panel on Climate Change (IPCC), 2007b. Summary for Policymakers. In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, , Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson C.E. (Eds.) Cambridge University Press, Cambridge, UK, 7-22. [Online] URL: http://www.ipcc.ch/ipccreports/assessments-reports.htm (Accessed 3 March 2009).

Jongman, R.H.G., Külvik, M., Kristiansen, I. 2003. European ecological networks and greenways. Landscape and Urban Planning 68, 305–319.

Kangas, A.S., Kangas, J. 2004. Probability, possibility and evidence: approaches to consider risk and uncertainty in forestry decision analysis. Forest Policy and Economics 6, 169–188.

Kitzberger, T., Brown, P.M., Heyerdahl, E.K., Swetnam, T.W., Veblen, T.T. 2007. Contingent Pacific-Atlantic Ocean influence on multicentuty wildfire synchrony over western North America. Proceedings of the National Academy of Science 104, 543-548.

Le Goff, H., Leduc, A., Bergeron, Y., Flannigan, M.D. 2005. The adaptive capacity of forest management to changing fire regimes in the boreal forest of Quebec. The Forestry Chronicle 81, 582-592.

Le Goff, H., Flannigan, M.D., Bergeron, Y., Girardin, M.P. 2007. Historical fire regime shifts related to climate teleconnections in the Waswanipi area, central Quebec, Canada. International Journal of Wildland Fire 16, 607-618.

Le Goff, H., Girardin, M.P., Flannigan, M.D., Bergeron, Y. 2008. Dendroclimatic inference of wildfire activity in Quebec over the 20th century and implications for natural disturbance-based forest management at the northern limit f the commercial forest. International Journal of Wildland Fire 17, 348-362.

Le Goff, H., Flannigan, M.D., Bergeron, Y., Leduc, A., Gauthier, S., Logan, K. 2009. Management solution to face climate change : the example of forest fires. In Gauthier, S., Vaillancourt, M.-A., Leduc, A., De Grandpré, L., Kneeshaw, D., Morin, H., Drapeau, P., Bergeron Y. (eds) "Ecosystem Management in the Boreal Forest" Presses de l'Université du Québec, Québec, QC. pp 103-127.

Lempert, R.J., Collins, M.T. 2007. Managing the Risk of Uncertain Threshold Responses: Comparison of Robust, Optimum, and Precautionary Approaches. Risk Analysis 27, 1009-1026. doi 10.1111/j.1539-6924.2007.00940.x

Lindenmayer, D.B., Foster, D.R., Franklin, J.F., Hunter, M.L., Noss, R.F., Schmiegelow, F.A., Perry, D. 2004. Salvage harvesting policiesafter natural disturbance. Science 303, 1303.

Machado, E.A., Stoms, D.M., Davis, F.W., Kreitler, J. 2006. Prioritizing farmland preservation cost-effectively for multiple objectives. Journal of Soil and Water Conservation 61, 250–258.

Macias-Fauria, M., Johnson, E.A. 2006. Large-scale climatic patterns control large lightning fire occurrence in Canada and Alaska forest regions. Journal of Geophysical Research Letters, 111: G04008, doi:10.1029/2006JG000181.

Martell, D.L. 1994. The impact of fire on timber supply in Ontario. The Forestry Chronicle 70, 164-173.

Martell, D.L., Hirsch, K., Malcolm, J., McAlpine, R., Weintraub, A., Acuna, M., Cui, W., Espinoza, A., Johnson, J., Palma C. 2004. A FireSmart approach to integrated fire and forest management in the boreal forest region of Canada. Project report 2003/2004. Sustainable Forest Management Network. [Online] URL: http://www.sfmnetwork.ca/docs/e/PR_200304martelldinte6.pdf (accessed on 10 March 2009).

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver A.J., Zhao, Z.-C. 2007: Global Climate Projections. In Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Millar, C.I., Stephenson, N.L., Stephens, S.L. 2007. Climate change and forest of the future: managing in the face of uncertainty. Ecological Applications 17, 2145-2151.

Ministère du Développement Durable, de l'Environnement et des Parcs. 2008. Plan d'action 2006-2012 sur les changements climatiques. [Online] URL : http://www.mddep.gouv.qc.ca/changements/plan_action/ (last access on April 2009, 8).

Ministry of the Environment. 2008. Ontario's Climate Change Action Plan. Full 2007-2008 Annual Report. Government of Ontario. [Online] URL : http://www.ene.gov.on.ca/en/air/climatechange/annualreport.php (last access on April 2009, 8).

Nash, C.H, Johnson, E.A 1996. Synoptic climatology of lightning-caused fires in subalpine and boreal forest. Canadian Journal of Forest Research 26, 1859-1874.

Nichols, J.D., Williams, B.K. 2006. Monitoring for conservation. Trends in Ecology and Evolution 21:668-673.

Nitschke, C.R., Innes J.L. 2008. Integrating climate change into forest management in south-Central British Columbia: an assessment of landscape vulnerability and development of a climate-smart framework 256, 313-327.

Ogden, A.E., Innes, J.L. 2007. Perspective of forest practitionners on climate adaptation in the Yukon and Northwest Territories of Canada. The Forestry Chronicle 83, 557-569.

Palma, C.D., Cui, W., Martell, D.L., Robak, D., Weintraub, A. 2007. Assessing the impact of stand-level harvests on the flammability of forest landscapes International Journal of Wildland Fire 16, 584-592.

Pilkey, O.H., Pilkey-Jarvis, L. 2007. Useless arithmetic: why environmental scientists can't predict the future. Columbia University Press, New York, New York, USA.

Sarr, D.A., Puettman, K.J. 2008. Forest management, restoration, and designer ecosystems: integrating strategies for a crowed planet. Ecoscience 15, 17-26.

Smit, B., Burton, I., Klein, R.J.T., Street, R. 1999. The science of adaptation: a framework for assessment.Mitig. Adaptation Stategy and Global Change 4, 199–213.

Smit, B., Burton, I., Klein, R.J.T., Wandel, J. 2000. An anatomy of adaptation to climate change and variability. Climatic Change 45, 223–251.

Spittlehouse, D.L. 1997. Forest management and climate change. In E. Taylor and B. Taylor (eds.). Responding to global climate change in British Columbia and Yukon. pp. 24-1–24-8 Environment Canada,Vancouver, BC.

Spittlehouse, D.L., Stewart, R.B. 2003. Adaptation to climate change in forest management. B.C. Journal of Ecosystem Management. 4(1). [Online] URL: http://www.forrex.org/jem/2003/vol4/no1/art1.pdf (last accesson March 2009, 3).

Seymour, R.S., Hunter, M.L. Jr. 1992. New forestry in eastern spruce-fir forests:principles and applications in Maine. Maine Agriculture and Forestry ExperimentStation Millaneous Publication 716.

Skinner, W.R., Stocks, B.J., Martell, D.L., Bonsal, B., Shabbar, A. 1999. The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada. Theoretical and Applied Climatology 63, 89–105. doi:10.1007/S007040050095.

Skinner, W.R., Flannigan, M.D., Stocks, B.J., Martell, D.L.,Wotton, B.M., Todd, J.B., Mason, J.A., Logan, K.A., Bosch, E.M. 2002. A 500 hPa synoptic wildland fire climatology for large Canadian forest fires, 1959–1996. Theoretical and Applied Climatology 71, 157–169. doi:10.1007/S007040200002.

Skinner, W.R., Shabbar, A., Flannigan, M.D., Logan, K. 2006. Large forest fires in Canada and the relationship to global sea surface temperatures. Journal of Geophysical Research 111, D14106. doi:10.1029/2005JD006738.

Trouet, V., Taylor, A.H., Carleton, A.M., Skinner, C.N. 2006. Fire-climate interactions in forests of the American Pacific coast. Geophysical Research Letters 33, L18704. doi:10.1029/2006GL027502.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W. 2006. Warming and earlier spring increase Western U.S. forest wildfire activity. Science 313, 940-943.

Wheaton, E.E. 2001. Changing fire risk in a changing climate: a literature review and assessment. Saskatchewan Research Council, Saskatoon, Sask. Publ. No. 11341-2E01.

Yohe, G.W., Lasco, R.D., Ahmad, Q.K., Arnell, N.W., Cohen, S.J., Hope, C., Janetos, A.C., Perez, R.T. 2007: Perspectives on climate change and sustainability. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.) Cambridge University Press, Cambridge, UK, 811-841. [Online] URL: http://www.ipcc.ch/ipccreports/assessments-reports.htm (last access on March 2009, 3).

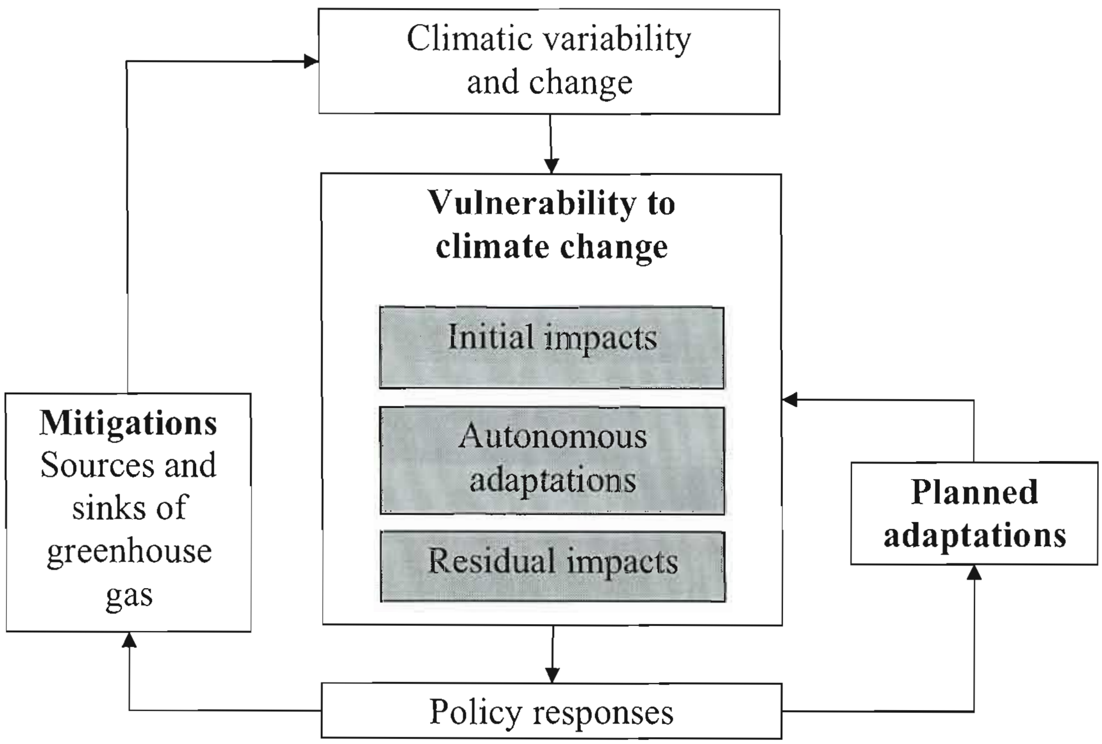

Figure 4.1 Conceptual framework of adaptation to climate change. Modified from Smit *et al.* (1999).

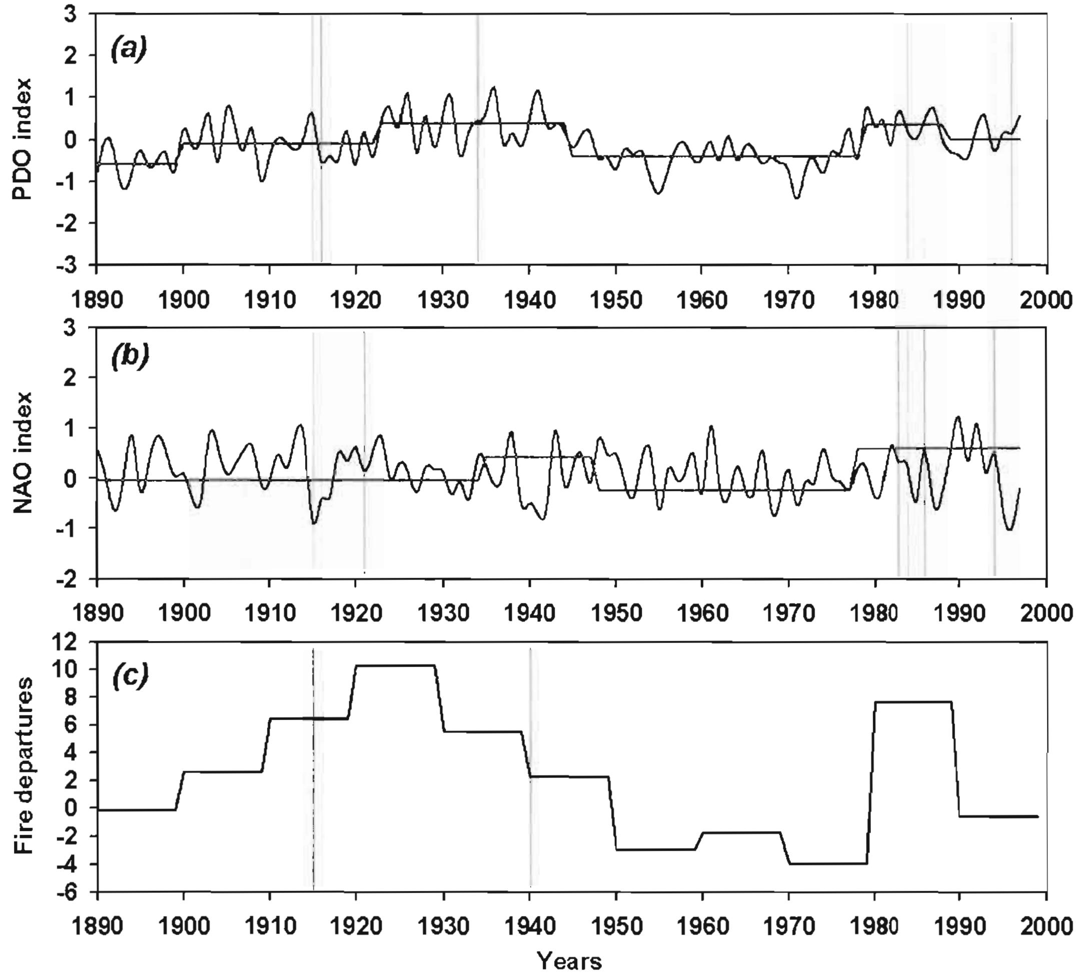

Figure 4.2 Pacific Decadal Oscillation (PDO, a), North-Atlantic Oscillation (NAO, b), and decadal fire departures in the Waswanipi area (c). Vertical grey bars indicate the fire years reported by replicated fire scars and major recent fire years. Thick line on ao and b) indicate the regime shift detection calculated using Climate Regime shift (Rodionov 2004) on PDO (probability σ = 0.10, cutoff length = 10 years; parameters for AR(1) were estimated using the IP4 method) and on NAO (probability σ = 0.10, cutoff length = 5 years; parameters for AR(1) were estimated using the IP4 method). Data from Le Goff *et al.* (2007). For details see Le Goff *et al.* 2007; chapter 1).

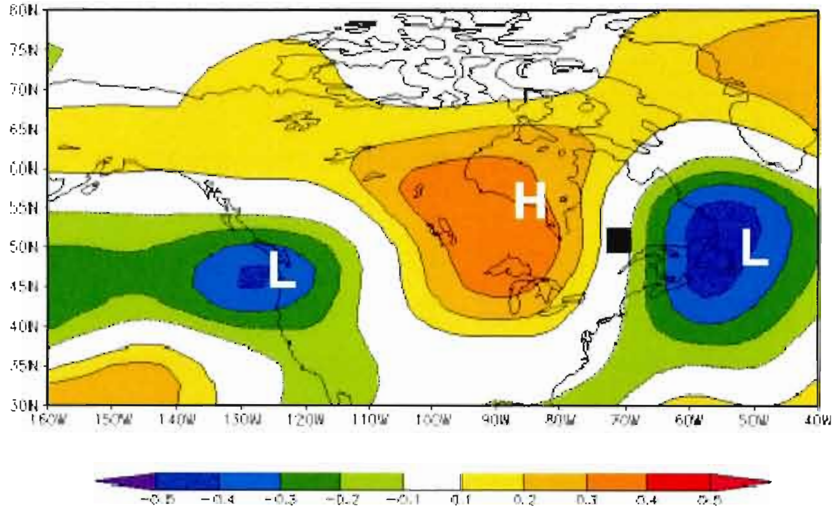

Figure 4.3 Correlation maps of the instrumental (1972-2002) annual area burned (log-transformed) in the Waswanipi area (located by the black square) and June 500 hPa geopotential heights. H identifies positive 500 hPa anomalies and L identifies negative 500 hPa anomalies (correspond to correlation coefficients |r|>0.3 significant at p < 0.10). This correlation map was produced using the KNMI Climate Explorer (http://climexp.knmi.nl). Data from Le Goff *et al.* (2008).

CONCLUSION GÉNÉRALE

Contributions originales

Cette thèse explore les opportunités de développer un aménagement forestier plus durable dans un territoire soumis à une fréquence de feu particulièrement élevée lorsqu'on la compare à celle observée dans d'autres régions de la forêt commerciale québécoise. Ces recherches ont apporté des contributions originales à l'étude des régimes de feu récents et futurs, ainsi qu'au développement de l'adaptation aux changements climatiques du secteur forestier.

Le premier chapitre constitue la première étude qui relie directement la distribution des classes d'âge avec des indices de circulation atmosphériques et climatiques. Les études précédentes reliait l'activité des feux telle que rapportée dans les archives gouvernementales (e.g., Skinner *et al.* 1999, 2002, 2006), ce qui ne permettait généralement pas de bénéficier d'une longue période de temps (limitée à environ 40 ans). En utilisant la distribution des classes d'âge, j'ai pu analyser la relation entre la variabilité climatique à grande échelle et l'activité des feux sur une plus longue période de temps (1880-2000) sans recourir aux reconstitutions dendroclimatiques (e.g., Girardin *et al.* 2007).

Le second chapitre documente pour la première fois les patrons de circulation atmosphérique responsables de l'aire brûlée dans différentes régions au Québec. En particulier, l'examen des zones de haute pression (anticyclone stationnaire) en juin sur l'Ontario et la Baie d'Hudson permet d'anticiper quelques jours à quelques semaines en avance l'occurrence de grands feux au Québec. La position, et en particulier la latitude à laquelle se trouve le centre de cet anticyclone pourrait permettre d'anticiper dans quelle zone du Québec le risque de feu serait particulièrement élevé dans les semaines suivantes. Cet indicateur du risque de feu fournit une information complémentaire à celle fournie par le système de l'Indice Forêt-Météo (IFM), utilisé quotidiennement à travers le Canada pour anticiper le risque de feu à l'échelle locale.

Le troisième chapitre marque la première utilisation de données issues du Modèle Régional Canadien du Climat (MRCC) pour le calcul des conditions futures de feu telles que représentées par les composantes du système de l'IFM dans l'Est du Canada. L'étude Tymstra *et al.* (2007) est la seule autre recherche publiée à ma connaissance qui utilise les données du MRCC pour calculer les composantes de l'IFM. Cette originalité constitue à la fois une force et une faiblesse. L'utilisation des données du MRCC constitue une force puisque leur résolution spatiale (un point de grille tous les 45 km environ) est bien adaptée aux études régionales. Les Modèles de Circulation Générale précédemment utilisés pour ce genre d'étude ont une résolution plus grossière (450 km) et ne permettent de mettre en évidence des variations spatiales qu'à l'échelle continentale (Flannigan *et al.* 1998, 2005) ou bien de n'utiliser qu'un à six points de grille pour calculer les conditions futures régionales (Nitschke and Innes 2008; Drever *et al. 2009*). L'utilisation des données du MRCC constitue également une faiblesse car il est recommandé d'utiliser plusieurs modèles et plusieurs scénarios de changements climatiques afin de déterminer une enveloppe des conditions possibles pour différents scénarios de changements climatiques, et de présenter la fourchette d'incertitude associée à cette enveloppe (Bernstein *et al.* 2007). Les données du MRCC ne sont disponibles que pour un seul modèle et pour un seul scénario de changements climatiques, le scénario A2. Ce scénario semble être à la fois le plus sévère et le plus réaliste de la famille de scénarios proposés par le Groupe d'experts intergouvernemental sur l'évolution du climat (Bernstein *et al.* 2007; Rahmstorf *et al.* 2007). Des études similaires utilisent les données des GCM pour des études régionales (Flannigan *et al.* 2005; Nitschke and Innes 2008; Drever *et al. 2009*) afin de suivre cette recommandation.

Le quatrième chapitre contribue de façon originale à l'effort de sensibilisation des intervenants forestiers aux enjeux reliés aux changements climatiques et à la nécessité de mettre en place une véritable stratégie d'adaptation pour le secteur forestier au Québec. Il intègre les connaissances développées lors des chapitres précédents et mes travaux sur l'adaptation aux changements climatique initiés lors de ma synthèse environnementale (Le Goff *et al.* 2005) et de ma réflexion poursuivie dans le livre « Aménagement Écosystémique en Forêt Boréale » (Gauthier *et al.* 2008; Le Goff *et al.* 2008).

Principaux résultats

Dans cette section, j'examine les éléments qui répondent à la question générale de cette thèse (est-il possible d'aménager durablement les forêts de la région de Waswanipi en tenant compte du régime de feu qui y prévaut?), en synthétisant les résultats qui répondent aux quatre questions spécifiques de la thèse

J'ai estimé le cycle de feu de la région de Waswanipi autour de 150 ans. Ce cycle de feu se situe parmi les plus courts rapportés dans forêt commerciale du Québec (Bergeron *et al.* 2001). Il se compare au cycle de feu rapporté pour l'Abitibi-Est (191 ans, pour la période 1920-1999, Bergeron *et al.* 2001) en forêt commerciale et confirme les résultats de Lefort *et al.* (2004, pour la période 1945-1998), qui ont rapporté un cycle de feu inférieur à 200 ans pour cette région. Le cycle de feu de la région de Waswanipi semble intermédiaire entre les cycles de feu plus longs rapportés plus au sud (Bergeron *et al.* 2001) et le cycle de feu plus court rapporté pour la forêt boréale située plus au nord qui n'est pas sous aménagement (100 ans, pour la période 1920-1984, Payette *et al.* 1989). Afin de déterminer si le cycle de feu de la région de Waswanipi est historiquement parmi les plus courts en forêt boréale commerciale ou bien s'il s'est mis en place sous l'effet des changements climatiques récents, j'ai vérifié la stabilité de la relation entre l'aire brulée et la circulation atmosphérique à 500 hPa. Ce patron est en place depuis au moins les 50 dernières années. Ces données géopotentielles n'étant disponibles qu'à partir de 1948, je n'ai pas pu vérifier plus loin dans le passé la stabilité de cette relation. Cependant, les cartes de corrélation avec les températures et les précipitations estivales suggèrent que l'influence du climat sur l'activité des feux dans la région de Waswanipi est relativement stable depuis 1904. De plus, j'ai examiné les variations temporelles du cycle de feu dans la région de Waswanipi, afin de déterminer si elles étaient similaires à celles rapportées ailleurs au Québec. Bergeron *et al.* (2001) rapportent que dans plusieurs régions, le cycle de feu actuel est plus long que celui prévalant entre 1850 et 1940, mais plus court que celui prévalant avant 1850. Dans la région de Waswanipi, j'ai rapporté un allongement du cycle de feu de 99 ans pour la période 1850-1940 à 264 ans pour la période 1940-2001, mais je n'ai pas trouvé de changement important du cycle de feu autour de 1850. Comme le cycle de feu s'est allongé, comme dans d'autre régions voisines après 1940, il semblerait que le cycle de feu dans la région de Waswanipi suive les mêmes variations temporelles que les régimes de feu ailleurs au Québec, mais qu'il est plus court depuis au moins un siècle. Ainsi, le cycle de feu particulièrement court prévalant dans la région de Waswanipi ne serait pas issu d'un changement climatique récent (i.e., les 30 dernières années), mais serait plutôt une caractéristique historique de ce territoire.

À l'aide des cartes de corrélation entre l'aire brûlée et la circulation atmosphérique à 500 hPa, j'ai aussi pu déterminer les patrons atmosphériques responsables de l'aire brûlée dans la région de Waswanipi, dans les zones de protection intensive (sud du Québec) et extensive (nord du Québec). Le patron climatique qui contrôle l'activité des feux dans la région d'étude est intermédiaire entre ceux responsables de l'activité des feux dans les zones de protection intensive et restreinte. Les corrélations entre la variabilité décennale de l'activité des feux et les indices climatiques indiquent une influence positive de l'Oscillation Pacifique. Cette relation a été validée à l'échelle interannuelle pour les années de grands feux entre 1899 et 1996. Ainsi, mes résultats suggèrent qu'un patron particulier de circulation atmosphérique permet d'expliquer une partie de la variabilité observée dans l'aire brûlée annuellement dans la région de Waswanipi, et qu'il se distingue des patrons atmosphériques responsables de l'aire brûlée ailleurs au Québec. Par ailleurs, la combinaison de phase de l'Oscillation Pacifique Décennale et de l'Oscillation Nord-Atlantique permet d'expliquer plus de 70% de la variabilité décennale de l'activité de feu dans la région de Waswanipi. Cette combinaison de phase spécifique à la région de Waswanipi confirme qu'un patron climatique particulier contrôle l'activité des feux dans cette région. Ailleurs sur le continent, des combinaisons d'indices climatiques différentes permettent d'expliquer la variabilité interdécennale des feux (Kitzberger *et al.* 2007; Trouet *et al.* 2006).

J'ai examiné les conditions futures de feu et l'activité future des feux à l'aide des données météorologiques quotidiennes simulées sur la période 1961-2100 par le Modèle Régional du Climat. Bien que mes résultats suggèrent une faible augmentation de l'activité des feux, sous l'influence des changements climatiques futurs, la variabilité interannuelle de l'activité des feux reste un défi bien plus important pour le développement d'un aménagement forestier durable. Mes résultats suggèrent aussi que le risque de feu du mois d'août pourrait doubler d'ici 2100 alors que le risque de feu du mois de mai pourrait diminuer. Ainsi, le pic saisonnier de l'activité des feux pourrait se réaliser et se prolonger plus tard dans la saison. Les feux vont continuer à exercer une contrainte importante pour l'aménagement forestier, c'est pourquoi il est nécessaire d'intégrer le risque de feu dans la planification forestière pour s'approcher davantage des principes de gestion durable des forêts.

Nos stratégies d'aménagement forestier durable pourraient échouer si elles n'intègrent les risques et incertitudes reliés aux changements climatiques (Yohe *et al.* 2007; Ogden and Innes 2007; Nitschke and Innes 2008). Si nous prétendons nous engager véritablement dans le développement d'un aménagement forestier plus durable, il est nécessaire d'évaluer et de gérer ces risques et incertitudes dans la planification forestière. C'est pourquoi l'adaptation aux changements climatiques peut être interprétée comme une composante de gestion de risque de l'aménagement forestier durable (Spittlehouse et Stewart 2003). Les récents développements réalisés en science de l'adaptation aux changements climatiques (Smit *et al.* 1999) peuvent contribuer à développer un aménagement forestier plus durable. Par exemple, la gestion de risque et la gestion adaptative sont des concepts communs à l'adaptation aux changements climatiques et à l'aménagement forestier durable. Au-delà de la perception, maintenant courante, que l'adaptation aux changements climatiques partage des objectifs communs avec l'aménagement forestier durable, il devient de plus en plus évident qu'on ne peut prétendre aménager durablement nos forêts sans gérer les risques climatiques impliqués à court, comme à plus long terme, c'est–à–dire, adaptater notre système d'aménagement forestier aux conditions climatiques actuelles et futures.

Différents indicateurs climatiques du risque de feu régional, comme la combinaison de phase de l'Oscillation Pacifique Décennale et de l'oscillation Nord-Atlantique peuvent contribuer à mieux prévoir le risque de feu dans la région de Waswanipi et pourrait être intégrée à la planification forestière stratégique. Par ailleurs, le patron atmosphérique associé à l'aire brûlée annuellement dans la région de Waswanipi, peut contribuer à évaluer la sévérité de la saison en cours (en termes d'aire brûlée) et aider à évaluer et à intégrer le risque de feu à la planification forestière opérationnelle et tactique. Certaines stratégies d'aménagement comme la Triade permettent de cartographier les priorités d'intervention en matière de suppression des feux, et pourraient également contribuer à développer un aménagement forestier plus durable si l'on décide de laisser certains feux brûler dans les zones de conservation et d'aménagement extensif. Enfin, l'aménagement Intelli-Feu, qui utilise la planification forestière pour diminuer le risque de feu à l'échelle de l'unité d'aménagement pourrait permettre de limiter les pertes de volumes ligneux associés aux feux dans les territoires sous aménagement soumis à une fréquence de feu élevée, comme c'est le cas dans la région de Waswanipi.

Perspectives et recommandations

Le secteur forestier canadien doit aujourd'hui faire face à la crise économique alors qu'il est déjà fragilisé par des changements des marchés internationaux, par le taux de change, les difficultés d'approvisionnement et l'augmentation des coûts de production. Ce contexte difficile met à rude épreuve la compétitivité de ce secteur économique vital de l'économie canadienne et pourrait laisser croire que le moment est inopportun pour investir et réfléchir aux défis que les changements climatiques posent à long terme au secteur industriel forestier (Lemprière *et al.* 2008). Pourtant, plusieurs considèrent qu'il faut profiter de ce contexte difficile pour innover et trouver des solutions qui permettront à l'industrie forestière canadienne de devenir plus compétitive à court comme à plus long terme. L'aménagement forestier durable est un moyen d'améliorer la compétitivité du secteur forestier canadien, comme le démontre le succès actuel de la certification forestière. L'engouement des industriels pour la certification forestière fournit une opportunité exceptionnelle pour les gouvernements de modifier les lois et les pratiques en matière d'aménagement forestier afin d'intégrer davantage les principes d'aménagement forestier durable.

Nous disposons de connaissances de base pour développer un aménagement forestier plus durable qui tienne mieux compte de la fréquence de feu particulièrement élevée dans la région de Waswanipi. Cependant ces connaissances scientifiques ne sont pas suffisantes pour modifier la mécanique de la planification forestière actuelle qui ne laisse pas d'emprise pour intégrer le risque de feu sous la forme d'une probabilité. Il est nécessaire de convaincre les décideurs politiques et l'industrie forestière de la nécessité d'intégrer le risque de feu au calcul de la possibilité forestière par des arguments d'ordre financier, politique et social. Par exemple, la mise en réserve de certains volumes de bois en prévision des risques de pertes par le feu est une solution permettrait de gérer le risque de pertes de volumes ligneux reliées aux feux. Cependant, cette approche est difficile à envisager pour les industriels dans un contexte où ils subissent déjà des pressions pour allouer une partie des territoires qu'ils aménagent à des objectifs autres que la production ligneuse (e.g., maintien d'autres attributs et processus naturels dans le cadre d'un aménagement écosystémique). Les outils développés dans cette thèse impliquent une gestion plus proactive des pertes de volume de bois reliées aux feux. Cependant plusieurs barrières sociales et politiques empêchent ou ralentissent le développement de l'aménagement forestier durable et de l'adaptation du secteur forestier québécois aux changements climatiques. Ces barrières persisteront si aucun effort n'est investit pour les examiner et pour proposer des solutions politiques, sociales et économiques qui permettraient de les lever.

RÉFÉRENCES CITÉES DANS L'INTRODUCTION ET LA CONCLUSION GÉNÉRALES

Bernstein, L., Bosch, P., Canziani, O., Chen, Z., Christ, R., Davidson, O., Hare, W., Huq, S. Karoly, D., Kattsov, V., Kundzewicz, Z., Liu, J., Lohmann, U., Manning, M., Matsuno, T., Menne, B., Metz, B., Mirza, M., Nicholls, N., Nurse, L., Pachauri, R., Palutikof, J., Parry, M., Qin, D., Ravindranath, N., Reisinger, A., Ren, J., Riahi, K., Rosenzweig, C., Rusticucci, M., Schneider, S., Sokona, Y., Solomon, S., Stott, P., Stouffer, R., Sugiyama, T., Swart, R., Tirpak, D., Vogel, C., et G. Yohe. 2007. Climate Change 2007: Synthesis Report. Intergovernmental Panel on Climate Change. Available online at http://www.ipcc.ch/ipccreports/ar4-syr.htm (access on August 2008).

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., et D. Lesieur. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. Canadian Journal of Forest Research 31(3): 384-391.

Bessie, W.C. et E.A. Johnson. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. Ecology 76(3): 747–762.

Blanchet, P. 2003. Forest Fires: The Story of a War. Cantos International Publishing, Montréal. 182 pp.

Drever, C.R., Bergeron, Y, Drever, M.C., Flannigan, M.D., Logan, T., et C. Messier. *2009*. Effects of climate on occurrence and size of large fires in a northern hardwood 1 landscape: historical trends, future predictions, and implications for climate change in Témiscamingue, Québec. Applied Vegetation Science 12(3): 261-272. DOI:10.1111/j.1654-109X.2009.01035.x.

Flannigan, M.D. et J.B. Harrington. 1988. A study of the relation of meteorological variables to monthly area burned by wildfire in Canada (1953–80). Journal of Applied Meteorology 27: 441–452.

Flannigan, M.D., Bergeron, Y., Engelmark O., et B.M. Wotton. 1998. Future wildfire in circumboreal forests in relation to global warming. Journal of Vegetation Science 9: 469–476.

Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., et B.J. Stocks. 2005. Future area burned in Canada. Climatic Change 72, 1-16.

Gauthier, S., Leduc, A., Harvey, B., Bergeron, Y., et P. Drapeau. 2001. Les perturbations naturelles et la diversité écosystémique. Le Naturaliste Canadien 125(3): 10-17.

Gauthier, S., Vaillancourt, M.-A., Leduc, A., De Grandpré, L., Kneeshaw, D., Morin, H., Drapeau, P., et Y. Bergeron. 2008. Aménagement Écosystémique en Forêt Boréale. Presses de l'Université du Québec, Québec, QC.

Gillett, N.P., Weaver, A.J., Zwiers, F.W., et M.D. Flannigan. 2004. Detecting the effect of climate change on Canadian forest fires Geophysical Research Letters 31(18): L18211 1-4.

Girardin, M.P., Ali, A.A., Carcaillet, C., Mudelsee, M., Drobyshev, I., Hély, C., et Y. Bergeron. In press. Heterogeneous response of circumboreal wildfire risk to climate change since the early 1900s. Global Change Biology, *in press*.

Girardin, M.P. 2007. Interannual to decadal changes in area burned in Canada from 1781 to 1982 and the relationship to Northern Hemisphere land temperatures. Global Ecology and Biogeography 16(5): 557-566.

Girardin, M.-P., Tardif, J., Flannigan, M.D., Wotton, B.M., et Y. Bergeron. 2004. Trends and periodicities in the Canadian Drought Code and their relationships with atmospheric circulation for the southern Canadian boreal forest. Canadian Journal of Forest Research 34(1): 103-119.

Hirsch, K.G. et P. Fuglem. 2006. Stratégie canadienne en matière de feux de forêt: synthèses de fond, analyses et perspectives. Conseil canadien des ministres des Forêts, Ressources naturelles Canada, Service canadien des forêts, Centre de foresterie du Nord, Edmonton, AB. Disponible en ligne URL http://ccfm.org/ (dernier accès le 2 avril 2009).

Kitzberger, T., Brown, P.M., Heyerdahl, E.K., Swetnam, T.W., et T.T. Veblen. 2007. Contingent Pacific-Atlantic Ocean influence on multicentury wildfire synchrony over western North America. Proceedings of the National Academy of Science of the United States of America 104(2): 543-548.

Le Goff, H., Leduc, A., Bergeron, Y., et M.D. Flannigan. 2005. The adaptive capacity of forest management to changing fire regimes in the boreal forest of Quebec. The Forestry Chronicle 81: 582-592.

Le Goff, H., Flannigan, M.D., Bergeron, Y., Leduc, A., Gauthier, S., et K. Logan. 2008. Des solutions d'aénagement pour faire face aux changements climatiques: l'exemple des feux de forêt. In Gauthier, S., Vaillancourt, M.-A., Leduc, A., De Grandpré, L., Kneeshaw, D., Morin, H., Drapeau, P., et Y. Bergeron (Eds.) "Aménageemnt Écosystémique en Forêt Boréale" Presses de l'Université du Québec, Québec, QC. pp 109-135.

Lefort, P., Gauthier, S., and Y. Bergeron. 2003. The influence of fire weather and land use on the fire activity of the Lake Abitibi area, Eastern Canada. Forest Science 49(4): 509-521.

Lefort, P., Leduc, A., Gauthier, S., et Y. Bergeron. 2004. Recent Fire Regime (1940–1998) in the Boreal Forest of Western Quebec. Ecoscience 11(4): 433–445.

Lemaire, G. 2002. Lutte directe: portée et limites.Dans Service Canadien des Forêts, Société de Protection des Forêts contre le Feu et Réseau de Gestion Durable des Forêts (eds.). Actes du colloque "L'Aménagement Forestier et le Feu," 9–11 Avril 2002, Chicoutimi, Québec. pp. 97–100. Ministère des Ressources Naturelles, Québec, Québec.

Lemprière, T.C., Bernier, P.Y., Carroll, A.L., Flannigan, M.D., Gilsenana, R.P., McKenney, D.W., Hogg, E.H., Pedlar, J.H., et D. Blain. 2008. L'importance d'adapter le secteur forestier aux changements climatiques. Ressources Naturelles Canada, Service canadien des forêts, Centre de forestry du Nord, Edmonton, AB.

Marlon, J.R., Bartlein, P.J., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E., Joos, F., Power, M.J., et I.C. Prentice. 2008. Climate and human influences on global biomass burning over the past two millennia. Nature Geoscience 1: 697-702.

McAlpine, R.S. et K.G. Hirsch. 1999. An overview of LEOPARDS: the level of protection analysis system. The Forestry Chronicle 75(4): 615–621.

MRNFQ. 2000. La limite nordique des forêts attribuables. Rapport final du comité, Ministère des Ressources Naturelles du Québec, Québec. 100 p.

Nitschke, C.R. et J.L. Innes. 2008. Integrating climate change into forest management in South-Central British Columbia: an assessment of landscape vulnerability and development of a climate-smart framework. Forest Ecology and Management 256(3): 313-327.

Patry, P. 2002. État des connaissances: récupération des bois après feu. Dans Service Canadien des Forêts, Société de Protection des Forêts contre le Feu et Réseau de Gestion Durable des Forêts (eds.). Actes du colloque "L'Aménagement Forestier et le Feu," 9–11 Avril 2002, Chicoutimi, Québec. pp. 97–100. Ministère des Ressources Naturelles, Québec, Québec.

Payette, S., Morneau, C., Sirois, L., et M. Desponts. 1989. Recent Fire History of the Northern Quebec Biomes. Ecology 70(3): 656-673.

Podur, J., Martell, D.L., et K. Knight. 2002. Statistical quality control analysis of forest fire activity in Canada. Journal Canadien de la Recherche Forestière 32(2): 195-205.

Rahmstorf, S., Cazenave, A., Church, J.A., Hansen, J.E., Keeling, R.F., Parker, D.E., et R.C.J. Somerville. 2007. Recent climate observations compared to projections. Science 316: 709.

Skinner, W.R., Stocks, B.J., Martell, D.L., Bonsal, B., et A. Shabbar. 1999. The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada. Theoretical and Applied Climatology 63 (1-2): 89-105.

Skinner, W.R., Flannigan, M.D., Stocks, B.J., Martell, D.L., Wotton, B.M., Todd, J.B., Mason, J.A., Logan, K.A., et E.M. Bosch. 2002. A 500 hPa synoptic wildland fire climatology for large Canadian forest fires, 1959-1996. Theoretical and Applied Climatology 71(3-4): 157-169.

Skinner, W.R., Shabbar, A., Flannigan, M.D., et K. Logan. 2006. Large forest fires in Canada and the relationship to global sea surface temperatures. Journal of Geophysical Research 111: D14106.

Smit, B., Burton, I., Klein, R.J.T., et R. Street. 1999. The science of adaptation: a framework for assessment. Mitig. Adaptation Stategy and Global Change 4: 199–213.

Trouet, V., Taylor, A.H., Carleton, A.M., et C.N. Skinner. 2006. Fire-climate interactions in forests of the American Pacific coast. Geophysical Research Letters 33: L18704.

Tymstra, C., Flannigan, M.D., Armitage, O.B., et K. Logan. 2007. Impact of climate change on area burned in Alberta's boreal forest International Journal of Wildland Fire 16 (2): 153-160.

Weber, M.G. et M.D. Flannigan. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. Environmental Reviews 5: 145-166.

Appendix A1 Description of the dendrochronological series; *1st-order autocorrelation refers to standard chronologies; ** the common interval is 1904-2002 except for E2P (1915-2002), N3P (1930-2002), and N4P (1925-2002). Site chronology idents: first letter indicates the transect (E for the longitudinal transect, N for the latitudinal transect), number indicates the position on the transect (increasing eastern or northern), and last letter indicates the species (E for black spruce and P for jack pine). See Fig. 2.1 for the location of the chronologies. Subsignal Signal Strength (SSS 0.85) measures the portion of the residual chronology (year y to present) with a common signal over 85% (Wigley *et al.* 1984).

Species	*Picea mariana*								*Pinus banksiana*							
chronology ident	E1E	E2E	E3E	E4E	N1E	N2E	N3E	N4E	E1P	E2P	E3P	E4P	N1P	N2P	N3P	N4P
Tree-ring chronology statistics																
No. of trees	28	25	30	31	31	31	32	27	21	30	29	33	30	33	13	27
No. of series	52	46	55	59	57	55	59	47	38	54	56	57	60	54	26	50
1^{st} yr of series	1860	1834	1858	1838	1840	1826	1802	1763	1852	1902	1853	1758	1852	1869	1864	1842
Total length	143	169	146	165	163	177	202	240	151	101	150	245	151	134	139	161
Mean length	112	103	122	102	99	131	100	122	122	85	103	90	101	107	92	93
Mean sensitivity	0.16	0.16	0.14	0.13	0.17	0.12	0.11	0.13	0.18	0.14	0.16	0.22	0.16	0.16	0.17	0.20
Standard deviation	0.14	0.14	0.12	0.11	0.14	0.11	0.10	0.12	0.15	0.13	0.14	0.19	0.13	0.14	0.15	0.17
1^{st}-order autocorr.*	0.60	0.43	0.44	0.36	0.62	0.66	0.43	0.39	0.34	0.32	0.45	0.60	0.35	0.41	0.63	0.57
Common interval analysis**																
No. of trees	24	12	27	17	14	21	11	19	18	14	14	12	10	19	11	16
No. of series	35	17	47	27	21	34	17	28	29	17	26	19	17	30	19	25
% variance in PC1	34.39	40.23	30.36	32.95	36.17	29.59	25.37	27.94	36.03	41.24	35.21	38.68	32.22	34.52	33.89	32.27
Pop. common sign.	0.92	0.87	0.91	0.87	0.86	0.88	0.67	0.85	0.89	0.89	0.86	0.86	0.76	0.89	0.81	0.86
Intercore corr.	0.32	0.36	0.28	0.30	0.31	0.27	0.17	0.24	0.33	0.37	0.32	0.35	0.26	0.31	0.30	0.29
Intertree corr.	0.31	0.35	0.27	0.29	0.30	0.26	0.15	0.23	0.32	0.36	0.30	0.33	0.24	0.31	0.28	0.28
Intratree corr.	0.70	0.71	0.64	0.62	0.63	0.64	0.51	0.61	0.70	0.58	0.67	0.74	0.61	0.56	0.64	0.64