UNIVERSITÉ DU QUÉBEC À MONTRÉAL

MODELISATION DES IMPACTS DES CHANGEMENTS CLIMATIQUES SUR LES FEUX ET LA VÉGÉTATION DE LA FORÊT BORÉALE DE LA CEINTURE D'ARGILE AU QUEBEC

THÈSE

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AVANT-PROPOS

Cette thèse se compose d'une introduction générale, de trois chapitres qui décrivent de façon non exhaustive le travail effectué au cours du doctorat et d'une conclusion générale. Les trois chapitres sont présentés sous forme d'articles scientifiques publiés ou engagés dans le processus de publication. Avec la collaboration des coauteurs, j'ai été la principale responsable des étapes du développement et de la rédaction des trois chapitres. Chaque chapitre répond à un objectif de recherche précis et intègre de façon systématique une introduction qui présente la problématique; les données et méthodes utilisées; les résultats et une discussion qui met en perspective les résultats obtenus. D'autres articles scientifiques ont été réalisés au cours du doctorat mais ne sont pas présentés dans le cadre de la thèse.

Le premier chapitre, intitulé *Potential changes in forest composition could reduce impacts of climate change on boreal wildfires*, a été publié en 2013 dans la revue *Ecological Applications, 23, 21-35*. Les coauteurs sont les cosuperviseurs de cette thèse Martin Girardin et Yves Bergeron, ainsi que Pierre Legendre et Catherine Périé. Martin Girardin et Yves Bergeon ont participé à la conception de la recherche, Pierre Legendre a contribué au développement de la méthode statistique et Catherine Périé a fourni les données de végétation. Chacun des coauteurs a révisé le texte.

Le deuxième chapitre, intitulé *Dynamics of moisture content in spruce-feather moss and spruce-Sphagnum organic layers during an extreme fire season and implications for future depths of burn in Clay Belt black spruce forests,* a été publié en juin 2014 dans la revue *International Journal of Wildland Fire*, 23, 490-502. Les coauteurs sont les cosuperviseurs de cette thèse Martin Girardin et Yves Bergeron ainsi que William de Groot. Martin Girardin, Yves Bergeon et William de Groot ont participé à la conception de la recherche ainsi qu'à la révision du texte.

Le troisième chapitre, intitulé *Disturbance legacies and paludification mediate the ecological impact of an intensifying wildfire regime in the Clay Belt forest of boreal North America*, a été accepté pour publication dans la revue *Journal of Vegetation Science.* Les coauteurs sont les cosuperviseurs de cette thèse Martin Girardin et Yves Bergeron ainsi qu'Alan Cantin, William de Groot, Kenneth Agbesi Anyomi et Sylvie Gauthier. Martin Girardin, Yves Bergeon et William de Groot ont participé à la conception de la recherche, Alan Cantin à la réalisation des simulations, Kenneth Agbesi Anyomi aux analyses statistiques. Sylvie Gauthier a fourni les données de biomasses. Chacun des coauteurs a révisé le texte.

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RÉSUMÉ GÉNÉRAL

Ce doctorat s'insère dans un contexte d'aménagement adaptatif des ressources forestières boréales à l'est du Canada en prévision de conditions climatiques futures plus propices à l'activité des feux.

L'importance des feux dans la dynamique végétale boréale a mené au développement de pratiques sylvicoles qui s'inspirent du régime actuel des feux. Il s'agit de cette manière de recréer des structures en âge et en composition similaires que celles observées dans les paysages naturels. Dans la région de la Ceinture d'Argile, à l'est du Canada, la récolte de bois et le retrait de couches organiques peuvent être justifiées par une activité actuelle de feux moins importante que celle connue dans le passé. Le régime des feux dépend des conditions météorologiques, le réchaufemment climatique attendu pour ces prochaines années induira des conditions de sécheresse plus propices aux feux et affecteront la dynamique forestière dans la région d'étude. Les pratiques sylvicoles pourraient engendrer ainsi des effets cumulatifs aux impacts des changements climatiques et par conséquent influencer la capacité de la forêt à s'adapter.

Dans une optique finale de permettre aux gestionnaires d'adapter leurs pratiques sylvicoles en vue d'anticiper les impacts des changements climatiques, l'objectif principal de ce doctorat consiste en l'évaluation de l'impact des changements climatiques sur l'activité des feux (occurence et profondeur de brûlage) et la végétation de la forêt boréale de la Ceinture d'Argile au Québec. Ce doctorat se divise en trois objectifs présentés en chapitres: (1) évaluer les impacts des changements climatiques sur l'occurrence des feux dans les prochaines décennies pour l'ensemble du Québec à une échelle appropriée pour l'aménagement (paysage),

(2) projeter la réponse aux changements climatiques de la profondeur de brûlage dans des pessières à mousses et des pessières à sphaignes, les peuplements dominant des paysages de la forêt boréale de la Ceinture d'Argile (3) simuler les modifications potentielles des paysages forestiers de la Ceinture d'Argile du Québec en réponse aux changements des régimes des feux obtenus lors de la réalisation des objectifs précédents.

La modélisation a été le principal outil utilisé pour la réalisation de ce projet. L'originalité réside dans l'intégration des effets rétroactifs de la végétation sur l'activité des feux dans un contexte de changements climatiques. Des modèles empiriques de l'occurrence de feux et de la profondeur de brûlage ont été développés à partir de données climatiques de feux et d'attributs de végétation. Ces modèles ont été ensuite appliqués à des données climatiques de feux futurs simulés à l'aide de modèles climatiques globaux ou régionaux selon les chapitres pour projeter le nombre de feu et la profondeur de brûlage potentiels pour la fin du 21ème siècle. Les relations empiriques ont été ensuite intégrées à un modèle basé sur des processus afin de calibrer la dynamique de la végétation de la Ceinture d'Argile en réponse à la profondeur de brûlage et de l'aire brûlée. Il a finalement été appliqué à des données de risque futur de feux afin de simuler la réponse de la végétation aux changements futurs de l'activité des feux.

Les résultas principaux de cette étude ont révélé que les changements climatiques induiront une augmentation de l'activité des feux dans la région de la Ceinture d'Argile à l'Est du Canada. La potentielle expansion des essences de feuillues limitées plus au sud ainsi que des pessières dominées par des sphaignes auront pour effet de réduire les impacts du climat sur les feux. La mise en place de pratiques sylvicoles qui modifient la composition et la structure des paysages est ainsi proposée afin de diminuer la vulnérabilité des forêts aux feux. Cette étude constitue une première tentative de simulation de la dynamique de végétation et des effets des

changements climatiques futurs dans la pessière a mousse de la Ceinture d'Argile. L'intégration des effets de rétroaction de la végétation sur les feux permet de comprendre les interactions futures entre le climat, la végétation et le feu. Les résultats de ce doctorat ont des implications importantes pour l'aménagement forestier, car ils ouvrent le débat sur de nouvelles statégies d'aménagement.

Mots-clefs : Changements climatiques, aménagement forestier, modélisation, forêt boréale, feux, dynamique de végétation

INTRODUCTION GÉNÉRALE

Le dernier rapport publié par le groupe d'experts intergouvernemental sur l'évolution du climat (GIEC ; IPCC en anglais), en automne 2013, présente des évidences empiriques d'un réchauffement climatique global depuis le début du 20ème siècle. Les gaz à effet de serre ont contribué à augmenter la température moyenne globale de 0,5 à 1,3 ˚C entre 1951 et 2010 et induiront un changement de climat ces prochaines décennies quelles que soient les politiques adoptées en terme de gestion d'émissions (IPCC, 2013). L'ensemble des modèles climatiques globaux projettent une augmentation moyenne de température de plus de 1,5 ˚C d'ici la fin de ce siècle en comparaison avec la période 1850-1900, conjointement à une diminution des précipitations estivales. Les forêts, et spécialement les forêts des régions boréales, ont été identifiées comme fortement vulnérables face à de tels changements. Bien que les forêts boréales sous un climat plus chaud pourraient gagner en productivité sur le long terme (e.g Chen et al., 2006; Euskirchen et al., 2006; Girardin et al., 2008; Kurz et al., 2009), une augmentation des périodes de sécheresse en été induira un risque plus élevé de perturbations naturelles (feux, épidémies d'insectes, maladies…) dont les dommages seront immédiats (IPCC, 2007). Une des priorités en aménagement forestier sera alors de faire face et de s'adapter à ces risques accrus (Spietelhouse et Stewart, 2003). Ce doctorat s'insère dans un contexte d'aménagement adaptatif des ressources forestières boréales à l'est du Canada en vue à de conditions climatiques futures plus propices à l'activité des feux (Yang et al., 2011). Il s'agit de simuler les impacts des changements climatiques sur les feux et la végétation de la Ceinture d'Argile au Québec afin d'en évaluer la vulnérabilité.

0.1 La forêt boréale, constamment modifée par les perturbations

Formant une ceinture cicumpolaire de l'Eurasie jusqu'à l'Amérique du Nord, la forêt boréale couvre près de 17% de la superficie mondiale net. Dominée par des essences de conifères, elle est composée de mosaïques de forêts de feuillus, de conifères et mixtes, parsemées de tourbières et de forêts entourbées. Le bois constitue une ressource naturelle importante contribuant à la richesse et à la structure sociale des pays boréaux (Canada, Russie,Suède, Norvège et Alaska) (Stewart et al., 1997). En adjonction à ses intérêts économiques, ces paysages diversifiés et vastes, non occupés, sont particulièrement adéquats pour la faune sauvage (mammifères, oiseaux, insectes,…) (Burton et al., 2003). La forêt boréale de l'hémisphère Nord est influencée par un climat froid et aride et se distingue des autres biomes forestiers par ses hivers longs, sévères et secs et par ses étés courts, modérément chauds et plus humides qu'en hiver (Bonan and Shugart 1989). La décomposition en est alors ralentie, la matière organique s'accumule à travers le temps sur les sols boréaux jouant un rôle particulièrement important dans le cycle du carbone : près de 37% du carbone forestier y est stocké (Kaschichkte et al., 1995).

La forêt boréale est caractérisée par une dynamique de peuplements périodiquement modifiée par un régime de feu (Johnson, 1992; McRae et al., 2001; Weber and Flannigan, 1997), les espèces se sont adaptées au cours du temps de manière à résister et à se maintenir (Bergeron et al., 2002; de Groot et al., 2002). Le régime de feu est généralement décrit par la fréquence, l'intensité, le type, la forme et la taille du feu ainsi que la profondeur de brûlage (quantité de matière organique brûlée lors d'un événement) et la saison de brûlage (de Groot et al., 2013a). Toutes ces caractéristiques sont à la base de la dynamique de la forêt boréale et en module les attributs physiques et biologiques (Payette, 1992). En adjonction, le régime des feux façonne la structure et la composition des paysages. Il augmente la productivité (Johnstone et Chapin, 2006; Lecomte et al., 2006) et favorise la conservation d'espèces intolérantes à l'ombre (e.g. *Pinus banksina* (Johnson, 1992) ou les essences feuillues (de Groot et al., 2003). Ainsi, les paysages affectés par des feux plus fréquents sont dominés par des forêts de feuillus ou du pin gris, alors que des feux moins fréquents (plus de 200 ans) permettent la succession sous la canopée de conifères tolérants à l'ombrage, comme par exemple le sapin baumier (Bergeron et Dansereau, 1993; de Groot et al., 2003). La profondeur de brûlage agit sur la régénération des forêts et les voies successionnelles (Greene et al., 2007; Johnstone et al., 2010; Johnstone and Chapin 2006; Lecomte et al., 2006a; Lecomte et al., 2006b). En effet, les essences feuillues ou le pin gris montrent une tolérance moins grande que l'épinette noire ou blanche à une épaisse couche de matière organique résiduelle. Les feux qui consumment une large quantité de couche organique au sol et y laissent une fine épaisseur permettent la régénération de forêts fermées composées d'espèces feuillues ou de pin gris. Tandis que si le feu laisse une épaisse couche organique, les forêts sont converties en des peuplements ouverts dominés par des épinettes.

0.2 L'aménagement écosystémique et les changements climatiques

L'aménagement écosystémique permet de protéger les attributs écologiques de la forêt tout en conservant ses bénéfices économiques (Gauthier et al., 2008). Dans ce contexte, l'utilisation de pratiques sylvicoles qui s'inspirent du régime des feux en tant qu'aménagement écosystémique a gagné en popularité ces dernières décennies au Canada (e.g. McRae et al. 2001; Perrera et al. 2008). Une sylviculture qui respecte les champs de variabilité de tolérance des espèces aux régimes des feux permettrait la durabilité fonctionnelle des écosystèmes forestiers (Perrera et al., 2008).

Actuellement, les pratiques de sylviculture dans un cadre d'aménagement écosystémique s'appuient sur les données historiques de l'activité des feux (Fulé, 2008; Gauthier et al., 2008). Par exemple, la fréquence, la quantité et la saison des récoltes de bois peuvent être évaluées respectivement à partir de la fréquence, la quantité d'aire brûlée et la saison d'un feu. Le brûlage dirigé ou la récolte mécanique des déchets au sol après les récoltes peuvent également être utilisés dans le but d'imiter la perte de la matière organique lors du feu. Néanmoins, des telles stratégies devraient également intégrer les effets des changements climatiques prévus pour ces prochaines décennies sur le régime des feux et la dynamique végétale qui en découle (Spittelhouse and Stewart, 2003). En effet, le climat agit quotidiennement sur les feux à travers les températures, les précipitations, l'humidité relative, la vitesse du vent en régissant les conditions d'humidités du combustible, les sources d'allumage naturelles ainsi que leur expansion (e.g. Johnson 1992; Van Wagner 1987; Weber and Flannigan 1997). L'augmentation récente des températures a déjà été associée à une augmentation de l'activité des feux au Canada (e.g. Gillet et al., 2004). Le réchauffement global attendu impactera directement le nombre de feux (Girardin and Mudelsee 2008, Flannigan et al. 2009, Wotton et al. 2010), l'aire brûlée (Amiro et al. 2009, Balshi et al. 2009, Flannigan et al. 2009, Le Goff et al. 2009, Bergeron et al. 2010) et la profondeur de brûlage (e.g. Harden et al., 2000). La structure et la composition de la végétation répond rapidement aux effets indirects d'un changement de régime de feux (Weber et Flannigan, 1997). Un enfeuillement et un rajeunissement des paysages boréaux pourraient notamment résulter de ces changements de régime de feux (Barrett et al., 2011; de Groot et al., 2003; Flannigan et al., 2013; Fulé, 2008; Johnstone et al., 2010, Thompson et al, 1998;. Weber et Flannigan, 1997), modifiant alors les habitats pour la faune (Rupp et al, 2006) et réduisant les stocks de carbone (Amiro et al., 2009; de Groot et al., 2013; Harden et al., 2000; Turetsky et al, 2011a; Turetsky et al, 2011b). Ces changements entraîneront également des dommages économiques pour le secteur forestier par la réduction de la quantité des produits commerciaux et de la qualité du bois (Kirilenko et Sedjo, 2007; Weber et Flannigan, 1997).

0.3 La forêt boréale de la Ceinture d'Argile

Ce doctorat s'est concentré sur la région de la forêt boréale de la Ceinture d'Argile, au nord-ouest du Québec, Canada (49°00 - 50°00N, 78°30 - 79°50W). Le territoire de l'étude se situe au niveau du domaine bioclimatique de la pessière à mousses (Saucier et al., 1998). Un ancien lac proglaciaire (lac Barlow-Ojibway) y a laissé un épais dépôt d'argile, formant l'unité physiographique connue aujourd'hui comme la ceinture d'argile, qui s'étend de part et d'autres de la frontière entre le Québec et l'Ontario et couvre une superficie d'environ 145 470 km^2 (Vincent et Hardy 1977). La topographie y est relativement plane, parsemée de petites collines rocheuses. Le cycle des feux (temps nécessaire pour brûler l'équivalent de la superficie du territoire) depuis les années 1920 a augmenté jusqu'à 398 ans, alors qu'il était de 101 ans avant 1850 (Bergeron et al., 2004b). La température moyenne annuelle de 1970 à 2009 était de 0,3 ˚C , allant d'une valeur minimale de - 22,2 ˚C en hiver à une valeur maximale de 17,4 ˚C en été, et la précipitation annuelle totale moyenne était de 862 mm (Environnement Canada, 2012).

Les paysages sont dominés par l'épinette noire, le pin gris et le peuplier faux-tremble qui constituent une ressource importante pour l'industrie forestière. L'intervalle long entre les feux, un sol mal drainé, la topographie plane et le climat froid favorisent l'accumulation d'une épaisse couche organique au sol, donnant lieu à un processus décrit comme de la paludification (Lavoie et al., 2005b). L'accumulation de la couche organique permet l'établissement et l'expansion des espèces de sphaignes au profit des mousses hypnacées (Fenton et al., 2007; Fenton and Bergeron, 2011; Lafleur et al., 2010; Lavoie et al., 2005a). Une fois les sphaignes établies sur les sols forestiers, l'eau de la nappe phréatique se déplace du sol minéral vers le sol organique (Fenton et al., 2006). Les racines des arbres sont alors incapables d'atteindre le sol minéral et poussent dans des environnements humides, froids et pauvres en éléments nutritifs, entraînant une baisse de la productivité des arbres (Payette , 2001).

Cette perte de productivité associée aux processus de paludification est une problématique importante pour l'industrie forestière puisqu'elle réduit la quantité de bois qui peut être récolté. Des pratiques ont été proposées afin d'empêcher l'établissement des sphaignes, de réduire la couche de matière organique et de favoriser des peuplements plus productifs, par exemple le mélange de la couche organique (e.g. Lafleur et al., 2010) ou le brûlage dirigé (e.g. Renard et al., 2009). De plus, appuyée par le fait que la fréquence de feu ait diminué depuis le Petit Age Glaciaire (1850) et que les peuplements jeunes issus de feux sévères soient plus productifs et diversifiés, une récolte de bois à un intervalle plus court que celui des feux actuels est justifiée en tant qu'aménagement écosystémique dans la pessière à mousse de la Ceinture d'Argile (Harper et al., 2003; Lecomte, 2005). Une augmentation de l'activité des feux qui réduiraient la proportion de forêts paludifiées pourraient avoir des effets cumulatifs aux pratiques sylvicoles. Par ailleurs, cette augmentation pourrait également avoir des impacts au niveau du climat global par l'augmentation des émissions de carbone vers l'atmosphère. En effet, l'accumulation de la matière organique dans les paysages amène la forêt de la Ceinture d'Argile à compter parmis les plus grands stocks de carbone au monde (Scharlemann et al. 2009).

0.4 Objectifs et structure de la thèse

Dans une optique principale de permettre aux gestionnaires d'adapter leurs pratiques sylvicoles en vue d'anticiper les impacts des changements climatiques, l'objectif principal de cette thèse consiste en l'évaluation de l'impact des changements climatiques sur l'activité des feux (occurence et profondeur de brûlage) et la végétation pour la forêt boréale de la Ceinture d'Argile du Québec. Alors que plusieurs projections de l'activité future des feux ont déjà été réalisées pour la Ceinture d'Argile à l'est du Canada, ces projections ont été généralement obtenues en utilisant des modèles empiriques calibrés avec des variables décrivant les processus d'assèchement dans les couches des sols et le régime de feux (Flannigan et al., 2005; Bergeron et al., 2006; Girardin et Mudelsee, 2008; Lafleur et al., 2010). La plupart des modèles ne considéraient pas directement les effets de la végétation et du type de combustible sur l'allumage et la propagation du feu (Flannigan et al., 2001; Hély et al., 2001; Krawchuk et al., 2009; Hessl 2011). La composante végétation a donc été intégrée dans les projections de feux. La thèse a été subdivisée de la manière suivantes :

1. Projections des impacts des changements climatiques prévus pour fin du 21ème siècle sur l'occurrence des feux à partir de conditions météorologiques de feux et d'enveloppes climatiques d'espèces d'arbres : comparaison de l'influence des changements de composition potentielle d'arbres sur le nombre de feux.

2. Predictions de la profondeur potentielle de brûlage potentielle à partir de l'humidité des sols et de l'indice de sécherresse (IS) : comparaison des projections futures du potentiel de la profondeur de brûlage dans des pessières à mousses et des pessières à sphaignes en réponse aux changements climatiques.

3. Simulations des impacts des changements du régime des feux projetés avec les changements climatiques à la fin du 21ème siècle sur la composition et la structure de la végétation.

Alors que le premier chapitre couvre tout le Québec, les deux autres se concentrent sur le territoire de la Ceinture d'Argile.

Dans le premier chapitre, intitulé '*Potential changes in forest composition could reduce impacts of climate change*', il s'agit de projeter l'occurrence des feux en forêt boréale d'ici la fin du 21ème siècle. La question suivante est abordée : Dans quelle mesure l'augmentation du nombre de feux prédit en forêt boréale d'ici la fin du 21ème siècle sera compensée par la modification de la composition de la forêt, soit naturellement, soit par l'aménagement forestier stratégique? Pour répondre à la question nous avons développé un modèle empirique décrivant l'occurrence des feux actuels au Québec en fonction d'indices de risque de feux et de la composition forestière. Ces modèles ont été ensuite appliqués à des données de risques de feux futurs (2071-2100) et de niches potentielles d'habitats d'espèces d'arbres pour projeter l'occurrence des feux futurs. Les projections ont été basées sur deux scénarios de dispersion des arbres : i) un scénario *statu quo* dans lequel la distribution future des arbres ne diffère pas de la distribution actuelle et ii) un scénario selon lequel les espèces ont la possibilité d'étendre leur niche à leur plein potentiel.

Le deuxième chapitre, '*Dynamics of moisture content in spruce-feather mosses and spruce-Sphagnum organic layers during an extreme fire season and implications for future depths of burns in Clay Belt black spruce forests*', avait pour objectif de projeter le potentiel de profondeur de brûlage dans les pessières à sphaignes de la Ceinture d'Argile à l'est du Canada. Des données d'humidité des sols à différentes profondeurs de la couche organique et des données d'indices de sécheresse extraites à des stations météorologiques *in situ* ont été récoltées dans des pessières à mousses et des pessières à sphaignes. Un modèle empirique linéaire mixte a été ensuite calibré afin de prédire les taux d'humidité des matériaux organiques à partir de l'indice de sécheresse, de la profondeur et du type de site. Alors que le combustible peut soutenir un feu si l'humidité du sol ne dépasse pas certaines valeurs, la profondeur de brûlage a été définie à partir de deux limites extrêmes d'humidité du sol à atteindre. La profondeur à laquelle ces limites ont été atteintes ont été calculées quotidiennement à partir des équations obtenues par un modèle mixte. Ce modèle a été ensuite appliqué à des données de risque futur de feu (2071-2100).

Le troisième chapitre s'intitule '*Disturbance legacies and paludification mediate the ecological impact of an intensifying wildfire regime in the Clay Belt forest of boreal North America*'. Il avait pour but d'investiguer les changements potentiels de la productivité et de la composition de la forêt boréale de la Ceinture d'Argile en réponse aux changements de régime de feux. Dans ce chapitre, la question suivante était abordée :'Est-ce que la courche organique pourrait diminuer avec l'augmentation prévue de l'activité des feux (occurrence et profondeur de brûlage) en réponse aux changements climatiques?' Nous avons effectué des expériences futures des régimes de feu en utilisant le modèle CanFIRE basé sur les processus de la dynamique de la végétation. Dans ce modèle, la dynamique de la végétation a été régi par le danger d'incendie et de comportement du feu qui affecte la mortalité des arbres et le recrutement après feu des espèces, ainsi que par des voies de succession à long terme qui sont entraînés par le recrutement après feu et l'âge de la forêt. Le modèle a été adapté au processus de paludification rencontré dans la région. Les relations empiriques développées au premier chapitre ont été utilisées afin de simuler des régimes de feux futurs (occurrence et superficie brûlée). Les équations de la profondeur de brûlage obtenuea dans le deuxième chapitre ont été intégrées le modèle CanFIRE.

CHAPITRE I

POTENTIAL CHANGES IN FORET COMPOSITION COULD REDUCE IMPACTS OF CLIMATE CHANGE ON BOREAL WILDFIRES

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1.1 Abstract

There is general consensus that wildfires in boreal forests will increase throughout this century in response to more severe and frequent drought conditions induced by climate change. However, prediction models generally assume that the vegetation component will remain static over the next few decades. As deciduous species are less flammable than conifer species, it is reasonable to believe that a potential expansion of deciduous species in boreal forests, either occurring naturally or through landscape management, could offset some of the impacts of climate change on the occurrence of boreal wildfires. The objective of this study was to determine the potential of this offsetting effect through a simulation experiment conducted in eastern boreal North America. Predictions of future fire activity were made using Multivariate Adaptive Regression Splines (MARS) with fire behavior indices and ecological niche models as predictor variables so as to take into account the effects of changing climate and tree distribution on fire activity. A regional climate model (RCM) was used for predictions of future fire risk conditions. The experiment was conducted under two tree dispersal scenarios: the *status quo* scenario, in which the distribution of forest types does not differ from the present one, and the unlimited dispersal scenario, which allows forest types to expand their range to fully occupy their climatic niche. Our results show that future warming will create climate conditions that are more prone to fire occurrence. However, unlimited dispersal of southern restricted deciduous species could reduce the impact of climate change on future fire occurrence. Hence, the use of deciduous species could be a good option for an efficient strategic fire mitigation strategy aimed at reducing fire propagation in coniferous landscapes and increasing public safety in remote populated areas of eastern boreal Canada under climate change.

Key words: boreal forest; climate change; climatic envelope; deciduous species; future fire occurrence; mitigation management; multivariate adaptative regression splines.

Résumé

Il est actuellement accepté que l’activité des feux en forêt boréale augmentera tout au long de ce siècle suite à conditions de sécheresse plus fréquentes et plus sévères induites par les changements climatiques. Les modèles développés pour ces projection se basent cependant sur l’hypothèse que la composition de la végétation devrait rester statique ces prochaines décennies. Alors que les essences feuillues sont moins inflammables que les essences conifériennes, une expansion potentielle des essences feuillues en forêt boréale, soit naturelle ou soit anthropique par une gestion du paysage, pourrait compenser en partie les effets des changements climatiques sur le risque de feu. L'objectif de cette étude est de déterminer à l’aide de simulations les effets potentiels de compensation d’une expansion des essences de feuillues dans la forêt boréale à l’est de l'Amérique du Nord. L’occurrence des feus a été calibrée à partir d’indices du comportement de feu et de niche écologique d’espèces d’arbres en utilisant l’analyse de régression multivariée par spline adaptative (RMSA). L’intégration de ces deux variables dans les prédictions ont permis d’intégrer non seulement les effets des changements climatiques, mais également les effets de la distribution des arbres sur l'activité des feux. Des données climatiques extraites d’un modèle climatique régional (MCR) ont été utilisée pour les simulations des indices futurs du comportement de feu. L'expérience a été menée selon deux scénarios de dispersion future des arbres: i) le scénario *statu quo*, selon lequel la distribution des types forestiers ne diffère pas de celle-ci, et ii) le scénario de dispersion illimitée qui permet aux arbres d’occuper pleinement leur niche climatique future. Nos résultats indiquent que le réchauffement créera des conditions climatiques plus propices au risque d’incendie. L’expansion potentielle des essences feuillues restreintes actuellement au sud pourrait toutefois réduire les impacts des changements climatiques sur la récurrence des incendies future. Ces réultats permettent ainsi de proposer l’utilisation des essences de feuillues en tant que stratégie adaptative visant à réduire le risque de feu dans les paysages conifériens boréaux ainsi qu’à accroître la sécurité de la population dans les zones à risques.

Mots-clefs : forêt boréale, occurrence des feux, , enveloppe climatiques, changemens climatiques, essences feuillues.

1.2 Introduction

It is now well recognized that wildland fires are essential to boreal forest dynamics. They shape forest structure and composition, for instance by increasing landscape-level forest productivity (Johnstone and Chapin III, 2006; Lecomte et al., 2006) and by favoring the conservation of shade-intolerant species (e.g., *Pinus banksiana*; (Johnson, 1992). However, fires in boreal forests also have their negative effects owing to their high suppression costs, the infrastructure disasters they cause in remotely-populated areas and the loss of harvestable forests during extreme fire years. In 2010, the Russian boreal forest was affected by several hundred fires due to exceptional drought conditions. A state of emergency was declared and damages were estimated at 15 million dollars (US) (http://www.huffingtonpost.com/2010/08/10/russia-fire-cost-wildfire_n_676602.html). Western boreal Canada was also hit in 2011 by major fires that forced a state of emergency and the evacuation of communities. In May 2011, for example, wildland fires spread in Alberta, and the Slave Lake fire (western boreal Canada), forced the evacuation of 15,000 residents, causing damage totaling over 700 million dollars (CAN) (Flat Top Complex Wildfire Review Committee 2012).

The processes governing wildland fire activity operate at several time scales (days, seasons, interannual, decadal) and are influenced by several climatic and environmental factors such as temperature, precipitation, wind, and the structure and composition of forests. From 1905 to 2005, rising concentrations of carbon dioxide in the atmosphere have contributed to a global warming estimated at 0.74 ^{o}C (± 0.18 ^{o}C) (IPCC, 2007). The response of the boreal forest to further warming is a major concern because high-latitude boreal regions are likely to be most affected by these changes (IPCC, 2007), and the expected response of fire activity is closely linked to warmer and drier weather (Balshi et al., 2009). Recent temperature increases have been associated with increasing fire activity in Canada since about 1970 (Gillett et al.,

2004) and exceptionally warm summer conditions in Russia during the 2010 fire season (Rahmstorf and Coumou, 2011). This increased warming will likely result in more fire-prone weather conditions by the end of the 21st century (Yang et al., 2011) that will directly impact the number of fire occurrences (Flannigan et al., 2009; Girardin and Mudelsee, 2008; Wotton et al., 2010) and area burned (Amiro et al., 2009; Balshi et al., 2009; Bergeron et al., 2010; Flannigan et al., 2009; Le Goff et al., 2009). Fire management capacity will eventually be overwhelmed (Podur and Wotton, 2010).

Predictions of future fire activity are generally obtained using empirical models calibrated with variables describing the processes of drying in organic soil layers and fire behavior (Bergeron et al., 2006; Flannigan et al., 2005; Girardin and Mudelsee, 2008; Rahmstorf and Coumou, 2011). Most of these models do not consider feedback effects on fire ignition and spread resulting from changes in vegetation and fuel types (Flannigan et al., 2001; Hély et al., 2001; Hessl, 2011; Krawchuk et al., 2009). Models assume that the vegetation component will remain relatively static in the course of the next few decades. However, deciduous species are less flammable than coniferous species (Arienti et al., 2006; Campbell and Flannigan, 2000; Hély et al., 2001; Hély et al., 2010; Krawchuk et al., 2006; Lefort et al., 2004; Päätalo, 1998) and thus one could expect that the increasing risks brought about by more fire-prone climatic conditions could be offset by an increasing deciduous component in boreal landscapes. While in the long term a potential northward migration of limited temperate deciduous species and an expansion of other deciduous species in the boreal forest are expected to occur in response to climate change (Berteaux et al., 2010; Iverson and Prasad, 1998; McKenney et al., 2007; O'ishi et al., 2009; O'ishi and Abe-Ouchi, 2009), it might not be the case in the medium-term owing to low species migration and dispersal rates. Nevertheless, the question of potential vegetation feedback on fire activity is important when placed in the following context: to what extent can changes in vegetation offset predicted increases in fire risk driven by more severe and frequent drought conditions if species dispersal is unlimited or facilitated through, for instance, strategic forest management planning aimed at mitigating increasing climate risks? Such planning could include fuel treatments through prescribed burning and modification of vegetation composition around forest communities to reduce the fuel load (e.g. Hirsch et al. 2004).

The objective of this study is to determine whether increases in the occurrence of boreal fires predicted to occur by the end of the 21st century can be mitigated by changing the vegetation composition. We used a previously published method of predicting future fire behavior coupled with ecological niche models that take into account the effect of changing tree species distribution. Ecological niche models present correlative descriptions of the current environment and species distribution and, based on predicted future environmental conditions, they can be used to project future species' suitable ranges (British Columbia Forest Service, 2011). In order to fulfill data requirements for the wildfire and ecological niche models, we focused our modeling effort on eastern boreal North America. Three hypotheses related to wildfire risk response to climate change were statistically tested. These hypotheses were formulated on the basis of the widely accepted evidence that temperatures will be rising in boreal regions over the present century (IPCC, 2007) and that fire activity will be increasing (Bergeron et al., 2010; Flannigan et al., 2009). The hypotheses are that (i) weather and tree composition are both important explanatory variables of fire occurrence in boreal forests; (ii) future climate conditions will be more conducive to fire; and (iii) changes in tree composition may limit the increase in fire occurrence.

1.3 Study area

Our study area is located in the province of Quebec, Canada (Fig. 1.1). The climate is predominantly continental, with warm and short summers, and cold, long and snowy winters (Natural Resources Canada, 2007). Temperature and precipitation differ across the province due to maritime effects, latitude, topography, and the presence of the Labrador Current along the east coast (Richard, 1987). Mean annual temperature decreases with latitude and elevation, ranging from 7°C in the south to -3.1°C in the north (Natural Resources Canada, 2007). Total annual precipitation varies from 800 to 1600 mm, with maximum values in the eastern part due to maritime effects (Natural Resources Canada, 2007; Richard, 1987). Forests located south of 47°N are dominated by deciduous and mixed stands. Dominant tree species include, but are not restricted to, sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britt.), beech (*Fagus* sp.), balsam fir (*Abies balsamea* (L.) Mill.), red pine (*Pinus resinosa* Ait.), and white pine (*Pinus strobus* L.). Coniferous species cover small areas (Bérard and Côté, 1996; Saucier et al., 1998) and the region is rich in vascular plants (>1,600 species) and tree species (~40 species) (Richard, 1987). Forests located between 47ºN and 58ºN are dominated by conifers, including black spruce (*Picea mariana* (Mill.) BSP.), white spruce (*Picea glauca* (Moench) Voss.), and balsam fir. However, deciduous species such as trembling aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* Marsh.), and yellow birch also occupy extended areas in these forests (Bérard and Côté, 1996; Saucier et al., 1998). Vascular plants are abundant in deciduous stands and abundance, diversity and evenness decrease with increasing coverage of conifer species (De Grandpre et al., 1993; Hart and Chen, 2006). Where coniferous trees dominate, lichens and mosses occupy the subarctic forest floor (Bergeron et al., 2002; Gauthier et al., 2000). Above 58ºN, the subarctic tundra forest extends from the continuous forest limit to the northernmost limit of tree growth (Payette, 2001). Plant diversity is poor and landscapes are generally occupied by scattered black spruce individuals (Payette, 2001; Richard, 1987).

1.4 Methods

The structure and organization of the methods used are illustrated in Fig. 1.1. Hereafter, we formulate the FireOcc quantity as:

$$FireOcc_j = \sum \left(c_1 BF_1 \times FW_j + c_2 BF_2 \times TreeComp \right) \tag{1.1}$$

where FireOcc is the number of fires per year per 1,000 km^2 for a given fire size class (≥1 ha; ≥10 ha; ≥200 ha) for the decade *j*. Predictor variables are sets of fire bioclimatic zones determined from fire weather (*FW*) variables and tree species composition (*TreeComp*). Finally, c_1 and c_2 correspond to constants, while BF_1 and BF_2 are basis functions for non-linear interactions (see below *Parametrization of the FireOcc model*). For the purpose of developing predictions of future FireOcc that take into account regional climate and tree composition changes, the following intermediate analyses were undertaken: (i) division of the study area into fire bioclimatic zones using a clustering method applied to gridded *FW* variables and tree species distributions; (ii) parameterization of the FireOcc model using a non-linear regression technique relating FireOcc to *FW* variables and *TreeComp*; (iii) inclusion of simulation outputs of a regional climate model into the FireOcc models. Data and methods are described in detail in the following sections.

1.4.1 Fire statistics

Forest fire data from the ministère des Resources naturelles et de la faune du Québec were used for this study. The database contains information on the location, date of detection, size (ha), and cause (lightning or human) of all fires recorded in the province of Quebec. The period covered by the data encompasses that during which systematic fire detection was made by detection planes. We considered lightning fires from 1971–2009 only. Fires of size < 1 ha were not included as the database for these fires is considered incomplete (Boulanger et al., 2012). Fires < 10ha of unknown origin were removed from the analysis. Remaining fires were grouped in the following size classes: ≥1 ha, ≥10 ha, and ≥200 ha. These classes correspond to the 1st, 2nd and 3rd percentiles of the fire size distribution.

1.4.2 Climate data and fire weather (FW) variables

We used the Canadian Fire Weather Index (FWI) System (Van Wagner, 1987) to estimate fuel moisture and generate a series of relative fire behavior indices based on weather observations and simulations. Briefly, the FWI System calculates three fuel moisture codes at different forest floor levels based on daily temperature, precipitation, relative humidity and wind velocity. These codes are the fine fuel moisture code (FFMC), duff moisture code (DMC), and drought code (DC). FFMC estimates the moisture contents of the litter and other fine fuels in a forest stand in a layer of ~0.25 kg m^{-2} dry weight. It is an indicator of sustained flaming ignition and fire spread. DMC represents the average moisture content of loosely compacted, decomposing organic layers of moderate depth weighing ~5 kg m^{-2} when dry. It relates to the probability of lightning ignition and fuel consumption. DC represents the average moisture content of deep, compact organic layers (about 10 to 25 cm from the surface) weighing ~25 kg m^{-2} when dry. It relates to the consumption of heavier fuels and the effort required to extinguish a fire. For a temperature of 25ºC, relative humidity of 30% and wind speed of 10 km/h, the response times of the FFMC, DMC and DC are approximately 0.5, 10 and 50 days, respectively (Wotton 2009). These moisture codes feed into other codes related to fire behavior, including a numerical rating of fire spread (initial spread index, ISI), the fuel available for combustion (build-up index, BUI), and an approximation of the difficulty of controlling fires (daily severity rating, DSR). It is important to note that the FWI System estimates fire behavior without regard for fuel types and, hence, forest composition (Van Wagner, 1987; Wotton, 2009). All indices are unitless, with the zero value indicating low fire risk and high values indicating high fire risk. Winter precipitation is included in the algorithms of the FWI so fire behavior indices also depend on snow accumulation (Girardin and Wotton, 2009). Additionally, we also considered the length of the fire season (FS) as a potential predictor of FireOcc. The start of the fire season was assumed to begin either on the third consecutive day with noon temperature above 12ºC, or 3 days after snowmelt (i.e., after 7 consecutive days with <2 cm of snow on the ground) (Brown et al., 2003), depending on which of the two criteria came first. The end of the season was set based on the accumulation of over 2 cm of snow on the ground for 7 consecutive days or on the occurrence of 3 consecutive days with daily minimum temperature below 0ºC, whichever happened first (Brown et al., 2003).

To begin with the computation of the *FW* variables, a set of 1,000 locations was randomly selected across the study area using a random location list generator, and weather data (maximum daily temperature, precipitation, wind, and relative humidity) were obtained for each location using the BioSIM software (Régnière and Bolstad, 1994). As part of the procedure, daily data were interpolated from the four closest weather stations, adjusted for differences in latitude, longitude and elevation between the data sources and the location, and averaged using a $1/d^2$ weight, where d is distance. Data for the 1971‒2009 period were interpolated from Environment Canada’s historical climate database (Environment Canada, 2013). Data for 2071‒2100 were obtained from gridded simulation outputs of the Canadian regional climate model, version 4.1.1 (CRM4.1.1 acs and act runs) (Biner et al., 2007; Music and Caya, 2007). The simulations were carried out on a horizontal grid-size mesh of 45 km. Simulations were performed using the IPCC SRES A2 emission scenario (Nakićenović et al. 2000). The A2 storyline from which it is developed represents a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other SRES storylines. The CO_2 concentration therein increases from 476 ppm in

1990 to 880 ppm by the late 21st century. To account for differences between model development data and RCM predictions, the delta method was applied. This method involves calculating differences in temperature and ratios of precipitation, wind speed and specific humidity projected by the RCM model in relation to the model's average climate during the time period for which historical climate data are available (i.e. 1971–2000). Those changes are then added (for temperature) or multiplied (for precipitation, wind speed and specific humidity) to historical climate data averages. Specific humidity was converted into relative humidity.

1.4.3 Mapping of tree species' potentially suitable habitats

Previously published tree species distributions predicted by ecological niche models for the baseline and future periods were used to estimate tree species presence and absence at each of our locations (Berteaux et al., 2010a). The potentially suitable habitats predicted by the models correspond to areas that species can occupy under current and changing climate conditions without any dispersal constraint (Engler and Guisan, 2009; McKenney et al., 2007). Details on the data and methods can be found in Berteaux et al. (2010a). Briefly, multiple statistical models of species- suitable habitats were parameterized using Quebec data on forest composition, altitude, soil types, soil drainage class and climate (1961–1990 normals). These multiple statistical models were then averaged to obtain ensemble means, and parameter settings were applied to adjusted outputs of the Canadian regional climate models and scenarios described earlier for the projection of future suitable habitats. We retained the following 10 tree species, which are generally considered dominant in Quebec's bioclimatic domain (Saucier et al., 1998): balsam fir, sugar maple, yellow birch, paper birch, bitternut hickory (*Carya cordiformis* (Mill.) K.), black spruce, white spruce, jack pine (*Pinus banksiana* Lamb.), trembling aspen and American basswood (*Tilia americana* L.). All results were centered on 2080 for future periods. Locations without tree information were deleted. We obtained a total of 638 random locations for analysis (Fig. 1.1).

1.4.4 Spatial clustering

Baseline reference conditions for the different *FW* variables were computed at each of our locations from the averages of the daily quantities over 1971–2000. Spatially constrained clustering (Legendre and Fortin, 1989; Legendre and Legendre, 1998) was then applied to the baseline *FW* variables, and to tree species distributions to divide the study area into homogeneous fire and tree composition zones, respectively (Fig. 1.1). For several of our locations, the fire weather variables were calculated from the same weather stations, which induces an overlap in location information and, hence, an inflated autocorrelation. Spatial clustering analysis made it possible to eliminate this autocorrelation. Owing to the high collinearity between some of the *FW* predictor variables, we restrained our application of the clustering method to DC, DSR, and FS variables; sensitivity analyses indicated that inclusion of other variables such as temperature and other *FW* variables did not improve model performance. We computed space-constrained agglomerative clustering using a multivariate dissimilarity (distance) matrix (Legendre, 2011). Ward's minimum variance hierarchical cluster analysis was used as the clustering method (Ward, 1963). Hellinger transformation was applied to the tree species distribution dataset followed by calculation of Euclidian distance: the result was a matrix of Hellinger distances among sites (Legendre and Gallagher, 2001). The number of clusters that minimized the cross-validated residual error (CVRE) was retained. One hundred cross-validation iterations were also conducted to calculate the CVRE. The clustering analysis was performed with the "const.clust" package (Legendre, 2011) included in the R freeware (R Development Core Team, 2010).

1.4.5 Fire bioclimatic and future tree composition zone delimitation

Fire bioclimatic zones were delimited using *FW* variables and *TreeComp* spatial clustering results. This was done to obtain homogeneous zones of both *FW* variables (*FW* clusters) and tree composition (*TreeComp* clusters). Spatial clustering analysis made it possible to assign each location two values corresponding to its cluster membership (*FW* variables and *TreeComp*). The “factor” function in the R freeware was used to encode each location with a cluster code (one fire bioclimatic zone). A new cluster was created when two points belonged to the same *FW* cluster while their *TreeComp* cluster was different, or vice-versa.

To reflect that tree-suitable habitats would change in response to climate change, new *TreeComp* clusters were assigned. Potential presence or absence of the 10 tree species over the 2071–2100 period was attributed to each of the 638 locations from habitat suitability models centered on 2080. New *TreeComp* clusters were obtained for each location by calculating Hellinger distances between locations and centroids of *TreeComp* clusters for the 1971–2000 period. The cluster with the shortest Hellinger distance was assigned to each location. Maps of fire and vegetation zones were then delimited by agglomerating the Thiessen polygons of the locations for each cluster using ESRI® ARCGIS 9.3.

1.4.6 Parameterization of the FireOcc model

Development of a predictive model for FireOcc was carried out using Multivariate Adaptative Regression Splines (MARS) (Friedman, 1991). Descriptions of the method are provided by Leathwick et al. (2006) and by Balshi et al. (2009). MARS is a non-parametric spline regression approach that models nonlinear relationships between a response variable (e.g., FireOcc) and predictor variables (e.g., *FW* variables and *TreeComp*). The main principle is the division of the space of explanatory variables into regions. A set of linear regressions, named basis functions (BF in equations), are then fitted for each region to describe the relationships between the response and explanatory variables. Knots separate regions and correspond to positions where the slope of basis functions changes. The procedure builds models in a parsimonious manner by minimizing mean square error (MSE) while selecting combinations of variables and the number and location of knots in a forward stepwise manner (Friedman and Roosen 1995). It starts with a maximum of candidate knot locations and all predictor variables. Progressively, knots and variables that contribute the least to the fitting are removed. Generalized cross-validation (GCV) selects the model with the best predictive fit. Various studies have illustrated the strong performance of MARS models in various ecological studies (Abraham and Steinberg, 2001; De Veaux et al., 1993; Leathwick et al., 2006; Moisen and Frescino, 2002), particularly under moderate sample sizes ($50<N<1000$) (Friedman and Roosen, 1995). This method has previously been used in the modeling of burned areas in Canada (Balshi et al., 2009; Bergeron et al., 2010).

Decadal averages (1971–1980, 1981–1990, 1991–2000, and 2001–2009) of the *FW* variables were computed at each of our locations from the averages of daily quantities. *FW* predictors were the same as those used for the cluster analysis. These decadal averages were then aggregated to the level of the fire bioclimatic zones using averaging and used as input in eq. 1 (Fig. 1.1). Decadal averages of annual FireOcc for the different size classes (≥1 ha; ≥10 ha; ≥200 ha) were also computed at the level of fire bioclimatic zones and used as the response variable in eq. 1. Decadal averages were used instead of annual or long-term averages to avoid having too many zeros in the response matrix and to satisfy variance requirements. *TreeComp* was entered in the form of binary variables to indicate the presence of a given vegetation category. Models were computed with the 1971–2000 *FW* decadal data and baseline *TreeComp* data (*n* = 117 observations), and verified with independent *FW* decadal data covering the 2001–2009 and baseline *TreeComp* data (*n* = 39 observations). Note that here we made the assumption that *TreeComp* did not change from one decade to the other. Goodness-of-fit over the independent period was measured using the regression R^2 of observed data as a function of predicted data. MARS models were computed using Salford System Software (Lafleur et al., 2010). The non-parametric method of this software has the advantage to support zero values. A maximum of two interactions was allowed, but interactions between *TreeComp* and *FW* variables were disabled. Other software parameters were set by default.

1.4.7 Predictions of FireOcc in a changing climate

Our final goal was to produce a map of the potential response of fire occurrence (FireOcc, eq. 1.1) to climate change over the 2071–2100 horizon. Two assumptions were made to account for the migration ability of each tree species. The no migration scenario assumed that species dispersal was null. It represents the status quo, in which $TreeComp_{2071\text{-}2100}$ is the same as $TreeComp_{1971\text{-}2000.}$ In the second scenario, unlimited dispersal assumes that climate, topographic and edaphic conditions are the only factors that limit dispersal of tree composition. Scenarios of no migration vs unlimited dispersion are widely used to interpret predictions from species distribution models (Araújo et al., 2005; Engler and Guisan, 2009; McKenney et al., 2007; Salford Systems; Thuiller et al., 2006). We applied the FireOcc models to the 1971–2000 decadal averages of the *FW* variables and to the *TreeComp* variables across the 638 locations. Prediction of future FireOcc was done by substituting historical *FW* and *TreeComp* conditions by the future ones obtained from the RCM simulations. Decadal results were averaged to obtain one value for a 30-year period. $FireOcc_{1971\text{-}2000}$, $FireOcc_{2071\text{-}2100,}$ and *FW* ratio of change ($FW_{2071\text{-}2100}/FW_{1971\text{-}2000}$) were interpolated from the 638 locations to obtain continuous maps. We used ordinary kriging interpolation in ESRI® ARCGIS 9.3 with 1-km grid mesh and a spherical model to fit the variograms. Significant differences between future projections and current values were tested using Student's *t*-test; points that passed the 5% significance level were projected on the map.

1.5 Results

1.5.1 Analysis of baseline conditions

Constrained spatial analysis led to the delimitation of 39 fire bioclimatic zones (Fig. 1.2). FireOcc varied spatially with values ranging from 0.02 to 0.90, 0 to 0.39, and 0 to 0.15 fires per year per 1,000 km^2 for FireOcc ≥1 ha, ≥10 ha, and ≥200 ha, respectively (results not shown). The lowest fire occurrences were observed in the eastern fire bioclimatic zones (Fig. 1.2C). Zones of low FireOcc ≥1 ha are coherent with the relatively low DC and DSR indices observed in eastern zones (I, III, VIII, XI) (Fig. 1.2A, Table 1.1). FireOcc ≥10 ha was low or null in the hotter and drier southern fire bioclimatic zones (Fig. 1.2C). The majority of these fires occurred in regions where habitats are unsuitable for American basswood, bitternut hickory and sugar maple (Fig. 1.2B, Table 1.2). FireOcc ≥200 ha was concentrated in the northwestern part of Quebec, where climatic conditions are suitable for fire-prone coniferous species and, to a much lesser extent, *Populus tremuloides* (Fig. 1.2B, Table 1.2). Values of DSR and FS are higher in the south than in the north (Fig. 1.2A, Table 1.1), indicating that fire risk should be higher in the south. Values of DC did not show the similar north-south trends.

1.5.2 Predictive models of FireOcc

We regressed the FireOcc quantity for each fire size class against FW variables and TreeComp variables using MARS. Models explained 64%, 79% and 30%, respectively, of the deviation between FireOcc ≥1 ha (GVC R2 = 0.62), FireOcc ≥10 ha (Generalized cross-validation (GVC) R2 = 0.76) and FireOcc ≥ 200 ha (GVC R2 =

0.22). Verification of model performance on independent data (2001–2009 period) indicated good predictive skills for size classes ≥1 ha and ≥10 ha (Figure 1.3) with R2 of 0.32 and 0.51, respectively. Predictive skills for size class ≥200 ha were low with R2 = 0.17. DSR was selected as a predictor of FireOcc for fire size classes ≥1 ha and ≥10 ha, while DC was selected as a predictor for fire size class ≥200 ha. Predictors and the model for fire size class ≥ 1 ha took on the following form:

$$FireOcc \geq 1ha = \max\left(0; 0.11 + 9.29 \times BF_2\right) \tag{1.2}$$

$$BF_1 = \left(J(0)\right) \tag{1.3}$$

$$BF_2 = \max\left(0; DSR - 0.92\right) \times BF_1 \tag{1.4}$$

so that FireOcc progressively increases as DSR increases above 0.92 units; if DSR is smaller than 0.92, BF2 of eq. 1.4 takes on the value of 0 (no fire). On the other hand, the presence of tree composition category J contributes significantly to a decrease in FireOcc (via eq. 1.3, in which BF1 takes on a value of 0 in the presence of this compositional group. This compositional group contains all tree species included in the analysis, except jack pine. More specifically, it is the only group that combines sugar maple, bitternut hickory and American basswood (Table 1.2).

Model results for size class ≥ 10 ha are more complex and include several compositional groups:

$$FireOcc \geq 10ha = 0.25 - 0.11 \times BF_3 - 0.10 \times BF_4 + 9.51 \times BF_6 \tag{1.5}$$

$$BF_3 = \left(F(0)\right) \tag{1.6}$$

$$BF_4 = \left(A(0)\right) \tag{1.7}$$

$$BF_5 = (J(0)) \tag{1.8}$$

$$BF_6 = \max(0; DSR - 1.02) \times BF_5 \tag{1.9}$$

so that FireOcc progressively increases as DSR increases above 1.02 units (eq. 1.9). The presence of tree composition category J contributes significantly to a decrease in FireOcc (eq. 1.8, in which BF5 takes on a value of 0 in the presence of this compositional group). In contrast, compositional groups F (eq. 1.6) and A (eq. 1.7) contribute significantly to increasing FireOcc as BF3 and BF4 take on a value of zero in their presence. Both compositional groups are dominated by coniferous species (Table 1.2).

Finally, the following model was selected for fire size class ≥200 ha:

$$FireOcc \geq 200ha = 0.08 - 0.07 \times BF_7 + 0.004 \times BF_9 \tag{1.10}$$

$$BF_7 = (F(0)) \tag{1.11}$$

$$BF_8 = (K(0)) \tag{1.12}$$

$$BF_9 = \max(0; DC - 125.14) \times BF_8 \tag{1.13}$$

so that FireOcc progressively increases as DC increases above 125.14 units (eq. 1.13). The presence of tree composition category K (essentially deciduous; eq. 1.12) contributes significantly to a decrease in FireOcc (via BF8, which takes on a value of 0 in the presence of this compositional group). In contrast, compositional group F contributes significantly to increasing FireOcc as BF7 (eq. 1.11) takes on a value of zero in its presence.

1.5.3 FireOcc projections over 2071-2100

Projections of explanatory variables and FireOcc under the A2 IPCC scenario (greenhouse gas and aerosol projected changes) are shown in Figs. 1.4 and 1.5. Increases of DSR and DC are predicted under the A2 IPCC climate change scenario over almost all of the study area (Fig. 1.4).

More specifically, the predicted increases of DSR are higher, with ratios of DSR2071-2100/DSR1971-2000 = 1.5–2.5, with a maximum reaching above 2.5. Higher increases are predicted for the northern and eastern parts of the study area. In response to DSR change, FireOcc ≥1 ha and FireOcc ≥10 ha are predicted to increase (Fig. 1.5, status quo scenario). The southern areas of the boreal forest will be affected by higher increases of FireOcc ≥1 ha and FireOcc ≥10 ha. Small DC increases are predicted for the north. DC increases get increasingly important in southern regions of the boreal forest (Fig. 1.4, DC2071-2100/DC1971-2000 = 1-1.5). Predicted changes in the frequency of large fires (≥200 ha) are generally not significant under the status quo scenario, except for some southern locations (Fig. 1.5).

The A2 IPCC unlimited tree dispersal scenario of tree composition showed that future climatic conditions in the north could be suitable for the expansion of southern tree species, especially for tree composition categories containing sugar maple, American basswood and bitternut hickory (expansion of categories G, H, I, J) (Fig. 1.4). Increases of FireOcc ≥1 ha and FireOcc ≥10 ha are predicted to be less important in the boreal forest, and trends could even be reversed under unlimited dispersal scenarios. More specifically in the southern boreal, FireOcc ≥1 ha is predicted to be similar to baseline conditions and FireOcc ≥10 ha is expected to decrease. Changes in FireOcc ≥200 ha should be more significant, since northwestern regions that are currently affected by frequent large fires are predicted to undergo a change toward a lower frequency of small and medium size fires if a change in tree composition category occurs (Figure 1.5)

1.6 Discussion

This study is the first that we are aware of to report on the integration of ecological niche models and fire weather indices in empirical fire models with the objective of projecting future spatial patterns of wildland fires in boreal forests. Our description of fire occurrence distributions was based on clustering of fire weather and vegetation components. This approach differs from previous studies in which fire properties were projected at the scale of ecozone and ecoregion classifications of the National Ecological Framework of Canada (NEFC) (e.g.,(Bergeron et al., 2004a; Flannigan et al., 2005; Girardin and Mudelsee, 2008; Lefort et al., 2004)). Boulanger et al. (2012) recently showed that the use of these NEFC zones could prevent researchers from capturing the real fire spatial variability. Spatially constrained clustering of fire weather indices should address some of the limitations reported by Boulanger et al. (2012). In addition, our approach made it possible to circumvent the problem of spatial dependence in locations induced by our modeling experimentation, notably that resulting from the spatial interpolation of weather data in the fire weather calculations. Finally, we used RCM output instead of global climate models. Unlike global climate models, RCMs simulate climatic characteristics at a fine scale; the boundaries are clearly defined and include realistic simulations of orographic effects (Plummer et al., 2006).

In agreement with Balshi et al. (2009), our results show that fire can occur only if particular weather conditions are reached (drought and wind speed through DC and DSR). For the whole study area, we found that decadal averages of fire occurrence increase significantly over a tipping point of DSR equaling about 0.92 and 1.02 units for all fires and medium fires (eq. 2b and eq. 3d), respectively, and of DC equaling

125 units for larger fires (eq. 4c). A strong statistical relationship between seasonal DC and annual large fire occurrences was previously found by Girardin and Mudelsee (2008). Also, the importance of DSR as a predictor of Canadian area burned has previously been highlighted (e.g., (Balshi et al., 2009; Flannigan et al., 2005)). Models developed by Wotton et al. (2010) to explain lightning-ignited fires in Canadian ecoregions selected DC, DMC and FFMC as explanatory fire weather variables and did not identify east-west differences in fire occurrence within Quebec. The latter study was slightly different from ours in that it included fires smaller than 1 ha and encompassed different periods (1985-2000). Moreover, the delimitation of fire occurrences along an east to west gradient is coherent with a previously published moisture map (expressed using July DC) presented by Girardin and Wotton (2009), suggesting that moister regions are less prone to fire than dry regions (Hély et al., 2001).

Our study also suggests that north-south distributions of various classes of fire occurrence in Quebec are governed by differences in tree composition. Generally, fire control is more effective in the southern part of the province due to the ease of detection and accessibility. However, fire suppression should not affect the analysis of fire size classes ≥10 ha and ≥200 ha because when a large fire occurs, weather conditions are extreme and the human capacity to control a fire is reduced. Fires of more than 3 ha (Arienti et al., 2006) or 4 ha (Podur and Wotton, 2010) are attributed to escaped fires. Their distribution can also be assigned to tree composition change. Previous comparisons between coniferous stands and deciduous or mixed stands in boreal forests highlighted the importance of tree composition in fire regimes (Hély et al., 2001; Hély et al., 2010). Lower fire activity in deciduous-dominated stands and landscapes has already been documented (Arienti et al., 2006; Campbell and Flannigan, 2000; Hély et al., 2001; Hély et al., 2010; Intergovernmental Panel Climate Change (IPCC), 2007; Krawchuk et al., 2006; Lefort et al., 2004; Päätalo, 1998; Quinby, 1987). These differences come from higher coniferous species flammability in comparison with deciduous species. Coniferous species contain highly flammable oils and resin, and moisture content in the needles is low, while deciduous species have leaves with a higher moisture content that acts as a fire break. Quinby (1987) compared temperate tree species flammability in laboratory experiments. Pine species showed high ignition probability, whereas sugar maple and poplar species showed the lowest probabilities of flammability. Our study highlighted the fire break role of sugar maple forests, largely because the presence of these forests is associated with a reduced frequency of medium and large fires, and because of offsetting effects in FireOcc models of tree composition categories that include sugar maple forests. This study confirmed that weather and tree composition are both important explanatory variables of fire occurrence in boreal forests.

Our analyses are consistent with previous studies indicating that future warming will create climatic conditions more prone to fire occurrence (Amiro et al., 2009; Flannigan et al., 2009; Forest Service British Columbia, 2011; Girardin and Mudelsee, 2008; Le Goff et al., 2009; Wotton et al., 2010). Across our study area, increases in fire occurrence will vary spatially, with the most important changes projected to occur at the eastern and southern limits of the boreal forest. The projected changes (an increase of 10-25% by 2090) are in the range of those predicted in an earlier study by Wotton et al. (2010), with the exception of two regions where the magnitude of change was predicted to be higher by Wotton et al. (2010). That being said, our experiment indicates that the projected increase in fire-conducive weather conditions could be offset by changing tree species distributions. Regions in which this offsetting effect holds true include the western fire bioclimatic zones and the southern limit of the boreal forest. It is important to remember that tree composition changes in this study are governed by climatic, edaphic and topographic conditions. However, other factors will influence tree migration in addition to these environmental variables. Notably, the fire regime itself is an important factor affecting species distribution (Asselin et al., 2003; Flannigan and Bergeron, 1998;

Tremblay et al., 2002). For example, fire frequency was a barrier in the past for jack pine expansion (Asselin et al., 2003). Red maple (Acer rubrum L.) (Tremblay et al., 2002) and red pine (*Pinus resinosa* Ait.) (Flannigan and Bergeron, 1998) are limited to the southern limits of their predicted climatic envelopes because the fire regime prevents these species from spreading further north. Competition could also play a role in limiting tree species migration (Engler and Guisan, 2009). The unlimited dispersal scenario of tree composition change shows that northward migration of tree composition clusters dominated by southern limited species (e.g., sugar maple, American basswood, and bitternut hickory) offsets the impact of climate change on fire occurrence. However, these species are unlikely to migrate to such high latitudes in the short to medium terms, even though areas of sugar maple can be found north of its specific climatic range, for example in the western boreal forest of Quebec (F. Tremblay, pers. comm.). Further studies are needed, but future fire regimes and climatic conditions could lead to increasing sugar maple abundance at its northern limit. Our results should be used preferentially when building scenarios of future fire occurrence that take into account a potential expansion of deciduous northern zones in boreal forests.

1.6.1 Uncertainties and limitations

Many uncertainties lie in the vegetation data. First, tree composition was represented here by the presence and absence of ten major tree species; uncertainties could be reduced by using abundance data. Forest type limits do not correspond to an abrupt transition from the presence of a species to an absence; exact species limits may be unknown (Berteaux et al., 2010a). The lack of empirical data for the baseline period prevented the use of abundance data. Second, climate change would not imply the sudden appearance of a species in a region where present climatic conditions are not suitable (for example sugar maple in the boreal forest). Climate change will have an impact on the relative abundance of deciduous compared with coniferous species

(Bergeron and Danserau, 1993; de Groot et al., 2003; Lecomte et al., 2006) and is also likely to change the understory vegetation. Future projections of fire occurrence should integrate the impacts of vegetation change in forest types as a whole (species abundance, including understory vegetation) rather than the presence/absence of species. On the other hand, the forest as a whole does not constitute a continuous set of forest; it should rather be seen as a fragmented landscape (human infrastructures, lakes, etc) that acts as a firebreak (Parisien et al. 2005). Finally, projections developed in this work assume that the current boreal vegetation distribution is governed only by climatic, edaphic and topographic factors. However, the climatic envelope observed does not necessarily translate into a potential climatic envelope (Environment Canada, 2011). Wildfires play a major role in the distribution of species, and vegetation can respond faster to indirect impacts from shifts in fire regimes than to direct climate change effects (Bergeron and Archambault, 1993; Weber and Flannigan, 1997). It has been suggested that the combined use of process-based models, including feedback effects of fire activity, in addition to niche-based models could reduce uncertainties related to species distribution (Environment Canada, 2011).

The characterization of fires also brings uncertainties related to random effects on fire distribution. Even if the conditions are favorable to fire, the ignition source (lightning, human) was not included in our predictive models. A prediction may therefore be incorrect if a significant change takes place in the frequency of fire occurrences (Hessl, 2011), particularly in connection with the increased use of forestland by humans. Other uncertainties are related to human control. Climate change may exceed our ability to control fires (Podur and Wotton 2010); however, this control ability influences fire size (Martell and Sun 2008). Improvements and a better knowledge could make it possible to better control fire and reduce burned areas in the future.

Finally, future projections are always associated with uncertainties because of the chaotic nature of climatic systems (Rind, 1999) and future anthropogenic greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC, 2001) recommends the use of multiple climate models and emission scenarios in a context of climate change impact assessment (Nakicenovic and Swar, 2000). Only one climate model (CRM4.1.1) and one climate change scenario (IPCC A2) were used for this study. The RCM runs used in this study were driven with atmospheric and oceanic data from the coupled Canadian General Circulation Model version 2 (CGCM2) (Flato and Boer 2001). Balshi et al. (2009) showed that the Canadian General Circulation Model ranks among the best IPCC models with respect to the level of predictability at high northern latitudes. On the other hand, the A2 scenario is at the higher end of other SRES emissions scenarios (Nakićenović et al. 2000); while it is not the highest, it is quite realistic in terms of greenhouse gas emissions estimate (Raupach et al. 2007). Within an ensemble of 19 GCM experimentations, the CGCM3 A2 ranks third in terms of level of increase in seasonal drought severity for western boreal Quebec from the late 20th to the late 21st century (Appendix). From an impact and adaptation point of view, if adaptation to a larger climate change is possible, then adaptation to the smaller climate changes at the lower end is also possible (NARCCAP 2007). Finally, a model correction (delta method) was used to reduce bias in modeled climate data. Although this method is considered a very robust method (Déqué 2007), it has the disadvantage of constraining the same frequency and magnitude of extreme weather events relative to the mean climate throughout all periods under study. Nevertheless, a sensitivity analysis on DC projections in which data were treated using different correction methods showed results similar to those reported in this study (T. Logan, pers. comm.). Future projections should use an ensemble approach with multiple corrections, models and scenarios.

1.7 Conclusion

The potential influence of changing forest composition on the impacts of climate change on fire activity in Quebec was examined. Both climate and forest compositions were important factors explaining the distribution of fire occurrences in this province. Each factor had its own relative importance with regard to fire size classes, with large fires being more influenced by forest composition. These results have important implications for fire management in a context of climate change adaptation. In fact, our results indicate that climate change will increase fire occurrence in boreal forests (Amiro et al., 2009; Flannigan et al., 2009; Forest Service British Columbia, 2011; Girardin and Mudelsee, 2008; Le Goff et al., 2009; Wotton et al., 2010). A change in tree composition toward an increasing deciduous component has the potential to significantly offset the impact of increased fire risk in many areas, particularly in areas affected by fires that are difficult to control (≥ 200 ha). These results suggest that the presence of deciduous species, and more specifically of forest types dominated by temperate species, should be promoted in fire management strategies that attempt to reduce communities' long-term vulnerability to climate change in eastern Canadian boreal forests. Given the uncertainties associated with the various assumptions inherent to the use of ecological niche models, these results should be seen as first estimates of the impacts of changing tree distributions on boreal wildfires in the context of global warming. Future studies should include feedback effects of fire on vegetation distribution and an ensemble modeling approach that integrates several anthropogenic gas emission scenarios and models. Notably, there is potential for expanding this study to the scale of the North American boreal forest using recently mapped tree distribution projections simulated using an ensemble approach of general circulation models (McKenney et al. 2011). The spatial resolution may be coarser, but analysis could gain robustness.

1.8 Acknowledements

We thank the North American Regional Climate Change Assessment Program (NARCCAP) for providing the data used in this paper. NARCCAP is funded by the National Science Foundation (NSF), the U.S. Department of Energy (DoE), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Environmental Protection Agency Office of Research and Development (EPA). Marie-Pierre Drouin (ministère des Ressources naturelles et de la Faune du Québec) provided the provincial data. We are particularly grateful to Mélanie Desrochers for her availability and helpful advices on ARCGIS analysis, to Rémi St-Amant for providing climatic data and help with the BioSIM software, and to Travis Logan and René Laprise for their helpful information about climatic models. We extend our thanks to Alain Leduc for reviewing the paper and providing helpful comments and Isabelle Lamarre for technical editing. Finally, we are grateful to two anonymous reviewers for their helpful comments on an earlier version of the manuscript.

Figure 1.1 Diagram of the statistical analyses conducted in this study. A) Quebec regionalization based on conditions (fire weather and tree composition) prone to fire from 1971 to 2000. B) Modeling of fire occurrence with fire weather variables and tree composition categories from 1971 to 2000. C) Fire occurrence projections for 2071 to 2100.

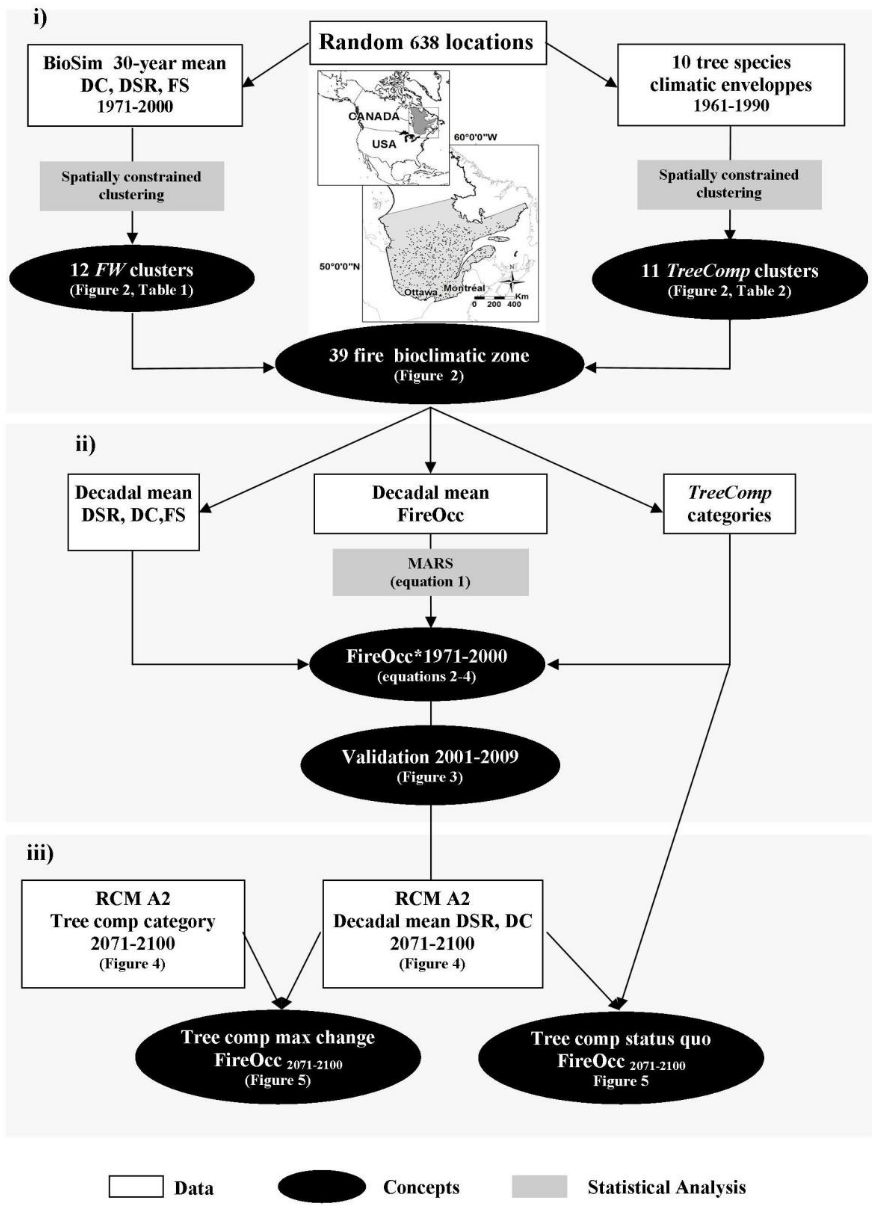

Figure 1.2 Map of fire bioclimatic zones in Quebec. Fire bioclimatic zones were obtained by intersecting the fire weather (*FW*) variables clustering (A) and the tree species distribution clustering (B). Annual natural forest fire occurrences (number of fires per year per 1000 km²) of all (fire ≥1 ha), medium (fire ≥10 ha) and large fires (fire ≥200 ha) were calculated for each fire bioclimatic zone (C). The period of analysis is 1971 to 2000.

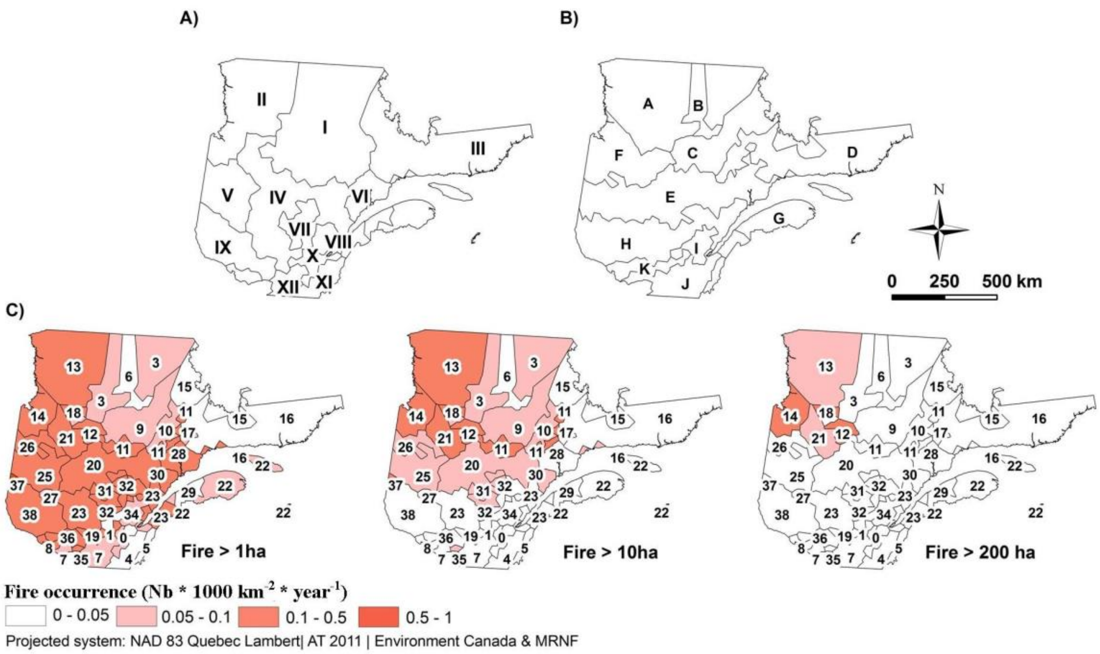

Figure 1.3 Observations vs. MARS (Multivariate Adaptative Regression Splines) model predictions from 2001 to 2009 of A) all fire occurrences (FireOcc ≥ 1 ha), B) medium fires (FireOcc ≥ 10 ha) and C) large fires (FireOcc ≥ 200 ha).

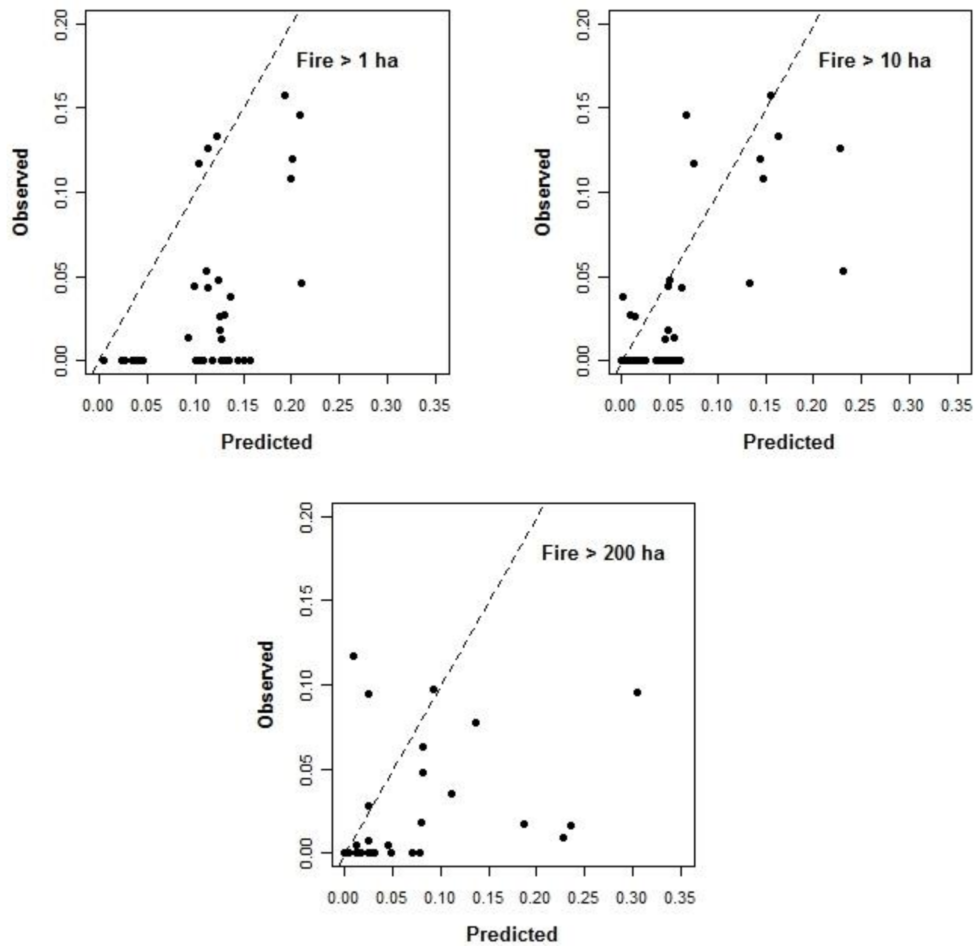

Figure 1.4 Maps of changing Drought code (DC), daily severity rating (DSR), and unlimited tree dispersal projected with the regional climate model (RCM, scenario A2) for the 2071–2100 period. DC and DSR changes are expressed as ratios of change (30-year average $_{2071\text{-}2100}$/30-year average $_{1971\text{-}2000}$). The unlimited tree dispersal scenario represents the dispersion of tree species clusters.

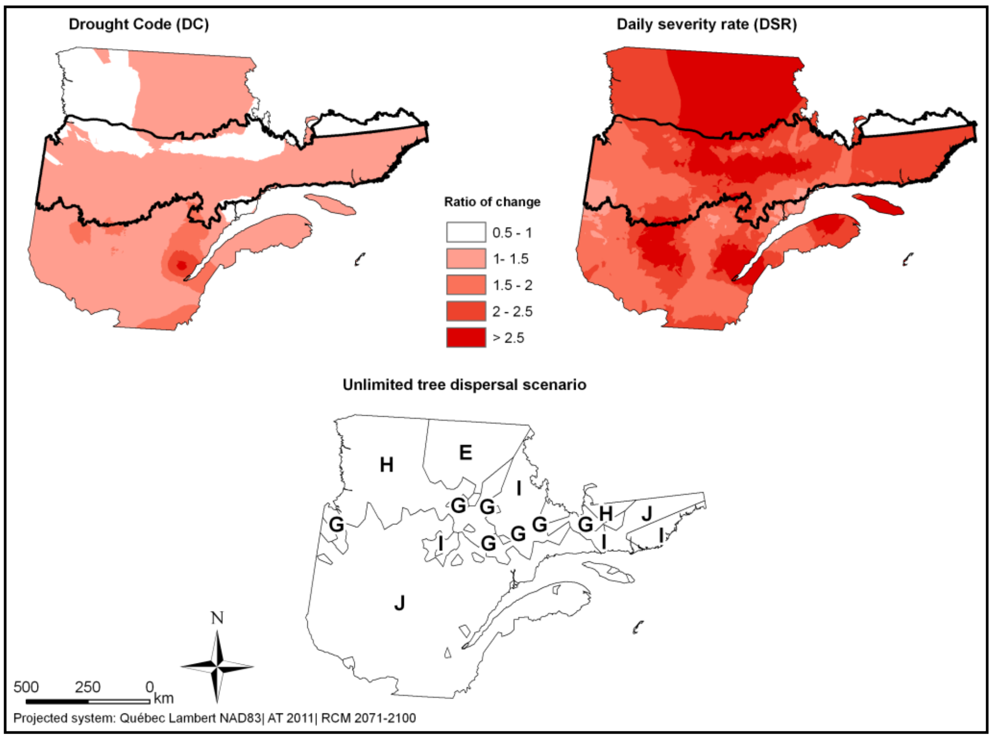

Figure 1.5 Map of Quebec showing baseline and 2071–2100 projections (*status quo* and unlimited dispersal scenarios) for the three classes of fire occurrence (FireOcc ≥1 ha; ≥10 ha; ≥200 ha). Interpretation of the results was limited to the closed-canopy boreal forest owing to biases associated with the application of kriging to northern regions (buffer effect, rarity of data). In the southern part of Quebec, future species composition should be different from the projected one owing to the potential northward migration of southern-limited species not included in our analysis. Points correspond to locations that showed significant differences between current and future projections (Student t-tests, $p < 0.05$).

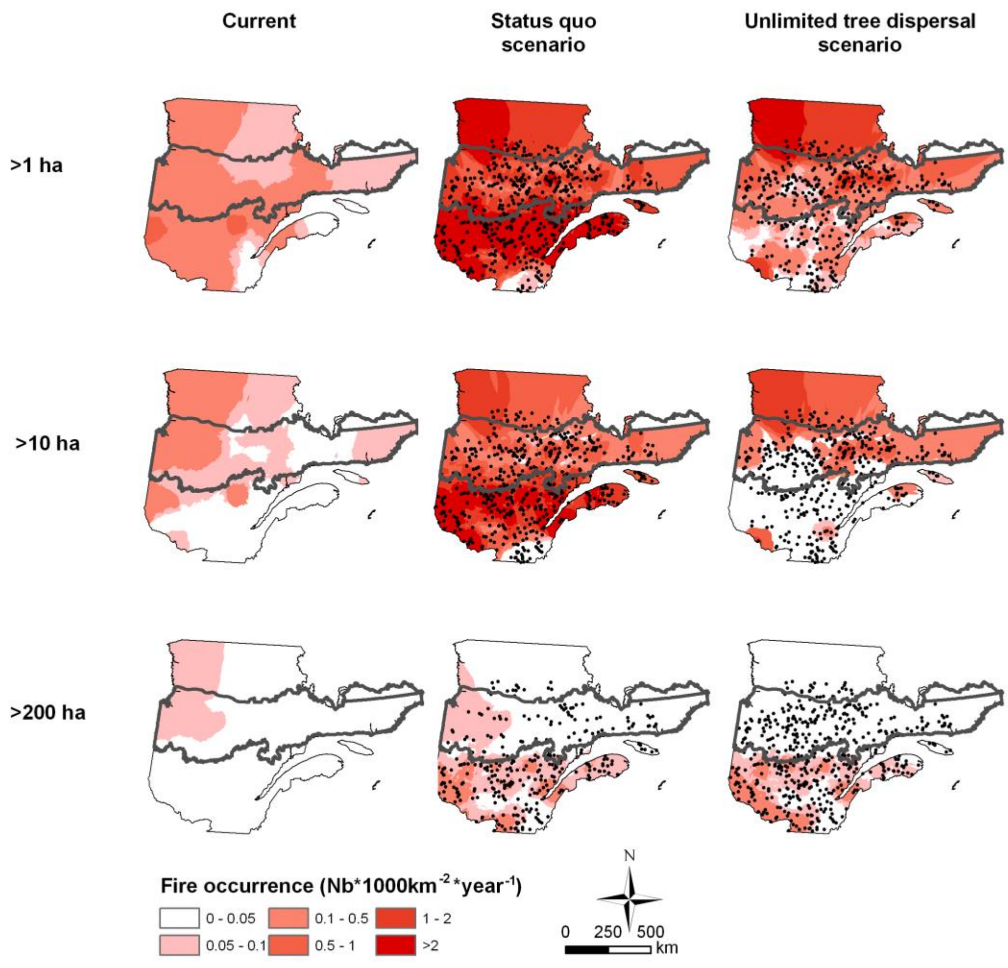

Tableau 1.1 Summary of 30-year averages of daily drought Code (DC), daily severity rating (DSR), and fire season length (FS, in days) for each region of Quebec (*FW* clusters) computed from the fire weather (*FW*) variables (DC, DSR and FS). The period of analysis is 1971 to 2000.

FW clusters	DC	DSR	FS
I	89.38	0.33	162.68
II	130.03	0.58	167.75
III	102.04	0.37	157.26
IV	101.34	0.51	174.56
V	108.04	0.71	180.04
VI	122.54	0.73	171.46
VII	118.69	0.80	181.26
VIII	61.19	0.39	164.21
IX	120.74	0.73	187.73
X	97.16	0.68	192.56
XI	74.94	0.41	193.03
XII	127.93	0.96	199.43

Tableau 1.2 Tree species composition in each region of the province of Quebec based on tree species occurrences. Spatially constrained site clusters (columns) are identified by letters A-K.

		Site clusters										
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**
Coniferous species	Balsam fir		1	1	1	1	1	1	1	1	1	1
	Jack pine	1		1	1	1	1	1	1	1		1
	White spruce				1	1		1	1	1	1	1
	Black spruce	1	1	1	1	1	1	1	1	1	1	1
Deciduous species	Sugar maple							1	1	1	1	1
	Bitternut hickory										1	
	Yellow birch					1		1	1	1	1	1
	White birch					1		1	1	1	1	1
	Trembling aspen				1	1	1	1	1	1	1	1
	American basswood								1		1	1

APPENDICE A

Climate model and emission scenario ranks based on the ratio of mean seasonal Drought Code 2 index of 2071-2100 to 1961-1990.

Model and scenario	**Rank**
BCM2.0 A1B	6
BCM2.0 A2	9
BCM2.0 B1	8
CGCM3 A1B	7
CGCM3 A2	**3**
CGCM3 B1	13
CSIROMk3.5 A1B	12
CSIROMk3.5 A2	14
CSIROMk3.5 B1	19
ECHAM4 A2	5
ECHAM4 B2	4
GISSAOM A1B	17
GISSAOM B1	18
INMCM3.0 A1B	11
INMCM3.0 A2	15
INMCM3.0 B1	16
MIROC3.2 medres A1B	2
MIROC3.2 medres A2	1
MIROC3.2 medres B1	10

Data from Bergeron et al. (2010). A high rank indicates a high level of increase in mean seasonal drought 4 severity between present and future periods.

CHAPITRE II

DYNAMICS OF MOISTURE CONTENT IN SPRUCE-FEATHER MOSS AND SPRUCE-*SPHAGNUM* ORGANIC LAYERS DURING AN EXTREME FIRE SEASON AND IMPLICATIONS FOR FUTURE DEPTHS OF BURN IN CLAY BELT BLACK SPRUCE FORESTS.

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2.1 Abstract

High moisture levels and low frequency of wildfires have contributed to the accumulation of the organic layer in open black spruce (*Picea mariana*)-*Sphagnum* dominated stands of eastern boreal North America. The anticipated increase in drought frequency with climate change could lead to moisture losses and a transfer of the stored carbon back into the atmosphere due to increased fire disturbance and decomposition. Here we studied the dynamics of soil moisture content and weather conditions in spruce-feather moss and spruce-*Sphagnum* dominated stands of the boreal Clay Belt of eastern Canada during particularly dry conditions. A linear mixed model was developed to predict the moisture content of the organic material according to weather, depth and site conditions. This model was then used to calculate potential depth of burn and applied to climate model projections to determine the sensitivity of depth of burn to future fire hazards. Our results suggest that depth of burn varies only slightly in response to changes in weather conditions in spruce-*Sphagnum* stands. The reverse holds true in spruce-feather moss stands. In conclusion, our results suggest that spruce-*Sphagnum* stands in the boreal Clay Belt will be relatively resistant to an increase in the depth of burn risk under climate change.

Key words: boreal forest, climate change, burn severity, carbon

Résumé

Les niveaux d'humidité élevés et la faible fréquence des feux en forêt boréale de l’est de l’Amérique du Nord ont contribué à l'accumulation de la couche organique au sol et ont favorisé le développemment de forêts ouvertes d’épinette noire (*Picea mariana*) dominées par la sphaigne. L'augmentation de conditions de sécheresse prévue avec les changements climatiques pourrait induire une perte d'humidité dans les sols et ainsi à un transfert du carbone stocké dans l'atmosphère par une augmentation des perturbations de feu et de la décomposition. Nous avons étudié la dynamique d'humidité du sol en réponse aux conditions météorologiques dans des pessières à mousses hypnacées et des pessières à sphaignes de la forêt boréale de la Ceinture d'Argile de l'est du Canada durant une année particulièrement sèches. Un modèle linéaire mixte a été développé afin de prédire la teneur en humidité dans la couche organique à partir des conditions météorologiques, de la profondeur et de l'état du site. Ce modèle a ensuite été utilisé afin de calculer la profondeur potentielle de brûlage et a été appliqué à des données météorologiques futures projetées par des modèles climatiques globaux afin de déterminer la sensibilité de la profondeur future de brûlage. Nos résultats suggèrent que la profondeur de brûlage ne varie que légèrement en réponse aux changements climatiques dans les pessières à sphaignes. L'inverse a été simulé pour les pessières à mousses hypnacées. Nos résultats concluent que les pessières à sphaignes situées dans la forêt boréale de la Ceinture d'Argile seront relativement résistantes à une augmentation de la profondeur de brûlage aux changements climatiques.

Mots clefs: forêt boréale, changements climatiques, sévérité de brûlage, carbone.

2.2 Introduction

In the context of growing global populations and global warming (IPCC, 2007), managers are confronted with the challenges generated by increasing human needs and the environmental impacts of a rapidly changing climate. Adaptive strategies should be developed to minimize natural resources degradation induced by climate change and to provide continuity of forest socio-economic benefits (Fulé, 2008). In Canada, the boreal forest represents approximately 60% of economic resources for the forest sector (Burton *et al.*, 2003). There the response of the boreal forest to future warming is a major concern because high-latitude boreal regions are likely to be among the most affected (IPCC, 2007) and the size of their carbon pools is particularly important (Dixon *et al.*, 1994, Prentice, 2001). Notably, projected increases in drought frequency and severity with climate change imply moisture loss and subsequent transfer of stored carbon into the atmosphere via increased fire disturbance and decomposition (e.g. Harden *et al.*, 2000). Increasing the resistance of forests to fire and drought could slow carbon emissions and maintain the sustainability of forest resources (Girardin *et al.*, 2013a, Millar *et al.*, 2007).

In the boreal forests of eastern Canada, at the border of the provinces of Quebec and Ontario, a long fire cycle (time to burn all the land area, or mean fire return interval), a flat topography and a cold climate facilitate the accumulation of thick layers of organic soil, a process often described as paludification (Fenton *et al.*, 2005, Lavoie *et al.*, 2005b). High organic layer depth allows the establishment and expansion of *Sphagnum* species (Fenton *et al.*, 2007, Fenton and Bergeron, 2011, Lafleur *et al.*, 2010, Lavoie *et al.*, 2005a). These forests differ from other forested peatlands created in low-lying areas and from the discontinuous permafrost by the fact that peat mosses accumulate on well-drained mesic soils independently from local topography or drainage and are primarily related to forest succession (Simard *et al.*, 2007). Once *Sphagnum* species increase on the forest floor, fluctuations in water saturation of the organic layer decrease (Bergeron *et al.*, 2012). The water table moves from the mineral soil into the organic forest floor, and organic layer depth becomes the dominant factor explaining the water table position (Fenton *et al.*, 2006). Tree roots are unable to reach the mineral soil, inducing moister, colder and less nutrient rich environments, resulting in a drop in tree productivity (Payette and Rochefort, 2001, Simard *et al.*, 2007). Consequently, in the prolonged absence of fire, productive mature black spruce (*Picea mariana* (Mill.) BSP) stands dominated by feather moss develop into open and less productive forested peatlands dominated by *Sphagnum* species (Fenton *et al.*, 2007, Harper *et al.*, 2003, Lafleur *et al.*, 2010, Lecomte *et al.*, 2006a).

Depth of burn, considered here as the depth of the soil organic layer consumed during a forest fire, is crucial for the return of these forests to productivity (Lavoie *et al.*, 2005a, Lecomte *et al.*, 2006a, Simard *et al.*, 2009). High depth of burn that consumes all of the organic layer on the ground leads to the establishment of dense pure black spruce stands on mesic sites with a dense structure (Lecomte *et al.*, 2006a, Lecomte *et al.*, 2006b). In contrast, low depth of burn leaves the untouched soil organic layer to accelerate the process of paludification (Lecomte *et al.*, 2006b, Simard *et al.*, 2009), which consequently tends to favour the establishment of open, less productive stands on mesic sites (Lecomte *et al.*, 2006a, Simard *et al.*, 2007).

The decrease in productivity associated with paludification is an important issue for the forest industry since it reduces the amount of harvestable timber. In spruce-*Sphagnum* stands, mixing of the organic layer (e.g. Lafleur *et al.*, 2010) or prescribed burning (e.g. Renard *et al.*, 2009) are practices that have been proposed to reduce *Sphagnum* establishment and favour the development of more productive spruce-feather moss stands. But there could be an unwanted feedback effect arising from such practices: since high organic layer depths in peatlands promote high moisture content, which helps to protect against burning (Benscoter *et al.*, 2011, Benscoter and Wieder, 2003, Harden *et al.*, 2006, Kasischke *et al.*, 2010, Shetler *et al.*, 2008, Turetsky *et al.*, 2011b). A return to more productive forests could increase the overall stand vulnerability to fire and high depth of burn with climatic warming, and accelerate carbon emissions. It is therefore necessary to understand the trade-off between the increase in forest productivity and the loss of resistance to fire. Currently, the strength of the offsetting potential of organic layer thickness on potential depth of burn in a climate change context is unknown.

Here we assessed the moisture dynamics in spruce-feather moss and spruce-*Sphagnum* organic soil layers during an extreme fire season and used moisture information to project the impacts of climate change on potential depth of burn in these stands for the period 2071-2100. We used *in situ* measurements of soil moisture content in deep layers (5-25 cm) of the forest floor and weather data for the parameterization of a soil moisture content model. This model was then used to calculate potential depth of burn and was applied to climate model projections to determine the sensitivity of depth of burn in stands to future fire hazards. We tested three hypotheses related to soil moisture content dynamics and depth of burn responses to climate change: (i) soil moisture dynamics in spruce-*Sphagnum* (hereafter SpSp) stands are less sensitive to drought severity than spruce-feather moss (SpMo) stands, (ii) as a consequence of hypothesis (i), drier weather conditions are required in SpSp stands to increase depth of burn in comparison with SpMo stands, and (iii) there will be less increase in depth of burn in SpSp stands in comparison with SpMo stands, within the predicted 2071-2100 climate change scenarios.

2.3 Materials and Methods

2.3.1 Study area and sampling design

The study area is located in the boreal forest of northwestern Quebec, Canada (49°00 – 50°00 N; 78°30W - 79°50) (Figure 1). A former proglacial lake (Lake Barlow-

Ojibway) left a thick deposit of clay, forming the physiographic unit known today as the Clay Belt, which stretches across the Quebec and Ontario border and covers an area of approximately 145,470 km^2 (Vincent and Hardy, 1977). The topography is relatively flat; however, small rocky hills are present. Landscapes are dominated by black spruce stands with some jack pine (*Pinus banksiana* Lamb.) and aspen (*Populus tremuloïdes* Michx.) stands. Around 60% of the landscape consists of black spruce dominated stands, of which about 80% are open forests (Pelletier *et al.*, 1996). The current level of fire activity is low, with a fire cycle estimated at 398 years from 1959 to 1999 (Bergeron *et al.*, 2004). The climate is subpolar and subhumid continental, characterized by long, harsh and dry winters and short, hot and humid summers (Environment Canada, 2012). The average annual temperature from 1970 to 2009 was 0.3˚C, ranging from a minimum value of –22.2˚C in winter to a maximum value of 17.4˚C in summer, and the mean total annual precipitation was 862 mm (Environment Canada, 2012).

Black spruce stands with either a feather moss or *Sphagnum* dominated understory were selected to represent i) spruce-feather moss (SpMo) stands and ii) spruce-*Sphagnum* (SpSp), stands respectively. One SpMo and one SpSp were selected in each of two regions (region A and region B) to obtain four stands in total (Figure 1). Two separate regions were on clay substrate and were selected to ensure that the sites originated from different fires. The distance between stands in the same region was less than 2 km. The thickness of the organic layer, the stand density and the *Sphagnum* dominance defined the type of site. Organic layer depth in the SpMo and SpSp stands were <30 cm and >40 cm respectively, as defined by Lafleur *et al.* (2010). SpMo stands had larger mean stem diameters and densities than SpSp stands (Table 1). Black spruce was the dominant species in each stand, but some white cedar (*Thuja occidentalis* L.) was present in SpSp stands and one balsam fir was recorded in one SpMo stand. The understory of SpMo stands was dominated by feather moss species, except in region B where a few patches of *Sphagnum* spp. were also present. SpSp stands were dominated by *Sphagnum* spp.

2.3.2 Daily weather data and Drought Code

Two meteorological stations, one in each region and within a 1 km radius of the selected forest stands, were installed during spring 2010 to measure precipitation, air temperature and relative humidity. These variables were recorded at 60 min intervals using Campbell Scientific data loggers (CR10X) (Campbell Scientific Inc., Logan, Utah) from spring 2010 to fall 2010 (technical system failures prevented 2011 data analysis). Precipitation was measured with TE525M sensors, and air temperature and relative humidity were measured with L9598 probes. There were no missing data for the 2010 fire season. The 2010 fire season ranked high in terms of fire danger, with extremely dry conditions from mid-May to late June stretching across a territory of 1000 km in the province of Quebec. Area burned during that season totalled 314,884 ha (10th largest year since 1971 in Quebec; Canadian Council of Forest Ministers, 2012). The 2010 season was therefore an interesting opportunity for conducting our analysis.

Air temperature and 24 h accumulated rainfall data at noon local standard time measured with the micrometeorological stations were used to calculate the Drought Code (DC). The DC is a component the Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987) used in Canada to evaluate the severity of fire weather conditions by providing indices of fuel moisture and fire behaviour (Wotton, 2009). DC is a relative indicator of the moisture content of deep, compact organic layers (about 10 to 25 cm from the surface) weighing ~25 kg m^{-2} when dry. It reflects the long-term drying and consumption of deep forest floor layers and the effort required to extinguish a fire. For a temperature of 25ºC and relative humidity of 30%, the response time of DC fuels to lose 2/3 of the free moisture is approximately 50 days (Van WagnerWotton, 2009). DC calculation, the layer absorbs moisture through precipitation and dry exponentially with increasing temperature (Wotton, 2009). DC is unitless, with the zero value indicating low fire risk and 400 values indicating high fire risk.

Additionally, daily precipitation, air temperature and relative humidity time-series for the 1971-2010 period were created by interpolation of Environment Canada's historical climate database using the BioSIM software (Environment Canada, 2012). As part of the procedure, daily data from the four closest weather stations were adjusted for differences in latitude, longitude and elevation between the data sources and stand location, and averaged using a $1/d^2$ weight, where d is distance. Next, FWI System components were computed on this second weather dataset (Régnière and Bolstad, 1994). Winter precipitation was included in the algorithms of the DC so fire behaviour indices also depended on snow accumulation (Girardin and Wotton, 2009).

As previously stated, the DC is a relative indicator of the moisture content of deep organic soil layers. As such, the DC is not a physical water budget in that it does not measure the fluxes of water into and out of fuel nor does it incorporate process equations responsible for these fluxes (Anderson and Otway, 2003; Otway *et al.*, 2007; Waddington *et al.*, 2011; Johnson *et al.*, 2013). Therefore, the DC requires significant calibration to suit local moisture processes (input and output flows, internal mechanisms of water movements, etc.) and improve accuracy for the particular fuel conditions such as those encountered in this study. Below we describe our approach to calibrating the DC to *in situ* measurements of SpSp and SpMo stands' moisture content.

2.3.3 Volumetric and gravimetric moisture contents

Volumetric moisture content (%) was measured once per hour in each stand using Campbell Scientific CS616 moisture probes (Campbell Scientific Inc., Logan, Utah).

In each stand, three holes were dug to obtain three replicates, in each of which probes with a length of 30 cm were installed horizontally at depths of 5, 15 and 25 cm in SpSp organic layers, and depths of 5 and 15 cm in SpMo stands (in these stand types, maximum organic soil depth was often <25 cm, so only two probes were installed). For data verification, soil samples centred on every 5-cm depth were also collected from the organic soil layer, with three replicates, seven times during the 2010 fire season (May 31, June 29, July 11, July 26, August 9, August 23, and September 9). Gravimetric moisture content (GMC) [%] was assessed by weighing the moist samples, oven drying them at 60˚C for 48 h, and reweighing when samples were dry (constant weight). GMC was calculated as follows:

$$GMC \ = \ [(wet\ mass - dry\ mass)/dry\ mass] \times \ 100 \qquad (2.1)$$

Bulk density (g/cm^3) was measured to convert volumetric moisture content to gravimetric moisture content (%) (GMC) for analyses. Other soil samples were collected especially for bulk density analysis four times at each location with a core of $(7.75)^2 \times \pi \times 17$ cm depth = 403.89 cm^3 of volume along the vertical organic soil profile. Bulk density was calculated using the equation:

$$Bulk\ density \ = dry\ sample/sample\ volume \qquad (2.2)$$

And finally, the probe volumetric moisture content was transformed into GMC as:

$$GMC \ = volumetric\ moisture\ content/bulk\ density \qquad (2.3)$$

The CS616 probes were calibrated for each stand type (SpMo and SpSp) by comparing CS616 values with moisture content measured by direct soil sampling similar to Lee *et al.* (2010) and Ferguson *et al.* (2002). We collected probe values for the same sampling day as soil sampling. We then calculated replicate means by depth and soil moisture content of each replicate by 5 cm depths above the probe depth (example: soil sampling moisture content of 0-5 cm for probes at 5 cm). Linear regressions were used to obtain the best fit between probe moisture means and soil sampling moisture means.

2.3.4 Soil moisture content calibration

Development of a predictive model for daily GMC was carried out using a linear mixed-effects model (lme) (Pinheiro and Bates, 2000). Mixed-effects models are flexible and powerful tools to describe relationships between response variables and covariates that are grouped according to classification factors. These models include fixed variables (as predictive variables in classical linear regression) and random variables, which describe the variability of some groups of observations and individual observations themselves. In our case, the mixed-effects model was an appropriate method to first consider the autocorrelation between our repeated daily observations. Secondly, organic layer depths in SpSp stands varied considerably (from 20 to >75 cm) inducing soil moisture content variations. Mixed-effects models allowed for inclusion of this variability.
Herein the GMC was formulated as:

Herein the GMC was formulated as:

$$\log\left(GMC_{jkdr}\right) = \beta_0 + \beta_1\, D + \beta_2\, DC_{jkdr} + \beta_3\, ST + \beta_4\, DC_{jkdr}\, ST + b_r + b_{dr} + b_{kdr} + e_{jkdr} \quad (2.4)$$

where GMC_{jkdr} [%] correspond to the gravimetric moisture content registered at day *j* in the *k*th replicate of depth *d* in region *r*, D_{jkdr} to the depth in the organic layer and DC_{jkdr} to the daily DC registered in each region. A logarithmic (log) transformation is herein applied to GMC to linearize the relationship. ST was the stand type with a categorical value of 0 in SpMo stands and 1 in SpSp stands. Coefficients β_0, $\beta_{1,}$ β_2, β_3 and β_4 are the parameter estimates of the intercept, D_{jkr}, DC_{jkr}, ST and the DC × ST interaction, respectively. Terms b_r, b_{dr} and b_{kdr} denote the random coefficients associated with the region, the depth and the replicates, respectively. Here, these random coefficients follow a normal distribution with mean of 0 and variance equal to σ_r^2 , σ_{dr}^2 and σ_{kdr}^2. Finally, e_{jkdr} is the error. The model also accounted for the correlated errors through a first-order autoregressive structure. Stand random parameter level was not included in the model because variability between stands of the same ST was low. Categorical variable ST was multiplied with DC to include a different response of GMC to DC according to stand type (SpMo or SpSp). Other fixed variables were tested for model calibration (the season, DC corrected with length of the day), but the results were not significant (not shown). Models were calibrated using the lme (Pinheiro and Bates, 2000) procedures included in the R freeware (R Development Core Team, 2010). The “corCAR1” class was selected to describe daily GMC correlation structure. This class implements an autoregressive correlation of order 1. Values vary from 0 to 1, with higher correlation attributed to observations closest in time. Serial correlation was evaluated with the correlation parameter p_x.

Model evaluation was done by analyzing residual dispersion and normality. Additionally, to ensure that our model did not result from a seasonal cycle effect (Vecchi *et al.*, 2012), we calculated Pearson’s correlations between linearly detrended log (GMC) and DC. The 95% non-parametric bootstrap confidence corrected for temporally correlated data was computed to test the significance of the correlations (Mudelsee, 2003). Finally, the predictive skills of the model were verified by correlating observed values and predicted values with the model-building dataset, as well as with the independent soil sampling data (GMC extracted from soil sampling).

While in this paper we focused on the DC as a predictor for GMC, similar analyses were also conducted using the Duff Moisture Content (DMC) of the FWI System as a predictor. The results of this second calibration led to the same conclusions. Appendice B presents the results obtained from the parameterization of GMC with DMC.

2.3.5 Depth of burn calculations and projections

Our analysis aimed at presenting a simple method for directly linking fire weather conditions to depth of burn for future fire behaviour projections. Critical cumulative heat load for ignition depends on GMC and fuels can sustain combustion under gravimetric moisture conditions ranging from 140% to 500% (Zoltai *et al.*, 1998, Benscoter *et al.*, 2011). We thus defined potential depth of burn as the depth where moisture content is favourable for fire to be sustained. Next, we calculated mathematically daily depths at which limits of GMC were archived by fixing GMC_{jkdr} at either 140% or 500% and by solving equation 4. The use of two GMC thresholds was intended to capture the inherent variability in burning potential attributed to heterogeneity in the organic bulk density (Benscoter *et al.*, 2011).

Our final objective was to project the potential daily response of depth of burn to climate change. We chose the 1971-2000 and 2071-2100 time horizons for model testing to underscore the heterogeneity of community responses in a context of highly contrasting fire hazards (Girardin *et al.*, 2013b). We used 1971-2000 interpolated data from Environment Canada's historical climate database described earlier to calculate daily-30 year means of DC for the whole study area by averaging values of our four studied sites. Monthly temperature and precipitation data were collected from six global climate models (GCMs) and used in the calculation of the monthly DC. The monthly DC is an adaptation to the daily DC calculation designed for modeling purposes in the absence of daily weather data (Girardin and Wotton, 2009, Girardin *et al.*, 2013b). The GCM simulations are those of the IPCC (2007) and include the Bjerknes Centre for Climate (BCM2.0), Canadian Centre for Climate Modelling and Analysis (CGCM3T63), Australia's Commonwealth Scientific and Industrial Research Organisation (CSIROMk3.5), GISS (GISSAOM), Institute for Numerical Mathematics (INMCM3.0), and National Institute for Environmental Studies (MIROC3.2 medres) models. Simulations were performed using the IPCC A2, A1 and B1 Special Report on Emission Scenarios (Nakićenović *et al.*, 2000). The A2 and

A1 storylines (intense forcing) projected an increase in annual temperatures of 5˚C and 4˚C, and an increase in precipitation of 13% and 11%, respectively. An increase in temperature of 3˚C and in precipitation of 8% was projected under the B1 storyline (intermediate forcing) (Appendix 2). Non-downscaled-GCM data were collected and averaged over the area encompassing 49.5°–51.5°N and 84°–78.0°W (four to six grid cells depending on model resolution), and debiased (i.e. corrected for systematic differences between simulated and observed current-climatic conditions; Bergeron *et al.*, 2010, Girardin *et al.*, 2013b). Differences in monthly DC between the future period (2071-2100) and the baseline period (1971-2000) were then computed and applied to the 30-year means of the daily DC computed from Environment Canada's historical climate database. Data on the baseline period were not detrended as we assumed that a parallel trend would characterize conditions 100 years later. The resulting DC means were used to calculate future depth of burn as described previously.

Significant differences between future projections and current values of DC were tested using Student's t-test at the 5% significance level.

2.4 Results

2.4.1 Spruce-feather moss stand and spruce-*Sphagnum* stand moisture content dynamics

With mean temperatures of 15.5˚C and 15.9˚C and amounts of total precipitation of 231.8 mm and 225 mm, respectively, for region A and region B during the sampling period, 2010 was a particularly warm and dry fire season in comparison with the 1971-2009 mean (Fig. 2a, 2b). Meteorological values computed from interpolated Environment Canada data by BioSIM were slightly underestimated when compared with values computed from *in situ* weather data. Nevertheless, the unusual nature of the 2010 water deficit was well captured by the interpolation routine, with cumulative daily-precipitation during the year 2010 being well below the 30-year averages (Fig. 2a, b).

Spring weather conditions during 2010 were particularly warm and dry, with air temperature values around 30˚C and almost no rain falling from May 30 to June 26. In response to these spring conditions, DC showed a rapid increase of almost 200 units from May to June (Fig. 3). The rise in DC persisted, with intermittent ups and downs, until September when it reached values of 317 and 338 in regions A and B, respectively. Overall, the 2010 drought season was exceptional as it ranked 1st in terms of mean May-July DC magnitude since 1971 (Fig. 2c, 2d).

GMC values varied generally from around 50% to 330% at 5 and 15 cm for SpMo, while SpSp showed higher values for each depth (from around 440% to 900%) (Fig. 3). GMC in SpSp stands at 25 cm was high ranging from an average of 700% and reaching 900% for region A. Rapid variations in GMC of region A in SpSp stands were indicative of the changing water table's level in the organic layer induced by rainfall events.

In general, DC was much more responsive to drying and wetting by steeper increases and decreases compared with GMC. Nonetheless, GMC in SpMo stands responded to weather conditions in a similar manner to the DC, with a decrease in moisture as the season progressed and some variations during precipitation events. Moisture content response in SpSp stands showed little variation in GMC (Fig. 3). Additionally, a gradual decrease in soil moisture content during the season was not observed in SpSp stands. Replicates of SpMo stands in region B showed a decrease in GMC with DC, while other replicates showed little variation. Linearly detrended daily GMC and DC values were significantly correlated and this was true for the entire vertical profile (Table 2).

2.4.2 GMC calibration

A model relating GMC to DC and depth was parameterized using linear mixed-effects. Our model expressed well the variability of GMC in SpMo and SpSp stands (Fig. 4a). It should be noted that moisture content derived from soil sampling reflected a specific temporal value in the day (one sample at different times in the day), while moisture content sampled with probes expressed a daily average of moisture content. These differences contributed to explaining the high variability seen between the observed and predicted values (crosses in Fig. 4a). However, Pearson's correlation between observed and predicted values confirmed the good predictive skill of the model (SpMo: r_{pearsonT} = 0.597 [0.491; 0.674]; SpSp: r_{pearsonT} = 0.88 [0.179; 0.622]).

All fixed variables included in the mixed model were significant ($p < 0.001$) with high temporal correlation in our data (correlation parameter $p_x = 0.99$). GMC was negatively correlated to the DC and positively correlated to the depth (Table 2). The coefficient associated with the SpSp stand type (ST = 1 in equation 4) tended to increase with GMC. Calibration curves in Fig. 4b showed a GMC decrease of 63% and 78% in SpMo stands respectively at 5 cm and 15 cm depth in response to varying DC of 400 units. GMC decrease is slightly lower for SpSp stands with differences of 35%, 43% and 52% for 5, 15, and 25 cm depths (Fig. 4b).

2.4.3 Depth of burn calculation and 2071-2100 projections

The 30-year daily means of DC for the period 1971-2000 varied from DC=8 in April to DC=179 in October with a mean of DC=100 (plot EC1971-2000 in Fig. 5). In response to these DC variations, potential depth of burn in SpMo increased up to 4 cm and 10 cm under burning limit scenarios of GMC=140% and GMC=500%, respectively. GMC = 140% was never reached in SpSp stands and potential depth of burn increased only up to 2 cm under 500% burning conditions (Fig. 6).

Climate change projections indicate that DC values should increase over the 21st century by an average of 26 units, using all models and scenarios. DC could decrease slightly during spring (DC decreases with a maximum of 10 units with the INMCM3.0 model under the B1 scenario) and increase greatly during summer and fall (DC increases by up to 153 units with the MIROC3.2 medres under scenario A2) (Fig. 5). Changes in DC are projected to be significant only during summer according to Student's t-test (Fig. 6, in grey). In response to changes in the DC, depth of burn in SpMo should follow the same trends as DC (decrease in spring, increase in summer); changes in depth of burn were projected to vary from -0.6 to 8.4 cm depending on the models and IPCC emission scenarios. In contrast, the DC increase should not be sufficient to permit moisture limits to reach 140% in SpSp stands or to greatly modify depth of burn in SpSp stands, varying from -0.09 cm to 1.23 cm when burning soil moisture conditions were 500%.

2.5 Dicussion

This study reports on the soil moisture content dynamics of Clay Belt stands during a year of particularly dry conditions. A fire weather-based gravimetric moisture model with *in situ* soil moisture data from deep forest floor layers was parameterized to calculate and project future depth of burn potential. Analysis of moisture contents confirmed our first hypothesis that soil moisture dynamics in spruce-*Sphagnum* (SpSp) stands are less sensitive to drought severity than in spruce-feather moss (SpMo) stands. A decrease in GMC with seasonal drought in SpMo stands is consistent with information acquired from analyses in other boreal stands (e.g. Lawson and Dalrymple, 1996, Otway *et al.*, 2007). As previously observed by Waddington *et al.* (2011), GMC of SpSp stands showed a relatively steady state with high values during the fire season. This "resistance to drought" is probably related to the presence of *Sphagnum* species (Dai *et al.*, 1974) that act as a physical soil isolating barrier from atmospheric temperature variations, notably via air spaces in the *Sphagnum* layer (Gornall *et al.*, 2007). The *Sphagnum* species are also composed of internal hyaline cells (water tanks) (Silvola, 1991) in which stocked water acts as insulation. This internal structure provides better protection against atmospheric temperature variations in comparison with the external structure found in feather moss (Busby and Whitfield, 1978), allowing lower evaporation and increasing isolative effects.

Modelling analysis highlighted first that drier weather conditions are required in SpSp stands to burn the same amount of organic layer as in SpMo forests. The water retention characteristics of some *Sphagnum* species protect forest soils not only from drought but also from high organic layer consumption during wildfire (Benscoter *et al.*, 2011, Benscoter and Wieder, 2003, Harden *et al.*, 2006, Kasischke *et al.*, 2010, Shetler *et al.*, 2008, Turetsky *et al.*, 2011b). Secondly depth of burn in SpSp stands was independent from date of burn. DOB in SpSp stands should thus be less affected by an increase in DC, as projected with the 2071-2100 climate change scenarios. Our results in Clay Belt forested peatlands hence contrast with previous studies conducted in peatlands located in the discontinuous permafrost. Therein it was suggested that DOB may increase in response to climate change (e.g. Kasischke *et al.*, 2010, Turetsky *et al.*, 2011a, Turetsky *et al.*, 2011b). This may be explained by the different mechanisms responsible for the poor drainage noted in this study. In the case of sites on the discontinuous permafrost, saturated soil conditions are promoted by the maintenance of ground temperatures below the freezing point of water (Bonan and Shugart, 1989). Climatic warming in recent years has induced permafrost degradation (Vitt *et al.*, 2000) and impacted water storage, leading to a decrease in moisture content (Frolking *et al.*, 2011, Zoltai *et al.*, 1998). In our case, flat topography and clay substrate, which originate from long geological processes, are the mechanisms responsible for poor drainage (Fenton *et al.*, 2005) and may not be directly alterable by climate change. Moisture conditions are mainly created by the accumulation of the organic layer leading to a rise in the water table (Fenton *et al.*, 2006). A study encompassing peatlands from different global regions could improve our knowledge about the importance of drainage mechanisms.

Other processes induced by climate change could provide feedback on the high depth of burn risk in the future by further contributing to the loss of the *Sphagnum* layer. Notably, an increasing number of fires (e.g. Amiro *et al.*, 2009, Bergeron *et al.*, 2010, Le Goff *et al.*, 2009, Terrier *et al.*, 2013, Wotton *et al.*, 2010) and area burned (e.g. Le Goff *et al.*, 2008, Le Goff *et al.*, 2009) could lead to successive fire events, which may in turn reduce the organic layer and eventually promote a switch from SpSp stands to SpMo stands. The *Sphagnum* layer could also be impacted by the direct effects of climate change even without fire regime changes. For instance, increasing drought duration could lead to a lowering of the water table and a shift from SpSp to SpMo covers (Breeuwer *et al.*, 2009) and an increase in tree cover (Breeuwer *et al.*, 2009, Gignac and Vitt, 1994). Temperature could also increase decomposition rate if saturation soil moisture reaches 25 to 75%, thereby further contributing to the loss of the *Sphagnum* layer (Wickland and Neff, 2008). That being said, increases in temperature could stimulate *Sphagnum* growth (Loisel *et al.*, 2012) and therefore counteract these potential effects.

Efforts are needed in data acquisition to improve estimates and knowledge of global impacts of climate change on peatlands (Frolking *et al.*, 2011, Zoltai *et al.*, 1998). This study represents only 1 year of data from four sites, which were used for model calibration. A larger number of soil moisture probes at more depths at each site would have been preferred, but this was limited by equipment availability. Additional data are also needed to estimate moisture limits that allow a fire to ignite and spread in Clay Belt stand types. The GMC of SpSp stands never reached values lower than

140% in either 2010 or 2071-2100 and the limit of 500% was overestimated for SpMo, since this moisture threshold was predicted to be deeper than the total organic layer depth. Weather conditions would probably not be sufficient for SpSp stands to reach this independent ignition limit. However, once a fire is started in peat, such as by lightning or by a larger sustained burning source like a burning log or other dead woody debris, the peat will continue to burn by smouldering combustion at GMC of 140-500%. As the results of this study indicate, these conditions can occur within the Clay Belt region.

2.6 Conclusions

The impacts of climate change on the depth of burn in stands of the Clay Belt of eastern Canada were examined. *Sphagnum* layers protect soils from drought and consequently from increasing depth of burn risks. These results have important implications for forest management in the context of climate change adaptation. Climate change would increase depth of burn of spruce-feather moss stands. However spruce-*Sphagnum* stands in the boreal Clay Belt should be more resistant to an increase in the depth of burn risk. Managers should consider that they could increase potential depth of burn if they apply practices to reduce *Sphagnum* establishment and favour the development of more productive spruce-feather moss stands. Peatland protection (such as reducing or preventing peatland drainage) could be an alternative way to increase forest resistance to fire and reduce future fire carbon emissions in eastern Canadian forests.

Given the uncertainties associated with field data and carbon cycle knowledge, these results should be seen as a first estimate of the impacts of climate change on depth of burn in the boreal forest of the eastern Canadian Clay Belt. Future studies should focus on the role of *Sphagnum* species layers in soil moisture content and how it could be impacted by climate change by monitoring over multiple sites and years.

Future studies should also be extrapolated to a larger scale by a meta-analysis of existing data according to the different regions to understand the role of poor drainage mechanisms.

2.7 Acknowledgements

The GCM (General Circulation Model) data were supplied by Environment Canada (www.cccsn.ec.gc.ca). This project was financially supported by the Natural Sciences and Engineering Research Council of Canada (NSERC; Strategic Project), the Ouranos Consortium, the Canada Chair in Forest Ecology and Management (Dr Yves Bergeron), the Canada Chair in Modeling Research (Changhui Peng), and the Canadian Forest Service funds. Sébastien Dagnault, Mario Major and Danielle Charron contributed to the installation of the experimental design and to the field work logistics. We are particularly grateful to Nicolas Houde, Lauriane Mietton, Julie Magnier and Mickaël Paut for assistance in the field, to Maryse Marchand, Dave Gervais, XiaoJing Guo and Marc Mazerolle for their help in mixed models analysis, to Rémi St-Amant for providing climate data and help with the BioSIM software and finally, to Raymond Berard (Campbell Scientific) for his advice on field material use. We extend our thanks to Nicole Fenton, to anonymous reviewers for reviewing the manuscript and providing helpful comments and to Pamela Cheers for technical editing.

Figure 2.1 Geographic location of the Clay Belt, eastern Canada, and the regions (A, B) within which stands were selected.

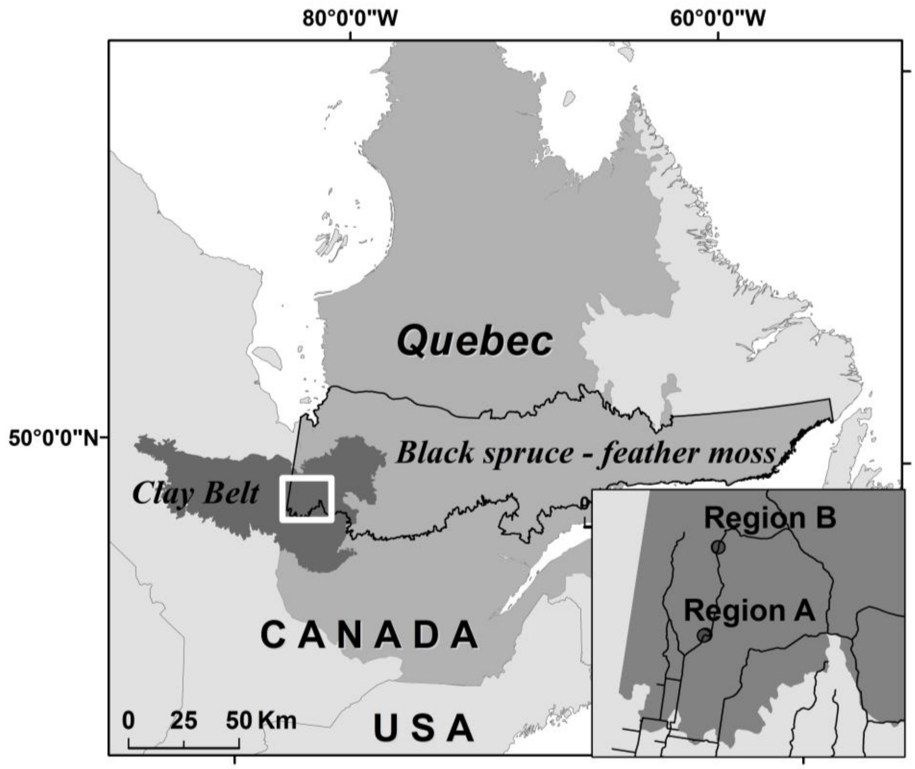

Figure 2.2 Daily means of temperature (curves) and cumulative daily precipitation (bars) during the 2010 fire season recorded by *in situ* meteorological stations for a) region A and b) region B. Also plotted are the daily means and 1970-2009 averages interpolated from Environment Canada (2012) weather station data. Annual and early-fire season means of the Drought Code (DC) from 1970-2010 computed from Environment Canada (2012) interpolated weather stations are also plotted for c) region A and d) region B.

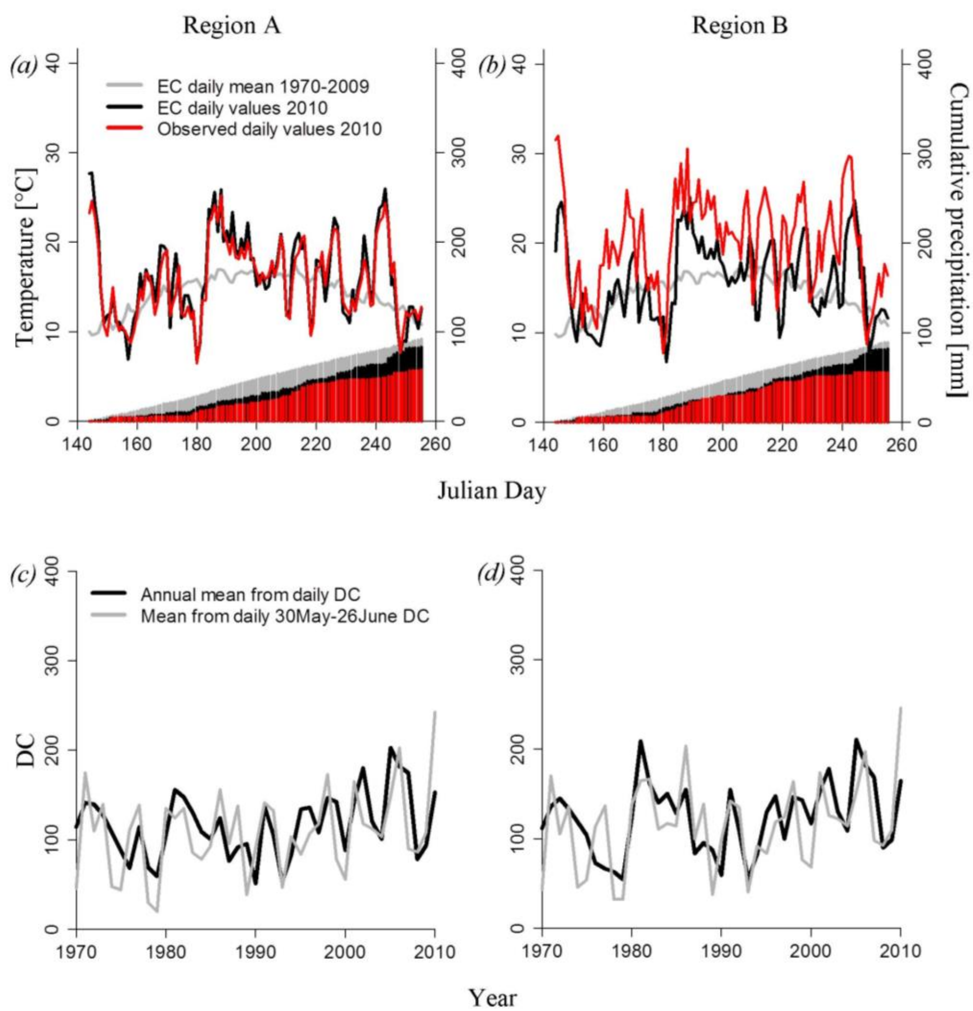

Figure 2.3 Daily gravimetric moisture content (%) recorded in spruce-feather moss (SpMo) stands at 5 cm and 15 cm, and in spruce-*Sphagnum* (SpSp) stands at 5 cm, 15 cm and 25 cm. Also plotted are the daily Drought Code (DC) values computed from *in situ* meteorological data.

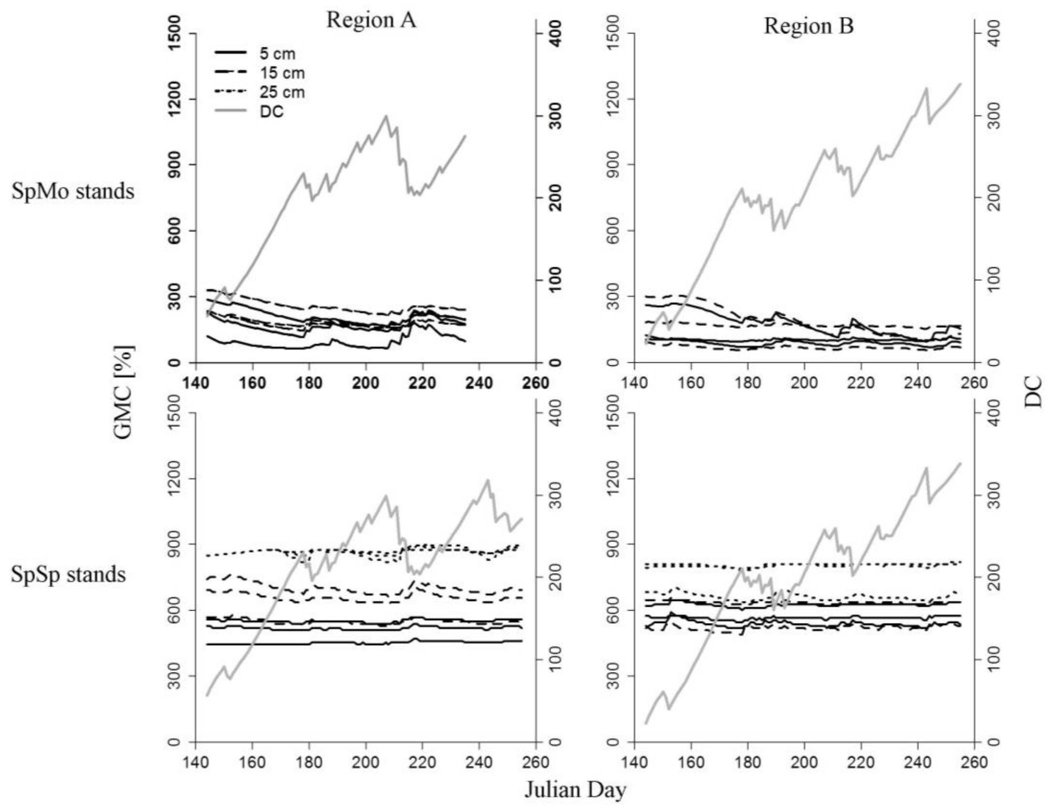

Figure 2.4 a) *Crosses*: Verification of gravimetric moisture content (GMC) model predictive skills on independent soil sample measurements in spruce-feather mosses (SpMo) (*in black*) and spruce-*Sphagnum* (SpSp) (*in grey*) stands. A logarithmic (log) transformation was applied to all data. Also shown are the predicted versus observed GMC values from the calibration dataset (*circles*). b) Curves of the gravimetric moisture content variation with the Drought Code (DC) per stand type and sampling depths.

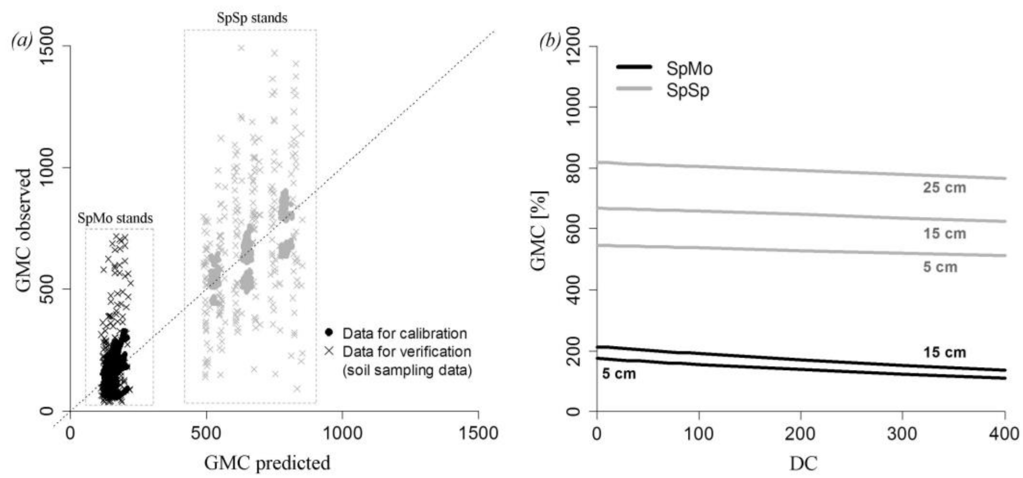

Figure 2.5 Observed (1971-2000) and projected (2071-2100) daily Drought Code (DC). Projected values are those simulated using the Bjerknes Centre for Climate (BCM2.0), Canadian Centre for Climate Modelling and Analysis (CGCM3T63), Australia's Commonwealth Scientific and Industrial Research Organisation (CSIROMk3.5), GISS (GISSAOM), Institute for Numerical Mathematics (INMCM3.0), and National Institute for Environmental Studies (MIROC3.2 medres) models under the IPCC A2, A1 and B1 emissions scenarios.

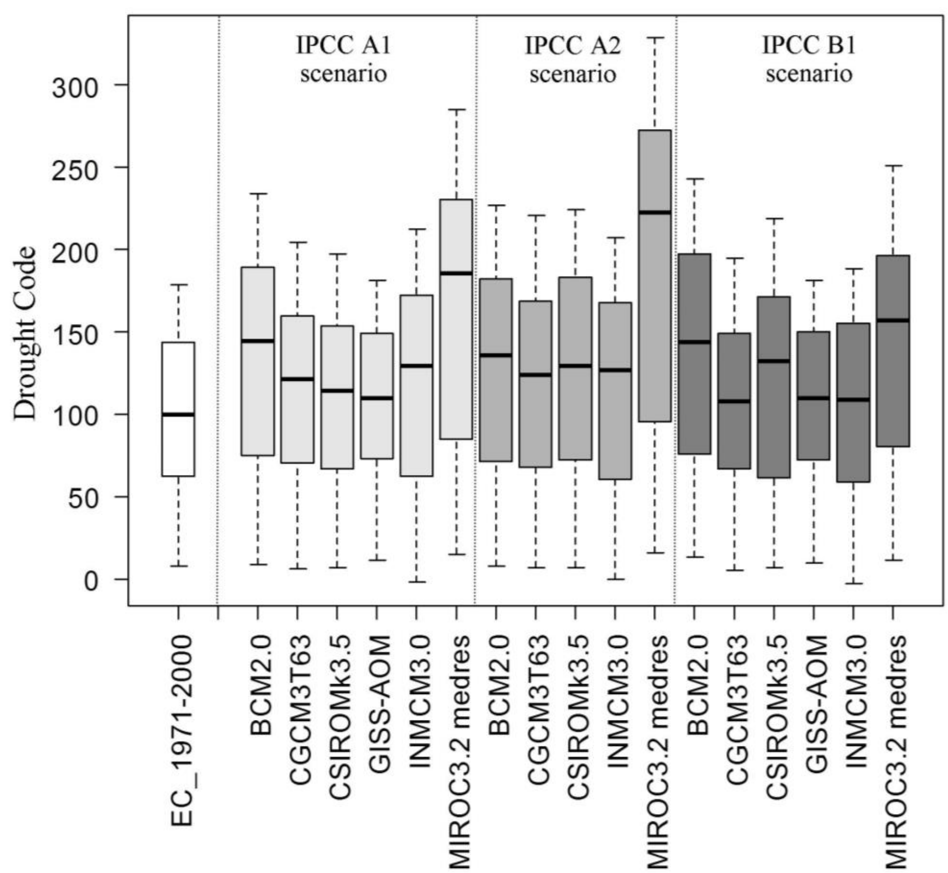

Figure 2.6 Current (1971-2000) and projected (2071-2100) daily depth of burn [cm] in a) spruce-feather moss (SpMo) and b) spruce-*Sphagnum* (SpSp) stands under GMC 140% (in black) and GMC 500% (in red) scenarios. The deviations (dotted lines) computed from the 2071-2100 minus the 1971-2010 projections are plotted. Vertical grey bar corresponds to days of months that showed significant differences between current and future projections of the DC (Student's t-tests, $p < 0.05$).

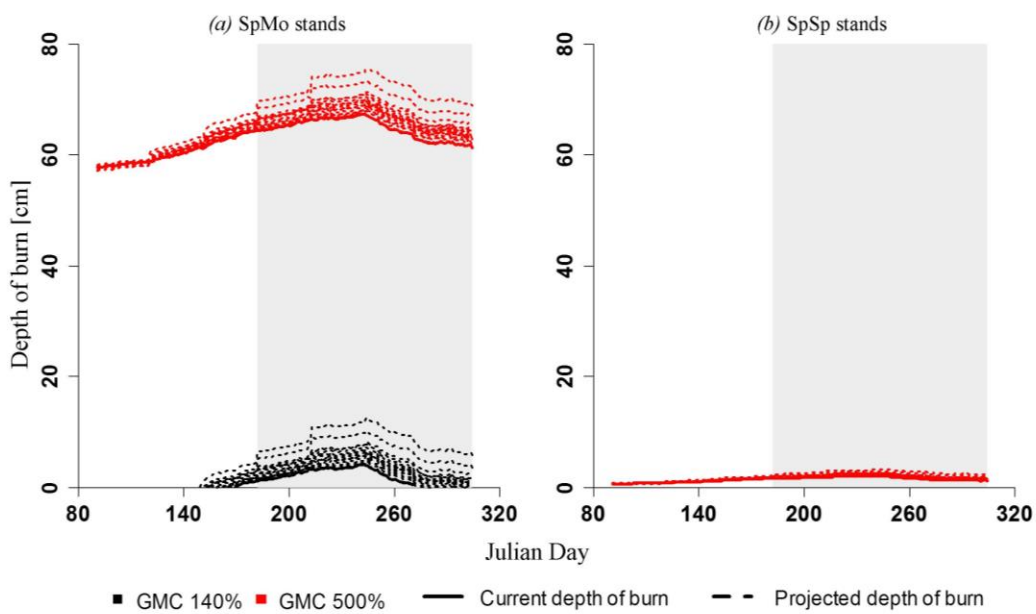

Tableau 2.1 Characteristics of sampling sites. Stand ages (time since the last fire) were extracted from a fire history map of the study area (Bergeron *et al.*, 2004). Organic layer depths and bulk densities represent mean (standard error) of *n* replicates per site. The number of trees and mean diameter at breast height (DBH mean) were sampled in a 100 m^2 plot encompassing the centre of the CS616 probes.

Stand types	Region	Stand age	Lat.	Long.	Depth organic layer (cm)	Bulk density (g/cm^3)	Nb trees/100 m^2 (stem DBH >9 cm)	DBH mean (cm)
					n = 15	*n* = 4		
SpMo[1]	A	1914	49.379	-79.046	15 (4)	0.0989 (0.013)	45	12.40
	B	1886	49.745	-79.036	26 (7)	0.1038 (0.05)	36	12.10
SpSp[2]	A	1775	49.383	-79.037	48 (15)	0.0766 (0.011)	42	4.53
	B	1725	49.745	-79.04	46 (16)	0.1098 (0.04)	30	7.43

[1]Spruce-feather moss stands; [2]Spruce-*Sphagnum* stands

Tableau 2.2 Pearson's correlation coefficients *r*, and associated 95% bootstrap confidence intervals (95% CI) corrected for autocorrelation, computed between linearly detrended daily 2010 logarithmic-scaled Gravimetric Moisture Content (GMC) and daily *in situ* 2010 Drought Code (DC).

Site type	Region	Depth	*r*	95% CI
SpMo[1]	A	5	-0.927	-0.946; -0.896
		15	-0.881	-0.908; -0.845
	B	5	-0.747	-0.829; -0.634
		15	-0.724	-0.808; -0.613
SpSp[2]	A	5	-0.829	-0.873; -0.773
		15	-0.918	-0.938; -0.890
		25	-0.697	-0.825; -0.359
	B	5	-0.766	-0.834; -0.651
		15	-0.811	-0.860; -0.743
		25	-0.768	-0.833; -0.671

Tableau 2.3 Coefficients and fit statistics for model of gravimetric moisture content (GMC). GMC$_{jkdr}$ correspond to the gravimetric moisture, D$_{jkdr}$ to the depth in the organic layer layer and DC$_{jkdr}$ to the daily Drought Code. Coefficients β_0, β_1, β_2, β_3 and β_4 are the parameter estimates, b_r, b_{dr} and b_{kdr} are the random coefficients.

$$\log(GMC_{jkdr}) = \beta_0 + \beta_1 D + \beta_2 DC_{jkdr} + \beta_3 ST + \beta_4 DC_{jkdr} ST + b_r + b_{dr} + b_{kdr} + e_{jkdr}$$

	Values	**Standard error**	**p-values**
Fixed effects			
β_0 (Intercept)	5.06	0.12	≤ 0.001
β_1	0.02	0.006	≤ 0.05
β_2	-0.0011	0.00007	≤ 0.001
β_3	1.143	0.01	≤ 0.001
β_4	0.00096	0.00009	≤ 0.001
Random effects			
Region	0.096		
Depth in region	0.00004		
Replicates in depth in region	0.223		

APPENDICE B

B.1 Calibration of GMC with Duff Moisture Code (DMC)

DMC represents the average moisture content of loosely compacted, decomposing organic layers of moderate depth weighing ~5 kg m^{-2} when dry. It relates to the probability of lightning ignition and fuel consumption. The DMC model is an exponential model of moisture exchange wherein layers gain moisture from precipitation and dry depending on relative humidity and air temperature (Wotton, 2009). The equivalent moisture Q can be calculated from DMC with the equation developed by Van Wagner (1987):

$$Q = 20 + \ln((DMC - 244.73)/-43.43) \quad \text{(B1)}$$

For a temperature of 25ºC, relative humidity of 30% and wind speed of 10 km/h, the response times of DMC and DC are approximately 10 days (Wotton 2009). Table B.1 shows coefficients and fit statistics for the model of gravimetric moisture content (GMC) with DMC.

Tableau B.1 Coefficients and fit statistics for model of gravimetric moisture content (GMC) with duff moisture code (DMC) as a predictor variable.

$$\log(GMC_{jkdr}) = \beta_0 + \beta_1\, D + \beta_2\, DMC_{jkdr} + \beta_3\, ST + \beta_4\, DMC_{jkdr}\, ST + b_r + b_{dr} + b_{kdr} + e_{jkdr}$$

	Values	Standard Error	p-value
Fixed effects			
β_0 (Intercept)	4.90	0.11	≤ 0.0001
β_1	0.02	0.007	≤ 0.05
β_2	-0.002	0.0002	≤ 0.0001
β_3	1.25	0.11	≤ 0.0001
β_4	0.0013	0.0002	≤ 0.0001
Random effects			
Region	0.05		
Depth in region	0.00005		
Replicates in depth in region	0.0003		

B.2 Temperature and Precipitation change projected with general circulation models

Tableau B.2 Mean temperature (°C) and total precitations (%) projected with general circulation models (GMC) and their greenhouse gas forcing scenarios for the period 2071-2100 at the study area. Data were downloaded from the Canadian Climate Change Scenarios Network (CCCSN) data portal, www.cccsn.ec.gc.ca.

Centre	Model	Forcing	Temperature change (°C)	Precipitation change (%)
Bjerknes Centre for Climate	BCM2.0	A1B	3.6	9.3
		A2	3.5	14.8
		B1	2.3	3.2
Canadian Centre for Climate Modelling and Analysis (CCCma)	CGCM3T63	A1B	4.1	16.8
		A2	5.3	18.7
		B1	2.8	8.8
Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO)	CSIROMk3.5	A1B	4.1	14.1
		A2	4.8	16.4
		B1	3.2	9.1
GISS	GISSAOM	A1B	3.3	13.3
		B1	2.3	10.9
Institute for Numerical Mathematics	INMCM3.0	A1B	3.6	4.8
		A2	4.9	11.9
		B1	3.6	8.8
National Institute for Environmental Studies	MIROC3.2 medres	A1B	5.7	7.9
		A2	6.2	3
		B1	4.2	8.6

CHAPITRE III

DISTURBANCE LEGACIES AND PALUDIFICATION MEDIATE THE ECOLOGICAL IMPACT OF AN INTENSIFYING WILDFIRE REGIME IN THE CLAY BELT FOREST OF BOREAL NORTH AMERICA.

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3.1 Abstract

Questions: High moisture levels and low occurrences of wildfires have contributed during recent millenia to the accumulation of thick layers of organic soil and to a succession into open black spruce (*Picea mariana*)-*Sphagnum* dominated forests in the Clay Belt boreal landscapes of eastern North America. In these forests, the anticipated increase in drought frequency with climate change could lead to a shift in forest structure and composition, and to a subsequent transfer of the stored carbon back into the atmosphere via increased fire disturbance and decomposition. Herein we investigated potential changes in forest structure and composition in response to a changing fire regime.

Location: A managed forest unit in the Clay Belt boreal forest of eastern North America.

Methods: We conducted modeling experiments using the Canadian Fire Effects Model (CanFIRE). Vegetation dynamic was governed by the fire danger and behaviour that affect tree mortality and postfire recruitment of species, and by long-term successional pathways that are driven by postfire recruitment and forest age.

Results: Results from multiple scenarios suggested that fire danger will rise significantly during the 21st century in the Clay Belt forest. The burn rate was projected to change from 4.2% decade^{-1} during 1971-2000 to 18.6% decade^{-1} during 2071-2100. Stand mortality, fire intensity and areas affected by crown fires were also projected to increase significantly. A shift in forest composition did not occur over the simulation period across most of our fire regime scenarios. Dominance of open black spruce *Sphagnum* forests was projected to remain in future landscapes.

Conclusions: Moist and cool conditions in these forests prevent high depth of burn and contribute to the ecological resistance of these forests to increasing fire danger. Managers should consider that practices that favour the development of hardwood and productive black spruce forest, or that reduce *Sphagnum* establishment (such as summer clear-cut or site preparation), could enhance forest productivity, but also decrease carbon storage by increasing potential vulnerability to severe depth of burn.

Key words: boreal forest dynamics, depth of burn, burned area, climate change, CanFIRE model.

Résumé

Questions: Les taux d'humidité élevés et une faible occurrence de feux ont contribués ces derniers millénaires à l'accumulation d'épaisses couches de sol organiqu, ainsi qu'à la succesion vers des peuplements d'épinette noire ouverts dominés par des sphaignes dans les paysages boréaux de la Ceinture d'Argile à l'Est de l'A,érique du Nord. Dans ces forêts l'augmentation de la fréquences des événements de sécheresses prévus avec les changements climatiques pourrait conduire à une changement de la structure et de la composition de la forêt, ainsi qu'à un transfert du carbone stocké vers l'atmosphère par le biais d'une augmentation des feux de forêts et de la décomposition. Dans cette étude, nous avons investigué les changements potentiels de la structure et de la composition de la forêt en réponse à un changement de régime de feu.

Localisation: Une unité d'aménagement forestier dans la forêt boréale de la ceinture d'Argile de l'est de l'Amérique du Nord.

Méthodes : On a conduit des expérience de modélisation en utilisant le Modèle Canadien des Effets du Feu (en anglaisL Canadian Fire Effects Model (CanFIRE)). La dynamique végétale était gouvernée par le danger du feu et son comportement qui affecte la mortalité et la la régénération après feu des espèces d'arbre, ainsi que par les trajets successionnels sur le long terme qui sont régis par la régénération après feu et l'âge de la forêt.

Résultats: Les résultats des divers scénaios suggèrent que le danger de feu devrait augmenter de manière significative durant le $21^{ème}$ siède dans la forêt boréale de la Ceinture d'Argile. Le taux de brûlage a été projeté de changer de 4.2 % décade^{-1} durant 1971-2000 à 18.6% durant la période de 2071-2100. La mortalité dans les peuplements, l'intensité du feu et les aires affectées par des feux de couronne ont aussi été projetés d'augmenter. Un changement de la composition forestière n'a pas eu lieu durant la période de simulation pour la plupart de nos scénarios de changements de geux. La dominance de forêts d'épinette noire ouvert dominée par la sphaigne a été projeté de rester dans les paysages futurs.

Conclusions: Les conditions froides et humides de ces forêts empêchent les forêts de brûler d'une importante profondeur de brûlage et contribuent à leur résistance écologique à une augmentation du danger de feu. Les aménagistes devraient considérer que les pratiques qui favorisent le développement de feuillus et de forêts d'épinette noire productives ou qui réduisent l'établiseement de la sphaigne (récolte en été ou préparation de site) pourrait augmenter la productivité des forêts, mais également réduire le stockage de carbone en augmentant leur vulnérabilité potentielle à une profondeur de brûalge sévère.

Mots clef: CanFIRE, composition des forêts, profondeur de brûlage, aire brûlée, changements climatiques.

3.2 Introduction

In the context of global warming (IPCC 2013), boreal forest vulnerability to climate change is a major concern. High-latitude boreal regions are projected to be amongst the most affected ones by climatic changes (IPCC 2013). There, warming is projected to result in more frequent and severe drought conditions by the end of the 21st century (Yang et al. 2011) that will directly impact wildfire activity (e.g. (Flannigan et al. 2005; Bergeron et al. 2010; Wotton et al. 2010; Turetsky et al. 2011; Boulanger et al. 2013; Girardin et al. 2013a,b; Terrier et al. 2013). Shifts in landscape forest cover and structure are expected in response to these changes (Weber & Flannigan 1997; Thompson et al. 1998; de Groot et al. 2003; Fulé 2008; Johnstone et al. 2010b; Barrett et al. 2011; Flannigan et al. 2013), altering wildlife habitat diversity (Rupp et al. 2006, Weber & Flannigan 1997) and reducing the carbon stocks (Harden et al. 2000; Amiro et al. 2009; Turetsky et al. 2011; de Groot et al. 2013b). These changes may also result in economic damage for the forest sector, which may include the reduction of commercial products and timber supplies (Weber & Flannigan 1997; Kirilenki & Sedjo 2007, Gauthier et al., in press).

The boreal forest of the Clay Belt region in eastern North America, at the border of the provinces of Quebec and Ontario (Fig. 3.1), constitute one of the world's largest carbon stocks estimated at 201 to 250 tons per hectare with a large proportion of forests reaching values up to 1,050 tons per hectare (Scharlemann et al. 2009). The physiographic unit of the Clay Belt (Vincent & Hardy 1977) originated from the retreat of the proglacial lake Barlow-Ojibway, which left a thick deposit of clay (Fig. 3.1). Poor drainage conditions induced by the presence of an impermeable clay substrate, a flat topography, and a cold climate facilitated the accumulation of thick layers of organic soil, a process often described as paludification (Fenton et al. 2005; Lavoie et al. 2005b). In parts of the region, peat mosses accumulate on initially mesic soils independently from topography or drainage and are primarily related to forest succession (Simard et al. 2007). Once *Sphagnum* species increase on the forest floor, fluctuations in water saturation of the organic layer decrease (Bergeron and Fenton, 2012). Water table moves from the mineral soil into the organic forest layer, and organic layer depth becomes the dominant factor explaining the water table position (Fenton et al., 2006). Additionally, tree roots are unable to reach the mineral soil inducing humid, colder and less nutrient rich environments that result in a drop of tree productivity (Payette 2001). Therefore, in the prolonged absence of fire, forests tend to converge to open or partially less productive spruce-*Sphagnum* forests regardless of the initial species composition (Harper et al. 2003; Lecomte et al. 2006a; Fenton et al. 2007; Simard et al. 2007; Lafleur et al. 2010; Belleau et al. 2011). A decrease of the fire activity in southeastern North American boreal forests during the past three milennenia in association with an orbitally-driven climatic cooling (Carcaillet et al., 2001; Girardin et al. 2013a, 2013b) likely contributed to an acceleration of peat accumulation in the Clay Belt forest and a decrease in its productivity (Simard et al., 2007; Girardin et al., 2011).

Burned area and residual organic layers (i.e. layers not consumed by the fire) jointly control forest structure and composition (Lecomte et al. 2006b). Shallow residual organic layer on the ground permits the establishment of dense forests composed of black spruce (*Picea mariana* (Mill.) BSP), trembling aspen (*Populus tremuloïdes* Michx.), white birch (*Betula papyrifera* [March]) or jack pine (*Pinus banksiana* Lamb.) on mesic sites (Lecomte et al. 2005; Johnstone & Chapin III 2006; Lecomte et al. 2006b; Greene et al. 2007; Johnstone et al. 2010a). In contrast, thick residual organic layers favor black spruce self-replacement (Van Cleve et al. 1983; Johnstone et al. 2010a) and accelerate the process of paludification (Lecomte et al. 2006b; Simard et al. 2009). As burned areas may be positively related to depth of burns in boreal forests (Turetsky et al. 2011), increasing fire activity over the next century under global warming could contribute to the removal of the organic layer, thereby promoting a decrease in black spruce-Sphagnum dominated forests and a shift to closed coniferous and deciduous forests. Although black spruce-Sphagnum dominated forests tend to be moister and resistant to high depth of burn (Terrier et al., 2014), paleoecological analyses of peat sediments indicated that such properties do not necessarily prevent the organic layer from burning (Simard et al., 2007; Cyr et al., 2005). There is therefore justification for an assessment of the risks posed by future climatic changes specifically in the Clay Belt forest. The purpose of this paper is to quantify the expected changes in fire behaviour, biomass burning and vegetation dynamics in the Clay Belt forest of North America over the next century that could arise under climatic change.

3.3 Sudy area

The study area is a managed forest unit (MFU 8551; 49°00 – 50°00 N; 78°30W - 79°50) in northwestern boreal Quebec, Canada, covering ~ 400,000 ha (Fig.3.1). The topography is flat; however, small rocky hills are present. The area lies mostly in the black spruce-moss bioclimatic domain, with the southern part lying in the balsam fir white-birch domain (Saucier et al. 1998). Landscapes are dominated by black spruce forests with the prominent presence of jack pine, trembling aspen, white birch and balsam fir forests on various surficial deposits from coarse till to clay (Harper et al. 2003) (Fig.3.2B). As of year 2000, 48% of the territory was occupied by open black spruce forests (Ministère des Ressources naturelles du Québec ; MRN) The climate is subpolar and subhumid continental, characterized by long, harsh and dry winters and short, hot and humid summers (Environment Canada 2013). The average annual temperature from 1970 to 2009 was 0.3 ˚C, ranging from monthly means of – 22.2 ˚C to 17.4˚C; the mean total annual precipitation was 862 mm (Environment Canada 2013).

3.4 Methods

The impact of a changing climate on fire behaviour and vegetation in the study area was investigated using the Canadian Fire Effects Model (CanFIRE, formerly the Boreal Fire Effects Model, BORFIRE) (de Groot et al. 2002; de Groot et al. 2003; de Groot 2006; de Groot et al. 2007; de Groot et al. 2013a; de Groot et al. 2013b). CanFIRE is a collection of Canadian fire behaviour models that are used to estimate first-order fire effects on physical characteristics, and to estimate ecological effects, at the stand level. Feedback and interactive effects between fire characteristics and vegetation are considered in the CanFIRE model, which makes it an interesting tool for addressing our research question (Flannigan et al. 2001; Hély et al. 2001; Keane et al. 2004; Krawchuk et al. 2009; Hessl 2011; Keane et al. 2013). Fire danger is therein described using the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) and the type of fuel available. The vegetation dynamics are governed by fire behaviour (fire rate of spread, fuel consumption, intensity, type of fire – crowning or surface fire, and depth of burn) which affects mortality and postfire recruitment of species based on fire ecology traits. Long-term successional pathways are driven by potential recruitment and natural mortality induced by intra- and interspecific competition (de Groot et al., 2003).

Several tasks were required before having the CanFIRE model applied on the Clay Belt boreal forest. These are illustrated in Fig. 3.2. Essentially they involved three undertakings: i) the construction of driving datasets for the CanFIRE model, ii) the determination of recruitment and successional rules, and iii) the simulation of fire-driven vegetation changes. In the following section we describe our approaches to these tasks

3.4.1 Driving datasets

3.4.1.1 Forest dataset

For CanFIRE simulation work, we used the SIFORT (Système d'Information FORestière par Tesselle) forest cover data derived from classification of aerial photography and plot-level ground surveys from the first (1970-1980) decadal forest inventories (© Gouvernement du Québec; Pelletier et al. 1996). Data from the third forest inventory (1990-2000) were also used to complete the age class data. The SIFORT forest cover data are represented in raster format at a resolution of 14 ha. Our study area therefore consists of 29,527 grid cells. Each grid cell was characterized by the species' cover percentages, forest type and forest age (Table 3.1, Fig.3.1B & 3.1C; see supplementary materials for details). Site index (i.e. height at 50 years old) was also assigned to each cell. It was determined for each species within a grid cell using growth and yield curves compiled by the Ministère des Ressources naturelles du Québec (MRN) during their last timber supply inventory (Pelletier, 1996). These yield curves were calculated using the model developed by Pothier and Savard (1998). Site index and cover percentages were averaged by species and by each forest type to obtain a single value of species in each forest type for the entire landscape (Table 3.1).

The CanFIRE model required quantitative information on the organic layer depth (cm) for the fuel load quantification and for the depth of burn algorithm. For estimation of total organic layer content, we made use of a data set comprising 4,217 temporary sample plots (circular 0.04 ha) selected from the third inventory program of the MRNQ (Anyomi et al. 2014). These measurements include a characterization of the forest strata and the site features (e.g. soil texture, depth of B and C horizons, drainage class, surface deposit type, humus type). From these data we deduced the model linking measured organic layer depth (OL depth) within each plot with stand age, forest type and surficial deposit (more details in supplementary materials). In parallel, the depth of the fibric layer (cm) was required for the black spruce to aspen post-fire recruitment rules (see Recruitment and successional rules). Herein, we deduced fibric layer depth [cm] using a linear functional relationship to the total organic layer depth (more details in supplementary materials). This relationship was determined using measurements of fibric and total organic layer depths sampled in sites that originated from one recent fire (1997) and eight older fires (1725-1880) (Leroy, personal communication). Characterization of the fibric layer was based on Von Post scale (Canadian Soil Survey Comittee 1978).

Finally, forest floor fuel loads (litter, moss, lichen; duff-fermentation; duff humus) and dead woody debris loads (coarse and medium) [kg/m^2] were required to describe biomass in the CanFIRE model. Forest floor and dead and downed woody fuel load information were estimated using the equations of Paquette (2011). Therein standard fuel (litter, moss, lichen; total duff) inventories were established in sites originating from different fire years and for four successional pathways (trembling aspen, jack pine, severe black spruce, non-severe black spruce). Total duff was separated into duff-fibric and duff-humus using fibric layers equations (more details in supplementary material). To be consistent with the work of Belleau et al. (2011), open black spruce stands of less than 100 years old were considered as stands originating from non-severe fires; black spruce stands of 100 years old and over were considered as originating from severe fires for the start of our simulation. We used trembling aspen fuel loads for all mixedwood stands, including white birch – coniferous stands and productive black spruce fuel loads for balsam fir stands.

3.4.1.2 Forest fire data

In this simulation work, the disturbance rate is guided by a random generator of fire sizes. To obtain an approximation of the size and frequency of fires in our region, we used fire data from the MRNQ. The database contains information on the location, the date of detection, the size (ha), and the cause (lightning or human) of all fires recorded in the province of Quebec from 1971 to 2011. The data set is provided in point-based format and as polygons. Fires that occurred in the eastern part of the black spruce-moss and balsam fir white-birch bioclimatic domains were extracted and used to generate the fire events distribution needed for the random generator. A total of 613 fires occurred between 1971 to 2000 and 97% of the total area was burned by fires larger than 1,000 ha.

3.4.1.3 Fire danger data

Daily FWI System component values were calculated for every fire starting points encountered during the interval 1971-2000 using the BioSIM software (Régnière & Bolstad 1994). The FWI System is used in Canada to evaluate the severity of fire weather conditions by providing indices of fuel moisture and fire behaviour (Wotton, 2009). All indices are unitless, with the zero value indicating low fire danger and high values indicating high fire danger. As part of the procedure, daily weather data were interpolated from Environment Canada's historical climate database (Environment Canada 2013) from the four closest weather stations, adjusted for differences in latitude, longitude and elevation between the data sources and stand location, and averaged using a 1/d2 weight, where d is distance. Winter precipitation was included in the algorithms to correct the onset and end of the fire season using snow accumulation (Terrier et al. 2013). Finally, the Daily Severity Rating (DSR) was computed. The DSR is a numeric rating of the difficulty of controling fires.

For determination of future fire danger at fire starting points, we used a procedure similar to that described by Flannigan et al. (2013) and de Groot et al.(2013b). We used monthly temperature, precipitations, relative humidity and wind speed collected from two General Climate Models (GCMs), namely the Canadian CGCM3.1 (Scinocca et al. 2008) and the United Kingdom HadCM3 (Gordon et al. 2000). Simulations were performed using the IPCC A2, A1B and B1 Special Report on

Emission Scenarios (Nakicenovic et al. 2000). In total, our work includes six GCM simulation experiments. CGCM3.1 and HadCM3 were selected among other GCMs to include a wide spectrum of climate change possibilities in our study area. GCM data was collected from four to eight cells, depending on model resolution and averaged for the whole area. Monthly weather changes between the GCM baseline data and future GCM data was summarized by decade until 2100. Those monthly changes were then added (for temperature, relative humidity and wind speed) or multiplied (for precipitation) to Environment Canada's historical daily data for each decade. Generally, increases in temperature and precipitations were projected with both GCMs for the periods 2031-2060 and 2071-2100 in comparison with the reference period (1971-2000) (Table S.1 in supplementaty material). Less changes were projected for the period of 2031-2060. The HadCM3 under the A2 storyline projected the highest temperature increase (+3.1◦C) and the lowest increase in precipitation (+13%). A slight decrease of temperature (-0.9 ◦C) and increase in precipitation (+13%) were projected with the CGCM3.1 under the B1 storyline (Table S.1 in supplementary material).

3.4.2 Modifications to the CanFIRE model

3.4.2.1 Depth of burn

In our study area, high soil moisture conditions in black spruce forest dominated by Sphagnum spp. imply lower depth of burn in comparison with other regions of the boreal forest (Terrier et al. 2014). Therefore, depth of burn algorithms in CanFIRE needed to be modified to reflect the regional specificity. We herein included depth of burn equations of Terrier et al. (2014) obtained by model calibration in black-spruce Sphagnum spp. dominated stands. Therein the moisture content of the organic layer was predicted using the DC component of the FWI System, depth of the organic layer (cm) and site conditions (dominated by Sphagnum species or dominated by feather-mosses). Accordingly with Lafleur et al. (2010) and Fenton et al. (2007), site conditions were determined using the depth of the organic layer: the criteria for the switch from black spruce–feather-mosses to black spruce–Sphagnum stands was set at ≤30 cm and >30 cm, respectively. Depth of burn was defined as depth where extreme gravimetric moisture contents of 140% and 500% were reached. The 140% limit represents an extremely low potential (LP) depth of burn; the 500% limit expresses an extreme high potential (HP) depth of burn. LP and HP scenarios were intended to capture the inherent variability in burning potential attributed to heterogeneity in the organic bulk density (Benscoter et al. 2011). Simulations were conducted separately for each of these scenarios of black spruce (BS) potential depth of burn.

3.4.2.2 Recruitment and successional rules

Recruitment in the CanFIRE model is based on tree species' adaptation to the fire environment (i.e. fire ecology using a plant functional type or PFT approach). In absence of fire, vegetation dynamics is governed by recruitment of annual (or non-disturbance) seedling species and natural mortality due to competition (de Groot et al. 2003). However, tree recruitment and forest successional pathways in the Clay Belt forest are also affected by the total organic layer depth and surficial deposit (Lavoie et al. 2005a; Lecomte & Bergeron 2005; Johnstone & Chapin III 2006; Lecomte et al. 2006a; Greene et al. 2007; Simard et al. 2009; Belleau et al. 2011). Here we modified the CanFIRE simulation setup by applying external recruitment and succession algorithms. Recruitment was based on pre-fire forest type, post-fire residual organic layer depth, and composition of neighbouring grid cells. It was also made possible only when tree mortality occurred. A severe depth of burn was defined as a fire that burned sufficient organic material to generate productive stands of coniferous and hardwood species. These conditions were achieved when residual organic layers were less than 3 cm (Greene et al. 2007), 20 cm (Simard et al. 2009) and 6 cm (Moore & Wein 1977) in jack pine, black spruce and white birch stand types, respectively. We defined severe depth of burn in trembling aspen types when fire burned the total fibric layer depth (Bergeron, pers. comm.) to consider sprouting of trembling aspen in the organic layer (de Groot et al. 2003). A severe depth of burn occurring in a pure black spruce stand could induce a shift in forest composition toward jack pine or hardwood stand types when neighbouring cells were dominated by those forest types. In this procedure, neighbouring forest types were assigned to each grid cell by selecting forest types which occupied the majority of neighbouring cells. The algorithm computed distance between points and returned the most frequent forest types in the k nearest neighbours. The classification is decided by the majority composition. No change in composition occurred after a non-severe fire in black spruce forests. Once recruitment was completed, cell age was changed to one year and a new forest type was attributed to the recruited grid cells. New organic layer depths were calculated by subtracting the depth of burn to pre-fire organic layer depths and we used depth of burn information to determine fire severity. Fires on the Clay Belt generally involve high mortality and thus are stand replacing (Bergeron et al. 2004). A validation analysis verified beforehand that the CanFIRE model yielded reasonable stand mortality and recruitment outcomes by comparing the modelled mortality rates with the vegetation structure of the third SIFORT inventories (see supplementary materials for details).

To include successional and structural changes with the time-since-fire (Lecomte & Bergeron 2005; Belleau et al. 2011; Bergeron & Fenton 2012), we applied the successional pathways of Belleau et al. (2011) to our cells. Belleau et al. (2011) estimated for each stand type and surface deposit type the transition age, the transition rate and the probability of transited stands (Table III in Belleau et al. 2011). For each decade, we selected a percentage of cells, expressed by the transition rates, among cells that reached age for transition. The transition rate reflects the fact that replacement of species is not synchronous to forests transition: not all forests transit at the same time even if the age criteria is reached. The probabilily of transited stands informed on the forest types changes and of their transiting proportions. Once succession was completed, forest attributes (organic layer depths, species age) were updated using class age and forest composition as described in the section forest dataset.

3.4.3 Projections of potential future fire occurrences and burnable cells

Projections of potential future fire occurrences in the Clay Belt forest were made using published empirical models (Terrier et al. 2013) describing the decadal distribution of wildfire occurrences for a given class (≥1 ha; ≥10 ha; ≥200 ha) in eastern Canada as a function of a set of fire bioclimatic zones determined from fire weather (FW) components and tree species composition (TreeComp). The model for fires of size class > 10 ha was selected for this study for its high predictive skills (Terrier et al. 2013) and to insure that approximately the entire grid cell (14ha) would be burned during a fire event. Using these equations we calculated the total number of fires that were encountered during each decade of simulation (1971-2100), and this was repeated for each GCM experiment. The fire sizes, dates-of-ignition (day of year), and associated fire danger were randomly selected from the fire events distribution discussed earlier.. Fires were prescribed to burn the first year of each decade under analysis (ex: 1971-1980, fires occurred in 1971). The potential total area burned for each decade was calculated and burned cells were selected randomly from the potential study area up to the cumulative simulated area burned. From this we obtained a large range of fire characteristics (fire occurrences, total burned areas, dates-of-ignition, types of fuels, etc) with several fire impact scenarios (e.g. fire depth of burn, species turnover, etc). Vegetation feedback on total burned area was finally evaluated by calculating the percentages of forest types in cells that underwent tree mortality (> 60% of tree mortality).

3.4.4 Data analysis

Our data analyses aimed first at summarizing simulated fire weather conditions, fire regimes and behaviour, and landscape forest type composition. Fire weather conditions were summarized for the periods 1971-2000, 2031-2060 and 2071-2100. FWI System components were averaged by GCM models and IPCC scenarios. The significance of increases in FWI System components was tested using the two-sample Student's t-test (one-sided) comparing the 1971-2000 with 2031-2060 and 2071-2100 intervals (n = 6 (3+3) decades per analysis). Student's t-test was performed in the R freeware (R Development Core Team 2010). Decadal percentages of burned cells, percentages of cells affected by severe depth of burn, mean fire intensities (kW/m) and the percentages of cells affected by crown fires provided information on fire regime and behaviour changes. Landscape composition was described by calculating the decadal relative percentage of cells grouped in three forest types categories: open black spruce, coniferous and mixed/deciduous forest types. Open black spruce forest types included open and partially open black spruce forests types. This class reflected late successional black spruce-Sphagnum dominated forests. Productive black spruce, jack pine and balsam fir forest types were grouped into coniferous forest types. Mixed and pure deciduous forest types were considered as one group because of their low relative proportions in the study area. To further evaluate the impacts of disturbance legacies and succession on our results a no fire scenario was also included in our CanFIRE model experiments. Therein, fires occurring from 1971 to 2000 were prescribed as in other simulations; from 2001 to 2100 it was run without fire.

Fire activity and landscape composition results of all experiments and BS potential depth of burn scenarios were summarized using visually-weighted regressions (Hsiang, 2012; Hsiang et al., 2013). The analysis was performed in the R freeware (R Development Core Team 2010) using vwREg function developed by F. Schönbrodt (2012). The visually-weighted regressions procedure consists on computing 1000 bootstrap smoothed regressions from the original sample points, computing a density estimate for each decade through the bootstrapped regressions, and illustrating the uncertainty using gradient-shaded confidence intervals (darker color for higher density). Samples points in our case corresponded to a total of 12 values per decade (six experiments x two BS potential depth of burn scenarios + no fire scenario for landscape composition) and regression were conducted using time (decade) as a predictor variable.

3.5 Results

3.5.1 Future fire weather conditions

Table 2 illustrates current (1971-2000) and future (2031-2060; 2071-2100) FWI System components projected using two GCMs (Canadian CGCM3.1; Hadley HadCM3) and three IPCC scenarios (A1B, A2, B1). For the current period, DC, FWI and DSR components equalled 113, 4.1 and 0.68 units, respectively. These values were projected to rise significantly from the mid to end of the 21st century in the HadCM3 simulations and less so in the CGCM3 simulations. From the least to the most severe case scenarios (lower and upper bounds) from 1971-2000 to 2071-2100 are the CGCM3 B1 and HadCM3 A2 simulations.

3.5.2 Projected number of fires and burned areas

A total of eight fires occurred between the first and the third SIFORT inventories in the study area, burning 13.6 % of the area (burn rate equivalent = 4.5% decade^{-1}). Three fires exceeded 200 ha, two of which reached respectively 24 168 and 30 876 ha in 1976 and 1997 (Fig. 3.3).

For the baseline period 1971 to 2000, nine fires were predicted from the FireOcc equation with DSR as input (Fig. 3.3A). The equivalent burn rate (which combined the FireOcc and the random generator of fire sizes) was 4.2 % decade^{-1} for the whole period (versus the observed burned rate of 4.5% decade^{-1} reported earlier; Fig. 3.3B). Decadal fire occurrences were projected to remain constant (three fires per decades) from 1971-2000 to 2071-2100 in the CGCM3 simulations (Fig. 3.3A). This is explained by the fact that the minimum DSR threshold for a significant increase in FireOcc was never reached in these simulations (Table 2). The opposite was true in the HadCM3 simulations: under the A1B and A2 IPCC scenarios, FireOcc was projected to increase to 162 and 296 fires in 2091-2100. Projected burnable cells were estimated at 73% and 15% decade^{-1}, respectively, for A1B and A2 scenarios. Of note is that such high values were consequent of the extremely high rate of change in the mean DSR over the end of the next century as projected by HadCM3 (Table 2; also see Wotton et al., 2010). While a burned area of 15% decade^{-1} is realistically plausible for the region on the basis of stand-replacing fire history studies (see Girardin et al. 2013a, their Fig. 3.3A), the same thing cannot be said for the most extreme value (discussed later). It was however kept in our simulation experiment to study the behaviour of the CanFIRE model runs when inducing extreme perturbations. Altogether, the amount of burnable cells averaged across all available simulations changed to 18.6% decade^{-1} during 2071 to 2100 (i.e. a fourfold increase relative to the baseline period).

3.5.3 CanFIRE simulated fire regimes and fire effects

Almost all burnable cells were predicted by CanFIRE model to record fire-induced mortality. The amount of cells affected by mortality for all simulations was in average 4.1% decade^{-1} (versus 4.2% decade^{-1} burnable cells) for the whole 1971-2000 period and changed to 17.9% decade^{-1} (versus 18.6% decade^{-1} burnable cells) for 2071-2100. Differences resulted from cells that were predicted to escape fire. Trends in the percentage of cells affected by mortality were projected to remain relatively constant from 1971 to 2060 and then increased for the remainder of the 21st century (Fig. 3.4A, white line). Greater dispersion of projections (lighter red colour) was observed during the 2061-2100 period, reflecting variability in the HADCM3 and CGCM3 runs. Fire intensity and percentage of cells affected by crown fire were also projected to increase. Fire intensities averaged at 300 kW/m in 1971-2000 and increased at up to an average of 1200 kW/m at the end of the century (Fig. 3.4C). Again, a high dispersion of projections occurred toward the end of the century. As for the average percentage of cells affected by crown fire, it increased from 5% to 15% decade^{-1} from the start to the end of the simulations (Fig. 3.4D). In contrast, percentage of cells affected by severe depth of burn decreased from around 50% to 30% decade^{-1} during 1971-2030 period, then stabilized at ~30% decade^{-1}, and remained at that level until 2100 (Fig. 3.4B).

3.5.4 Simulated future landscape compositions

Simulated landscape composition was presented as the relative percentage of each forest type (Fig. 3.5). Simulations with observed fire projected a mean of 57% of open black spruce forests (versus 48% estimated by the MRN). The percentage of open black spruce forests was projected to increase by roughly 30% from 1971-2000 to mid 21st century, while coniferous and mixed/deciduous forests were projected to decrease by 20% and 2%, respectively. The overall composition was then projected to stabilize until 2080. After 2080 the proportion of cells occupied by open black spruce forests was projected to undertake, on average, a slight decrease. Coniferous percentages showed a negligible increase. The larger was the climate change impact scenario, the larger was the change in composition. The no-fire scenario (grey line) likewise showed stabilization from 2050 to 2080 and open black spruce percentages increased slightly from then. In contrast, landscapes recovered their productivity (high coniferous increase and abrupt open black spruce decrease) under the extreme HadCM3 simulations (grey line, A1B scenario and BS HP DOB).

3.6 Discussion

This study used an ensemble-mean of six GCM experiments and two scenarios of potential black spruce depth of burn to project the impacts of climate change on fire activity and landscape composition in the Clay Belt boreal forest of eastern boreal North America. Succession and fire were incorporated into the modeling setup to simulate interactions between disturbance and vegetation (Keane et al. 2013). Our simulations analysis suggested that depth of burn will decrease from 1971 to 2050 and level-off afterward with the rapid increase in the dominance of open black spruce-Sphagnum forests. Landscape productivity and composition will be primarily driven by succession until 2100 despite global climate change impacts on fire. This intepretation is supported by the fact that both no-fire and the conditional mean of all fire scenarios yielded similar outcomes in relation to levels of trends in percentages of open black spruce-Sphagnum dominated forests.

We attribute our results to two processes, that is, the influence of disturbance legacies on the future response of the Clay Belt forest to climate change, and the low potential for severe depth of burns in open black spruce-Sphagnum dominated forests. The Clay Belt forest was affected by pulses of major fires during periods 1830-1850 and 1910-1920 (Bergeron et al. 2004). During upcoming decades, the stands affected by these fires will reach suitable ages for the transition into open black spruce-Sphagnum dominated forests (Lecomte & Bergeron 2005; Lecomte et al. 2006a; Belleau et al. 2011). This transition implies higher soil moisture conditions (Fenton et al. 2006; Simard et al. 2007; Terrier et al. 2014) induced by the water retention characteristics of Sphagnum species. Forest soils will consequently be protected from high organic layer consumption during future wildfires (Benscoter & Wieder 2003; Harden et al. 2006; Shetler et al. 2008; Kasischke et al. 2010; Benscoter et al. 2011; Turetsky et al. 2011; Magnan et al. 2012). Depth of burn severity will decrease in the landscape, fires will burn the aboveground biomass, but peat deposit will remain relatively intact (Magnan et al. 2012) and the probability of a return into closed forests will be reduced (Simard et al. 2007; Terrier et al. 2014). A reversal of the phenomena by the end of the 21th century is unlikely according to our experiment, but might be possible under an extreme climate pertubation scenario (i.e. our HadCM3 A2 run).

Our projections of climate change impacts on fire activity in the study area are consistent with earlier assessments. Previous projections were obtained by empirical models describing the relationship between area burned and the variables describing the drying of fuels and fire behavior processes (Amiro et al 2009. Flannigan et al 2009. Mudelsee and Girardin 2008; Balshi et al, 2009.). These studies were generally conducted with the assumption that vegetation would remain constant over time. Here, area burned simulations were based on fire occurrence projections and random selection of fire sizes in the forest fire database to meet with the CanFIRE model data requirements (date of burning, burned area). Unlike in previous assessments, our simulations included a vegetation feedback mechanism. Although they don't apply to the exact same periods and territories, our burn rate estimate for the reference period (4.2% decade^{-1}, 1971-2000) was within the range estimated by Boulanger et al. (2013) (burn rates 2-5% decade^{-1}). As for the fourfold increase in burn rate projected in this study, it is also coherent with projections obtained by previous studies.

Bergeron et al. (2010) projected a two-fold increase of the burn rate from 1961-1999 to 2081-2100. An increase of 150% to 200% of the burned areas was projected by Flannigan et al. (2005), and of 286 to 409% by Boulanger et al. (2014). Noteworthy is that, in our experiments, cells affected by mortality followed the same trends as found in fire weather data. The same correlation occurred between predicted burnable cells (only climate effects) and cells affected by fire-induced mortality (climate + vegetation effects). Hence, potential vegetation feedback on burned areas can be excluded. In absence of a changing landscape composition and particularly without increase in deciduous proportions arising from forest management, climate will remain the main driver of burned areas in the Clay Belt forest over the next century (Carcaillet et al. 2001; Girardin et al. 2013a).

Accompanying the increase of drought conditions and burned areas were fire intensities and crown fires as projected in other parts of the Canadian boreal forest (Flannigan et al. 2005; Flannigan et al. 2009; de Groot et al. 2013b). Values in our study area were nonetheless lower. For instance, de Groot et al. (2013b) projected values reaching 6047 kW/m in the west and 57-69% of crown fires in coniferous forests at the end of the century (against up to 3000 kW/m and 15% of crown fire for 2100 in our study). These differences result from higher rainfall amounts in our territory (Environnement Canada, 2013) and milder fire weather conditions (Table 2). In our simulations, trends in fire intensities and crown fires also followed the overall climatic trends: the projected increase in black spruce-Sphagnum dominated forests will unlikely influence these fires characteristics. Despite their low potential fuel consumption, under intense fires the vertical and horizontal fuel structures of open black spruce forests is particularly conducive to intense crown fires. These forests are composed of a high density of small trees (height < 3cm) (Paquette 2011) and black spruce layering further imply a fuel vertical continuity from the organic layer to the tree crown. Fire can therein propagate with forest floor litter and herbs and move to the crown (Paquette 2011). The projected increase in fire intensities and crown fires under climate change inevitably will imply a greater difficulty for fire control in these forests in the future (de Groot et al., 2013b, Podur et Wotton, 2010).

3.6.1 Uncertainties and limitations

Although a higher proportion of black spruce-Sphagnum dominated forests was projected for the end of the 21st century, a slight decreasing trend was observed starting from 2080. Changes in landscapes structure requires ½ to 2 rotations of a new disturbances regime to adjust (Baker 1995). Our simulation period was probably too short to observe a long-term impact of the increasing burned areas. We believe that open black spruce forests from the Clay Belt may not be completely protected from fire: a return into productivity was simulated under our extreme climate change scenario HadCM3 A2. This scenario reflects potential fire effects under extreme drought conditions and high fire intensities. Under such conditions, fire generates particularly high amounts of radiative heat drying ahead of the fire, and fuel can ignite without direct contact with the main front (Cyr et al., 2005). Future simulation experiments should be extended to forthcoming centuries to fully capture these effects.

The modeling setup and assumptions made in this study are not without limitations. Cells occupied by more than 75% of black spruce coverage were rounded to 100%, implying that the coverage of deciduous and mixed forests may be underestimated at the landscape level. Low proportion of deciduous species could favor mixed forests recruitment in pure black spruce forests. Future studies should thus look into more details the contribution of small patches of deciduous species on the long-term dynamics of these forests. We think, however, that this limitation may not change the projected proportion of conifer versus deciduous forests at the landscape scale for the end of the 21st century because this horizon is too early for a reversal of the transition from mixed to coniferous forests.

Direct impacts of climatic change on vegetation were not considered in our simulation work. This includes the potential increase of tree growth with the lenghtening of the growing season (Dunn et al., 2007; Girardin et al., 2008; Grant et al., 2009), decomposition (Wickland and Neff, 2008) and northward migration of temperate species on peat accumulation (Iverson & Prasad 1998; McKenney et al. 2007; O'ishi et al. 2009; O'ishi & Abe-Ouchi 2009; Berteaux et al. 2010; McKenney et al. 2011). The particularly high organic layer thickness and high soil moisture content may prevent such impacts by limiting tree growth (Gewehr et al. in press) and establishment of southern species (Lafleur et al. 2010). Hence, these two factors are not expected to significantly affect our conclusion. However, smoldering combustion can burn for hours to weeks after flaming (Ryan 2002) and decomposition may be accelerated with increasing temperatures. Residual post-fire organic layer depths could therefore be overestimated in our simulations, implying a faster paludification process under the low potential depth of burn scenario.

3.7 Conclusion

We have evaluated how future increases of wildfire activity might affect the forest structure and composition of the Clay Belt forest in eastern North America through their impacts on the depth of burns, mortality and postfire recruitment. In boreal forests, increasing depth of burn and/or total area burned will lead to shifts from coniferous dominated cover to a mixed/deciduous one (de Groot et al. 2003; Bonan 2008; Johnstone et al. 2010b; Barrett et al. 2011; Johnstone et al. 2011). Dynamic drivers could eventually shift from vegetation to climate-driven fire processes under future warmer and drier climates (Keane et al. 2013). Our results suggested the opposite for the Clay Belt forest, as the proportion of conifers is therein projected to increase. The legacy of past fire-pulses implies a rapid succession of closed forests into open black spruce forest in upcoming decades, and moist conditions encountered in these forests will provide a level of resistance to some adverse impacts of the increasing fire activity (Johnstone et al. 2010b; Jafarov et al. 2013; Terrier et al. 2014). That said, future shift in landscape composition and structure are unlikely to offset climatic effects on fire behavior (Podur and Wotton, 2010, de Groot et al., 2013b): increased fire intensity and area burned are likely outcomes of continued warming in the Clay Belt boreal forest. Managers should consider that practices that favour the development of hardwood and productive black spruce forest, or that reduce Sphagnum establishment (such as summer clear-cut or site preparation), enhance forest productivity, but also increase potential vulnerability to severe depth of burn and decrease long-term carbon storage (Terrier et al. 2014). Vulnerability of forests to climate change will inevitably depend on landscape legacies related to land use and future studies should include the impacts of forestry practices in simulations (Loudermilk et al. 2013).

3.8 Acknowledgements

The GCM (General Circulation Model) data have been supplied by the Environment Canada (www.cccsn.ec.gc.ca). This project was financially supported by the Natural Sciences and Engineering Research Council of Canada (NSERC; Strategic Project), the Ouranos Consortium, the Canada Chair in Forest Ecology and Management (Dr Yves Bergeron), Canada Chair in Modeling Research (Changhui Peng), and the Canadian Forest Service funds. Authors are particularly grateful to A.Belleau, L. Dumas, A. Leduc, C.Leroy, D.Lessieur, S.Gauthier, P.Grondin, M.Paquette for providing data and for their helpful comments for modelling decision, to M. Desrochers for ArcGIS analysis help ,to R. St Amant for BioSIM informations and finally to Steve Kembel for computing resource. We extend our thanks to Michèle Garneau, Pierre Bernier and Jill Johnstone for reviewing the manuscript and providing helpful comments.

Figure 3.1 A) Study area in the Clay Belt forest of northeastern North America. B) Relative percentages of cells grouped in different forest types according to the dominant surficial deposits. Forests types and abbreviations are described in Table 3.1. C) Relative percentages of cells grouped in age classes according to the forest classes (oBS: open black spruce forests, C: coniferous forests, MD: mixed and deciduous forests).

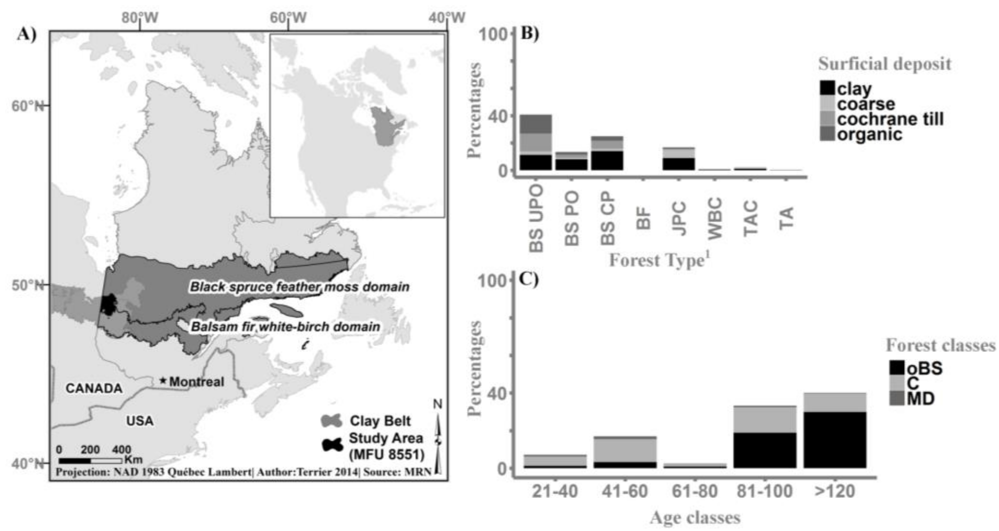

Figure 3.2 Tasks conducted in this study to simulate fire regimes and landscape forest composition: i) the construction of driving datasets for the CanFIRE model, ii) the determination of recruitment and successional rules, and iii) the simulation of fire-driven vegetation changes.

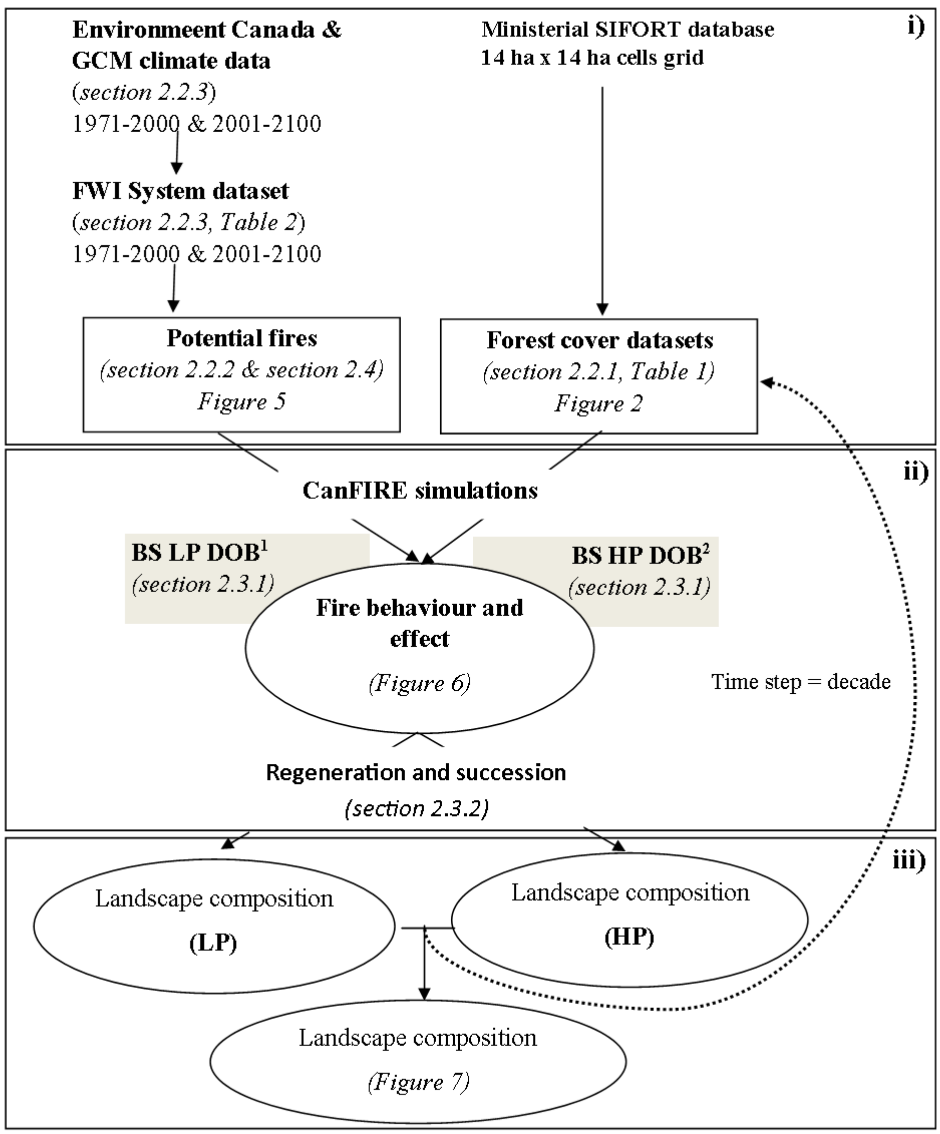

Figure 3.3 Observed and projected decadal A) number of fires and B) percentage of burnable cells from 1970 to 2100. Current number of fires (1971-2000) was predicted using environment Canada's historical climate database (Environment Canada, 2013). Future number of fires (2001-2100) was projected using weather data from the CGCM3.1 and HadCM3 global climate models with forcing scenarios A1B, A2, and B1.

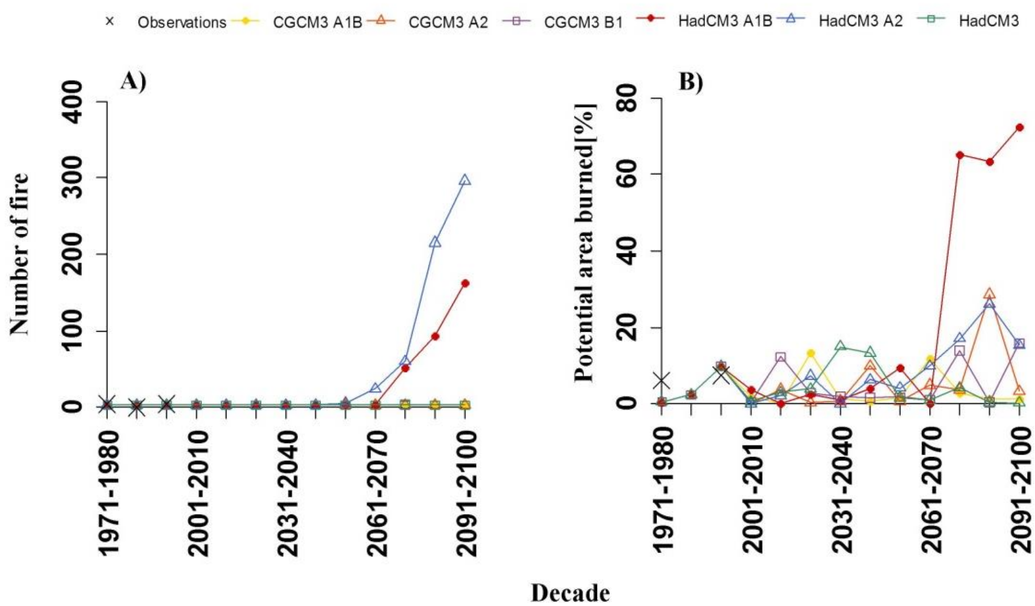

Figure 3.4 Fire regime and behaviour simulated using the Canadian Fire Effects (CanFIRE) model. Shown are trends in A) the decadal percentages of cells affected by more than 60% of mortality, B) percentages of cells affected by severe depth of burn, C) head fire intensities [kW/m]. and D) percentages of cells affected by crown fires. Each point expresses a GCM experiment for a given decade and black spruce potential depth of burn scenario. Trends are shown using the Visually-Weighted Regression where color intensity depicts points density (darker is lower points dispersion). The white line in each panel denotes the conditional mean. Crosses expressed values simulated with observed fires.

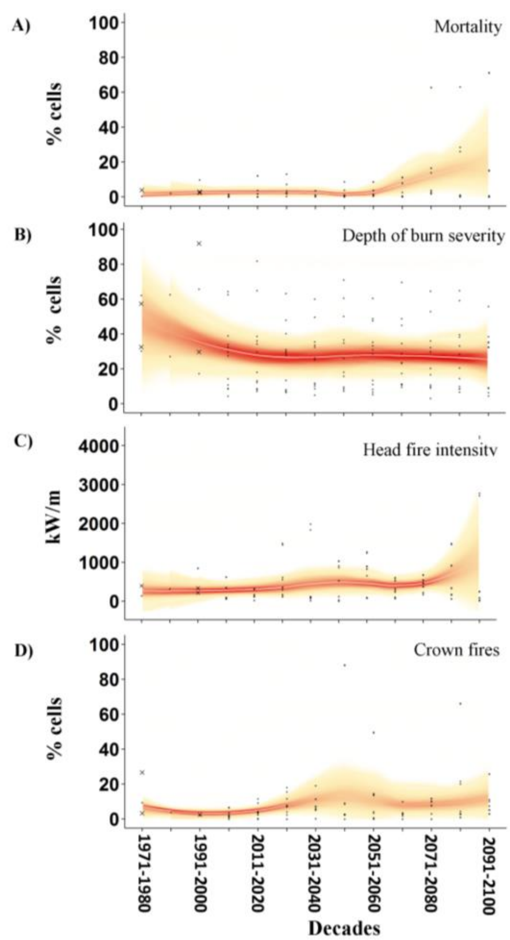

Figure 3.5 Relative percentages of each forest class projected from 1971 to 2000. Each point expresses a GCM experiment for a given decade and black spruce potential depth of burn scenario. Grey lines denote the upper and lower bounds of the multiple simulation runs that are given by the no-fire and extreme HadCM3 A2 scenarios. Crosses expressed values simulated with observed fires.

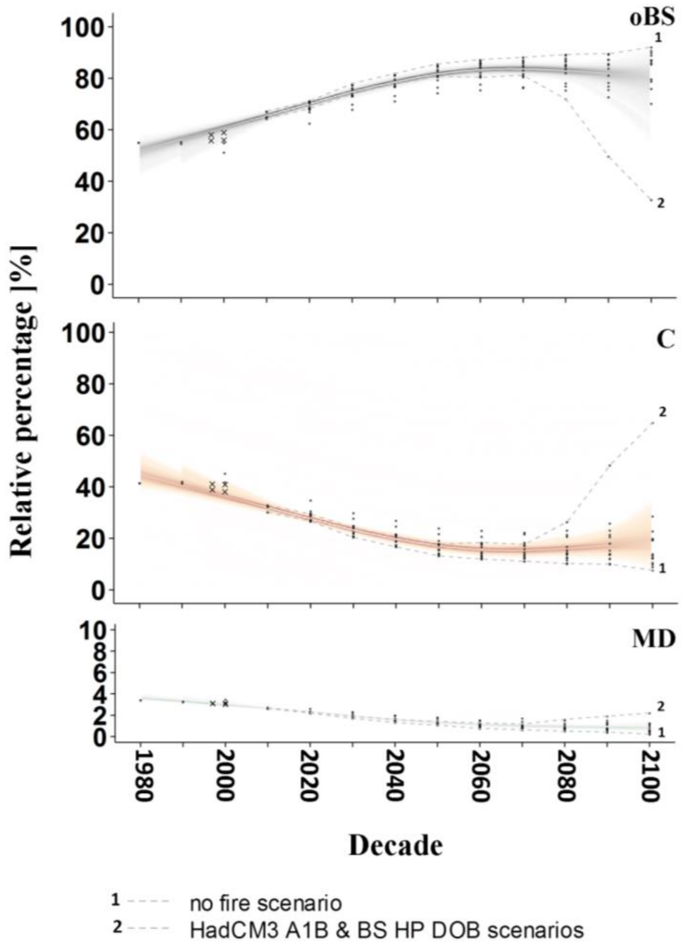

Tableau 3.1 Forest types, forest cover and site index describing the study area (adapted from Belleau et al. 2011). Percentage of species covers and site indexes were averaged by forest type.

Forest cover type	Name	Code	Species	% cover	Site index
Coniferous	Black spruce	**BS**			
	closed	**BS CP**	BS[1]	100	14
	Partially open	**BS PO**	BS	100	12
	unproductive	**BS UPO**	BS	100	12
	Balsam fir	**BF**	BF[1]	100	14
Hardwood	Trembling aspen	**TA**	TA[1]	100	19
Mixed	Trembling aspen coniferous	**TAC**	WB[1]	10	16
			TA	30	18
			BS	35	15
			JP[1]	10	16
			BF	15	14
	White birch coniferous	**WBC**	WB	30	15
			TA	10	18
			BS	25	14
			JP	5	16
			BF	30	14
	Jack pine coniferous	**JPC**	WB	5	16
			TA	5	18
			BS	45	15
			JP	40	16
			BF	15	14

[1]WB: white birch, TA: trembling aspen, BS: black spruce, JP: jack pine, BF: balsam fir

Tableau 3.2 Comparison of empirical current (1975-2000) and future projected (2031-2060; 2071-2100) means of the Canadian Forests Fire Weather Index (FWIs) System components for the study area. Future indexes were projected using two global climate models (GCM) (Canadian CGMCM3.1; Hardley HadCM3) and three IPCC scenarios (A1B; A2; B1). FWI System components that showed significant increases between current levels and future projections are denoted by an asterisk (Student t tests, p ≤ 0.05). All FWI System components values are unitless.

		1975 - 2000	2031-2060			2071-2100		
			A1B	A2	B1	A1B	A2	B1
FFMC[1]	*CGCM3.1*		69.3	68.8	69.7*	69.6	69.6	69.1
	HadCM3	68.9	71.1**	71*	71.3**	73.5**	74.3***	71.6**
DMC[2]	*CGCM3.1*		10.1	9.9	10.5***	10.6	10.7	10.1
	HadCM3	10.1	11.4**	11.4	11.4***	13.3**	14.7**	11.8**
DC[3]	*CGCM3.1*	113	108	106	124*	116	123	114
	HadCM3		110	116	118	127	161*	119*
ISI[4]	*CGCM3.1*		2.9*	2.9*	2.9	3	3.1	2.9
	HadCM3	2.8	3.3	3.3	3.3*	3.9**	4.1**	3.4*
BUI[5]	*CGCM3.1*	14.6	14.4**	14	15.3*	15	15.3	14.5
	HadCM3		16.1	16.1	16.1**	18.5*	21*	16.6**
FWI[6]	*CGCM3.1*	4.1	4.2**	4	4.3	4.4	4.6	4.1
	HadCM3		5	4.9	4.9*	6.12**	6.9*	5.1**
DSR[7]	*CGCM3.1*		0.7**	0.72	0.72	0.78	0.81	0.69
	HadCM3	0.68	0.93***	0.89	0.89*	1.3**	1.53*	0.98**

Student's t-test: *p < 0.05; ** p < 0.01; *** p < 0.001
[1] Fine Fuel Moisture Content; [2]Duff Moisture Content; [3]Drought Code; [4]Initial Spread Index[5]; Buildup Index[6] ; Fire Weather Index; [7] Daily Severity Rating.

APPENDICE C

C.1 Driving dataset

C.1.1 Forest driving dataset

Forest driving dataset

The SIFORT data were assembled in collaboration with the Forest Protection Division of the Ministère des Ressources naturelles du Québec (MRN), the Quebec forest fire control agency (SOPFEU) and the Quebec forest pest and disease control agency (Société de protection des forêts contre les insectes et maladies) (© Gouvernement du Québec ; Pelletier et al., 2007). Each SIFORT (Système d'Information FORestière par Tesselle) grid cell of our study area was characterized by the species' cover percentages, forest type, forest age and site index (i.e. height at 50 years old) (Table 3.1, Fig.3.1B & 3.1C). Percentages of cover were calculated from the relative percentage of the basal area (basal area of a species/sum of basal area of all species). A forest type (trembling aspen (TA), white birch (WB), balsam fir (BF), black spruce (BS) and jack pine (JP)) was assigned to each grid cell using the mean relative percentage of the basal area (m^2/ha) as a criteria (Belleau et al. 2011). Black spruce forests were additionally divided into three developments stages based on tree height and cover density in order to apply successional pathways provided by Belleau et al. (2001) (see Recruitment and successional rules) (Table 3.1; Fig. 3.1B). The age distribution was adjusted relative to 1970 and stratified into 5 age classes: 21-40, 41-60, 60-80, 80-100, and >100 (Fig. 3.1C). Species that co-existed in a given cell were all given the same age.

C.1.2 Organic and fibric layer depth calibration

For CanFIRE requirement we first calibrated a model linking measured organic layer depth (OL depth) within each plot with stand age, forest type and surficial deposit using Multivariate Adaptive Regression Splines (MARS) (Friedman, 1991), We made use of a data set comprising 4,217 temporary sample plots (circular 0.04 ha) selected from the third inventory program of the MRN in western Québec that spans from the southern mixedwood to the northern conifer dominated limit of commercial forests. The resulting MARS model explained 66% of the variance in observed organic layer depths (GVC R^2 = 0.66). The model took on the following form (see Table 3.1 for definition of abbreviations):

$$\mathrm{OM\ depth} = 10.13 + 58.09 \times \mathrm{BF}_1 + 6.31 \times \mathrm{BF}_3 + 0.19 \times \mathrm{BF}_5 + 4.89 \times \mathrm{BF}_7 - 1.74 \times \mathrm{BF}_9 - 2.36 \times \mathrm{BF}_{11} - 2.41 \times \mathrm{BF}_{13} \qquad \text{(C.1)}$$

$$BF_1 = (surficial\ deposit(4)) \qquad \text{(C.1.1)}$$

$$BF_3 = (forest\ type\ \ (BS)) \qquad \text{(C.1.2)}$$

$$BF_5 = \max(0;\ stand\ age - 74) \qquad \text{(C.1.3)}$$

$$BF_7 = (forest\ type\ (\ BF, BS, JPC, WBC, mixed\ coniferous)) \qquad \text{(C.1.4)}$$

$$BF_9 = (forest\ type\ (WB, BS, HJP, JPC, TA, WBC, mixed\ hardwood)) \qquad \text{(C.1.5)}$$

$$BF_{11} = (surficial\ deposit(1{,}4)) \qquad \text{(C.1.6)}$$

$$BF_{13} = (forest\ type\ (BF, TA)) \qquad \text{(C.1.7)}$$

Therein organic layer depth progressively increases as stands age increases above 74 years. If stands age is smaller than 74, BF5 of eq. C.1.3 takes on the value of 0. Organic layer depth also varies accordingly with forest type and surficial deposit via other basis functions. Notably, organic layer depth tends to be significantly higher in black spruce forest types (BS) (BF3, BF7 and BF9, eq C.1.1, C.1.2 and C.1.5).

Coarse surficial deposits and trembling aspen forest types (TA) contributes to decrease organic layer depths respectively via BF9 and BF11 in eq. C.1.6 and C.1.7. Comparison of observed and predicted values indicated relatively good predictive skills for values ranging from 0 to 40 cm, and less so for values beyond 40 cm (Fig. C.1A). Potential explanations for the low performance of the MARS model at high values may be related to the low sample size of plots originating from open stands (samples with organic layer depths exceeding 40 cm account for only 10% of the entire data set). This shortcoming was not inherent to the use of MARS and was found in other types of analysis (e.g. combination of mixed linear models and general-purpose regressions; Anyomi et al. 2014).

Our second task was to calibrate a model for prediction of the fibric layer depth using the total organic layer depth. Fibric layer depth [cm] was deduced using a linear functional relationship to the total organic layer depth. To determine this relationship, we used measurements of fibric and total organic layer depths sampled in sites that originated from one recent fire (1997) and 8 older fires (1725-1880) (Leroy et al. 2012, personal communication).Model estimates explained 93% of the observed organic layer depths (R^2 = 0.93; Fig. C.1B). Fibric layer depth [cm] was formulated as:

$$Fibric\ horizon\ depth\ = 0.654\ \times OM\ depth \qquad \text{(C.2)}$$

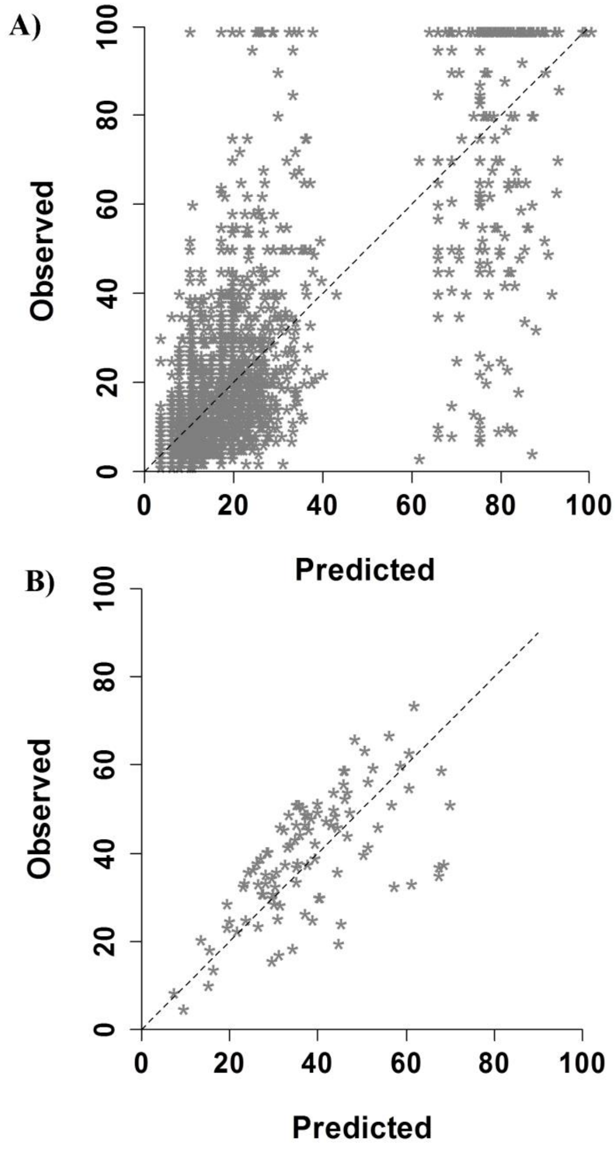

Figure C.1 Observations vs. model predictions of A) the total organic layer depths [cm] and B) the fibric horizon depths [cm].

C.1.3 Differention of the duff-humus from the duff-fibric layers

CanFIRE differentiated the duff-humus from the duff-fibric layers. As Paquette's (2011) equations gave only one value for the total duff, we calculated the ratio of the fibric layer and substracted it from the total organic layer depth. This ratio was then multiplied to the total duff values to obtain the duff fibric layers [kg/m^2]. The duff-humus [kg/m^2] was obtained by substracting duff-fibric from the total duff as follow:

$$Fibric\ layer\ ratio = \left({}^{fibric\ layer\ depth}/_{total\ organic\ layer\ depth} \right) \quad (C.3)$$

$$duff_{fibric\ layers} = duff_{total} \times Fibric\ layer\ ratio \quad (C.4)$$

$$duff_{humic\ layers} = duff_{total} - duff_{fibric\ layers} \quad (C.5)$$

C.2 Global Climate Model (GCM) change projections

Tableau C.1 Comparison of fire-season mean temperature (°C) and total precipitation (%) as simulated by two general circulation models (GMC) and their greenhouse gas forcing scenarios for the periods 2031-2060 and 2071-2100 relative to 1971-2000 at the study area.

			Reference period 1971-2000	
			Δ Temperature [°C]	**Δ Precipitations [%]**
2031-2060	*CGCM3.1*	*A1B*	1.3	15
		A2	1	14
		B1	0.9	4
	HadCM3	*A1B*	1.5	16
		A2	1.4	12
		B1	1.2	8
2071-2100	*CGCM3.1*	*A1B*	1.6	20
		A2	2	24
		B1	0.9	13
	HadCM3	*A1B*	2.6	23
		A2	3.1	13
		B1	1.6	17

C.3 Fire occurrence calibration

Fire occurrence was formulated by Terrier et al. (2013) as:

$$FireOcc \geq 10ha = 0.25 - 0.11 \times BF_1 - 0.10 + 9.51 \times BF_2 \quad \text{(C.6)}$$

$$BF_1 = (pure\ coniferous(0)) \quad \text{(C.6.1)}$$

$$BF_2 = \max(0; DSR - 1.02) \quad \text{(C.6.2)}$$

where FireOcc is the number of fires per year per 1,000 km^2. FireOcc progressively increases as Daily Severity Rating (DSR), an index of the FWI System reflecting the fire control difficulty, increases above 1.02 units (eq. C.6.2). The presence of a tree composition dominated by pure coniferous species also contribute to increase FireOcc (eq. C.6.1).

C.4 Model validation

Our validation aimed at verifying that the CanFIRE model yielded reasonable stand mortality and recruitment outcomes. Fires on the Clay Belt generally involve high mortality and thus are stand replacing (Bergeron et al. 2004). For this validation, fires that occurred between the first and the third SIFORT inventories were selected and their polygons were overlaid on the SIFORT raster maps. In SIFORT, vegetation information is not collected if forest cover is inferior to 25%. Hence, we made the assumption that absence of vegetation information from one inventory to another reflected the advent of a high stand mortality (>75% dead stems). We binned all cells containing forest information in the third SIFORT inventory as class 0 when vegetation is present, and the others as class 1 by assuming that they underwent fire-driven mortality. A similar setup was repeated on the CanFIRE simulations: cells were considered class 1 when simulated mortality values were greater than 60 %. Results were presented on maps. Uncertainties in percentages of cells with mortality were reported using binomial confidence interval (95% CI) (‘MultinomialCI’ package’ of the R Development Core Team 2010; Villacorta Iglesias 2012). Vegetation feedback on fire behaviour was finally evaluated by comparing the relatives percentages of forest types in cells that underwent tree mortality from those that resisted to fire.

From analysis of the SIFORT raster maps, we estimated that 91% (95% CI [89, 92]) of cells underwent fire-related mortality within the burnt areas. Fires affected mainly open black spruce and coniferous forests (total of 87%, versus 4% MD; Fig. S2.B). Cells that escaped from mortality were mainly from the coniferous forests (8% versus 1% for mixed/deciduous) (Fig. C2.A). CanFIRE predicted mortality in 89% (95% CI [88, 91]) and 97% (95% CI [97, 99]) of the cells for BS LP DOB and BS HP DOB scenario, respectively. Only old black spruce forests were predicted to escape fire (Fig. C2 B&C).

As expected, mortality was predicted to be lower under the LP scenario and higher under the HP scenario. It is reasonable to expect that some error in the predicted mortality can occur because vegetation composition in a given cell may differ from the real composition of that cell. However, this error is minimized when scaling-up at the regional level. Overall, the CanFIRE outputs suggest that 6.15% (95% CI [6.15,6.16]) of all cells in the study area underwent mortality during 1971-2000 in the BS LP DOB scenario. In the BS HP DOB scenario, this value approximated 6.75% (95% CI [6.75,6.77]). The percent mortality inferred from the analysis of SIFORT data lies within the range of these two CanFIRE estimates (6.27% with 95% CI [6.26,6.27]).

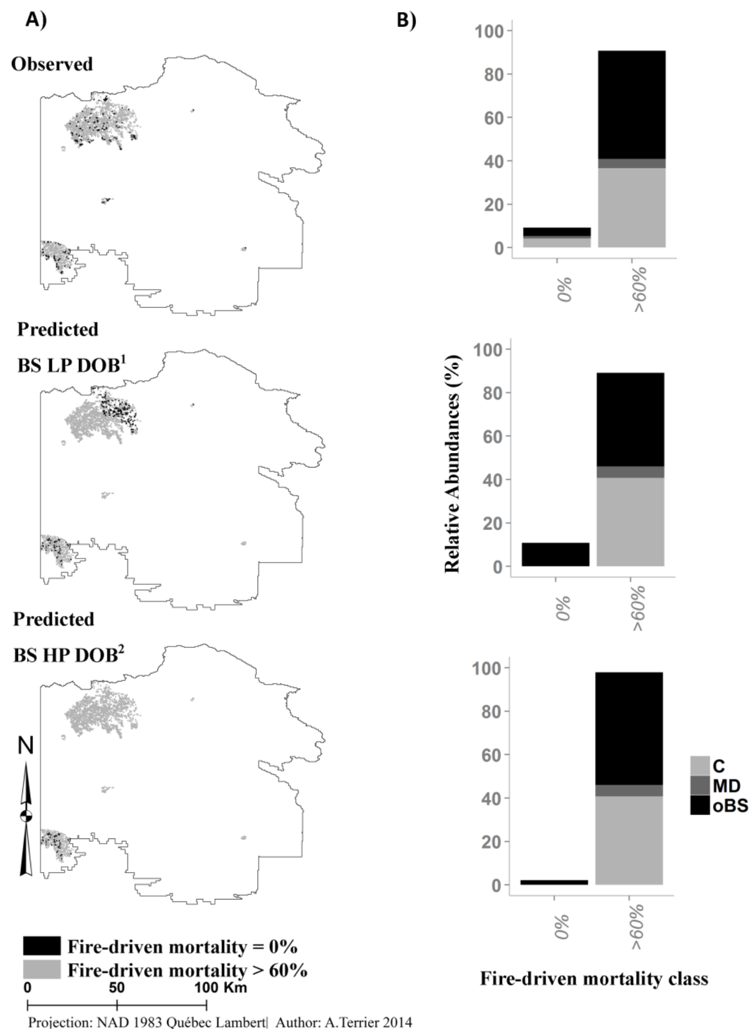

Figure C.2 SIFORT data observations vs. CanFIRE predictions of fire-induced mortality from 1971 to 2000. A) Map representation of the observed and predicted relative percentage of cells affected by mortality under two scenarios of black spruce potential depth of burn (BS LP DOB: Black spruce low potential depth of burn scenario; BS HP DOB: Black spruce high potential depth of burn scenario.). B) Percentages of forest classes that escaped fire versus forest classes affected by fire mortality (oBS: open black spruce forests, C: coniferous forests, MD: mixed and deciduous forests).

CONCLUSION GÉNÉRALE

Ce doctorat s'insère dans un contexte d'aménagement adaptatif des ressources forestières boréales à l'est du Canada en prévision de conditions climatiques futures plus propices à l'activité des feux. La mise en place d'un aménagement adaptatif requiert une connaissance approfondie de la dynamique de la forêt future, notamment à travers une meilleure compréhension de la réponse de la végétation aux changements de régimes de feu. Par ailleurs, la vulnérabilité des forêts de la Ceinture d'Argile aux changements climatiques revêt un intérêt global par les grandes quantités de carbone emmagasinées dans le sol forestier: un retour de ce carbone dans l'atmosphère pourrait contribuer à amplifier le réchauffement global.

Ce doctorat avait comme objectif de comprendre les impacts des changements climatiques sur les feux de la forêt boréale et comment ces changements pourraient affecter la composition des paysages boréaux de la Ceinture d'Argile au Québec. Il s'agissait alors de proposer des statégies d'aménagement adaptatif. Cette conclusion expose les nouvelles connaissances apportées à travers ce doctorat concernant i) la réponse des feux aux changements climatiques, ii) les changements de composition induits par les modifications potentielles d'un régime de feu futur et, finalement, iii) la vulnérabilité de la forêt boréale aux changements climatiques et les implications pour l'aménagement forestier.

La réponse des feux aux changements climatiques

Plusieurs projections de l'activité future des feux avaient déjà été réalisées pour le territoire de la forêt boréale à l'est du Canada. Ces projections s'accordaient sur les tendances d'une augmentation de l'activité des feux (Amiro et al., 2009; Flannigan et al., 2009; Girardin and Mudelsee 2008; Balshi et al., 2009). Toutefois ces projections avaient été obtenues par des approches de modélisation empirique s'appuyant sur des variables décrivant les processus d'assèchement des différentes couches de matière organique des sols et de comportement des feux. Ainsi, la majorité des modèles ne considéraient pas les rétroactions des changements dans la végétation sur les comportements des feux. Par ailleurs, aucun modèle ne fournissait encore l'information sur la profondeur de brûlage (quantité de matière organique lors de l'événement), composante du régime de feu particulièrement importante pour comprendre la dynamique future de la végétation de la Ceinture d'Argile au Québec.

Les projections de feux obtenues par les analyses des trois chapitres de ce doctorat concluent, similairement aux études précédentes, que le climat futur induira des conditions de sécheresses plus élevées d'ici la fin du 21ème siècle, malgré les projections d'une augmentation des précipitations (IPCC, 2013). De telles conditions seront plus favorables à l'allumage et à la propagation des feux. Ainsi, la forêt boréale de la Ceinture d'Argile devrait être affectée par une plus grande occurrence de feux (chapitre 1), de plus grandes superficies brûlées (chapitre 3) et de plus grandes profondeurs de brûlages (chapitre 2), montrant des intensités plus élevées et une plus grande quantité de feux de couronne (chapitre 3).

L'intégration de la végétation dans les projections de cette thèse amène cependant de nouvelles connaissances sur l'influence de la végétation sur les feux futurs. Les résultats soulignent que la réponse des feux aux changements climatiques dépendra de la composition future des forêts. En premier lieu, les changements climatiques induiront des conditions climatiques plus favorables en forêt boréale pour les espèces de feuillus limitées au sud (Iverson and Prasad 1998; McKenney et al., 2007; O'ishi and AbeOuchi 2009; O'ishi et al., 2009; Berteaux et al., 2010; McKenney et al., 2011). L'augmentation de l'occurrence des feux sera moindre dans les régions boréales où ces essences de feuillues moins inflammables pourront s'étendre (chapitre 1). En second lieu, au niveau plus régional de la Ceinture d'Argile, les processus de paludifications devraient rester le principal contrôle de la dynamique végétale malgré l'augmentation de l'activité des feux projetée. L'établissement progressif des sphaignes impliqueront des taux d'humidité particulièrement élevés (e.g. Bergeron et Fenton, 2012) et protègeront ainsi les sols de la sécheresse et les forêts des impacts écologiques générés par l'augmentation des feux (chapitres 1 et 2).

Les études portant sur la caractérisation des feux apportent cependant leur lot d'incertitudes liées à l'aspect aléatoire du feu. En effet, même si les conditions sont favorables pour un feu, la source d'allumage (foudre, humain) est souvent absente de l'élaboration des modèles prédictifs. Une prédiction pourrait donc s'avérer erronée si un changement important avait lieu dans la fréquence des sources d'allumages. L'utilisation des niches écologiques est également associée à une source d'incertitude liée à l'absence de plusieurs processus déterminants pour la distribution des arbres et les changements de composition, comme par exemple les processus de compétition ou des régimes de perturbations. Malgré ces incertitudes, les analyses présentées dans ce doctorat permettent d'amener la nouvelle connaissance que les changements climatiques induiront une activité de feux plus importants en forêt boréale, toutefois les peuplements de feuillus limités au sud et les pessières à sphaignes seront plus résistants à ces risques.

Les changements de composition en réponse aux changements des régimes de feux futurs

Des changements de la dominance de peuplements de conifères vers une dominance de peuplements de feuillus ont été précédemment suggérés en réponse à une augmentation de la profondeur de brûlage et/ou la superficie brûlée totale pour la forêt boréale (Barrett et al., 2011; Bonan, 2008; de Groot et al., 2003; Johnstone et al., 2010b; Johnstone et al., 2011). Les simulations entreprises dans ce doctorat mettent cependant en évidence la variabilité spatiale de la réponse des forêts aux changements climatiques au sein d'un même biome. En effet, une expansion des pessières à sphaignes ouvertes a été projetée pour les prochaines décennies (chapitre 3). L'épinette noire devrait rester l'espèce dominante des paysages boréaux de la Ceinture d'Argile au Québec d'ici la fin du 21ème siècle. La réduction de l'activité des feux ces 2000 dernières années (Bergeron et al., 2004b, Simard et al., 2007) ont permis l'ouverture progressive des forêts d'épinettes et l'établissement des espèces de sphaignes au sol. Les pessières fermées mixtes ou pures composées d'essences feuillues ou conifériennes ont été formées suite à des pics d'activité de feux qui ont eu lieu à la fin du 19ème siècle et au début du 20ème siècle (Bergeron et al., 2004). Alors que ces forêts devraient atteindre l'âge de transition vers des pessières ouvertes ces prochaines décennies, la dominance progressive de la sphaigne protégera les paysages d'un changement de composition. Le faible potentiel de brûlage de ces forêts (chapitre 2) réduira ainsi le retour des paysages vers des compositions de début de succession lorsque l'augmentation des feux sera plus importante à la fin du 21ème siècle.

Ces résultats permettent de conclure que la composition actuelle des forêts et l'activité des feux à eux seuls ne sont ainsi pas suffisants pour comprendre l'évolution future des paysages. L'âge des peuplements ainsi que la succession sont deux paramètres importants à intégrer dans les simulations.

La vulnérabilité de la forêt boréale aux changements climatiques et implications pour l'aménagement forestier

Les connaissances jusqu'à présent ne permettaient pas d'évaluer les effets des changements climatiques sur la superficie des feux, la sévérité au sol et sur la végétation (Simard et al. 2008). Grâce aux avancées scientifiques en matière de modélisation et des connaissances sur le territoire de l'étude, ce projet constitue la première étude qui projette la dynamique de la végétation et des feux en association avec les changements climatiques prévus pour ces prochaines décennies sur le territoire d'étude. Par ailleurs, l'intégration des effets de la paludification dans la dynamique végétale de la forêt constitue une première. Alors que le choix des stratégies d'aménagement détermine largement les caractéristiques futures de la forêt (Lindner 2000), les changements climatiques ajoutent une nouvelle dimension d'incertitudes qui rend difficile le choix des stratégies à adopter (Lindner 2000). A travers ce doctorat, les résultats permettent ainsi aux gestionnaires d'adapter leur stratégie d'aménagement en tenant compte des futures conséquences des changements climatiques.

La forêt boréale de la Ceinture d'Argile devrait être contrôlée par les processus de paludifications ces prochaines décennies. Une résistance à une augmentation de l'activité des feux en découlera (chapitres 2 et 3). Les stocks de carbone par exemple devraient être moins vulnérables que d'autres régions de la forêt boréale, comme par exemple en Alaska (Turestsky et al., 2011), dans l'ouest Canadien et en Russie (de Groot et al., 2013b). En effet, la transition des forêts vers des pessières à sphaignes implique non seulement une accumulation de la matière organique dans le paysage (chapitre 3), mais également une protection contre la combustion de grandes quantités de matière organique au sol (chapitre 2). A l'inverse, l'établissement progressif de la sphaigne posera de problèmes à l'industrie forestière puisqu'il implique une réduction de la quantité de récolte du bois. La coupe avec protection de la régénération et des sols (CPRS) appliquée actuellement dans le secteur ne permet pas de contrer les processus de paludification. L'utilisation de pratiques sylvicoles qui empêche l'établissement des sphaignes, et qui réduit la couche de matière organique peut favoriser des peuplements plus productifs commercialement (Bureau du forestier en chef, 2013), mais expose les forêts à une plus grande sévérité induite par les feux (chapitre 2). Une solution serait la mise en place de zones de protection d'une superficie de pessières à sphaignes. De telles statégies permettraient de protéger les stocks de carbone tout en offrant une récolte productive dans les forêts fermées (chapitres 2 et 3). Toutefois les prochaines études devraient évaluer quelles proportions de pessières à sphaignes minimales sont requises afin d'éviter de menacer la vulnérabilité des forêts.

Malgré le peu d'impacts écologiques simulés sur la composition de la Ceinture d'Argile, nos résultats suggèrent que ces forêts ne seront pas complètement protégées des effets du climat sur le comportement des feux. Comme mentionné c-dessus, nos simulations projettent une augmentation de la superficie brûlée, l'intensité des feux et du pourcentage de feux de couronnes (chapitre 3). Ces changements impliqueront une plus grande difficulté de contrôle pour les sociétés de protection de feux impliquant des dégâts importants pour la société (pertes de bois, destructions d'infrastructure …). Favoriser l'expansion des essences feuillues des milieux tempérés déjà présentes en sous dominance dans la région, comme par exemple l'érable à sucre, pourrait être une alternative afin de réduire la vulnérabilité des forêts à ces changements (chapitre 1).

Les retombées scientifiques et les recherches futures

Les résultats de ce doctorat ont des implications particulièrement importantes et novatrices pour l'aménagement forestier. Alors que plusieurs études avaient déjà fait état d'une potentielle augmentation de l'activité des feux, peu avaient considérer des solutions pour les réduire. Les résultats ici ouvrent le débat sur l'utilisation de la résistance naturelle des forêts en tant qu'aménagement adaptatif pour réduire les impacts d'un changement de régime de feux. La modification de la composition des forêts pourrait être alors utilisée comme aménagement préventif afin de diminuer la vulnérabilité au feu. Le modèle développé dans le premier chapite, et ré-utilisé dans le 3^{e} chapitre, a d'ailleurs été validé par une études paléocologiques (Girardin et al. 2013b) renforçant ainsi la crédibilité du modèle.

L'application d'un tel aménagement préventif requiert toutefois encore des études supplémentaires afin de confirmer sa pertinence et son applicabilité par la considération de ces statégies dans les projections. En effet, comme le mentionne Noss (2001), les forêts occupent la planète depuis plus de 40 millions d'années. Elles ont vécu tous les bouleversements climatiques à travers les temps géologiques reliés aux changements de l'axe de rotation de la terre, les variations de la radiation solaire, la tectonique des plaques, le volcanisme, des collisions avec les astéroïdes ou les glaciations. Les forêts devraient continuer à persister aux changements futurs, si les activités anthropiques ne menacent pas sa résistance (Lindner, 2000; Loudermilk, 2013). Les projections des impacts des changements climatiques devraient dès lors inclure les statégies d'aménagements afin de considérer les impacts anthropiques.

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