UNIVERSITÉ DU QUÉBEC EN ABITIBI-TÉMISCAMINGUE

SPATIO-TEMPORALITÉ DES DYNAMIQUES DE FEUX ET DE VÉGÉTATION AU COURS DE L'HOLOCÈNE EN FORÊT BORÉALE CONIFÉRIENNE (QUÉBEC-LABRADOR)

THÈSE

PRÉSENTÉE

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PAR
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Comme je l'ai souvent dit, faire une thèse c'est un peu comme marcher sur une sangle tendue reliant deux sommets de montagnes. L'objectif est de dépasser ses limites pour arriver jusqu'au bout sans tomber, mais aussi sans oublier de profiter du paysage. Mes parents et ma sœur m'ont donné l'équilibre sans lequel je n'aurais pas pu atteindre l'autre sommet, et m'ont sans cesse rappelé que le plus important n'est pas l'exploit dans l'acte mais le bonheur qu'il doit m'apporter. Je les remercie infiniment pour la constance de leur soutien et leur bienveillance.

AVANT-PROPOS

Le corps de cette thèse se décline en trois articles en plus d'une introduction générale et d'une conclusion. L'objectif des deux premiers articles (Chapitres 2 et 3) est de caractériser l'influence régionale sur les interactions entre le climat, le régime de feux et la dynamique de végétation au cours de l'Holocène dans la forêt boréale coniférienne du Québec-Labrador (Canada). Le troisième article (Chapitre 4) est à caractère méthodologique et vise à améliorer les techniques de détection des feux locaux à partir des charbons séquestrés dans les sédiments lacustres. Des redondances d'informations peuvent être observées dans chacun des chapitres et leurs annexes dû au format de la thèse qui est par articles.

Chapitre 2 – Remy, C.C., Lavoie, M., Girardin, M.P., Hély, C., Bergeron, Y., Grondin, P., Oris, F., Asselin, H., Ali, A.A. (2017) *Wildfire size alters long-term vegetation trajectories in boreal forests of eastern North America.* Journal of Biogeography (DOI: 10.1111/jbi.12921)

Chapitre 3 – Remy, C.C., Hély, C., Blarquez, O., Magnan, G., Bergeron, Y., Lavoie, M., Ali, A.A. (2017) *Different regional climatic drivers of Holocene large wildfires in boreal forests of northeastern America.* Environmental Research Letters (DOI: 10.1088/1748-9326/aa5aff)

Chapitre 4 – Remy, C.C., Andrieux, B., Bonhomme, V., Hély, C., Bergeron, Y., Lavoie, M., Girardin, M.P., Grondin, P., Oris, F., Ali, A.A. (en préparation) *Improving detection of local fire events in lacustrine deposits with analysis of large charcoal counts.*

Je suis la première auteure de chacun des chapitres de ce manuscrit. J'ai réalisé toutes les étapes de cette thèse, de l'acquisition du matériel d'étude à l'écriture et la soumission des articles, avec la contribution de mes directeurs et co-directeurs Yves Bergeron, Christelle Hély, Adam Ali et Martin Lavoie. L'ensemble des co-auteurs ont suivi et participé à l'élaboration des articles auquels ils sont rattachés. Martin Girardin et Olivier Blarquez m'ont apporté leurs connaissances et leurs aides dans l'analyse des données. France Oris et Hugo Asselin m'ont fourni l'intégralité des données paléoécologiques des sites qu'ils ont étudiés dans la zone ouest utilisées dans cette thèse. Pierre Grondin m'a apporté son expertise dans la compréhension de la dynamique paysagère des écosystèmes boréaux. Gabriel Magnan m'a procuré les données hydrologiques passées issues de tourbières et les outils pour les interpréter dans le Chapitre 3. Benjamin Andrieux a participé à l'élaboration de la méthode de détection des feux locaux présentée dans le Chapitre 4 et Vincent Bonhomme a optimisé le script (sous R) permettant d'utiliser cette méthode afin de la rendre accessible à la communauté scientifique.

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AD	Anno domini
ARCO	Area-count method
BCI	Bootstrap confidence interval
$C_{\#}$	Number of charcoals per sample
C_A	Sum of charcoal areas per sample
cal. yr BP, kyr BP	Calibrated years before present, Calibrated kilo years before present
CHAR	Charcoal accumulation rate
CSD	Charcoal size distribution
DC	Drought code
FRI	Fire-return interval
FS index	Regional fire size
GCM	Global climate model
HadCM3	Hadley Centre Coupled Model version 3
KS-test	non-parametric Kolmogorov-Smirnov test
LCC	Large charcoal count
RegBB	Regional biomass burned
RegFF	Regional fire frequency
ROC	Rate of change
UGAMP	Universities Global Atmospheric Modelling Programme

RÉSUMÉ

Les changements climatiques en cours semblent être à l'origine d'une intensification de l'activité de feux dans les forêts circumboréales. Des modèles prédictifs basés sur des données historiques sont couramment utilisés pour essayer d'anticiper les régimes des feux et leurs impacts pour l'horizon 2100. Cependant, les concepts alimentant ces modèles reposent sur l'interprétation de données issues de seulement quelques régions alors que de nombreuses études ont montré que des facteurs régionaux à locaux tels que la topographie, la nature des sols, la composition et la structure de la végétation, ainsi qu'un profil climatique et une météorologie particulière, peuvent impacter l'activité de feux.

Au nord-est du Canada, la région de l'est du Québec et du Labrador se caractérise, comparativement aux régions de l'ouest et du centre du Québec, par un relief plus vallonné, une végétation différente (plus riche en sapin baumier (*Abies balsamea*) et plus pauvre en pin gris (*Pinus banksiana*)) et un climat plus froid et plus humide. L'étude des processus liés aux dynamiques de feux et de végétation dans cette région, et leur comparaison avec ceux des régions de l'ouest et du centre au cours de l'Holocène ont donc été réalisées dans cette thèse. L'objectif global était de savoir si l'on peut se contenter de travailler à une échelle supra-régionale plutôt qu'à une échelle régionale ou locale pour prédire les conséquences des changements climatiques en cours sur la dynamique des forêts conifériennes du Québec-Labrador.

Les résultats mettent en évidence l'impact de la taille des feux, jusqu'alors sous-estimé, sur la dynamique à long terme de la végétation au sein de chacune des régions. La présence de grands feux a favorisé la propagation du pin gris depuis 7000 ans à l'ouest du Québec et autour de 2000 ans avant aujourd'hui à l'est du Québec-Labrador. Par opposition, la rareté des événements de grands feux à l'est jusqu'à 2000 ans avant aujourd'hui a engendré une densification de sapin baumier et de bouleau dans le paysage. De plus, les conditions pré-requises à l'éclosion des grands feux diffèrent entre la région de l'est et celles de l'ouest et du centre. Dans les régions continentales de l'ouest et du centre, ces événements ont été déclenchés par une augmentation des températures printanières et estivales, et une saison de feux plus longue. Dans la région de l'est, les grands feux ont été probablement causés par une forte variabilité hydrologique (précipitations/évapotranspiration). Cette divergence s'explique en grande partie par l'influence prédominante de la topographie régionale au détriment de l'impact des grandes tendances climatiques sur l'activité de feux dans l'est.

Au regard de nos résultats, les scénarios climatiques annoncés risquent d'augmenter l'occurrence des grands feux dans les régions de l'ouest et du centre du Québec sans qu'il y ait pour autant de conséquence significative sur la composition du couvert forestier. À l'est, les projections restent plus incertaines car les causes à l'origine des grands feux passés dans cette région n'ont pas été totalement élucidées. Cependant, toutes les hypothèses de trajectoires de végétation futures formulées dans cette thèse vont dans le sens d'un maintien du sapin baumier dans le paysage.

Compte-tenu de la diversité des interactions susceptibles d'impacter significativement la taille des feux à l'échelle régionale, notre compréhension des processus liés aux dynamiques de perturbation et de végétation semble encore insuffisante pour pouvoir les prédire à large échelle. Il serait donc raisonnable, dans un premier temps, d'étudier plus finement ces processus à l'échelle de zones les plus homogènes possibles en termes de composition végétale, de topographie et de climat. C'est dans cette optique que la méhode de détection des feux locaux passés à partir des charbons lacustres présentée dans cette thèse a été développée. Elle vise à améliorer la différenciation des feux ayant eu lieu dans le bassin versant du lac étudié (local) de ceux s'étant produits à une plus grande distance (régional), et ce, à l'échelle plurimillénaire. Elle se base sur l'hypothèse qu'un feu local a engendré une plus forte séquestration de gros charbons dans le lac qu'un feu régional. Nos résultats montrent que, sur la base de cette hypothèse, notre méthode permet de détecter plus efficacement les feux locaux passés que la méthode actuellement disponible. Conjuguée à l'étude d'autres bio-indicateurs permettant de reconstruire l'environnement passé à l'échelle locale, nous devrions être capables de mieux comprendre les causes et conséquences des variations de taille des feux au regard des différentes combinaisons observées de facteurs environnementaux dans l'avenir.

Mots clés : forêt boréale coniférienne, Holocène, feux de forêt, feux locaux, charbons de bois, pollen, changements climatiques

CHAPITRE I

INTRODUCTION GÉNÉRALE

Plus d'un quart des forêts mondiales, soit environ 12,5 millions de km², se situe dans la zone circumboréale (Food and Agriculture Organization of the United Nations, 2015). En plus de renfermer environ 32% du carbone mondial (Pan *et al.*, 2011), elles contribuent largement au capital environnemental, social et économique des pays concernés (Burton *et al.*, 2003). Aujourd'hui, près des deux-tiers de ces forêts sont gérées en grande partie pour assurer la production industrielle de pâte à papier et de bois d'œuvre principalement (Gauthier *et al.*, 2015). Depuis la conférence des Nations Unies sur l'environnement et le développement en 1992, les activités anthropiques doivent permettre le maintien de la résilience des forêts. Ainsi, l'aménagement forestier conventionnel basé exclusivement sur le rendement est de plus en plus délaissé au profit d'une gestion durable qui s'efforce de conserver la biodiversité et la capacité de régénération des forêts. Or, la végétation des écosystèmes en général est caractérisée par une composition et une structure dépendante du climat et des régimes de perturbations naturelles que sont, dans le cas de la forêt boréale, les feux, les épidémies d'insectes défoliateurs et les chablis (Johnson, 1996 ; Kneeshaw et Bergeron, 1998 ; McCullough *et al.*, 1998). Les nouveaux plans d'aménagement devraient donc être conçus sur le long terme en adéquation avec les risques de perturbations et de migration des espèces liées aux changements climatiques (Bergeron *et al.*, 2002 ; Chapin *et al.*, 2004 ; Niemelä, 1999).

Ces exigences ont déclenché un intérêt grandissant envers les modèles qui simulent des variables du régime de feux (comme par exemple l'aire brûlée, la sévérité, l'intensité ou encore la fréquence) et les trajectoires de végétation qui en dépendent (Bonan *et al.*, 1992 ; Flannigan *et al.*, 2001 ; Hély *et al.*, 2001 ; Terrier *et al.*, 2014). Les plus récents travaux s'accordent à dire que le régime de feux va s'intensifier au sein de plusieurs régions de la zone circumboréale au cours des prochaines décennies (de Groot *et al.*, 2013 ; Girardin *et al.*, 2013). En effet, les changements climatiques en cours devraient mener à des épisodes de sécheresse plus nombreux (IPCC, 2014) ainsi qu'à un allongement de la saison de feu, ce qui aurait pour conséquence une augmentation du régime de feux dans les régions boréales (de Groot *et al.*, 2013 ; Rogers *et al.*, 2015). Toutefois, le réchauffement climatique devrait aussi favoriser la migration des espèces feuillues peu inflammables vers les zones de hautes latitudes, minimisant ainsi l'augmentation de l'activité de feux annoncée (Hély *et al.*, 2001 ; Randerson *et al.*, 2006). À l'inverse, une diminution de l'albedo due à l'absence de couvert neigeux sur une plus grande période de l'année, ainsi qu'une expansion de la forêt et des espèces arbustives dans les zones de toundra pourraient aussi intensifier l'activité de feux dans certaines régions nordiques (Chapin *et al.*, 2005 ; Pearson *et al.*, 2013).

Au cours des dernières décennies, les travaux de recherche sur les incendies de forêt en zone boréale se sont multipliés. Ils ont non seulement permis d'améliorer les modèles de prédiction (Girardin *et al.*, 2010 ; Terrier *et al.*, 2013 ; Thonicke *et al.*, 2001), mais aussi de mettre en évidence la complexité des interactions climat-feux-végétation entre régions et au sein même d'une région. En plus de l'impact du climat global et du type de végétation (conifères *versus* feuillus), de nombreux facteurs régionaux tels que la fragmentation du couvert forestier d'origine humaine, le climat régional, le type de dépôts de sols ou encore le relief peuvent significativement influencer l'activité de feux (Ali *et al.*, 2009a ; Lynch *et al.*, 2004 ; Wu *et al.*, 2014). Comprendre l'influence et l'importance de ces facteurs régionaux dans les dynamiques de perturbation et leurs conséquences sur les paysages boréaux est devenu un enjeu majeur pour augmenter la fiabilité des prédictions. En effet, la plupart des modèles de simulation de l'activité de feux et de la dynamique de végétation future supposent une homogénéité des processus écologiques à grande échelle spatiale en raison d'un manque de données empiriques dans certaines zones (Hyde *et al.*, 2013; Mckenzie *et al.*, 1996).

À ce jour, très peu d'études paléoécologiques visant à comprendre les interactions climat-feux-végétation au cours de l'Holocène ont été réalisée dans les forêts conifériennes de l'est du Québec et du Labrador (de Lafontaine et Payette, 2011; Magnan *et al.*, 2012). Par conséquent, les concepts liés à la dynamique plurimillénaire des paysages et des incendies de forêt de l'est canadien reposent en grande partie sur des interprétations issues des données paléoécologiques (anthracologiques, polliniques, dendrochronologiques) provenant de l'ouest et du centre du Québec qui ont ensuite été généralisées à l'ensemble du territoire de la pessière de l'est du Canada (Ali *et al.*, 2012 ; Blarquez *et al.*, 2015 ; Carcaillet *et al.*, 2010 ; Oris *et al.*, 2014). Ainsi, cette thèse a pour objectif principal de comprendre les interactions entre le climat, les régimes de feux et la dynamique de végétation dans l'est du Québec et de les comparer au reste du territoire afin de répondre à la question suivante: « Peut-on se contenter de travailler à l'échelle suprarégionale plutôt qu'à l'échelle régionale ou locale pour prédire les conséquences des changements climatiques en cours sur la dynamique des forêts conifériennes du Québec-Labrador? ». Nous émettons comme hypothèse que des facteurs abiotiques (ex : climat, météorologie, topographie) et biotiques (végétation) régionaux et/ou locaux peuvent contrôler la dynamique des feux de forêts et, par conséquent, les trajectoires à long terme de la végétation. Pour tester cette hypothèse, nous avons élaboré un plan expérimental fondé sur l'étude paléoécologique des sédiments de plusieurs lacs au sein de la forêt boréale coniférienne au Québec-Labrador. Les régions étudiées ont été choisies pour leurs degrés de disparité actuelle.

1.1 Régions d'étude

Tous les lacs étudiés se situent en forêt boréale coniférienne au Québec et au Labrador sur un gradient est-ouest entre les latitudes 50 et 53°N, et les longitudes 67 et 79°O (Figure 1.1). Ces lacs ont été regroupés en trois régions (ouest, centre et est), nous permettant d'étudier des données historiques de végétation et d'activité de feux à l'échelle régionale. La détermination des trois régions s'appuie sur leurs différences de caractéristiques climatiques, végétationelle, de relief et d'activité de feux actuels (est *versus* ouest et centre) et la proximité des lacs (ouest *versus* centre).

Les lacs situés dans l'est du Québec-Labrador ont été analysés durant cette thèse (Innu, Steeve, Ayla). Ils sont localisés le long de la route 389, reliant les villes de Baie-Comeau et Fermont, qui se prolonge sur la route 500 vers Labrador City. Les stations météorologiques aux environs de Baie-Comeau et de Labrador City enregistrent des températures annuelles moyennes de 1.5 à -3.5°C et des précipitations annuelles entre 1014 et 852 mm avec approximativement 33 et 55 % de chute de neige, respectivement ((moyennes sur la période 1971-2000; Environment Canada, 2014). Le relief y est vallonné et la végétation dominée par l'épinette noire (*Picea mariana* (Mill.) B.S.P.) et, de façon plus éparse, par l'épinette blanche (*Picea glauca* (Moench) Voss) et le sapin baumier (*Abies balsamea* (L.) Mill.). Le cycle de feux caculé sur la période 1800-2000 est d'environ 270 ans dans la partie sud (Bouchard *et al.*, 2008) et sur la période 1972-2009 d'environ 710 et 180 ans dans les parties centre et nord, respectivement (Portier *et al.*, 2016)

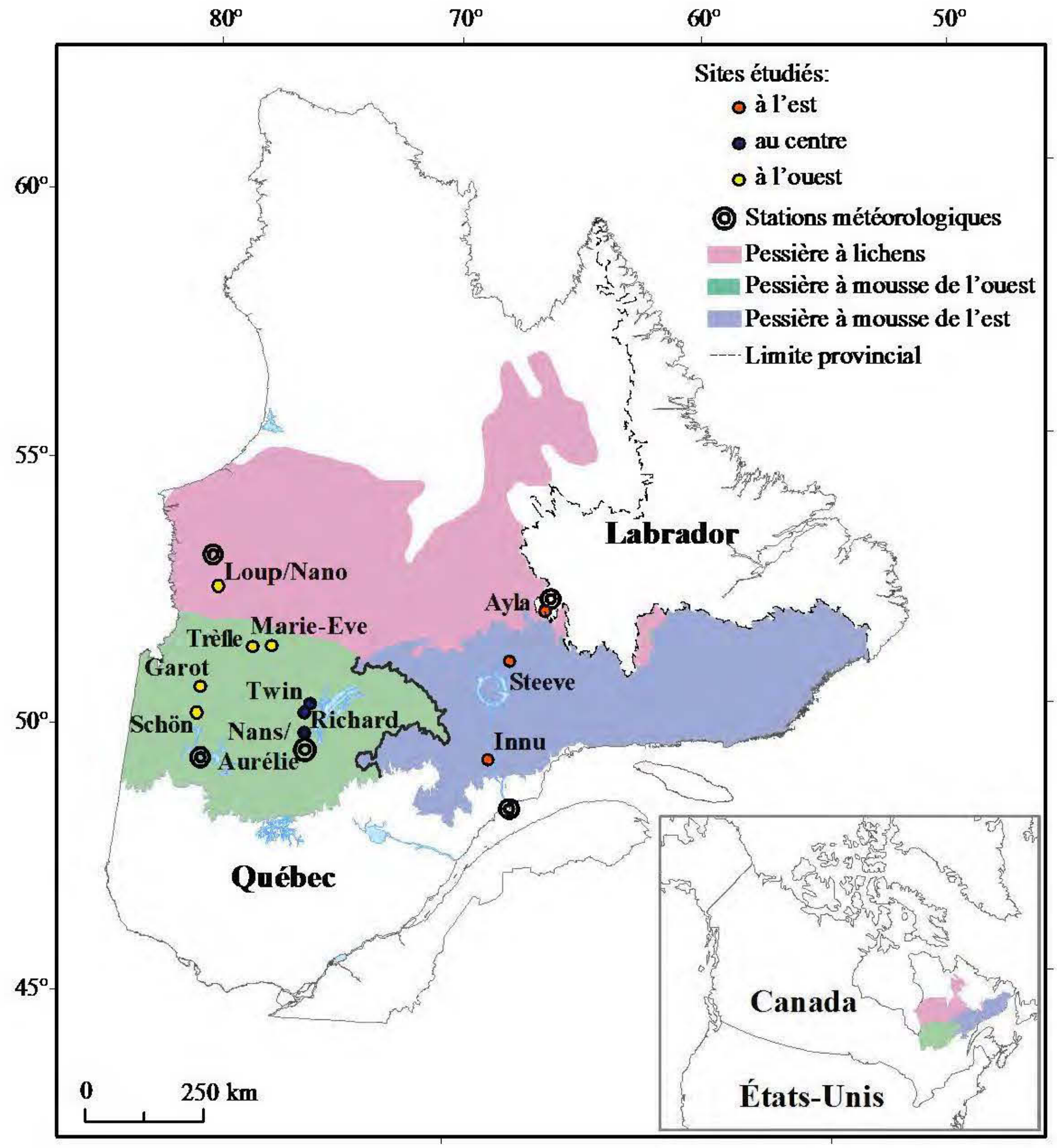

Figure 1.1 Localisation des sites étudiés

Les sites se trouvant dans les régions à l'ouest (6 lacs) et au centre du Québec (4 lacs) ont déjà été étudiés et incorporés à la thèse à des fins de comparaison de données entre régions. À l'ouest, ils sont localisés dans la région de la Jamésie, le long de la route reliant les villages de Matagami et de Radisson et de celle reliant le village de Némiscau au barrage Eastmain de Hydro-Québec. Les données anthracologiques et polliniques ont été fournies par France Oris, doctorante (2010 à 2014) sous la supervision de Adam A. Ali et Hugo Asselin. Les stations météorologiques situées à Matagami et à La Grande Rivière (Radisson) relèvent des températures annuelles moyennes de -0.7 à -3.1°C, des précipitations annuelles moyennes de 905 et 684 mm avec environ 37 % de chute de neige, respectivement (moyennes sur la période 1971-2000; Environment Canada, 2014a). Le territoire, de relief plus plat que celui de la région à l'est, est essentiellement dominé par l'épinette noire et, dans une moindre mesure, par le pin gris (*Pinus banksiana* Lamb.). Le cycle de feux actuel estimé à partir d'analyse spatiale des feux survenus entre 1930 et 1998 varie d'un endroit à l'autre, mais est inférieur à 170 ans (Bergeron *et al.*, 2004; Parisien et Sirois, 2003).

Au centre de notre transect, les sites sont localisés à proximité du lac Mistassini et de la ville de Chibougamau. Leurs histoires de feux ont été étudiées précédemment par Ahmed El-Guellab, étudiant en maîtrise (2009-2011) sous la supervision de Adam A. Ali et Hugo Asselin. La station météorologique de Chapais 2, à 50-100 km au sud-ouest des lacs étudiés, enregistre des températures annuelles moyennes de -0.4°C et des précipitations annuelles moyennes de 961 mm, dont 31 % sous forme de neige ((moyennes sur la période 1971-2000; Environment Canada, 2014). Le territoire au relief relativement plat est dominé, tout comme pour la région ouest, par l'épinette noire et parsemé de pin gris. Le cycle de feux actuel, estimé à partir d'analyse de photographies aériennes et d'études dendrochronologiques sur la période allant de 1800 à 2000, est d'environ 150 ans (Mansuy *et al.*, 2010).

1.2 Dynamique passée de la forêt boréale coniférienne

L'étude de la dynamique holocène (depuis 11 700 ans) du climat, des incendies de forêts et de la végétation peut nous permettre d'anticiper les trajectoires écologiques amorcées par les changements climatiques en cours. Différentes configurations climatiques ont prévalu dans le passé nous permettant, à partir de données simulées et reconstruites, d'étudier un large panel d'interactions entre le climat, les feux et la végétation au cours du temps.

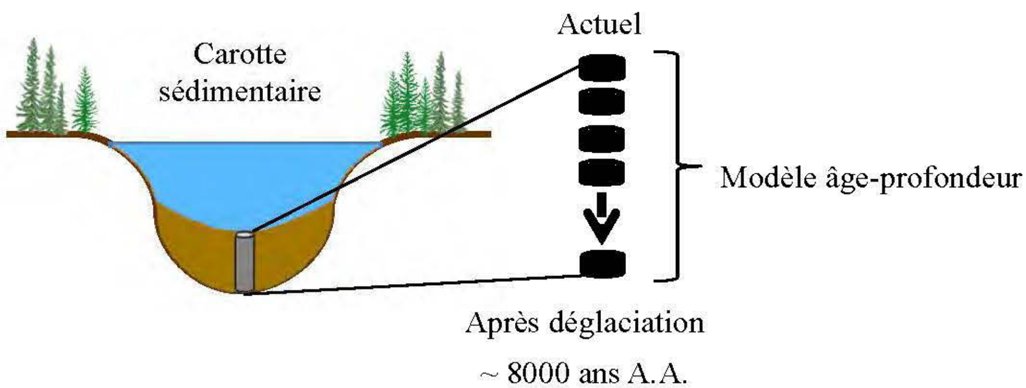

Figure 1.2 Illustration du processus d'obtention d'une série temporelle de données à partir de sédiments lacustres

La genèse de la plupart des lacs du nord-est de l'Amérique du Nord remonte à la dernière déglaciation et, selon le cas, au retrait des lacs et des mers proglaciaires, il y a environ 7000 à 8000 ans (Figure 1.2; Dyke, 2004). L'accumulation continue de sédiments depuis leur création a permis la séquestration et la conservation de nombreux bio-indicateurs dont, entre autres, les charbons de bois et les grains de pollen. Ceux-ci ont été utilisés pour reconstruire l'histoire des feux et de la végétation autour des lacs. Pour chaque séquence lacustre, des datations au ^{14}C ont été effectuées sur des macrorestes végétaux ou de la gyttja. Ces datations ont été étalonnées pour produire un modèle âge-profondeur 'classique' (Blaauw, 2010a) ou bayésien (Parnell et al., 2008) afin d'inférer un âge probable aux différents niveaux sédimentaires analysés (Figure 1.2).

1.2.1 Reconstitutions des paléo-incendies à partir des charbons de bois

Le régime de feux passé a été caractérisé à travers la fréquence des feux (occurrence), la quantité de biomasse et la surface qu'ils ont brûlées. Pour cela, les charbons de bois de taille macroscopique (> 160 µm) ont été mesurés en superficie ($mm^2.cm^{-3}$) ou en nombre ($\#.cm^{-3}$) à partir de sous-échantillons de 1 cm^3 de volume extraits en continu le long des séquences sédimentaires. Ces données ont été transformées en taux d'accumulation de charbons (CHAR: $mm^2.cm^2.an^{-1}$) en multipliant la concentration en charbons de bois de chaque niveau ($mm^2.cm^{-3}$) par le taux d'accumulation sédimentaire ($cm.an^{-1}$) déduit des modèles d'âge. L'histoire de la biomasse brûlée totale des sites est reconstruite à partir des valeurs de CHARs (Blarquez *et al.*, 2014). La détection des évènements de feux passés de chaque lac utilisé pour reconstruire leur histoire en terme de fréquence de feux s'effectue grâce au programme CharAnalysis développé par Higuera *et al.* (2009), disponible en libre accès (https://sites.google.com/site/charanalysis/). Pour chaque région étudiée (ouest, centre et est), les données portant sur l'histoire de chacun des sites ont été compilées afin d'obtenir l'histoire régionale de la biomasse brûlée (Ali *et al.*, 2012a ; Blarquez *et al.*, 2014) et de la fréquence des feux (*RegFF*; Blarquez *et al.*, 2013; 2014). La taille des feux à l'échelle régionale (*FS* index) est une approche semi-quantitative obtenue par le ratio *RegBB/RegFF* (Ali *et al.*, 2012a).

Notre démarche visant à reconstituer les activités de feux à une échelle spatiale régionale, et non locale, repose sur le fait que les particules de charbons de bois dans les sédiments peuvent provenir de feux qui ont eu lieu au-delà du bassin versant du lac étudié. En effet, même si les charbons de bois séquestrés dans les dépôts lacustres proviennent majoritairement de feux qui se sont produits jusqu'à 10 km des abords du lac (Clark et Royall, 1996 ; Higuera *et al.*, 2007a, 2009 ; R. Kelly *et al.*, 2013), plusieurs études ont montré que des particules de charbon peuvent être transportées sur de longues distances, et ce, même au-delà de 30 km (Clark *et al.*, 1998 ; Pisaric, 2002; Tinner *et al.*, 2006; Oris *et al.*, 2014). De ce fait, les sédiments lacustres peuvent renfermer des charbons issus de feux locaux et régionaux qui sont difficiles à discriminer.

Réussir à détecter uniquement les feux locaux pourrait pourtant nous aider à mieux comprendre l'importance de certains facteurs sur l'activité de feux. En effet, plusieurs études montrent que des facteurs locaux comme la météorologie, le relief, le type de sol ou encore le type de végétation peuvent significativement impacter le régime de feux à l'échelle locale (Colombaroli et Gavin, 2010 ; Dunnette *et al.*, 2014 ; Gavin *et al.*, 2006a ; Genries *et al.*, 2012a ; Senici *et al.*, 2013a). Des efforts ont donc été déployés au cours des dernières années pour améliorer la détection des 'vrais feux locaux' (Asselin et Payette, 2005 ; Finsinger *et al.*, 2014 ; Gavin *et al.*, 2006a ; Higuera Gavin *et al.*, 2010a). Parmi ceux-ci, la méthode de distribution des tailles de charbons (CSD) développée par Asselin et Payette (2005) a été élaborée pour discriminer les feux régionaux des feux locaux. Cette méthode se base sur l'hypothèse que les événements de feux locaux, contrairement aux feux régionaux, engendrent un dépôt plus important de gros charbons que de petits charbons dans le lac avoisinant (Clark *et al.*, 1998 ; Gardner et Whitlock, 2001; Whitlock et Larsen, 2002; Lynch *et al.*, 2004). Ainsi, un événement de feu local est détecté à partir de la pente de la régression linéaire de la distribution de taille de particules de charbons dans le 'pic' de charbons détecté comme étant un évènement de feu passé (Clark *et al.*, 1998). Cette pente doit se situer au-dessus d'une valeur seuil calculée à partir de 'pics' de charbons reconnus comme étant des événements de feux locaux récents enregistrés, par exemple, par les cicatrices de feux sur des arbres à proximité du lac (Brossier *et al.*, 2014 ; Oris *et al.*, 2014). Cependant, cette valeur seuil unique entre -1.5 et -2.2, déduite de l'étude de quelques feux récents, peut être problématique car elle ne prend pas en compte l'impact des processus taphonomiques (fragmentation et dispersion de gros charbons dans les niveaux sédimentaires adjacents) qui ont pu varier et moduler l'enregistrement des gros charbons de bois dans les sédiments. Ainsi, il suffit qu'un pic soit formé d'un seul gros charbon ou d'une plus grosse proportion de charbons de tailles moyennes plutôt que de petites tailles pour que la pente soit supérieure à la valeur seuil requise. Deux verrous méthodologiques doivent donc être levés dans l'objectif de créer une méthode améliorée de détection des feux locaux. Le premier nécessite de parvenir à introduire un seuil non pas unique comme c'était le cas pour la méthode CSD, mais fluctuant selon les variations temporelles de production et de séquestration des gros charbons dans les dépôts lacustres. Le deuxième verrou, reprenant l'hypothèse de base de la méthode CSD, consiste à conserver un nombre minimum de charbons totaux et de gros charbons dans le 'pic' pour que celui-ci puisse être considéré comme un événement de feu local. Oris *et al.* (2014) ont montré que les feux locaux produisent une proportion de gros charbons de bois (> 0.1 mm^2) plus importante que les feux régionaux. Cette métrique servira de point d'ancrage pour développer les améliorations méthodologiques attendues.

1.2.2 Reconstitutions des paléovégétations à partir des grains de pollen

Pour reconstruire les paléovégétations, les grains de pollen séquestrés dans les sédiments lacustres ont été extraits suivant une version modifiée du protocole de (Faegri et Iversen, 1989a). Un minimum de 300 grains de plantes vasculaires terricoles (somme pollinique) a été compté et identifié à différents niveaux de la carotte sédimentaire afin de reconstruire l'histoire de la végétation au cours de l'Holocène à une résolution temporelle inférieure à 150 ans. Les changements rapides ayant eu lieu au sein du couvert végétal au cours du temps ont été caractérisés par la technique du taux de changement pollinique (Jacobson et Grimm, 1986). Les périodes de relative stabilité, quant à elles, ont été déterminées sur la base de « périodes polliniques » identifiées par des analyses de groupements stratigraphiquement contraints à partir du programme CONISS (Grimm, 1987a).

La fréquence et la taille des feux peuvent chacune influencer les dynamiques de végétation. De nombreux travaux ont caractérisé leurs conséquences sur les derniers siècles (Bergeron *et al.*, 2004 ; Harper *et al.*, 2002 ; Johnson, 1996) mais très peu l'ont fait à une échelle de temps plurimillénaire (Carcaillet *et al.*, 2010 ; Kelly *et al.*, 2013). Comprendre l'influence de la taille et de la fréquence des feux sur les trajectoires de végétation au cours de l'Holocène, et ce, dans différentes régions, permettrait de renforcer les conclusions faites à l'échelle pluricentenaire et de mieux caractériser les dynamiques futures de la végétation en réponse à des changements dans le régime des feux.

1.2.3 Simulations du climat passé

Les modèles de circulation générale (MCGs), basés sur des équations permettant de simuler les processus et circulations océaniques et atmosphériques, sont utilisés pour étudier les climats passés et futurs. Le modèle climatique anglais du *Hadley Centre* (HadCM3 ; Singarayer et Valdes, 2010) fait partie des modèles utilisés dans les rapports d'évaluation du Groupe d'experts intergouvernemental sur les changements climatiques (GIEC–IPCC; éditions 2001 et 2007). De plus, les données issues des simulations paléoclimatiques fournies par le *Programme de modélisation atmosphérique mondial des universités britanniques* (UGAMP) à partir de ce MCG ont déjà été utilisées dans plusieurs zones de la forêt boréale canadienne (Ali *et al.*, 2012 ; Blarquez *et al.*, 2015 ; Girardin *et al.*, 2013 ; Hély *et al.*, 2010). Ces études ont permis de tester la cohérence des données de sorties et de mettre en évidence les limites de ce modèle dans cette zone.

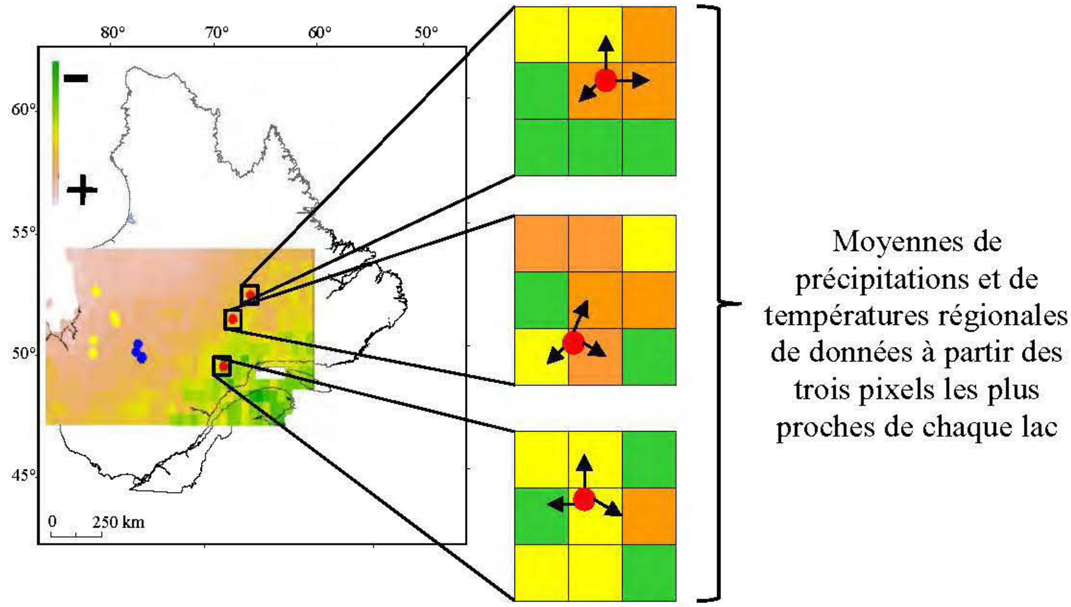

Figure 1.3 Illustration du traitement de données issues du MCG afin d'obtenir des moyennes climatiques régionales

Les températures et les précipitations mensuelles simulées par pixel de 3.75°×2.5° tous les 1000 ans sont converties pour chaque millénaire en anomalies par rapport à la période contrôle pré-industrielle (1750) du modèle MCG. Elles sont ensuite appliquées aux normales mensuelles post-industrielles (1901 à 2002) calculées sur la grille spatiale de 0.5°×0.5° TS 2.1 de l'Unité de Recherche Climatique de l'University of East Anglia pour obtenir des séries temporelles sur 0.5° (Mitchell et Jones, 2005). Pour chacun des pixels, une série de 30 ans de températures et précipitations mensuelles est reconstruite tous les 1000 ans en utilisant pour chaque variables mensuelles une distribution normale (température) ou gamma (précipitation) paramétrée grâce à la moyenne reconstruite passée (pré-industrielle avec anomalie) et la variance actuelle (post-industrielle) (New *et al.*, 2002 ; Ramstein *et al.*, 2007). Ces séries mensuelles sont ensuite transformées en données journalières grâce au générateur météo de Richardson (Richardson, 1981). À partir de ces données quotidiennes obtenues à l'échelle régionale

(Figure 1.3), l'indice de sécheresse (DC), faisant partie des indices composant l'Indice Forêt Météo (Van Wagner, 1987), est calculé. Le cumul des jours dont le DC est supérieur ou égal à 80 unités, évalué à partir d'analyses de valeurs de DC historiques comme étant le seuil d'un risque modéré de feu dans cette région, permet d'obtenir la longueur de saison de feu (Hély *et al.*, 2010a). Celle-ci est scindée en deux saisons (printemps et été) afin d'observer l'impact respectif de son allongement ou rétrécissement sur le régime de feux.

Des études menées en Alaska et dans l'ouest des États-Unis portant sur les dernières décennies ont suggéré qu'une saison de feux débutant plus précocement engendrait des feux plus sévères ou plus grands (Turetsky *et al.*, 2011 ; Westerling *et al.*, 2006). Cela serait dû à la disponibilité plus importante de combustible sec avant le début de la saison de croissance que plus tardivement dans la saison. Cependant, d'autres études réalisées au Canada et en Sibérie montrent, pour leur part, que les précipitations pourraient également avoir un impact sur le régime de feux en affectant la croissance et l'accumulation de combustible l'année précédant la saison de feux (Balzter *et al.*, 2007 ; Flannigan *et al.*, 2009 ; Kasischke *et al.*, 2002). À l'échelle de l'Holocène, les feux les plus grands (et/ou les plus sévères) dans l'ouest du Québec ont également eu lieu durant les périodes caractérisées par une saison de feux plus précoce attribuable à une augmentation des températures printanières non compensée en terme de risque d'incendie, par une augmentation des précipitations (Ali *et al.*, 2012a).

1.3 Objectif de la thèse

L'objectif général de la thèse est de mieux comprendre les interactions entre le climat, les feux et la végétation dans les forêts boréales du Québec-Labrador à différentes échelles spatiales (globale, régionale et locale). Ces résultats permettront d'améliorer les prédictions sur les régimes de feux et les dynamiques de végétation en précisant à quelles échelles spatiales les différents processus d'interactions ce sont produits dans le passé et quels facteurs ont eu une importance prédominante sur les changements de régime de feux et de végétation. Ils devraient, à terme, apporter une aide dans la décision des futurs plans d'aménagement forestiers, notamment sur la position future de la limite nordique d'exploitation forestière. La thèse s'articule autour trois sections qui traitent à la fois des aspects d'écologie des perturbations, de biogéographie et de méthodologie de reconstitutions des feux locaux qui se sont produits dans les bassins versants des lacs étudiés.

La première partie (Chapitre 2) étudie les interactions entre le régime feux, en termes de fréquence et de taille, et les trajectoires de végétation qui en découlent au cours de l'Holocène dans l'ouest et dans l'est du Québec-Labrador. Les résultats permettront d'estimer l'importance de la fréquence et de la taille des feux dans la dynamique de végétation.

La deuxième partie (Chapitre 3) porte sur les paramètres climatiques à l'origine des variations des régimes de feux à l'est, au centre et à l'ouest du Québec-Labrador. Cela nous aidera à mieux comprendre le rôle de la température, des précipitations et de la longueur de la saison de feux sur la dynamique de perturbations par le feu.

La dernière partie (Chapitre 4) est à caractère méthodologique. Elle vise à améliorer la détection des feux locaux à partir des charbons séquestrés dans les dépôts sédimentaires lacustres, afin de permettre des études plus approfondies sur l'influence des facteurs locaux dans la dynamique des forêts boréales.

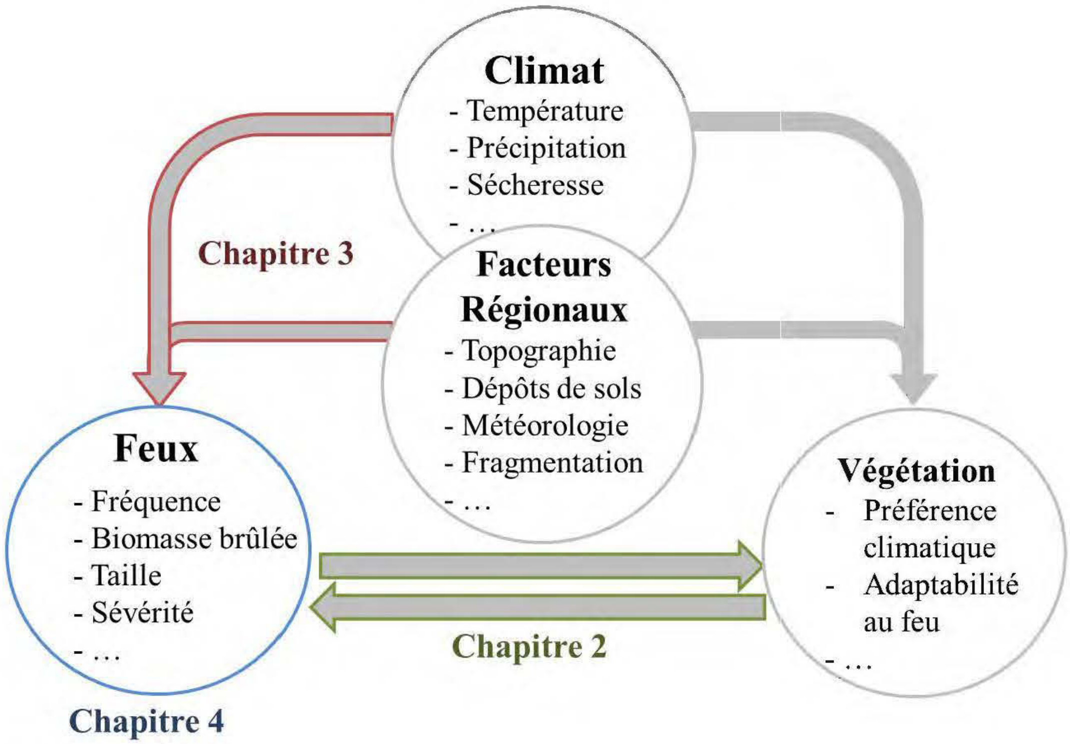

Figure 1.4 Schéma des différentes interactions et paramètres traités dans les chapitres de cette thèse

CHAPITRE II

WILDFIRE SIZE ALTERS LONG-TERM VEGETATION TRAJECTORIES IN BOREAL FORESTS OF EASTERN NORTH AMERICA

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2.1 Abstract

Aim. Wildfire activity is projected to increase under global warming in many parts of the world. Knowledge of the role of these disturbances in shaping the composition of boreal forests is needed to better anticipate their future impacts. Here, we investigate the incidence of wildfire activity (burned biomass, frequency and size) on multi-millennia vegetation trajectories in two coniferous boreal forest regions that display different types of vegetation composition and relief. We hypothesize that this difference in vegetation results from dissimilar wildfire activity during the Holocene.

Location. Conifer-dominated boreal forests in Quebec-Labrador, eastern North America.

Methods. Fire and vegetation histories during the last 8000 years were reconstructed and compared through analyses of charcoal and pollen records extracted from nine lacustrine deposits located in two spruce-moss forests: the western region, co-dominated by *Pinus banksiana,* and the eastern region, co-dominated by *Abies balsamea.*

Results. Between 7000 and 2000 cal. yr BP, the western region experienced fewer fires than the eastern region, but they were larger in size. The main species adapted to fire, *P. banksiana* and *Alnus viridis* ssp. *crispa,* progressively co-dominated with *Picea* sp. Conversely, in the eastern region, *P. banksiana* and *A. viridis* ssp. *crispa* were very rare, and *Picea* sp. co-dominated with non-fire adapted *A. balsamea*, and *Betula* sp. Then, around 2000 cal. yr BP, fires decreased in frequency but were larger in size in the eastern region than in the western one, thus allowing densification of *P. banksiana* and *A. viridis* ssp. *crispa* in these landscapes.

Main conclusions. In the coniferous boreal forests of eastern North America, fire size was relatively more important in determining the long-term vegetation trajectories in comparison with fire frequency. Changes in the rate of occurrence of large fire episodes

will have significant impacts on vegetation dynamics over the next decades under continuing warming.

2.2 Résumé

Objectif. Les prédictions montrent que les feux d'origine naturelle vont s'intensifier sous le réchauffement global dans plusieurs parties du monde. Comprendre le rôle de ces perturbations sur la composition des forêts boréales pourrait aider à mieux anticiper leurs futurs impacts. Ici, nous étudions l'incidence de l'activité de feux (biomasse brûlée, fréquence et taille) sur les trajectoires de végtation à l'échelle plurimillénaire dans deux régions de la forêt boréale coniférienne, caractérisées par une composition de végétation et un relief différent. Notre hypothèse est que cette différence de végétation résulte d'activité de feux différentes durant l'Holocène.

Aire d'étude. Forêts boréales conifériennes du Québec-Labrador, au nord-est de l'Amérique du Nord.

Méthodes. Les histoires de feux et de végétation durant les derniers 8000 ans ont été reconstruits et comparés à partir de l'analyse d'enregistrements anthracologiques et polliniques. Ces bio-indicateurs ont été extraits de neuf dépôts lacustres situés dans deux régions de la pessière à mousse: la région ouest co-dominée par *Pinus banksiana*, et la région est co-dominée par *Abies balsamea*.

Résultats. Entre 7000 et 2000 ans cal. avant l'actuel, la région de l'ouest enregistrait moins de feux que la région de l'est, mais ceux-ci étaient plus grands en terme de surface brûlée. Les espèces principales adaptées aux feux, *P. banksiana* et *Alnus viridis* ssp. *crispa*, ont progressivement co-dominé le paysage avec *Picea* sp. Au contraire, dans la région de l'est, *P. banksiana* et *Alnus viridis* ssp. *crispa* étaient très rares et *Picea* sp. co-dominait avec *A. balsamea* et *Betula* sp., deux espèces non-adaptés aux feux. Puis, autour de 2000 ans cal. avant l'actuel, la fréquence des feux a diminué mais ces derniers étaient plus grands dans la région de l'est que dans celle de l'ouest. Cela a engendré une densification de *P. banksiana* et *Alnus viridis* ssp. *crispa* dans les paysages de l'est.

Conclusions principales. Dans les forêts boréales conifériennes du nord-est de l'Amérique du Nord, la taille des feux semble avoir eu plus d'impact que la fréquence des feux sur les trajectoires de végétation à long-terme. Durant les prochaines décennies, les changements dans le taux d'occurrence des épisodes de grands feux pourraient significativement impacter les dynamiques de végétation sous le réchauffement climatique.

2.3 Introduction

In the next decades, it is anticipated that global warming will cause a global increase in wildfires, leading to unprecedented negative ecological and socioeconomic consequences (Flannigan *et al.*, 2009). This scenario feeds debates in scientific consortiums that aim to define the consequences of this increase in wildfire activity on ecosystems functioning. However, model-based fire predictions depend mostly on data collected over short time periods (less than 100 years) that do not cover a wide range of fire-climate interactions and feedback processes arising from changes in vegetation features. This impairment reduces the robustness of fire predictions that must therefore be supplemented with paleoecological data (Withlock *et al.*, 2010).

Fire is the major perturbation in the circumboreal ecosystem which contains ca. 33% of the global vegetation cover and ca. 33% of the terrestrial carbon storage (Flannigan *et al.* 2009). According to paleoecological analyses performed on pollen and charcoal at millennial time-scales, major transformations of the eastern North American boreal forests were mostly controlled by regional climate trends rather than by fire frequency (Carcaillet *et al.*, 2010b). Nevertheless, this conclusion must be supported (or not) by other studies due to, among other things, the non-uniform impacts of climate, vegetation and humans on fire activity across regional scales (Blarquez *et al.*, 2015). In addition, fires could significantly impact the composition of boreal forests at the century time-scale (Harper *et al.*, 2002). Indeed, after the opening of the forest by wildfires, boreal woodlands are rapidly dominated by early successional species such as *Pinus banksiana* Lamb. (serotinous species adapted to fire) and *Alnus viridis* subsp. *crispa* (Ait.), especially on xeric soils, and *Betula papyrifera* Marsh. and *Populus tremuloides* Michx. on mesic soils (Harper *et al.*, 2002). Then, these species are progressively replaced by *Picea mariana* (Mill.) B.S.P. In 200-year-old stands or older, early successional species become rare and the forests are largely dominated by *Picea* *mariana* and *A. balsamea* (L.) Mill. in the absence of insect outbreaks (Cyr *et al.*, 2012 ; Harper *et al.*, 2002).

Several studies have also shown that in addition to fire frequency, fire size impacts the vegetation composition at the landscape scale. Indeed, small wildfires imply a mosaic landscape structure, ultimately with the presence of small forest refuges that are representative of unburned or partially-burned forest patches composed of non-fire adapted conifers such as *A. balsamea*, *Thuja occidentalis* L. and *Picea glauca* (Moench) Voss (Bergeron *et al.*, 2004). Natural firebreaks such as wetlands, lakes and hilly areas may contribute to decreasing the size and severity of wildfires (Cyr *et al.*, 2005 ; Terrier *et al.*, 2014). In contrast, flat areas allow the propagation of large wildfires (> 200 ha) that create a continuous landscape structure and promote fire-adapted species such as *P. banksiana* (Asselin *et al.*, 2003 ; Parisien et Sirois, 2003).

The relative importance of fire frequency and fire size on shaping the long-term dynamics of boreal forests is uncertain and require studies that make it possible to retrace environmental changes at different spatial and temporal time-scale (Ali *et al.*, 2012; Marlon *et al.*, 2013). Here, we assess the influence of wildfires (frequency and size) on long-term vegetation trajectories in the boreal forests of eastern North America during the last 8,000 years through analyses of macroscopic charcoal and pollen grains sequestered in lake sediments. To test the spatial extent of our conclusions, we targeted two regions that are currently subject to different climate conditions and that display distinctive types of relief and vegetation for sampling. Based on the regional climate differences that exist nowadays between the two studied regions, as well as on previous palaeoecological studies conducted in the western region (Ali *et al.*, 2012 ; Oris *et al.*, 2014), we hypothesize that over the Holocene, the more humid (maritime) climate of the eastern region was less favourable to fire compared with the western region, which is characterised today by drier (continental) conditions. We postulate that differences in the long-term fire activity could explain the current vegetation composition (more or less fire-adapted species) in the two study zones.

2.4 Material and methods

2.4.1 Study area

We used nine lacustrine records sampled between 50°N and 53°N, encompassing both the spruce-moss and spruce-lichen forests of Quebec and Labrador (Fig. 2.1). Six lakes that had previously been sampled (Loup, Nano, Marie-Eve, Trèfle, Garot and Schön; unofficial names) are located in the western spruce forest of Quebec between 67°W and 69°W (Oris *et al.*, 2014). We sampled three new lakes (Ayla, Steeve and Innu; unofficial names) located in the eastern spruce forest of Quebec and Labrador between 75°W and 78°W (Table 2.1).

In the western region, meteorological stations located near the southernmost lakes (Matagami, 49°46'N, 77°19'W; 281 m above sea level [a.s.l.]) and near the northernmost lakes (La Grande Rivière, 53°39'N, 77°42'W; 194 m a.s.l.) recorded mean annual temperatures of -0.7°C and -3.1°C, respectively. Annual precipitations at these locations averaged 905 and 684 mm, respectively, with approximately 37% falling as snow (Environment Canada, 2014). The closest weather stations to the lakes in the eastern region, Baie-Comeau A (49°08'N, 68°12'W; 22 m a.s.l.) and Wabush Lake (52°55'N, 66°52'W; 551 m a.s.l.), recorded mean annual temperatures of 1.5 and -3.5°C and mean annual precipitations ranging from 1014 to 852 mm, with approximately 33% and 50% falling as snow (Environment Canada, 2014), respectively. These climatic data underline that the eastern region is currently more humid and colder than the western region.

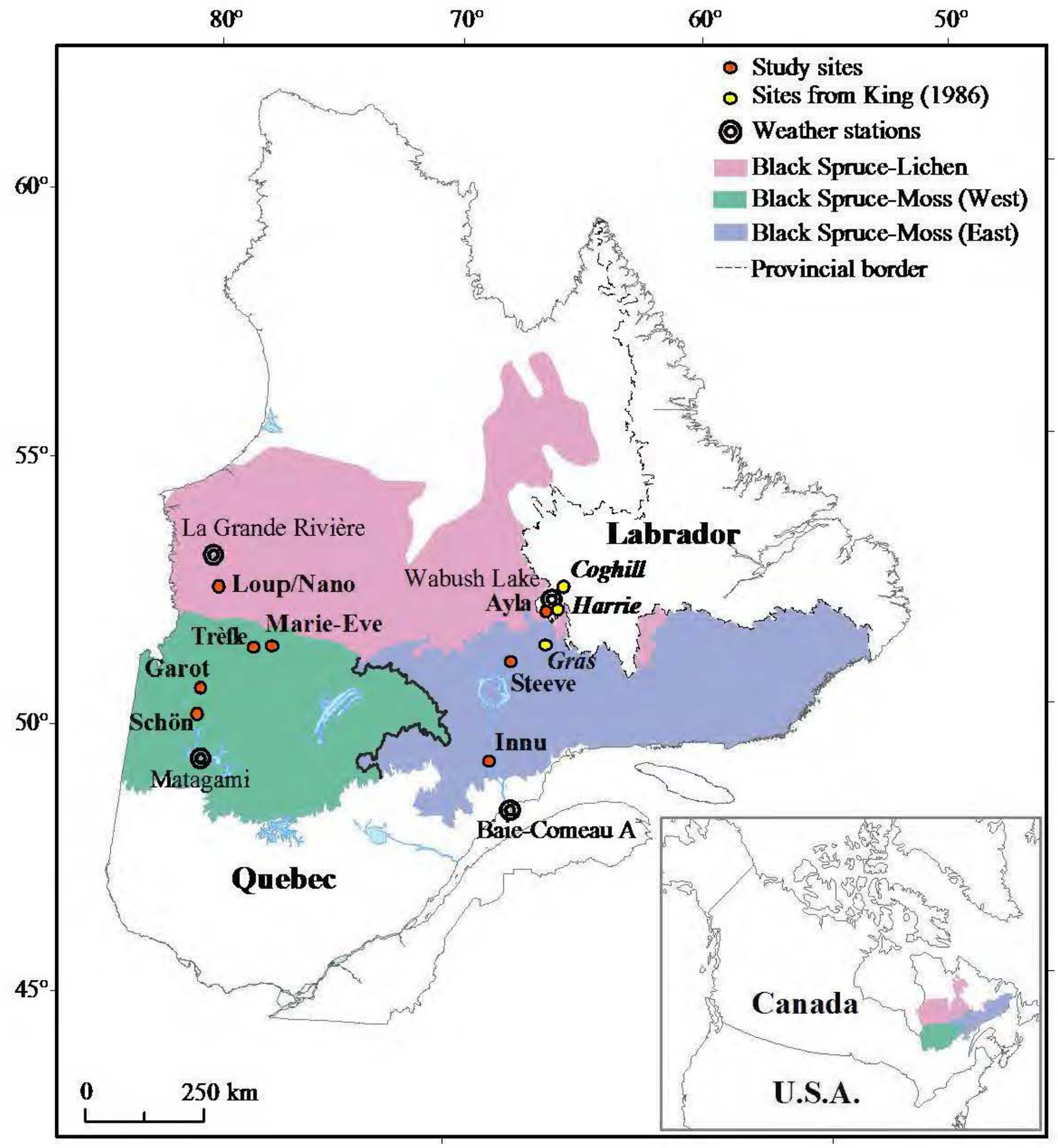

Figure 2.1 Location of the study sites and cited sites in the western and eastern regions of Quebec-Labrador

Table 2.1 Main characteristics of the lakes studied. Mean sediment accumulation rates and median time-resolutions of each individual core were derived from their respective age-depth models

	Lake	Coordinates	Elevation (m a.s.l.)	Current local vegetation	Superficial deposits	Lake surface (ha)	Water depth (m)	Length of organic core (cm)	Mean sediment accumulation rate (cm $year^{-1}$)	Median time-resolution (year per sampl
East										
	Ayla	52°53'39.3" N 67°02'27.3" W	582	*Picea mariana, Picea glauca, Abies balsamea*	Organic	10.8	10.16	408	0.0499	10
	Steeve	51°56'23.9" N 68°09'19.2" W	548	*Picea mariana*	Sand (Till)	3.4	3.5	327	0.0349	17
	Innu	50°04'10.9" N 68°48'40.7" W	399	*Picea mariana, Abies balsamea*	Till (Sand)	1.4	7.7	370	0.0415	13
West										
	Loup	53°03'18.1" N 77°24'01.9" W	206	*Picea mariana, Pinus banksiana*	Rock (Till)	1.6	3.0	106	0.0145	37
	Nano	53°01'25.5" N 77°21'51.3" W	206	*Picea mariana, Pinus banksiana*	Moraine	0.4	3.2	140	0.0185	22
	Marie -Eve	52°01'47.4" N 75°31'14.6" W	296	*Picea mariana, Pinus banksiana*	Till	16.5	8.7	290	0.0416	15
	Trèfle	51°57'54.7" N 76°04'52.0" W	270	*Picea mariana, Pinus banksiana*	Till	6.8	5.4	150	0.0208	24
	Garot	51°05'58.7" N 77°33'12.9" W	291	*Picea mariana, Pinus banksiana*	Marine	2.8	7.0	133	0.0181	26
	Schön	50°35'41.7" N 77°34'06.1" W	248	*Picea mariana, Pinus banksiana*	Organic	5.1	6.9	100	0.0133	37

According to Dyke (2004), the deglaciation of the two study regions occurred approximately between 8000 and 7000 calendar years BP (hereafter 8.0 and 7.0 kyr BP). In the western region, Lakes Garot and Schön were underneath the proglacial Ojibway Lake until 7.0 kyr BP, whereas Lakes Loup and Nano remained submerged under the Tyrell Sea transgression until ca. 6.0 kyr BP (Dyke, 2004). The two study regions display distinctive types of relief and vegetation. The drier and flatter western region is mainly dominated by *Pinus banksiana* and *Picea mariana*. *Pinus banksiana* is more abundant around Lakes Trèfle and Marie-Eve, on dry superficial deposits (moraine). The more humid and hilly eastern region is dominated by *Abies balsamea*, *Picea glauca* and *P. mariana*. The current mean fire cycles are less than 170 years in the western region (Parisien & Sirois, 2003) and 270 years in the eastern region (Bouchard *et al.*, 2008). According to Oris *et al.* (2014), the fire history inferred from lacustrine charcoal deposits in the western region indicates that wildfires were frequent between 7.0 and 3.0 kyr BP. The highest fire frequency occurred around 4.0-3.0 kyr BP, followed by a gradual decrease until 1.5 kyr BP, then increasing again to present values, close to those recorded at 7.0 kyr BP. There is no fire history available at a regional scale for the eastern region that covers the postglacial period.

2.4.2 Sediment sampling and chronologies

Lakes were selected based on their small surface area and organic core length (Table 2.1). Sediments were extracted from the centre of frozen lakes using a Livingstone corer in March 2011 (Lakes Loup, Nano, Marie-Eve, Trèfle, Garot and Schön) and March 2013 (Lakes Innu, Steeve and Ayla). Water-sediment interfaces were sampled using a Kajak-Brinkhurst gravity corer. Sedimentary cores were sliced into continuous 0.5-cm-thick subsamples to obtain fine-scale time resolution for charcoal and pollen analyses. At Lake Innu, a lack of materials in the uppermost 20 cm of the sequence (~ 450 years) prevented us from conducting the charcoal analysis. Sediment accumulation chronologies were based on radiocarbon measurements of terrestrial plant macroremains and/or gyttja samples (Appendice A; Oris *et al.*, 2014). The ^{14}C dates were calibrated using the CLAM 2.2 program based on the IntCal13.14C and the postbomb_NH1.14C data set (Hua *et al.*, 2013; Reimer *et al.*, 2013). Age-depth models were obtained using 'classical' age-depth models with a smoothing spline function (Blaauw, 2010b). These age-depth models were compared to other ones obtained using up-to-date Bayesian age-depth models (Parnell *et al.*, 2008); results were similar under both methods, but the Bayesian method highlighted higher uncertainties around age-depth models.

2.4.3 Fire history reconstructions

For each 0.5-cm-thick slice, a subsample of 1 cm^3 was shaken for 24 h in an aqueous solution of 3% $(NaPO_3)_6$, 5% KOH (for Lakes Innu, Steeve and Ayla) and 10% NaOCl to facilitate deflocculation as well as to differentiate between black charcoal and bleached organic matter. The solution was then passed through a sieve to collect charcoal particles >160 µm assumed to come from local fire events (≤ 1-3 km from the lake shore; Higuera *et al.* 2007). These particles were measured using an image-analysis software (WinSEEDLE™, Regent Instruments Inc.) and transformed into charcoal accumulation rates (CHAR; $mm^2\ cm^2\ yr^{-1}$) based on numerical age-depth models. To remove bias induced by the different sedimentation rates and taphonomic processes involved in the sequestration of charcoal in the sediments, individual CHAR series were interpolated using a constant time-resolution of 20 years corresponding to the median sample resolution of lakes in each region. These series were then pooled to build the past regional biomass burned (hereafter *RegBB*) by (i) rescaling initial CHAR values using min-max transformation, (ii) homogenizing the variance using Box-Cox transformation, and (iii) rescaling the values to Z-scores (Ali *et al.*, 2012).

CHAR series were analyzed using CharAnalysis v1.1 software (Higuera *et al.*, 2009; available at https://sites.google.com/site/charanalysis/) to identify local fire events (Appendice B). The dates of local fire events were extracted from $CHAR_{fire}$ series and the local fire frequency was calculated by smoothing these series with a kernel density function (Ali *et al.*, 2012). The past regional fire frequency (hereafter *RegFF)* for each region was constructed by polling these smoothed series using *paleofire* R package (Ali *et al.*, 2012; Kelly *et al.*, 2013; Blarquez *et al.*, 2013). We assessed the significance of changes in both *RegFF* and *RegBB* by repeating the bootstrap procedure 999 times (BCI; 90%).

For each region, we used the ratio between *RegBB* and *RegFF* to assess the fluctuation in fire size through time (hereafter *FS* index; Ali *et al.* 2012). *RegBB* values are correlated to long-term changes in the area burned inferred from fire histories (Ali *et al.*, 2012 ; Higuera Whitlock *et al.*, 2010 ; R. Kelly *et al.*, 2013). Thus, we consider that fire size is related to the temporal trajectory of mean biomass burned per fire, reflecting part of the loss of organic matter (*RegBB*), and modulated by the number of fires through time (*RegFF*). High values of *FS* index are indicative of a high mean area burned per fire, whereas low *FS* index values reflect a low mean area burned per fire.

2.4.4 Reconstructions of vegetation dynamics

Three lakes in the western region (Lakes Nano, Marie-Eve and Schön) and two lakes in the eastern region (Lakes Steeve and Innu) were used to reconstruct the postglacial regional vegetation dynamics based on pollen analysis. For each site, subsamples (1 cm^3) were collected at 0.5- or 4-cm intervals throughout the cores, providing temporal resolutions lower than ca. 150 years. *Lycopodium* spores tracer tablets were added to each subsample in order to estimate the pollen concentration (grains cm^{-3}). Pollen grains and spores were extracted according to a modified methodology (Faegri et Iversen, 1989). Subsamples were deflocculated with 10% hot KOH and sieved through a 650-µm mesh. Silicates, carbonates and cellulose were removed by successive suspensions in 40% HF, 10% HCl and an acetolysis, respectively. A minimum of 300 grains of terrestrial vascular plants was counted per subsample at 400× on a light microscope. Pollen grains were identified using the modern pollen collection of the

Centre for Northern Studies (Université Laval, QC) and of the Institut des Sciences de l'Évolution de Montpellier (ISEM, Université de Montpellier, France), and with a published key (Richard, 1970). Pollen percentages were calculated using the pollen sum of terrestrial vascular plants, and pollen accumulation rates (grains cm^{-2} yr^{-1}) were based on their pollen concentration. Pollen grains of *Picea* are mostly attributable to *P. mariana* in the western region and to a mix of *P. mariana* and *P. glauca* in the eastern region (Payette, 1993).

We characterized vegetation changes through time using the rate of change (hereafter ROC) technique. ROC corresponds to the amount of ecological change in the vegetation cover per time unit and allows the detection of rapid vegetation changes caused by a sudden change in climatic conditions and/or disturbance events (Jacobson et Grimm, 1986). We calculated ROC as the dissimilarity between pollen assemblages composed only by taxa having a mean frequency greater than 1% during a given time interval. The dissimilarity measurement is based on the Euclidean distance computation between two adjacent pollen spectra. ROC peaks were identified when they exceeded a time-dependent background computed from running median smoothing using the CLIM-X-DETECT program (Mudelsee, 2006). We also identified pollen periods based on stratigraphically-constrained cluster analysis of the pollen percentage means of each region using CONISS (Grimm, 1987). These two procedures allowed us to highlight the main vegetation changes over time. We used the occurrence of "exotic" pollen taxa (pollen grains transported over long distances from southern mixed and deciduous forests, such as those of *Acer* sp., *Quercus* sp. and *Fraxinus* sp.) representing more than 1% in pollen assemblages as a proxy to evaluate the opening of the landscape following a disturbance. We assumed that the incorporation of such exotic taxa in the pollen assemblage was only possible when large opened burned areas occurred in the landscape (Richard, 1979).

2.4.5 Statistical analyses

We explored the relationships between multi-millennial variability in fire metrics and vegetation using Pearson's correlation coefficients. *FS* index values and pollen percentages time-series were resampled to the equally spaced time-step of the *RegFF* (i.e. 500 years) using spline interpolation. Exotic pollen assemblages were not analysed due to high heterogeneity in pollen production, conservation and historical migration between species. Time-series from the eastern and western regions were pooled for the correlation analysis (total sample size N = 31). The statistical significance of correlations was determined using bootstrap resampling (von Storch & Zwiers, 1999; n = 10,000 simulations): the 5^{th} and 95^{th} quantiles were used to determine the confidence interval. When the confidence interval contained zero, the hypothesis of 'no correlation' between vegetation and fire from 8.0 kyr BP to present couldn't be rejected at the 95% level.

2.5 Results

2.5.1 Fire histories

In the western region, the number of fires detected per lacustrine record during the last 7000 years ranged from 22 to 42 (Appendice C). Regional fire frequency (*RegFF*) increased progressively up to 0.0054 fires.year^{-1} (90% CI: ± 0.0011) from ca. 7.0 to ca. 4.0 kyr BP, and then decreased to reach a minimum value of 0.0032 fires.year^{-1} (90% CI: ± 0.0006) at ca. 2.2 kyr BP (Fig. 2.2a). Finally, it increased until the present day, reaching the value of 0.0048 fires.year^{-1} (90% CI: ± 0.0006), which corresponds to a mean fire interval (hereafter MFI) of 208 years (between 185 and 238). Regional biomass burned (*RegBB*) values increased from 7.0 to 4.0 kyr BP, decreased up to ca. 2.4 kyr BP, and then remained relatively stable afterwards (Fig. 2.2b). The fire size index (*FS* index) increased between ca. 7.0 and 5.0 kyr BP from 1 to 1.5 units, then decreased until ca. 3.8 kyr BP (1.1), before increasing again to reach a maximum value of 1.7 at ca. 2.1 kyr BP (Fig. 2.2c). After 2.0 kyr BP, it decreased to reach the value of 0.8 units to the present day.

In the eastern region, the time-span covered by individual lacustrine records is unequal; consequently, one must be cautious when interpreting the period between 8.4 and 7.5 kyr BP and that of the last 500 years owing to the presence of only two lakes. Between 44 and 55 fires were detected per lacustrine record (Appendice C). At ca. 7.5 kyr BP, *RegFF* was approximately 0.0058 $fires.year^{-1}$ (90% CI: ± 0.0018), and increased up to ca. 5.6 kyr BP, reaching the value of 0.0076 $fires.year^{-1}$ (90% CI: ± 0.0008) (Fig. 2.2a). Between ca. 5.6 and 2.5 kyr BP, *RegFF* varied among sites (Appendice D) with a mean of 0.0059 $fires.year^{-1}$ (90% CI: ± 0.0048). Then, between ca. 2.5 and 1.2 kyr BP, *RegFF* decreased to 0.0042 $fires.year^{-1}$ (90% CI: ± 0.0010) to finally approximate 0.0050 $fires.year^{-1}$ (90% CI: ± 0.0013) at the present day (Fig. 2a). On the other hand, *RegBB* values were somewhat stable between 8.4 and 2.2 kyr BP (Fig. 2.2b; Appendice E), and then increased until 1.4 kyr BP, followed by a gradual decrease up to the present day. Finally, the *FS* index values were high before 7.0 kyr BP, and then decreased and remained low until 2.0 kyr BP. A high increase occurred between 2.0 and 1.4 kyr BP, followed by a decrease to present-day values (Fig. 2.2c).

In summary, except between 6.7 and 5.3 kyr BP and between 3.0 and 1.9 kyr BP, the two regions displayed overall comparable *RegFF* trends (Fig. 2.2a; as indicated by the overlapping confidence intervals). In both regions, high values of *RegFF* were recorded between 6.0 and 3.5 kyr BP. Between 7.0 and 1.9 kyr BP, individual fire events affected larger areas in the western region (Fig. 2.2c; *FS* index above the global mean). Afterwards and up to 0.5 kyr BP, individual fire events affected larger areas in the eastern region.

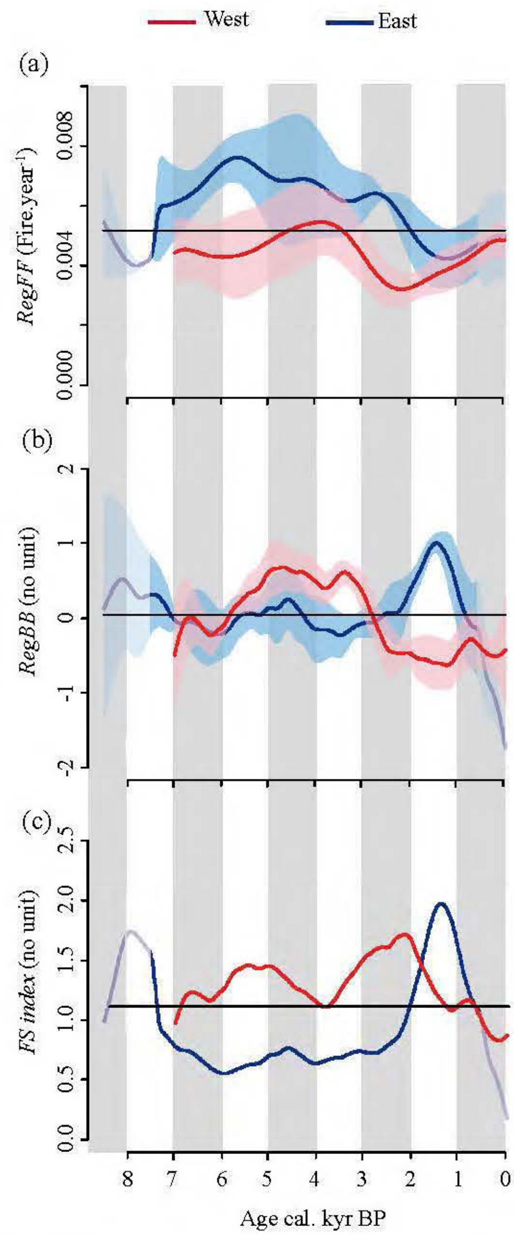

Figure 2.2 Reconstructed fire histories in the western (from Lakes Nano, Loup, Marie-Eve, Trèfle, Schön and Garot) and eastern (from Lakes Innu, Steeve and Ayla) regions of Quebec-Labrador. (a) Fire frequency (*RegFF*), (b) biomass burned (*RegBB*) and (c) fire size (*FS* index) are calculated for the 500-year bandwidth. The blue and red areas correspond to the 90% bootstrap confidence intervals. The light blue line indicates the *RegBB*, *RegFF* and *FS* index values in the eastern region calculated only from two lakes (Lakes Steeve and Ayla). The black horizontal lines indicate the mean values throughout the last 8400 years from the two regions.

2.5.2 Vegetation dynamics

In the western region, we observed several peaks of ROC ca. 7.2 kyr BP (W2 period; Fig. 2.3) and an increase in *Picea* (Fig. 2.4, Appendice F). During this particular period, *A. viridis* ssp. *crispa* represented 10% or more of the pollen assemblages and remained around this value until the present day, except at Lake Schön (the southernmost lake), where it reached no more than 3% during the last 7000 years (Fig. 2.4). Between ca. 7.2 and 6.2 kyr BP (W2 period), we observed a slight increase in *A. balsamea*, mostly at lakes Schön and Marie-Eve (Fig. 2.4, Appendice F). This species has poor pollen dispersal and low pollen production, and is therefore generally underrepresented in pollen records (Jackson *et al.*, 1997). Thus, the low pollen value of this taxon in the records could still reflect the presence of stands at the landscape scale.

Peaks of ROC recorded between 6.2 and 4.1 kyr BP (W3 period) were concomitant with a gradual increase in exotic species and/or in *Pinus banksiana* at Lakes Marie-Eve, Schön and Nano (Figs. 2.3 and 2.4). Then, between ca. 4.1 and 2.7 kyr BP (W4 period), ROC peaks (Fig. 2.3) correspond, among other things, to a decrease in *Betula* sp. pollen percentages at all sites (Fig. 2.4; Appendice F). Since ca. 2.7 kyr BP (W5 period), *Picea* sp. and *P. banksiana* have represented almost 60% of pollen assemblages and the lowest pollen percentages of *A. balsamea* and *Betula* sp. in the entire record have been observed (Fig. 2.4). *Pinus banksiana* increased by approximately 20% at Lake Schön and by 10% at Lake Nano during the last 500 years (Fig. 2.4; Appendice F). In addition, *A. viridis* ssp. *crispa* has increased by approximately 15% at Lake Marie-Eve during the last millennium (Fig. 2.4). These vegetation changes coincided with peaks of ROC for the three lakes (Fig. 2.3).

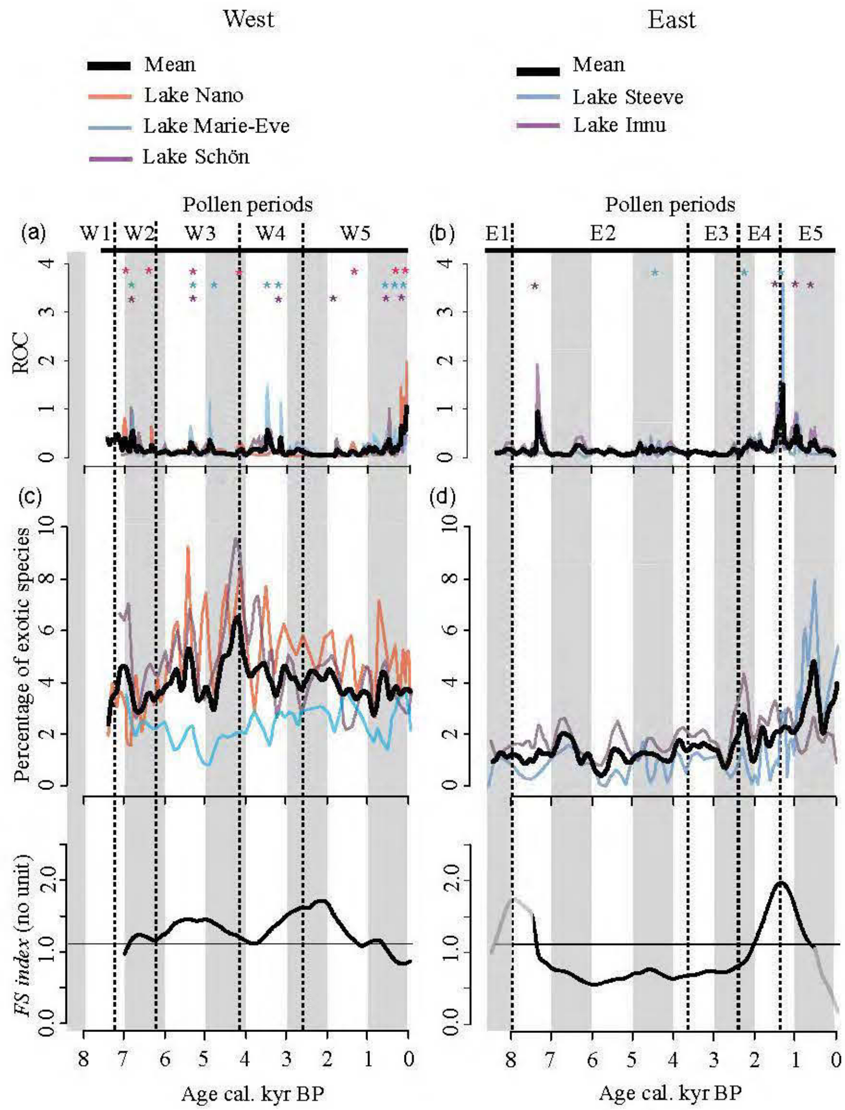

Figure 2.3 Indices of vegetation changes calculated from the pollen data in western (from Lakes Nano, Schön and Marie-Eve) and eastern (from Lakes Innu and Steeve) Quebec. (a, b) Rate of vegetation change (ROC), and (c, d) percentage of exotic species included (*Acer saccharum* Marsh. or *sacharrinum* L., *Acer spicatum* Lam., *Acer pensylvanicum* L., *Tsuga canadensis* L., *Quercus* L., *Fagus grandifolia* Ehrh., *Carpinus* sp. L., *Ostrya* sp. Scop., *Juglans cinerea* L., *Ulmus americana* L., *Fraxinus nigra* Marsh., *Fraxinus pennsylvanica* Marsh., *Tilia americana* L., *Carya ovata* (Mill.) K. Koch, *Thuja occidentalis* L. or *Juniperus communis* L., *Castanea dentata* (Marsh.) Borkh, *Liquidambar* L. and *Corylus cornuta* (Marsh.)). Asterisks indicate ROC peaks exceeding the time-dependent background. (e, f) Fire size index from Fig. 2.2. The vertical dotted lines correspond to the pollen assemblage period boundaries.

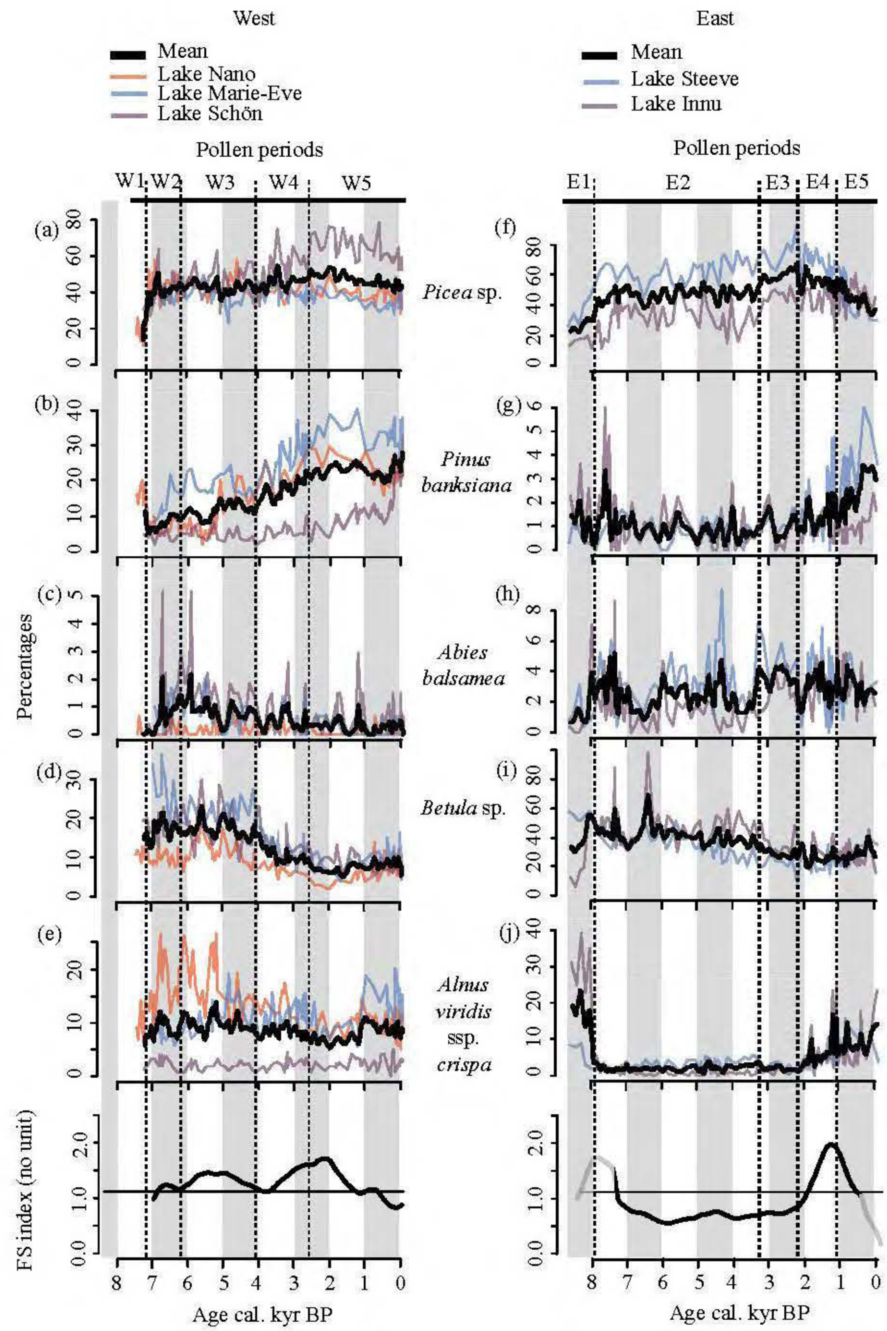

Figure 2.4 Pollen percentages (selected taxa) from Lakes Nano, Schön and Marie-Eve in the western region (left), and from Lakes Innu and Steeve in the eastern region (right) of Quebec-Labrador. The vertical dotted lines correspond to the pollen assemblage period boundaries. The fire size index comes from Fig. 2.2.

In the eastern region, increases in *Picea* sp., *A. balsamea* and *Betula* sp. were recorded around 8.0 kyr BP, concomitant with a decrease in *A. viridis* ssp. *crispa* (E1 period; Fig. 2.4). The beginning of the E2 period (ca. 7.8 kyr BP) was characterised by an increase in *A. balsamea* (at both sites) and *P. banksiana* (5-6% at Lake Innu), associated with ROC peaks (Figs. 2.3 and 2.4). Then, lower values of *P. banksiana* were recorded, oscillating close to 1%, until 2.2 kyr BP (E2 and E3 periods; Fig. 2.4). Simultaneously, mean values of *A. balsamea* pollen oscillated between 2 and 4%, reaching a maximum of 8% at Lake Steeve around 4.2 kyr BP (Fig. 2. 4). Between ca. 3.6 and 2.2 kyr BP (E3 period), an increase in *Picea* sp. was recorded, while *Betula* sp. became gradually less abundant in pollen records (Fig. 2.4). Since ca. 2.2 kyr BP (E4 and E5 periods), there have been several ROC peaks corresponding to an increase in pollen percentages of *P. banksiana* (Lake Steeve) and *A. viridis* ssp. *crispa* (both lakes) (Figs. 2.3 and 2.4). This period has also been characterised by an increase in the pollen abundance of exotic species since ca. 2.0 kyr BP at Lake Steeve and since ca. 1.0 kyr BP at Lake Innu (Fig. 2.3).

2.5.3 Statistical relationships between fire activity and vegetation

The pollen abundance of *Picea* was uncorrelated with variability in *RegFF* and *FS* index ($p > 0.05$; Table 2.2). In contrast, *A. balsamea* and *Betula* sp. were significantly more abundant during periods of high *RegFF* but low *FS* index ($p < 0.05$; Table 2.2). *Pinus banksiana* and *A. viridis* ssp. *crispa*, on the other hand, were significantly more abundant in landscapes during periods of low *RegFF* and high *FS* index.

Table 2.2 Pearson's correlation coefficients (ρ) and confidence intervals at the 95% level between reconstructed fire regime history and percentage of main vegetation species.

	FS			FF		
Species	***ρ***	**0.05**	**0.95**	***ρ***	**0.05**	**0.95**
Picea sp.	-0.14	-0.45	0.17	0.23	-0.01	0.43
Pinus banksiana	0.41*	0.16	0.67	-0.67*	-0.81	-0.50
Abies balsamea	-0.26	-0.61	0.00	0.48*	0.25	0.69
Betula sp.	-0.47*	-0.76	-0.12	0.69*	0.46	0.86
Alnus viridis ssp. *crispa*	0.49*	0.22	0.72	-0.62*	-0.79	-0.42

Asterisks indicate significant correlations.

2.6 Discussion

2.6.1 Fire activity

Our data show that during the last 7000 years, fire frequency in the eastern region was higher than or equal to that of the western region (Fig. 2.2a). The variation in fire histories between lakes located in a same region is indicative of the influence of local factors such as soil deposits, topography and vegetation on wildfires (Fig. 2.2 and Appendice C and D; Gavin *et al.* 2006; Ali *et al.* 2009). However, the lower differences in frequency between composite records from the different regions likely correspond to long-term changes in climate (Blarquez *et al.*, 2015 ; Hély *et al.*, 2010).

The first period of higher fire activity in the eastern region (6.7-5.3 kyr BP) could be explained by an earlier afforestation of this region after the retreat of the Laurentian ice sheet (King, 1986). This region has been free of ice since 8.4 kyr BP and has not been affected by the presence of a proglacial lake and/or marine transgression. In contrast, the onset of sedimentation at Lakes Garot and Schön in the western region began ca. 7.0 kyr BP after the withdrawal of the proglacial Lake Ojibway, and ca. 6.0 kyr BP at Lakes

Loup and Nano after the withdrawal of the Tyrrell Sea (Dyke, 2004), thus delaying vegetation development. In the western region, the slow and gradual increase in *RegFF* up to 5.5 kyr BP (Fig. 2.2a) could have been caused by high soil moisture due to the Tyrrell Sea transgression, which limited fire spread as well.

Between 7.0 and 2.5 kyr BP, the *FS* index of the western region was twice that of the eastern one (Fig. 2.2c). A flat relief, such as that characterising the western region, is known to favour fire spread over large areas (Cyr *et al.*, 2005). Furthermore, the extensive peatlands also characterising the western region seemingly did not act as efficient firebreaks. In contrast, the eastern region has fire-break features that make it less prone to the development of large fires, including a more hilly relief and more humid climate (Gauthier *et al.*, 2015). In both regions, high *RegFF* were recorded between 5.5 and 3.5 kyr BP (Fig. 2.2a). Previous studies on Holocene climate simulations based on general circulation models (GCM) related to the western region have shown that dry and warm conditions combined with a long fire season promoted this high fire activity (Hély *et al.*, 2010; Ali *et al.*, 2012; Oris *et al.*, 2014). Then, since 3.5 kyr BP, a gradual decrease in fire frequency has been recorded in the western region. In the eastern region, this decrease has occurred since 2.5 kyr BP. The Neoglacial period (since ca. 3.5 to 0.2 kyr BP; Cayer & Bhiry, 2014; Viau & Gajewski, 2009), which was characterised by colder and wetter conditions than before, was considered less conductive to fires in North America (Gavin *et al.* 2006). However, a gradual increase in fire frequency has been recorded in the western region since 2.0 kyr BP (Fig. 2.2a). Moreover, in the eastern region, the decrease in fire frequency occurred significantly later than the Neoglacial onset (Fig. 2.2a). These results suggest that unexplored regional forcing controlled the fire activity. Unstable climatic conditions have been highlighted during the Neoglacial period in several parts of the Northern Hemisphere without a clear understanding of the causes, but they are potentially linked to a decrease in solar irradiance (Kaplan *et al.*, 2002; Mellström *et al.*, 2015). In our case, changes in the Pacific Ocean's sea surface temperature and in the position and strength of blocking ridges in the upper-atmosphere (Girardin *et al.*, 2006) could be involved.

Between 2.0 and 1.5 kyr BP, the eastern region was affected by larger wildfires than previously (Fig. 2.2c). It was probably due to climate modifications, with drier/warmer summers and/or springs (Ali *et al.*, 2012). At present, the *FS* index indicates that fires are smaller in the eastern than in the western region, as also observed in analyses of contemporary Canadian fire statistics (Stocks *et al.*, 2003).

A positive feedback of vegetation composition is also worth considering. Indeed, an increase in coniferous species (*Picea* sp., *Pinus banksiana*) since 4.0 kyr BP in the western region and since 3.0 kyr BP in the eastern region can be observed (W4-5 and E3-5 periods; Fig. 2.4). This increase in fire-prone species could partly explain the periods of high fire frequency and the larger fire sizes during the last 4000 years in each region through enhanced fire spread and ignition (Hély *et al.* 2001; Higuera *et al.*, 2009; Carcaillet *et al.* 2010; Kelly *et al.*, 2013).

2.6.2 Vegetation trajectories

After the deglaciation and the retreat of the proglacial Lake Ojibway and the Tyrell Sea, the vegetation rapidly colonised the landscape (Fig. 2.4). All tree species considered in this study (*Picea* sp., *Betula* sp., *Pinus banksiana*, *Abies balsamea*) were already present in both studied regions (King, 1986; Richard, 1979). However, *Betula* sp. seems to have been more abundant in the eastern than in the western region, where soils are more xeric and compacted in the flat Clay Belt (Foster & King, 1986). In the western region, *A. balsamea* was rare around Lake Nano, which is nowadays located close to the northern limit of the distribution range of this species (Payette, 1993). In the eastern region, *P. banksiana* was initially most abundant around Lake Innu than Lake Steeve (Fig. 2.4g). A study of King (1986), who has reconstructed the regional vegetation from pollen assemblages of Lakes Coghill, Harrie and Gras (Fig. 2.1), also shows this higher percentage of *P. banksiana* in the early-Holocene period than after. Glacial refuges for this species may have existed on the Canadian coast of the Atlantic (Godbout *et al.*, 2005), explaining its presence in north eastern territories 8000 years ago.

Since the afforestation period between 7.0 and 6.0 kyr BP, *Picea* sp. has become the permanently dominant species in the landscapes of both regions, independently of variations in wildfire activity (Table 2.2). In addition, vegetation changes (Figs. 2.3 and 2.4) favoured, on the one hand, *A. viridis* ssp. *crispa* and *P. banksiana* in the western region, except at Lake Schön which is located in a closed spruce-moss forest on organic soil, and, on the other hand, *A. balsamea* in the eastern region (Fig. 2.4). Statistical analyses show that the dynamics of *P. banksiana* and *A. viridis* ssp. *crispa,* two fire-adapted species, were more closely linked to fire size than to fire frequency (Table 2.2). In contrary, *A. balsamea,* a poorly fire-adapted species, was more abundant in landscapes subject to small but frequent fires. In addition, the major vegetation transformations over long and short time intervals (i.e. pollen assemblage boundaries and rates of vegetation change; Fig. 2.3a and 3b) occurred during periods when landscapes were affected by large fires. Consequently, we assumed that the difference in the historical dynamics of the fire size could explain the present-day vegetation configuration in both regions.

In the western region, between 7.0 and 2.0 kyr BP, the opening of the landscape caused by large fires allowed both the development of *A. viridis* ssp. *crispa* stands (early successional species) and the expansion of *P. banksiana* (Asselin *et al.*, 2003). This was particularly true between 4.0 and 2.0 kyr BP at Lakes Nano and Marie-Eve (located in the black spruce-lichen and in the northern part of the black spruce moss-vegetation domains, respectively; Fig. 2.1), when the size of fires reached the highest values (Figs. 2.2a and 2.4c). The continuous input of exotic species pollen grains coming from the south and from outside of the boreal region (Fig. 2.3c and 3d) attests to this opening.

Between 7.0 and 2.0 kyr BP, in the eastern region, the significant presence of *A. balsamea* at Lakes Innu and Steeve, and also near the northernmost Lakes Harrie and Coghill (Fig. 2.1; King, 1986), was made possible because fires were generally small (Fig. 2.2c). The high abundance of *Betula* sp. in this region probably contributed to reducing fire size (Hély *et al.*, 2001). Then, 2000 years ago, the region was affected by the largest fires recorded in the last 7000 years for both regions (Fig. 2.2c). This change in fire regime allowed an increase in *P. banksiana,* mostly around Lake Steeve, which is surrounded by more xeric edaphic conditions than Lake Innu (Fig. 2.4g; Table 2.1). This increase, which was also recorded in the pollen diagrams of Lakes Gras and Coghill (Fig. 2.1; King, 1986), was also concomitant with an increase in exotic species as well as *A. viridis* ssp. *crispa* in the pollen assemblages of Lakes Steeve and Innu (Figs. 2.3d and 2.4j). However, despite these larger fires, *A. balsamea* remained a predominant species in the eastern landscape and *P. banksiana* never reached the abundance recorded in the western region. We assumed that during this large-fire period, some parts of the landscape may have escaped from fire, notably on moist hillsides such as the leeward or north, shaded sides, and have therefore acted as refuge areas for *A. balsamea* and *Betula* sp. (Asselin *et al.*, 2001; Bergeron *et al.*, 2004), allowing them to reinvade burned areas. Those results also suggest that even if large fires can cause rapid vegetation changes in the landscape (e.g. ROC analysis), a long period (millennial time-scale) with many large fires is necessary to impact long-term vegetation trajectories at the regional scale, especially in hilly regions.

2.7 Conclusion

This study underlines the consequences of past vegetation-fire interactions on the present-day vegetation structure of boreal forests in eastern North America. Our data suggest that changes in forest composition were mostly driven by fire size rather than by fire frequency. Indeed, differences in long-term dynamics of fire size have explained the major vegetation trajectories recorded in the eastern and western coniferous boreal forests of Quebec. The positive feedback of vegetation on fire activity could also have played a key role, notably when fire-prone conifers gradually developed in the regional landscape. However, the causes and impacts of these large fires seem to be more complex than expected because they are largely modulated by biotic (vegetation types) and abiotic (climate, topography, waterbodies, soils, etc.) factors at the small spatial scale. For example, the eastern region, which is currently experiencing a colder and moister climate than the western region, has been submitted to higher fire frequency and larger fires than the western part during some periods, which is certainly due to a combination of local factors inducing an increase in fire ignition and/or spread.

As already observed in others parts of the Northern Hemisphere (Barton, 2002; Keane *et al.*, 2008), the projected increase in wildfires over the next decades could enhance the propagation of large fire events in the boreal ecosystem. The impact of climate change on the rate of occurrence of large-fire episodes must be a focal point in future investigations. A higher spatial-scale accuracy of paleoecological data and a better understanding of past climatic changes are required to predict fire regime more efficiently. Furthermore, the period between 3.0 and 2.0 kyr BP, characterized by the largest fires ever recorded in north eastern America and by a widespread increase in burned biomass in the majority of continents (Marlon *et al.*, 2013), is a relevant period for targeting future research efforts.

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CHAPITRE III

DIFFERENT REGIONAL CLIMATIC DRIVERS OF HOLOCENE LARGE WILDFIRES IN BOREAL FORESTS OF NORTHEASTERN AMERICA

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3.1 Abstract

Global warming could increase climatic instability and large wildfire activity in circumboreal regions, potentially impairing both ecosystem functioning and human health. However, links between large wildfire events and climatic and/or meteorological conditions are still poorly understood, partly because few studies have covered a wide range of past climate-fire interactions. We compared palaeofire and simulated climatic data over the last 7000 years to assess causes of large wildfire events in three coniferous boreal forest regions in north-eastern Canada. These regions span an east-west cline, from a hilly region influenced by the Atlantic Ocean currently dominated by *Picea mariana* and *Abies balsamea* to a flatter continental region dominated by *Picea mariana* and *Pinus banksiana*. The largest wildfires occurred across the entire study zone between 3000 and 1000 cal. BP. In western and central continental regions these events were triggered by increases in both the fire-season length and summer/spring temperatures, while in the eastern region close to the ocean they were likely responses to hydrological (precipitation/evapotranspiration) variability. The impact of climatic drivers on fire size varied spatially across the study zone, confirming that regional climate dynamics could modulate effects of global climate change on wildfire regimes.

3.2 Résumé

Le réchauffement climatique pourrait augmenter l'instabilité climatique et l'occurrence des grands feux dans les régions circumboréales, altérant potentiellement à la fois le fonctionnement des écosystèmes et la santé humaine. Cependant, les liens entre les événements de grands feux et les conditions climatiques et/ou météorologiques sont encore mal connus, en partie en raison du fait que peu d'études ont porté à ce jour sur un large éventail d'interactions passées entre le climat et les feux. Nous avons donc comparé des données de paléofeux avec des données climatiques simulées au cours des 7000 dernières années pour évaluer les causes à l'origine de l'éclosion de grands feux de forêt dans trois forêts boréales conifériennes du nord-est du Canada. Ces régions couvrent un gradient est-ouest, allant d'une région vallonnée influencée par l'océan Atlantique dominée par *Picea mariana* et *Abies balsamea*, à une région continentale à topographie plus plane et dominée par *Picea mariana* et *Pinus banksiana*. Nos résultats montrent que les plus grands incendies ont eu lieu entre 3000 et 1000 ans cal. AA à travers la zone d'étude entière. Dans les régions continentales de l'ouest et du centre, ces événements ont été déclenchés par une augmentation des températures printanières et estivales, et une saison de feux plus longue. Dans la région de l'est, plus proche de l'océan Atlantique, les grands feux ont été probablement causés par une forte variabilité hydrologique (précipitations/évapotranspiration). L'impact de ces facteurs climatiques varie spatialement à travers la zone d'étude, confirmant que la dynamique climatique régionale pourrait moduler les effets du changement climatique à l'échelle mondiale sur les régimes de feux de forêt.

3.3 Introduction

Fire is the most important natural disturbance in the boreal forest biome, affecting vegetation dynamics, biodiversity (Granström 2001, Bond *et al* 2005), biogeochemical cycles and atmospheric aerosols (Stocks *et al* 1998, Kasischke *et al* 2005, Kelly *et al* 2016). Model-based predictions suggest that the severity of fire regimes will increase in the future in response to global warming (Turetsky *et al* 2011, de Groot *et al* 2013). Some scenarios even suggest that frequencies of large fires may increase sufficiently to push current fire suppression capacity beyond a tipping point (Amiro *et al* 2001, Balshi *et al* 2009, de Groot *et al* 2013, Lehsten *et al* 2016). Such changes could threaten human safety, impair the viability of some economic sectors (Simms 2016), and trigger substantial changes in vegetation structure and composition (Flannigan *et al* 2005, Remy *et al* 2016). However, robust prediction of the changes, evaluation of likely consequences, and formulation of appropriate adjustments to forest management strategies are hindered by paucity of understanding of the climate factors inducing large wildfires. The infrequent and random nature of these events, coupled with the short historical period covered by fire statistics (usually less than 100 years), further reduce the robustness of fire predictions. In this context, paleoecological investigations based on analysis of lacustrine sedimentary cores are valuable as they enable exploration of the relationships between fire size and climate in long-term perspectives (Ali *et al* 2012), and identification of the main climatic drivers of eclosion of large fire events.

During the last 7000 years, fires in boreal forest of northeastern Canada have mostly been larger in the continental region than in the region closer to the Atlantic Ocean (Remy *et al* 2016), hereafter referred to as the western and eastern regions of our study zone, respectively. According to previous studies (Balshi *et al* 2009, Ali *et al* 2012, Remy *et al* 2016) large fires in the western region have been triggered by long late fire-seasons, with warmer than today springs and dry summers. Thus, based on these results, we hypothesize that the fire season in the eastern region was mostly shorter, with colder springs and moister summers, than in the western one during the study period (Girardin and Wotton 2009, Boulanger *et al* 2013). However, around 1500 years cal. BP, fires in the eastern region became dramatically larger, more than those in the western region (Remy *et al* 2016). Two possible explanations for this are that the climate in western and eastern regions became similar, or climatic changes that favored large fire ignition specifically occurred in the eastern region.

The main objective of this study was to assess the spatial variation (if any) in drivers of large fires in coniferous boreal forests of eastern North America. A specific hypothesis tested is that periods of large-fires during the Holocene were associated with long late fire-seasons, with warm springs and dry summers, across the entire study zone and thus independently of regional characteristics. For this purpose we studied both past climate variations and fire size histories in three regions of boreal forests in Quebec-Labrador (western, central and eastern regions) displaying same or different relief, current climate conditions, fire activity and vegetation composition. We used macroscopic charcoal fragments previously extracted from lake sediments to reconstruct regional fire size histories during the last 7000 years. Then, we compared these fire reconstructions with simulated climate data obtained from a general circulation model (GCM) that we downscaled at regional scales to detect relationships between climate and fire size. The results highlight the importance of several climatic drivers of large fire occurrences linked to some regional characteristics during the Holocene, and we discuss their potential profound implications for future fire regimes across eastern Canada.

3.4 Materials and methods

3.4.1 Study area

We used 13 charcoal records from lacustrine sediments located along a 500-km east-west transect within spruce woodlands (spruce-moss in the south and spruce-lichen in the north) of Quebec-Labrador (between 50 and 53°N, and 67 and 79°W; Figure 3.1). Six of the lakes are located near the James Bay Lowlands in western Quebec (Oris *et al* 2014), four near Mistassini Lake in central Quebec (El-Guellab *et al* 2015) and three in eastern Quebec or Labrador (Remy *et al* 2016; Figure 3.; Appendice H). These areas were rapidly colonized by trees after the last deglaciation, between ca. 8000 and 7000 years cal. BP (Richard 1995). Since then, the western and central regions have been mainly dominated by *Picea mariana* (Mill.) B.S.P. and *Pinus banksiana* Lamb. (Richard 1979, Gajewski *et al* 1993, Payette 1993), while the eastern region has been mainly dominated by *P. mariana* along with *Abies balsamea* (L.) Mill., and *Picea glauca* (Moench) Voss (Mott 1976, King 1986, Payette 1993). Mean annual temperature (from 1966 to 1996) are between -1.1 and -3.1 °C in western and central regions and are between -3.1 and -5.0 °C in eastern region (DesJarlais C *et al* 2004). Mean annual precipitations (from 1966 to 1996) are between 710 and 989 mm in western region, 850 and 989 mm in central region, and 850 and 1129 mm in eastern region (DesJarlais C *et al* 2004). In recent decades, fires in the eastern region have been less frequent than in the western and central one, but may have been episodically larger (Stocks *et al* 2003, Bergeron *et al* 2004, Bouchard *et al* 2008).

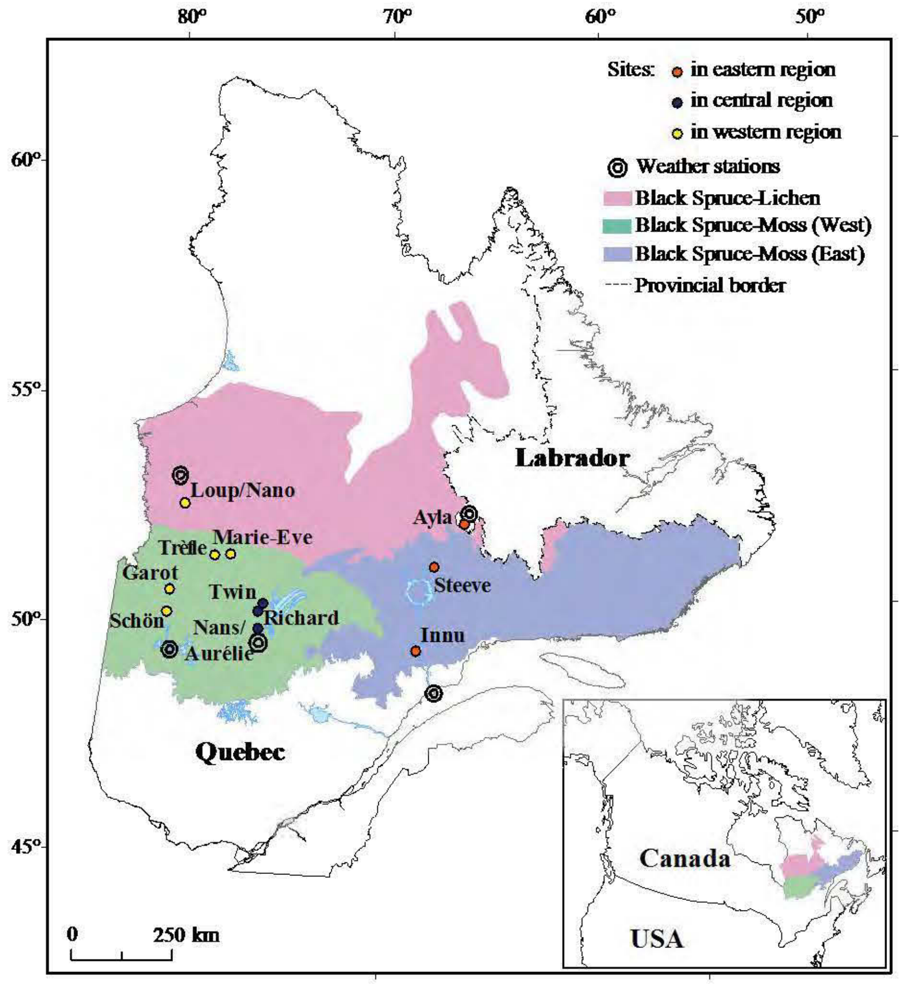

Figure 3.1 Locations of the study sites in the western, central and eastern regions of Quebec-Labrador.

3.4.2 Fire-history reconstructions

Lakes with small surface areas and sufficiently long sediment cores to provide robust sedimentary records of fires at the local scale (i.e. at the watershed scale) were selected (Appendice H). Sediment cores composed of gyttja were extracted between 2007 and 2013. To obtain fine-scale temporal resolution, they were cut into contiguous 0.5- to 1-cm thick slices depending on total sequence length (Appendice H). Sediment accumulation chronologies were generated based on AMS radiocarbon dating of terrestrial plant macroremains and/or total organic content extracted from gyttja samples. 14C dates were calibrated using the Bchron R package based on the IntCal13.14C data set (Hua *et al* 2013, Reimer 2013). Age-depth models were obtained using Bayesian models (Parnell *et al* 2008). All dates were expressed in calibrated years before present (hereafter BP).

Charcoal samples from all lacustrine cores were obtained from previous studies (Appendice H) in which a common protocol for extracting charcoal was applied. Particles were measured and the resulting data were transformed into charcoal accumulation rates (CHAR; mm^2 cm^{-2} yr-1) based on numerical age-depth models to reconstruct past regional biomass burning (hereafter RegBB; no unit) and past regional fire frequency (hereafter RegFF; # of fires yr-1) values. Individual CHAR series were homogenized to reduce the influence of sedimentation rate and potential taphonomic biasing factors linked to sequestration of charcoal in the sediments (Power *et al* 2008). Homogenized series were then pooled to build the RegBB by (i) rescaling initial CHAR values using min-max transformation, (ii) homogenizing the variance using Box-Cox transformation, and (iii) rescaling the values to Z-scores (Power *et al* 2008).

The dates of local fire events (≤ 1-3 km from the lake shore; (Higuera *et al* 2007) were extracted from CHAR series using CharAnalysis v1.1 software (Higuera *et al* 2010a) available at https://sites.google.com/site/charanalysis/ (Appendice G). The local fire frequency was calculated using the 'paleofire' R package (Blarquez *et al* 2014). The RegFF for each region was constructed by pooling individual lake smoothed series (Ali *et al* 2012, Kelly *et al* 2013). We assessed the significance of changes in both RegFF and RegBB by bootstrap resampling the pooled means 999 times (BCI; 90%).

For each region, we used the ratio between RegBB and RegFF (hereafter FS index; Ali *et al* 2012) to assess changes in fire size through time. The significance of changes in the FS index was derived from ratios between maximum and minimum values of

RegBB and RegFF. The RegBB values are correlated to long-term changes in areas burned inferred from fire histories (Higuera *et al* 2010b, Ali *et al* 2012, Kelly *et al* 2013). FS index values are indicative of mean areas burned per fire.

3.4.3 Climate data

We applied the method developed by (Hély *et al* 2010) to climate simulations from the UK Universities Global Atmospheric Modeling Program GCM (hereafter HadCM3; Hall and Valdes 1997) to compute the fire-season length centered on each millennium over the last 7000 years (Singarayer and Valdes 2010) in each region. For each millennium of HadCM3 dataset, we computed the twelve monthly temperature and precipitation anomalies as compared to those from the HadCM3 pre-industrial control (i.e. 1750 AD). To obtain spatial resolution more compatible with our palaeodata, we downscaled these Holocene datasets at 0.5° by applying HadCM3 temperature and precipitation anomalies to the modern 1971-2000 climate normals computed from the Climate Research Unit spatial grid TS 2.1 (Time Series at 0.5°; Mitchell and Jones 2005). Then, within each 0.5° pixel, we used the Gaussian distribution for temperature and the Gamma distribution for precipitation (New *et al* 2002) to reconstruct 30-year time series in which each specific monthly distribution was parameterized with the reconstructed downscaled monthly mean and the modern variance computed from the 1971-2000 climate normals (Ramstein *et al* 2007). The weather generator presented by (Richardson 1981) was applied to the reconstructed 30-year monthly temperature and precipitation time-series to derive the daily values needed to compute the Drought Code index (hereafter DC index) of the Canadian Forest Fire Weather Index System (FWI; Van Wagner *et al* 1987). The DC index relates to deep humus dryness and is used to assess fire risks based on weather conditions with a 52-day lag (De Groot *et al* 2007). According to Hély *et al* (2010), the DC values computed from Canadian weather data (1981-2010) starts to be higher than 80 units in June in eastern North America when spring fires began to occur. Consequently, we calculated the fire-season length based on the cumulative number of days in months with mean DC index value >80 units, to which is added the number of days for the fire-season onset and termination computed as the number of days with DC value >80 units preceding and following the first or the last month with monthly mean DC value >80 units, respectively, based on interpolations of monthly mean DC values (Hély *et al* 2010). Spring fire onset (April–June), summer fire termination (July–October) and hence fire season length in spring, summer and over the year (spring and summer) were determined. The regional simulated climate and fire-season length datasets, expressed as anomalies relative to the control period (0 BP), represent average conditions computed from the three nearest 0.5° pixels to each sampled lake within the western, central and eastern regions of the study area.

Correlations between the reconstructed climate outputs and RegBB, RegFF or the FS index were computed using Pearson's correlation coefficients and assessing their significance using permutation tests (Robinson 2007).

3.5 Results

3.5.1 Fire histories

The Holocene RegFF and RegBB series for the western and central regions displayed the same trends, with fire occurrence peaking around 4000 BP and biomass burning peaking between 5000 and 3000 BP (Figure 3.2). The RegFF gradually increased from ca. four or five fires per millennium at 7000 BP to approximately six per millennium at 4000 BP. It then decreased below ca. three fires per millennium around 2500 BP, before slightly increasing again to present values, close to those recorded during the early-Holocene period. Similarly, RegBB gradually increased from 0 at 7000 BP to 0.6 between 5000 and 3000 BP in the western region and to 0.9 in the central region around 4000 BP, before decreasing to present values, mostly lower than 0. In both of these areas, the FS index values oscillated around 1 before 3000 BP, then rose to 1.4 and 1.6 in the western and central regions, respectively, at ca. 2000 BP before decreasing back close to 1 until the present day. The derived RegFF, RegBB and FS index dynamics through the last 7000 years are independent of changes in sedimentation rates (Appendice J).

In the eastern region, the reconstructions indicated that fire occurrence peaked between 6000 and 2500 BP, whereas biomass burning peaked around 1500 BP (Figure 3.2). RegFF increased gradually from approximately six fires per millennium at 7000 BP to ca. seven between 6000 and 2500 BP. Then, it decreased below four fires per millennium at 1500 BP before increasing again to present values, close to those recorded at 7000 BP. The RegBB value was equal to those in western and central regions at 7000 BP. It oscillated around 0 until 3000 BP and increased during the 3000-1500 BP period, reaching ca. 0.9 around 1500 BP. Then, it decreased rapidly to the present-day value, ca. -1.5; the lowest over the last 7000 years. FS index values of the eastern region stayed lower than 0.8 from 7000 to 2500 BP, and subsequently increased to ca. 1.9 at 1500 BP. This increase in FS index was not linked to a sudden increase in lacustrine sedimentation rates, but coincided with the largest peaks of charcoal area recorded in the three study lakes (Appendice K). Finally, FS index values decreased to 0.3 at present-day.

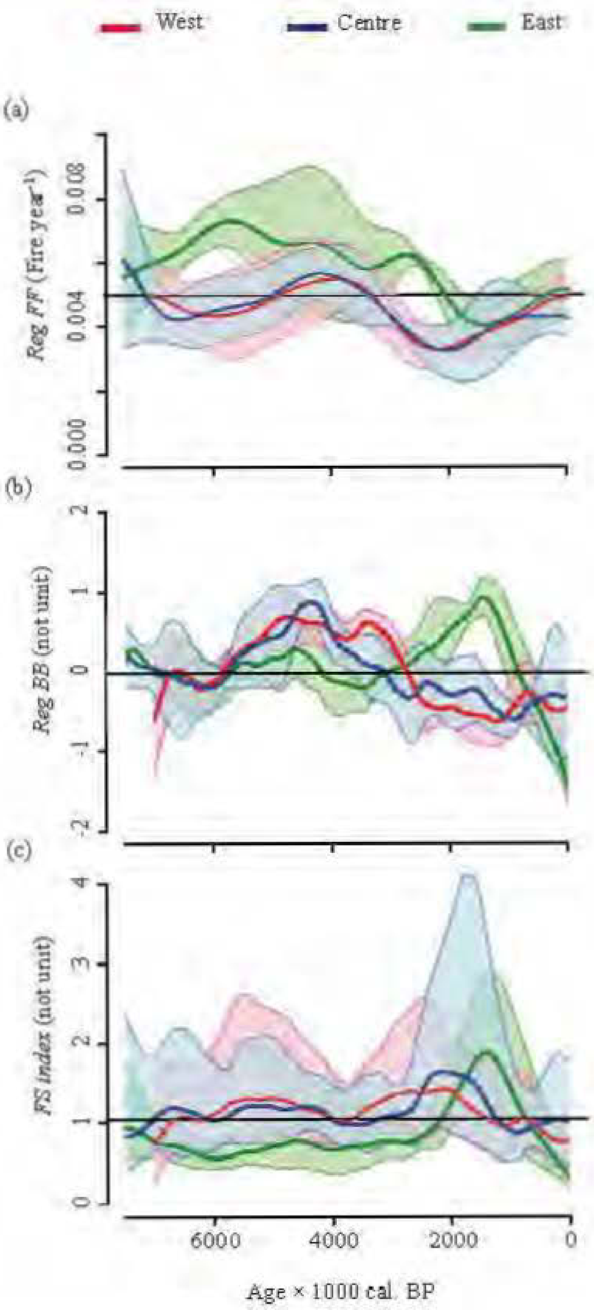

Figure 3.2 Reconstructed fire regime histories based on the analysis of lacustrine charcoal deposits for the western, central and eastern regions of the study area. (a) Fire frequency (*RegFF*), (b) Biomass burning (*RegBB*) and (c) Fire size (Fire size index) calculated for the 500-year bandwidth. The colored areas indicate 90% bootstrap confidence intervals. The black lines indicate the means of *RegBB*, *RegFF* and *FS* index throughout the last 8400 years in the three regions.

3.5.2 Past climate

We have reconstructed Holocene climate data for eight periods centered on each millennium. Thus, although results are reported as temporal trends, climate data between two successive millennia must be interpreted with caution as there is no available data from this HadCM3 Holocene simulation experiment. During the last 7000 years, the fire-season length ranged between 164 and 175 days in the western studied region, and between 155 and 164 days in the central region (Figure 3.3). In these regions, the fire-season started 2-3 days later in spring at 7000 BP than today. Between 6000 and 4000 BP, it began progressively earlier in spring and terminated earlier in summer-fall. During this period, the fire-season was slightly (two-three days) shorter than it is today. Then, between 3000 and 2000 BP, the fire-season extended in fall. At 2000 BP, the fire-seasons in the western and central regions were similar to the present-day seasons in terms of lengths (174 and 161 days, respectively) and time period in the year. However, the fire-season ended 8 and 4 days earlier in the two regions, respectively, and thus was markedly shorter at 1000 BP.

Overall, the fire-season in the eastern region was a third shorter (ranging from 105 to 135 days) than those of western and central regions during the Holocene (Figure 3.3). At 7000 BP, the fire-season length was seven days shorter than today (ca. 130 days), mainly due to a later spring onset. The longest reconstructed fire-season was at 6000 BP, ca. 128 days, similar to the present-day length, and covering the same period in the year. Between 6000 and 4000 BP, the fire-season began progressively later and finished earlier. It was shortest at 4000 BP, when it began three days later and finished 12 days earlier than today. Then, between 3000 and 1000 BP the timings of fire-season length varied between 0-2 days later onset and 7-10 days earlier termination than today.

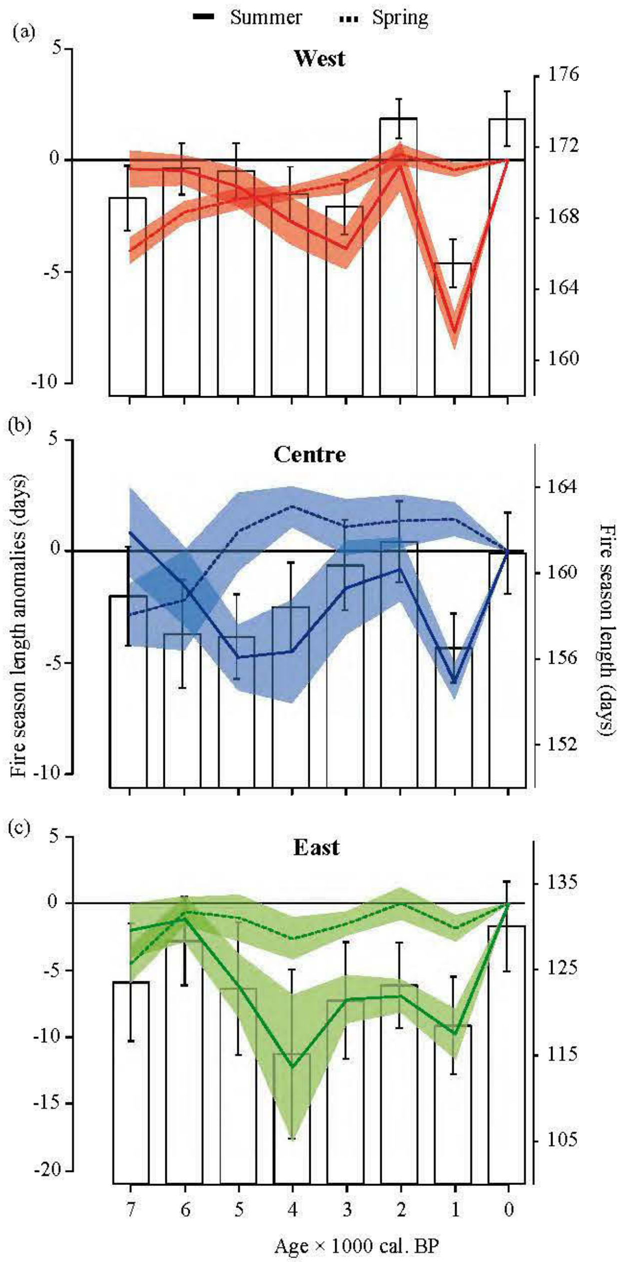

Figure 3.3 Fire season lengths (histograms with standard errors) based on numbers of days with simulated monthly daily Drought Code means higher than 80 (moderate wildfire risks). Holocene departure (in number of days, anomalies relative to 0 BP) of fire-season start (spring from April to June) and end (summer from July to September) are indicated by dashed and solid lines, respectively. Axis values range varying between the regions.

3.5.3 Fire-climate relationships

In the western and central regions, the *FS* index values were significantly higher during periods with warm springs and summers, and when the fire-season began early in spring (Table 3.1). In the eastern region, the *FS* index values were not correlated with either spring or summer temperatures, and were significantly higher during periods when fire-seasons ended relatively early in fall. In the western and eastern parts, *FS* index values were significantly higher during moist periods.

Table 3.1 Pearson's correlation coefficients between past fire size and main climatic variables, fire occurrence and biomass burning for the three regions. Fire season is split into two periods: "spring" from April to June and "summer" from July to September. Significant correlation coefficients are marked in boldface type and asterisks indicate P values (* $P < 0.1$, ** $P < 0.05$, *** $P < 0.01$) determined by permutation tests (sample size: n= 8 millennia).

		West	Centre	East
Temperature	spring	**0.316*** **	**0.416*** **	0.099
	summer	**0.560*** **	**0.216*** **	0.047
Precipitation	spring	**0.633*** **	0.161	0.086
	summer	**0.530*** **	-0.091	**0.764*** **
Fire season length	spring	**0,174* **	**0,228** **	-0,031
	summer	-0,037	**0,236** **	**-0,504*** **
RegBB		0,318	0,036	**0,836** **
RegFF		-0,401	-0,65	**-0,832* **

3.6 Discussion

Our findings clearly show that fire histories during the last 7000 years were similar in the western and central regions, but differed in the eastern region (Figure 3.2). These results suggest that fire regime in oceanic region (east) was driven by different climatic factors than in continental regions (west and centre). Three main chronological periods can be distinguished in the fire size dynamics during this period: 7000 to 3000 BP, when there were larger fires in the west and center than in the east; 3000 to 1000 BP, when the largest fires were recorded in all three regions; and the last 1000 years, when fires were again larger in the west and center than in the east. Detected regional climatic effects on the fire regimes during these three periods are discussed below.

3.6.1 7000-3000 BP

Between 7000 and 3000 BP, fires were mostly larger in the western and central regions than in the eastern one (Figure 3.2), probably partly because the fire-seasons were longer and drier (Figure 3.3 and Appendice L). Other influential factors presumably included the flatter relief and dominance of more fire-prone conifers (which favor the spread of fires), notably *Pinus banksiana* Lamb., in the western and central regions than in the eastern region (Hély *et al* 2001, Blarquez and Aleman 2015, Remy *et al* 2016). In the eastern region, fires were smaller but more frequent, possibly due to the more pronounced variations in relief, which reportedly increased lightning frequencies (Foster 1983, Reap 1986). The environmental conditions were more favorable for fire ignition and frequency in the eastern region before 5000 BP.

High fire frequency and biomass burning during the Holocene were significantly associated with warm and/or dry summers, but cold springs (Appendice I). In the western and central regions, fire frequency and biomass burning both peaked during the mid- to late Holocene period (between 5000-3000 BP) without any increase in fire size (Figure 3.2). According to paleoclimate reconstructions based on pollen data and the modern analog technique, this period corresponds to the Holocene Thermal Maximum, characterized by warm and dry conditions in northern Quebec (Viau and Gajewski 2009) and in various other locations across North America (Bartlein *et al* 1998, Viau *et al* 2006). The simulated climate data used here confirm this climatic scenario in spring with a gradual increase of temperature and DC relative to before, but not in summer Appendice L and M). We therefore assume that between 5000 and 3000 BP higher precipitation and temperature during spring led to increases in combustible biomass (Appendice M). We conclude that series of consecutive days in spring and summer may often have been warm enough to favor fire ignition and spread, but fuel dried insufficiently for fires to spread over large areas, as the springs would have been generally too cool and the fire-seasons in summer too brief (Table 3.1; Figure 3.3; Appendice L) (Ali *et al* 2012).

3.6.2 3000-1000 BP

The decrease in fire frequency between 3000 and 1000 BP (Figure 3.2) has been already observed by other studies in northern boreal forests and previously attributed to a cooler and wetter annual climate corresponding to the Neoglacial period (Gavin *et al* 2006, Ali *et al* 2009, 2012, Oris *et al* 2014, El-Guellab *et al* 2015). It has also been putatively linked to an abrupt decrease in solar activity around 2900-2800 BP (van Geel *et al* 2000, Wanner *et al* 2008). However, the largest fires were recorded in all regions of the study area during this period (Figure 3.2), more specifically around 2500-2000 BP in the western and central regions, and around 1500 BP in the eastern region.

In the western and central regions, large fires were significantly dependent upon warmer springs and summers, relative to those in the preceding period (Figure 3.3; Appendice M), and upon the abundance of fire-prone coniferous species such as *Picea* sp. (mainly *Picea mariana*) and *Pinus banksiana* (Blarquez and Aleman 2015, Remy *et al* 2016). These findings are similar to conclusions from previous studies on boreal forests of North America (Balshi *et al* 2009, Turetsky *et al* 2011, Ali *et al* 2012, Blarquez *et al* 2015). However, such large fires in the western region occurred despite an increase in precipitation during the fire-season (Table 3.1; Appendice M). Intra-seasonal variations in precipitation distribution coupled with warm springs and summers may explain the low impact of precipitation on fire size (Ali *et al* 2012). We suggest that, like today, weather patterns creating long-lasting blocking events of high-pressure ridges inducing droughts lasting several days to several weeks during the fire-season (Harrington and Flannigan 1987, Flannigan and Harrington 1988, Skinner *et al* 1999, Girardin *et al* 2006) could have favored the occurrence of large fires during the course of fire-seasons.

In the eastern region, the largest fires during the whole 7000-years study period (and the highest increase in fire size in any part of the study zone) occurred between ca. 2000 and 1000 BP (Figure 3.2), contributing to an increase in the abundance of *Pinus banksiana* in regional vegetation (Remy *et al* 2016). The fire frequency was approximately as low as that recorded around 2500 BP in western and central regions, but the biomass burning was substantially higher (Figure 3.2). In addition, fires were not significantly linked to the same climatic conditions that induced large wildfires in other regions (Table 3.1 and Appendice M). More specifically, warm and/or dry springs and summers do not seem to have triggered these large wildfires. However, reconstructions of past water table levels in ombrotrophic peatlands based on testate amoeba communities analysis indicate there was high interannual to interdecadal hydrological variability (precipitation versus evapotranspiration) between 2500 and 1500 BP in the eastern region (Appendice N; Magnan and Garneau 2014). To limit uncertainties associated with autogenic influences of peatlands on water table depth results, these paleoclimate data reconstructions correspond to means recorded from four sites (two batches of two sites distanced by 450 km) and pooled into 500-year bins. This epoch between 2500 and 1500 BP corresponds to the Roman Warm Period in Eurasia and to high moisture shifts recorded in Greenland and North America, although the nature and causes of those are not yet clearly understood, especially in North

America (Seidenkrantz *et al* 2007, Holmquist *et al* 2016). Such hydrological variability cannot be captured and confirmed (or refuted) with the available HadCM3 climate data due to the ”snapshot” format of these simulated data, causing an absence of information between each millennia. However, it could at least partially explain the reconstructed fire regime, as it could have resulted in series of moist years favorable to fine fuel production interspersed by one or several drier years with relatively low precipitation and/or very high temperature and/or strong winds, all of which cause high evapotranspiration (Li *et al* 2000) and thereby inducing few but large wildfires (Zumbrunnen *et al* 2008; Appendice K). Palaeohydrological reconstructions in ombrotrophic peatlands in the western region (based on means results of three sites situated on a ca. 10 km radius) indicate there was less variability in the atmospheric moisture balance between 3000 and 1000 BP (period of largest fires in western and central regions) than in the eastern region (Appendice N; van Bellen *et al* 2011). Thus, large wildfires in the western and central regions seem to have been mainly induced by high temperatures in spring and summer coupled with intra-seasonal variability in precipitation, while high interannual to interdecadal variability in precipitation may have been the major climatic driver of the development of large wildfire events in the eastern region. The latter hypothesis is corroborated by the eastern region’s uneven topography, which favors fire ignition in dryness zones (mostly altitudinal tops and south slopes; Romme and Knight 1981, Parisien and Moritz 2009) but limits the spread of fire over large areas, implying that conditions were sometimes dry over large areas, as currently observed during some fire years in others regions (Kasischke *et al* 2002, Stocks *et al* 2003).

3.6.3 1000 BP to present-day

During the last 1000 years, the fire regimes of the three regions became similar (in terms of fire frequency, size, and biomass burning) to those recorded just after the deglaciation, with frequent but relatively small fires (Figure 3.2). This change was likely caused by a slight shift of the fire-season timeframe towards earlier termination around 1000 BP, but without high intra-seasonal or interannual variations in precipitation (Figure 3.3 and Appendice L). This stable climatic pattern would have led to more years with optimal conditions for fire ignition, but also more frequent rainfall during the entire fire-season, which would have inhibited fire spread and, to some degree, efficient fire ignition.

Current regional fire-season lengths are similar (in the western and central regions) or longer (in the eastern region) than those recorded during the period of large wildfire events (Figure 3.3), mainly due to a reduction in summer precipitation (Appendice M). However, no significant changes in the fire regime were recorded during the last 1000 years (Figure 3.2). In the western and central regions, the fire-season may have only begun to lengthen since the industrial era, but this possibility cannot be evaluated because the control period, which is the pre-industrial period, has been assumed to be equivalent to the modern period (1971-2000) in our simulations. Another possibility is that the lower summer temperatures which prevailed during the last 1000 years, according to our simulations, decreased the fire size, independently of the reduction in precipitation (Appendice M), by limiting evapotranspiration late in the fire-season, and thus restricting the development of large wildfire events. This possibility is supported by pollen-based climate reconstructions in eastern North America indicating that summer temperatures have declined continuously, although not progressively, since ca. 1000 BP (Viau *et al* 2012). However, in the eastern region, temperatures during the fire season, which was cooler than in other regions during all of the Holocene periods, do not seems to have affected fire sizes (Table 3.1). Consequently, the less frequent dry years due to a decrease in interannual hydrological variability since 1000 BP seems to be the best explanation for the rarity of large fire events in the eastern region, despite a decrease in summer precipitation in this region during this period (Appendice N).

3.7 Conclusion

The largest fires recorded in boreal forests of eastern Canada during the last 7000 years occurred between 3000 and 1000 BP, but their causes varied spatially. In continental regions, warm summers and early fire-season onsets seem to have provided optimal conditions for large wildfires, as already shown by Ali *et al* (2012). However, closer to the Atlantic coast, large wildfires occurred during periods of high variability in atmospheric moisture balance, independently of temperatures over the entire fire-season. Thus, climatic variables that have most strongly influenced fire size differed between continental and oceanic regions. The predicted climatic changes for the next decades across eastern Canada seem to include trends towards both sets of conditions (warmer summers and increases in interannual precipitation-evaporation variability) that promote large fires (Bergeron *et al* 2010, Seager *et al* 2012, IPCC 2014). Thus, their frequency seems likely to increase. Focusing on climate conditions during the large-fire period from 3000 to 1000 BP with higher temporal resolution data and better understanding of associated atmospheric circulation patterns could help efforts to predict consequences of future climate changes on sizes and frequencies of fires in boreal forests more robustly.

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CHAPITRE IV

IMPROVING DETECTION OF LOCAL FIRE EVENTS IN LACUSTRINE DEPOSITS WITH ANALYSIS OF LARGE CHARCOAL COUNTS

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En préparation

4.1 Abstract

In boreal ecosystems, lacustrine charcoal deposits result from both local (watershed) and regional (distant) wildfires. Here, we develop a method based on the quantification of large charcoal particles (> 0.1 mm^2) to enhance the detection of local fire events. We consider that interpretation of large particles requires that enough are counted to ensure that variability is not simply noise. Our approach should be applied to charcoal-count records previously submitted to the minimum-count test method to minimize the detection of false local fire events.

Key Points:

- A new method to detect local fire events based on large (> 0.1mm^2) charcoal counts sequestered in lacustrine deposits
- Our method takes into account the taphonomical processes controlling the production and sequestration of large charcoal particles through time
- This method should be applied to charcoal particle counts previously submitted to the minimum-count test method

4.2 Résumé

Dans les écosystèmes boréaux, les dépôts de charbons dans les sédiments lacustres résultent de feux de forêts locaux (bassin versant) et régionaux (distant). Dans cet article, nous développons une méthode basée sur la quantification des particules de gros charbons de bois (> 0.1 mm^2) pour améliorer la détection des événements de feux locaux. Nous considérons que l'interprétation des grosses particules exige qu'une quantité suffisante de particules soit comptée pour s'assurer que leur variabilité ne soit pas un simple bruit de fond. Notre approche devrait être appliquée aux enregistrments de nombre de charbons précédemment soumis à la méthode du 'minimum-count test' pour minimiser la détection de faux événements de feux locaux.

Points clés :

- Une nouvelle méthode pour détecter des événements de feux locaux basée sur le nombre de gros charbons (> 0.1 mm^2) séquestrés dans les sédiments lacustres
- Notre méthode prend en compte les processus taphonomiques contrôlant la production et la séquestration des grosses particules de charbon de bois à travers le temps
- Cette méthode devrait être appliquée aux comptages de particules de charbon de bois préalablement soumis à la méthode du 'minimum-count test'

4.3 Introduction

Long-term fire history reconstructions (over 300 years) are commonly based on analysis of lacustrine charcoal particles larger than 125-150 μm [Whitlock and Millspaugh, 1996; Carcaillet *et al.*, 2001; Gardner and Whitlock, 2001]. Over the last two decades, several studies have both investigated major processes involved in production of charcoal particles and their deposition in lakes, and improved numerical analysis of continuous macroscopic charcoal accumulation records (hereafter referred to as CHAR). These studies focused on the detection of past local fire events, which are defined as wildfires occurring within the watershed of the lake under study [Bradbury, 1996; Clark and Royall, 1996; Whitlock and Millspaugh, 1996; Clark and Patterson III, 1997; Long *et al.*, 1998; Kelly *et al.*, 2011]. A method often used for this purpose involves identifying "peaks" in CHAR series using charcoal counts (number of charcoals per sample; hereafter $C_{\#}$) or total charcoal area (sum of charcoal areas per sample; hereafter C_A) by removing the "background component", which corresponds to charcoal particles resulting from re-deposition processes, sampling effects, or extra-local/regional fires, i.e. occurring outside of the lake watershed [Clark and Royall, 1996; Higuera *et al.*, 2007; Higuera *et al.*, 2009; Kelly *et al.*, 2011] (Figure 4.1). A frequent challenge with this method is the persistence of false peaks after the background component has been eliminated [Whitlock and Millspaugh, 1996; Lynch *et al.*, 2004; Gavin *et al.*, 2006; Higuera *et al.*, 2010]. False peaks, composed of few charcoal particles resulting notably from sampling, taphonomic effects and/or long-distance transportation, may be detected by chance [Gavin *et al.*, 2006; Higuera *et al.*, 2010; Finsinger *et al.*, 2014]. To minimize the detection of false-peaks in CHAR series, the following two screening-peak tests have been implemented (Figure 4.1). The minimum-count test, built to be applied on $C_{\#}$ records [Gavin *et al.*, 2006; Higuera *et al.*, 2010], uses a double Poisson-distribution to determine the minimum increase of the charcoal count in a sample that can be considered as a different population (peak) than a previous sample. Presented as an equivalent to the minimum-count test but developed for the analysis of C_A records, the charcoal ARea-COunt method (hereafter ARCO, Finsinger *et al.* [2014]) applies a threshold defined by the pth percentile of the bootstrapped values distribution generated by random sampling of particle areas in each peak.

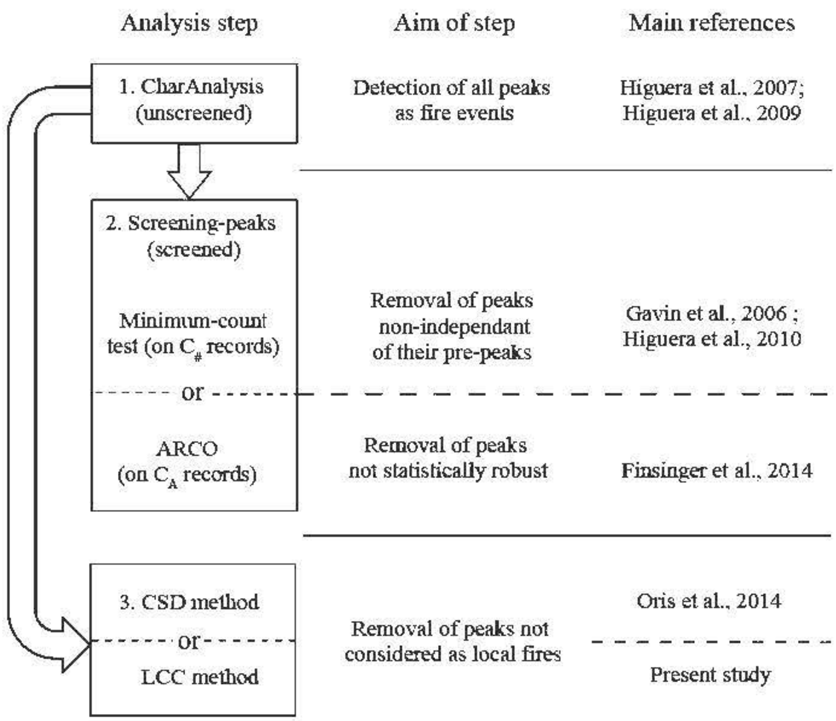

Figure 4.1 Synthesis of steps for analyzing charcoal time series from lacustrine deposits

Even if these two types of screening methods allow evaluating the statistical robustness of each peak, they could fail to discriminate peaks generated by long distance transportation of charcoal particles from those resulting from local fire events. Charcoal long-distance transport (5-30 km) has been many times reported [Clark *et al.* 1998; Pisaric 2002; Tinner *et al.*, 2006; Oris *et al.*, 2014] and fire events recorded in lakes without their watersheds having burned [Whitlock and Millspaugh, 1996]. In some cases, the detection of false local fire events could induce misleading interpretations on environmental processes related to local fire episodes such as watershed erosion, biogeochemical and local vegetation dynamics [Gavin *et al.*, 2006; Colombaroli and Gavin, 2010; Genries *et al.*, 2012; Senici *et al.*, 2013; Dunnette *et al.*, 2014].

Based on Clark *et al.* [1998] work, Asselin and Payette [2005] suggested a method, called 'charcoal size distribution' (hereafter CSD; Figure 4.1), in which local fire events are characterized by charcoal particle assemblages with higher proportion of large particles than other peaks resulting from regional fire events and/or reported as false peak [Clark *et al.*, 1998; Gardner and Whitlock, 2001; Whitlock and Larsen, 2001; Lynch *et al.*, 2004].

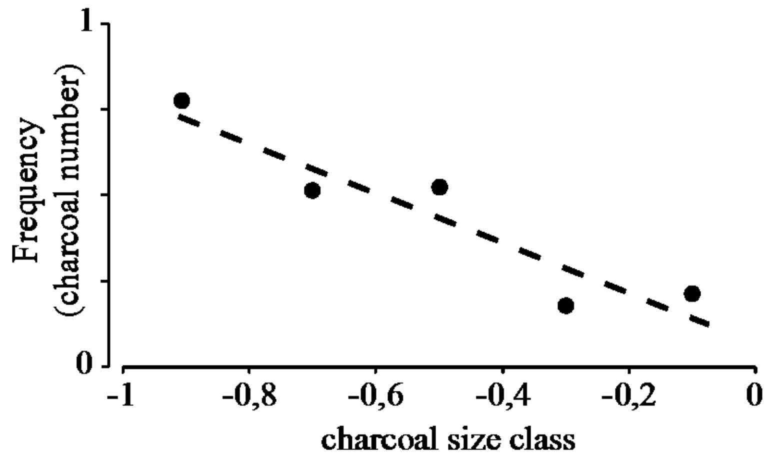

Figure 4.2 Conceptual illustration of the CSD method for charcoal particles data adapted from Asselin and Payette [2005]. The dashed line correspond to the threshold slope (linear regression) computed from the proportion of charcoal particles in each size class (both log-transfromed). When the charcoal size distribution in a peak shown a slope of the linear regression steeper than the threshold slope, it was considered as a past local fire event.

This method computes a linear regression slopes for each peak detected (CA records) from the charcoal particle size distribution (Figure 4.2), and a unique slope threshold value varying between from -1.5 to -2.2 is used to detect local fire events [Clark *et al.*, 1998; Oris *et al.*, 2014]. However, the production and the sequestration of large charcoal particles are variable processes, tightly related to fire behavior (spread, intensity and frequency), and local vegetation features [Clark *et al.*, 1998; Lynch *et al.*, 2004]. Using a unique threshold may be problematic because impacts of the taphonomical dynamic of the lake on charcoal particle accumulation are not taken into account.

As suggested by several authors since the last two decades but not fully available in current methods, local fire events should be detected based on the quantification of large charcoal in CHAR series [Whitlock and Millspaugh, 1996; Clark *et al.*, 1998; Lynch *et al.*, 2004; Oris *et al.*, 2014]. Here, we propose a new method focusing on large charcoal particle count to detect local fire events, called 'Large Charcoal Count' (hereafter LCC). Based on the lacustrine charcoal deposition monitoring carried out and analyzed by Oris *et al.* [2014], we define as 'large charcoal particles' the particles larger than 0.1 mm^2 (~300 µm in diameter). These authors showed indeed that local fire events are characterized by a higher proportion of charcoal particles larger than 0.1 mm^2 compared to regional fires. However, interpretation of large particles requires that enough are counted to ensure that variability is not simply noise [Clark *et al.*, 1998]. Accordingly, the method that we propose takes into account the temporal variation in large charcoal production and its sequestration into lacustrine deposits.

We first compared the LCC and CSD methods on two previously published CHAR series from Oris *et al.* [2014], for which the reconstructions of local fire history with the CSD method has been validated by comparison with dendrochronological investigations [Brossier *et al.*, 2014]. The aim of this comparison was to find whether these two methods display comparable fire histories. We then applied the LCC method to samples from two new Holocene lacustrine charcoal cores from the northeastern coniferous boreal forest of Canada. Finally, we discussed on the effectiveness of the LCC method to enhance local fire event identification from CHAR series.

4.4 Material and methods

4.4.1 Study area

Four lakes located in the spruce-moss bioclimatic domain [Rowe, 1972] were used in the present study. Nano and Loup lakes are situated in the James Bay area of north-western Quebec (Canada) and were previously described in detail by Oris *et al.* [2014] and Brossier *et al.* [2014], while Inuk and Steeve lakes, sampled for the present study, are in the Côte-Nord area of northeastern Quebec (Appendice Q). Inuk and Steeve lakes lie in a sub-arctic climate characterized by long cold winters and short cool summers. The closest weather stations (Baie-Comeau A [49°08'N, 68°12'W; 22 m above sea level (asl)] and Wabush Lake [52°55'N, 66°52'W; 551 m asl]) record mean annual temperatures of 1.5 and -3.5°C, mean annual precipitation of 1014 mm and 852 mm, with approximately one third and one half, falling as snow [Environment Canada, 2014], respectively.

4.4.2 Sampling design and charcoal quantification

Lakes were selected based on their small surface area and organic core length (Appendice Q). Lake sediment sequences were extracted from the center of frozen lakes in March 2011 (Nano and Loup lakes) and March 2013 (Inuk and Steeve lakes) using a Livingstone corer [Deevey, 1965]. Water-sediment interfaces were sampled using a Kajak-Brinkhurst gravity corer [Glew, 1988]. All cores were sliced into continuous 0.5 cm thick samples. For each sample, a sub-sample of 1 cm^3 was shaken for 24 hours in an aqueous solution of 3% $(NaPO3)6$, 5% KOH and 10% NaOCl to facilitate deflocculation as well as to differentiate between black charcoal and bleached organic matter. The solution was then passed through a sieve to collect charcoal particles >160 µm assumed to come from local fire events (<1 km from the lakeshores) [Higuera *et al.*, 2007]. Charcoal particles were analyzed under a binocular microscope (×40) coupled with a camera connected to a computer equipped with image-analysis software (WinSEEDLETM 2009, Regent Instruments Canada Inc.) that made it possible to measure the area of each particle as well as the number and total charcoal area of each sub-sample.

4.4.3 Chronological setting and fire event reconstructions

Information on chronology and age-depth models for Nano and Loup lakes are available in Brossier *et al.* [2014]. Age-depth models for Inuk and Steeve lakes were based on eight and seven ^{14}C AMS dating, respectively (Appendice R). We used CLAM 2.2 software to calibrate the dates based on the IntCal13.14C and the postbomb_NH1.14C dataset [Hua *et al.*, 2013; Reimer *et al.*, 2013] and to simulate the Bayesian age-depth models with a smoothing spline function [Blaauw, 2010]. We expressed charcoal particle abundance as accumulation rates by number and by area (CHAR, i.e., #. $cm^{-2}.yr^{-1}$ and $mm^2.cm^{-2}.yr^{-1}$).

CHAR series were analyzed using CharAnalysis v1.1 software (available via https://sites.google.com/site/charanalysis/) (Appendice O). To eliminate false peaks, we screened charcoal-count peaks series by the minimum-count test and charcoal-area peaks series using the ARCO method (Figure 4.1).

4.4.4 Identifying true local fire events

In order to identify local fires, the LCC method was applied on CHARfire series. Peaks containing less than 10 charcoal particles, commonly considered as statistically insufficiently robust to reveal fire events [Clark *et al.*, 1998; Higuera *et al.*, 2010; Oris *et al.*, 2014], were removed. For each remaining peak, we counted the number of large charcoal particles (area ≥ 0.1 mm^2).

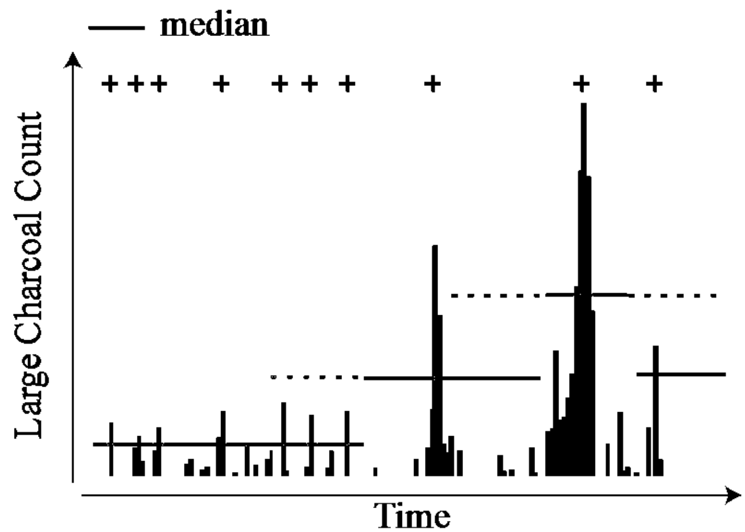

Figure 4.3 Conceptual illustration of the LCC method for charcoal particles data. The grey lines correspond to the threshold computed as the medians of large charcoal particles (> 0.1mm²) number in moving time-windows. When the number of large charcoal particles in a peak was higher than the median threshold, it was considered as a past local fire event.

As a threshold to detect local fire events, we used the median number of large charcoal particles calculated in moving time-windows of 1000-years, sliding on the same time-window width when estimating the CHARbackground (Figure 4.3). Thus, peaks with a number of large charcoal particles higher than the threshold were considered as local fire events (R-code available via https://github.com/vbonhomme/LCC). This approach allows removing the large charcoal noise component related to regional fire inputs and/or redeposition processes [Clark *et al.*, 1998; Oris *et al.*, 2014]. By opposition to the CSD method, this procedure allowed us to take into account the fluctuation in production and deposition of large charcoal particles through time. The time-window width of 1000 years was used to ensure a sufficient number of peaks for calculating the median values. We assumed that in this time-window width, both local and regional fires occurred.

We applied the LCC method on CHAR series from Nano and Loup lakes previously analyzed with the CSD method [Oris *et al.*, 2014] in order to compare the two methods and evaluate their effectiveness in detecting local fire events. We used a non-parametric Kolmogorov-Smirnov test (hereafter KS-test) to evaluate the null hypothesis that any two fire-return interval distributions (hereafter FRI), based on the two different methods applied to the same site (CSD versus LCC), did not differ statistically. We also quantified the degree of synchrony between local fire events that had been separately inferred from LCC and CSD methods using a bivariate Ripley's K-function modified to one dimension (i.e., time, as by Gavin *et al.* [2006]). Finally, we also applied the KS-test to evaluate the nature of the FRI distributions from the Inuk and Steeve CHAR series according to screened (minimum-count test and ARCO) and LCC outputs.

4.5 Results and Discussion

4.5.1 Insights from the LCC method for identifying local fire events

At Nano and Loup lakes, local fire histories reconstructed by both CSD and LCC methods were very similar, with 74 and 79% of identical local fire events detected at Nano (KS-test, p-value = 0.775) and Loup (KS-test, p-value = 0.916) lakes, respectively (Figure 4.4). Moreover, the temporal patterns of local fire frequencies were synchronous between the two methods at decadal to centennial time-scales (p-value > 0.05; Appendice P). However, almost 25% of fire events were not common between the two methods. Two peaks composed of 19 (at 4100 cal. BP) and 14 (at 3230 cal. BP) large charcoal particles at Nano and Loup lakes, respectively, were detected only by the LCC method (Figure 4.4). Such peaks with high quantities of large charcoal particles should be indicative of local fire events. However, these peaks were not detected by the CSD method because they were composed by a lot of small charcoal particles and few large charcoal particles, inducing a linear regression slope on particle size distribution steeper than the threshold slope [Oris *et al.*, 2014].

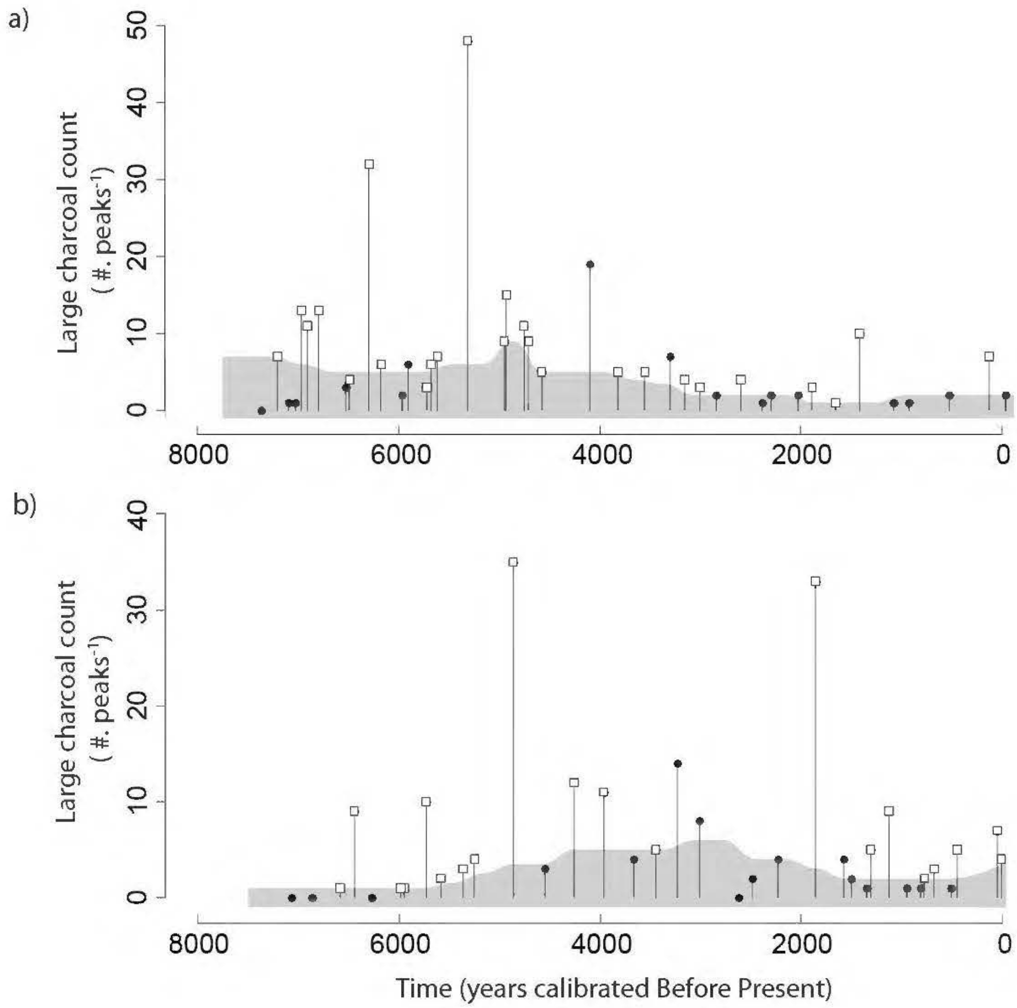

Figure 4.4 Large charcoal count in local fire events detected by CSD and LCC methods at (a) Nano and (b) Loup lakes. Circles strictly above the medians threshold (grey zone) correspond to local fire events only detected by the LCC method. Squares strictly above the medians threshold correspond to local fire events both detected by the LCC and CSD methods.

Peaks identified as local fire events with the CSD method presented between 1 and 48 large charcoals particles with a median of 9 by peaks (Figure 4.4). Conversely, charcoal peaks detected only by the LCC method included a higher number of large charcoal particles strictly higher than only one large particle (between 2 and 48 large charcoal particles with a median of 11; Figure 4.4). The detection of peaks as local fire events by the CSD method, with insignificant large charcoal counts (below the threshold) result from the fact that this method is only centered on charcoal size class distribution, without taking into account the number of large charcoal particles in peaks. As suggested by Clark *et al.* [1998], the interpretation of large particles requires that enough are counted to ensure that variability is not simply noise, a requirement fully considered by the LCC method.

4.5.2 Which is the accurate method to detect local fire events?

At Inuk and Steeve lakes, fire histories from original unscreened peaks of $C_{\#}$ and C_A series provided comparable results (Table 4.1), as previously observed by Ali *et al.* [2009]. However, the two screening tests provided significantly different fire histories (Table 4.1), suggesting that the minimum-count test [Gavin *et al.*, 2006] and ARCO [Finsinger *et al.*, 2014] could not be considered as analogous approaches.

Fire histories reconstruction from C_A records using ARCO and LCC outputs were not significantly different (Table 4.1). Nevertheless, as noted by Finsinger *et al.* [2014], several true peaks can go undetected by ARCO when they are located in a time-window where peaks include a high number of large charcoal particles. Such impairment was primarily observed at Inuk Lake (ca. 940, 1680 and 2600 cal. BP), where several peaks characterized by a high number of large charcoal particles were rejected by ARCO (Figure 4.5). It is worth noting that the fire event that occurred at ca. 940 cal. BP presented the highest peak magnitude with the highest proportion of large charcoal particles of the entire C_A series, and such peak should obviously be considered as a local fire event. This result could be explained by the random samplings of charcoal particles used to establish the area-threshold, which unfortunately took mostly large charcoal particles into account, thus did not allow the detection of this peak. This random sampling approach to establish the threshold is problematic because the input of charcoal particles into the lacustrine sediments after fires is not a random process [Clark *et al.*, 1998; Lynch *et al.*, 2004].

In contrary, fire histories reconstruction from $C_{\#}$ records using the minimum-count test and LCC outputs were significantly different (Table 4.1). Some peaks, enclosing significant large charcoal particles (between 3 and 11), failed to pass the minimum-count test (ca. 4580 and 5390 cal. BP at Steeve Lake) (Figure 4.6), but could be considered as local fire events. However, these peaks were not significantly different from their associated pre-peaks [Gavin *et al.*, 2006; Higuera *et al.*, 2010]. Nevertheless, conversely to ARCO, the minimum-count test removed less peaks assigned as local fire events by the LCC method (Figures 4.3 & 4.4), even though the minimum-count test kept several peaks below the threshold that were automatically eliminated by the LCC step. Consequently, we advice that the detection of local fire events must be performed using the LCC method applied on $C_{\#}$ series after the minimum-count test step rather than on C_A series after the ARCO step.

Lakes	Count versus Area		LCC versus Screening-peaks outputs	
	CharAnalysis outputs	Screening-peaks outputs	Area	Count
Steeve	0.996	0.002**	0.958	0.002**
Inuk	0.320	0.009**	0.135	0.018**

Table 4.1 Two-sample Kolmogorov-Smirnov-test comparisons between fire-return interval (FRI) distributions based on charcoal-count (Count) and charcoal-area (Area) records.
The FRI distributions were respectively obtained from the three methods: LCC method, screening-peaks method (ARCO for particle area and minimum-count test for particle counts, and CharAnalysis (unscreened) for Inuk and Steeve lakes. Significant differences between FRI distributions are indicated by stars ($p < 0.05$: **).

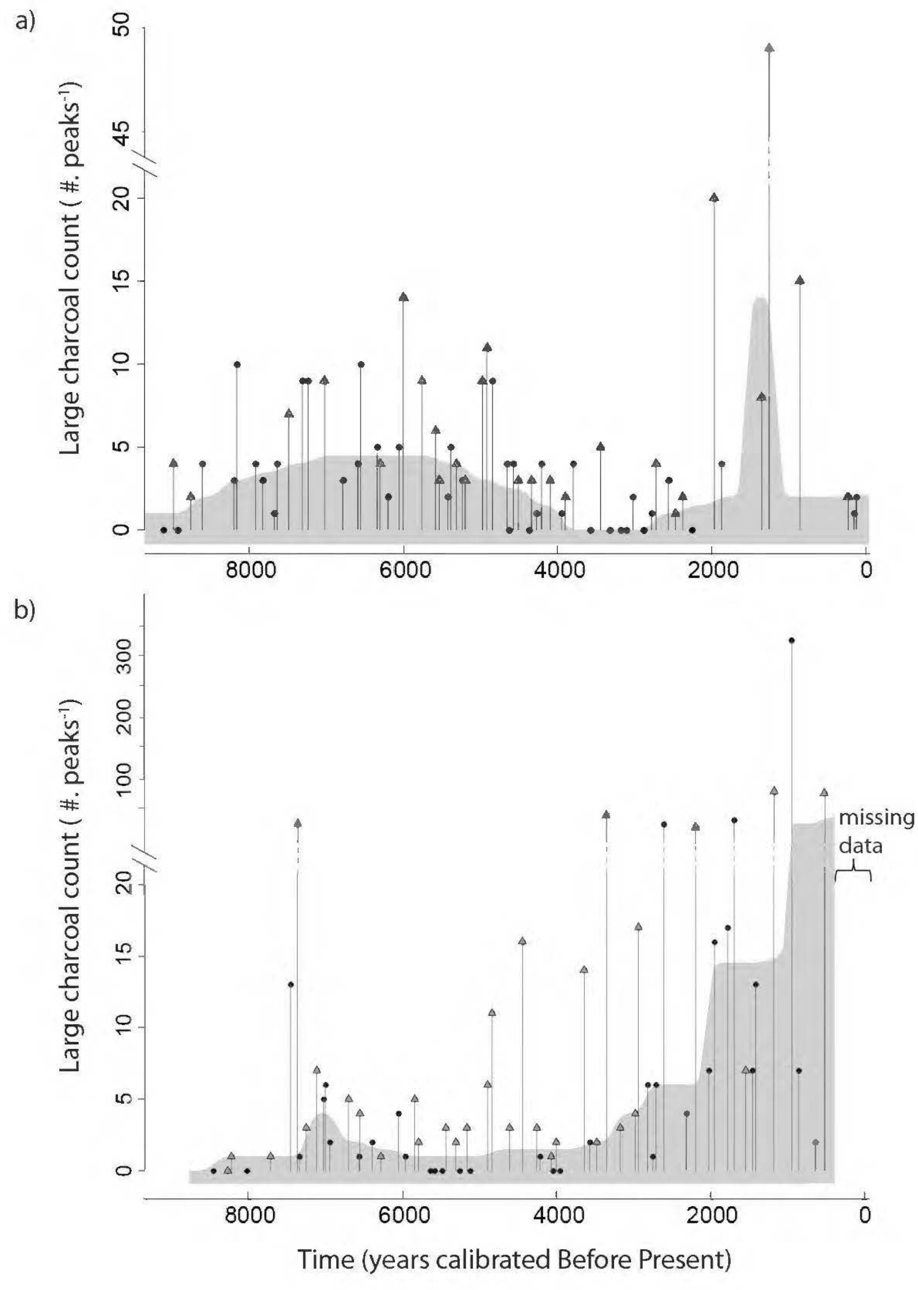

Figure 4.5 Large charcoal count in peaks detected as fire events with charcoal area records from (a) Steeve and (b) Inuk lakes. Charcoal peaks were detected by CharAnalysis from count records (all peaks). The step of screening-peaks (ARCO) was applied on CHAR series to identify robust fire events

(triangles). The LCC method was also applied on CHAR series to identify local fire events (symbols above the median threshold in grey).

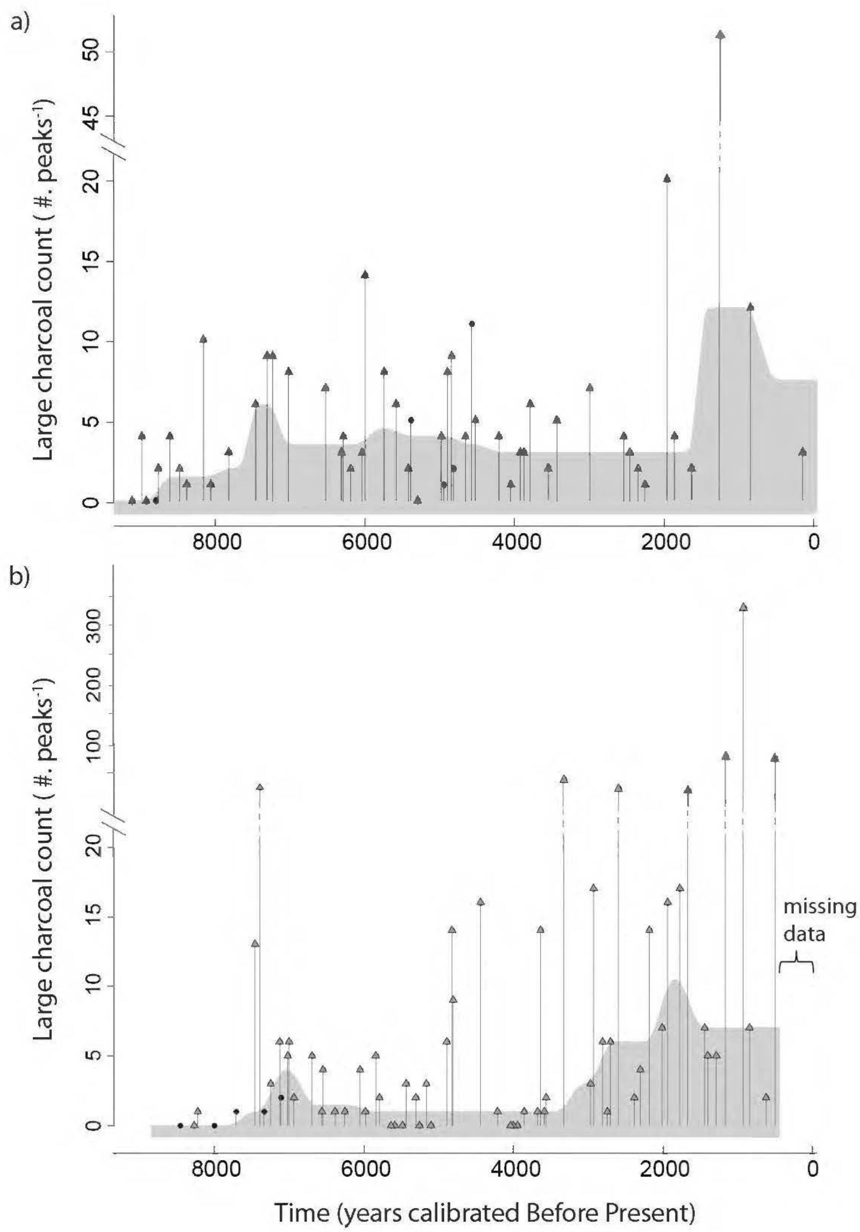

Figure 4.6 Large charcoal count in peaks detected as fire events with charcoal count records from (a) Steeve and (b) Inuk lakes.Charcoal peaks were detected by CharAnalysis from area records (all peaks). The step of screening-peaks (minimum-count test) was applied on CHAR series to identify robust fire

events (triangles). The LCC method was also applied on CHAR series to identify local fire events (symbols above the median threshold in grey).

4.5.3 Recommendations and limitations of the LCC method

Boreal ecosystems are recurrently affected by large, intense and convective wildfires that favor long distance transport of charcoal particles [Clark *et al.*, 1998; Lynch *et al.*, 2004; Higuera *et al.* 2010]. Consequently both regional and local fire events are recorded in lacustrine deposits [Whitlock and Larsen, 2001; Oris *et al.*, 2014]. Thus, the LCC method was developed according these findings. Local fires input more large charcoals in the surrounding lakes than regional fires do, or than sediment mixing [Clark *et al.*, 1998; Gardner and Whitlock, 2001; Lynch *et al.*, 2004; Oris *et al.*, 2014].

Previous studies considered particles > 250 µm in diameter as large charcoals [Clark *et al.*, 1998; Lynch *et al.*, 2004]. Thus, taking into account charcoal particles > 0.1 mm^2 (≈ 300 µm in diameter) to detect local fire events with greater accuracy is a reasonable assumption. Practitioners must to ensure that the number of large charcoal count in peaks is above the noise corresponding to long-distance transportation, redeposition, fuel modification, etc. All peaks detected by the LCC method could be assigned as 'true local fire events', but this does not mean that the method detect all local fire events. In fact, taphonomical processes such as charcoal breakages could have reduced the number of large particles in some peaks therefore unselected by the LCC method. Another limitation of the method is evident in portions of CHAR series with few peaks (less than four peaks in 1000 years time-window) used to obtain robust median thresholds. A possible solution to avoid this bias is to exclude results from the LCC method for such problematic periods and only retain fire events detected after the screening-peak step (minimum-count test).

The production and sequestration of large charcoal particles are related to complex interactions between biotic (vegetation) and abiotic (airborne, salvation, erosion, etc.) processes during and after the fire has occurred. Thus, palaeofire scientists need more monitoring studies focusing on the source areas of charcoals to better interpret fire histories deduced from charcoal lacustrine deposits. Studies focusing on the production, transport and sequestration of large charcoal particles (>0.1 mm²) must be privileged.

4.6 Acknowledgments

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CHAPITRE V

CONCLUSION

Cette thèse a permis de mettre en évidence l'impact, jusqu'alors sous-estimé, de la taille des feux sur la dynamique de végétation à long terme au sein de la forêt boréale (Chapitre 2). Les trajectoires de végétation des forêts conifériennes du nord-est canadien au cours des 7000 dernières années ont été davantage modulées par la taille que par la fréquence des feux. D'un point de vue général, la présence ou l'absence de grands feux a favorisé, selon le cas, la propagation du pin gris ou du sapin baumier, co-dominants dans le paysage avec l'épinette noire. Malgré une tendance climatique multimillénaire spatialement homogène dans le nord-est de l'Amérique du Nord (Viau et Gajewski, 2009), l'histoire de la taille des feux n'a pas été la même dans toutes les régions.

5.1 Les origines complexes des grands feux

L'influence climatique régionale s'est révélée être un facteur crucial contrôlant la dynamique des grands feux (Chapitre 3). Conformément aux résultats de Ali *et al.* (2012), l'histoire de la taille des feux dans les forêts boréales continentales sur relief peu accidenté de l'ouest québécois est intimement liée aux fluctuations de températures durant la saison des feux. Cependant, dans les régions sous influence océanique et à relief vallonné de l'est du Québec-Labrador, l'apparition de grands feux s'avère être indépendante des variations de température et semble être due à des fluctuations importantes d'humidité induisant des années de sécheresse. D'autres études réalisées en Amérique du Nord sur une période plus récente (jusqu'à 150 ans) montrent également que, selon les régions, les feux de grande superficie peuvent être soit principalement liés à une augmentation de température (Duffy *et al.*, 2005 ; Flannigan *et al.*, 2005), soit à des variations interannuelles d'humidité (Abatzoglou et Kolden, 2011 ; Slocum *et al.*, 2010). Comme l'avaient déjà suggéré Burton *et al.* (2008) et Kasischke et Turetsky (2006), les interactions climat-feux ne peuvent donc pas être généralisées à grande échelle spatiale. De plus, d'autres facteurs régionaux autres que climatiques pourraient avoir influencé la taille des feux (Fang *et al.*, 2015 ; Genries *et al.*, 2012 ; Senici *et al.*, 2013).

Le relief d'une région (orientation de la pente, rugosité topographique) peut réduire l'influence des facteurs climatiques sur l'occurrence et la taille des feux en créant des gradients d'humidité de sol (et donc de combustible mort) et de température dans le paysage (Parisien et Moritz, 2009 ; Romme et Knight, 1981). Les répercussions d'un terrain accidenté sur l'activité de feux semblent pouvoir être diverses, voire même antinomique selon la région concernée. En effet, le relief peut tout aussi bien agir comme barrière naturelle à la propagation du feu (Iniguez *et al.*, 2008 ; Kafka *et al.*, 2001 ; Lefort *et al.*, 2004) qu'accélérer cette propagation par le transfert d'énergie des fronts de feu vers le combustible de haut de pente qui est par nature plus sec en raison du drainage plus efficace (Rothermel, 1983). De même, il peut engendrer des gradients d'humidité et de température qui sont susceptibles d'influencer indirectement l'occurrence et la propagation des feux en faisant varier le type et la structuration des combustibles dans le paysage (Taylor et Skinner, 2003). Peu d'études intégrant la topographie dans la compréhension des processus liés à l'activité de feu ont été réalisées à ce jour en forêt boréale (Bergeron, 1991 ; Cyr et al., 2007 ; Engelmark, 1987 ; Larsen, 1997 ; Lertzman et Fall, 1998) et ces dernières, autant que celles les plus récemment menées pour d'autres écosystèmes (Bigio *et al.*, 2016 ; Holsinger *et al.*, 2016), s'accordent à dire que ces processus sont très complexes et spatialement variables.

Un autre facteur pouvant faire varier l'activité de feux est le type de sol. Suivant sa capacité de drainage et sa texture, un sol va plus ou moins favoriser le départ et la propagation des feux de par son humidité, sa composition chimique, ainsi que la composition végétale et la litière qu'il va favoriser (Mansuy *et al.*, 2010 ; Senici *et al.*, 2010). Tous ces paramètres interagissent entre eux mais également avec les feux qui interviennent sur la structure et la composition de la matière organique à la surface du sol, par exemple, en brûlant une partie ou l'intégralité des horizons de surface (Johnstone et Chapin, 2006 ; Neff *et al.*, 2005). Les diverses barrières à la propagation des feux dans les paysages constitue un troisième facteur d'importance régionale à locale important à prendre en compte. Les lacs, les tourbières, les rivières, les zones sévèrement brûlées et les chemins d'avalanche en zones montagnardes, au même titre que certains reliefs, sont autant d'obstacles naturels à la progression des feux sur un territoire (Foster, 1983 ; Ryan, 2002).

Ainsi, pour une même composition forestière, le climat, le type de sol, le relief et le degré de fragmentation du paysage sont autant de variables qui, combinées ensemble, offrent une multitude de possibilités plus ou moins propices à l'éclosion et la propagation de grands feux. Cependant, au sein d'une même région, les causes inhérentes aux variations de la taille des feux semblent avoir été constantes au cours des 7000 dernières années (Chapitre 3). Cette stabilité pourrait s'expliquer par le fait qu'un seul ou un petit nombre de ces facteurs, dépendamment de la région concernée, aurait une influence prédominante par rapport aux autres sur le régime des feux. Dans les régions de l'ouest et du centre, les grands feux semblent avoir été principalement causées par une hausse des températures printannières et estivales, et facilités par la connectivité paysagère induite par la topographie relativement plane ainsi que la forte proportion de conifères. Dans la région de l'est, la topographie accidentée a probablement restreint la propagation des feux à de petites surfaces. Les variations d'humidité associéees au relief ainsi que l'arrangement spatial des zones principalement touchée par les feux au cours du temps ont créé une mosaïque paysagère plus complexe (plus ou moins riche en espèces feuillues *versus* conifériennes) que dans les autres régions, entrainant elle-même une rétroaction négative ou positive sur l'activité de feux. Les fortes variations d'humidité induisant des périodes particulièrement sèches semblent être le seul facteur qui puisse contrecarrer l'effet en cascade de la topographie sur la propagation des feux et ainsi favoriser l'occurrence de grands feux dans cette région.

5.2 Trajectoires de végétations futures

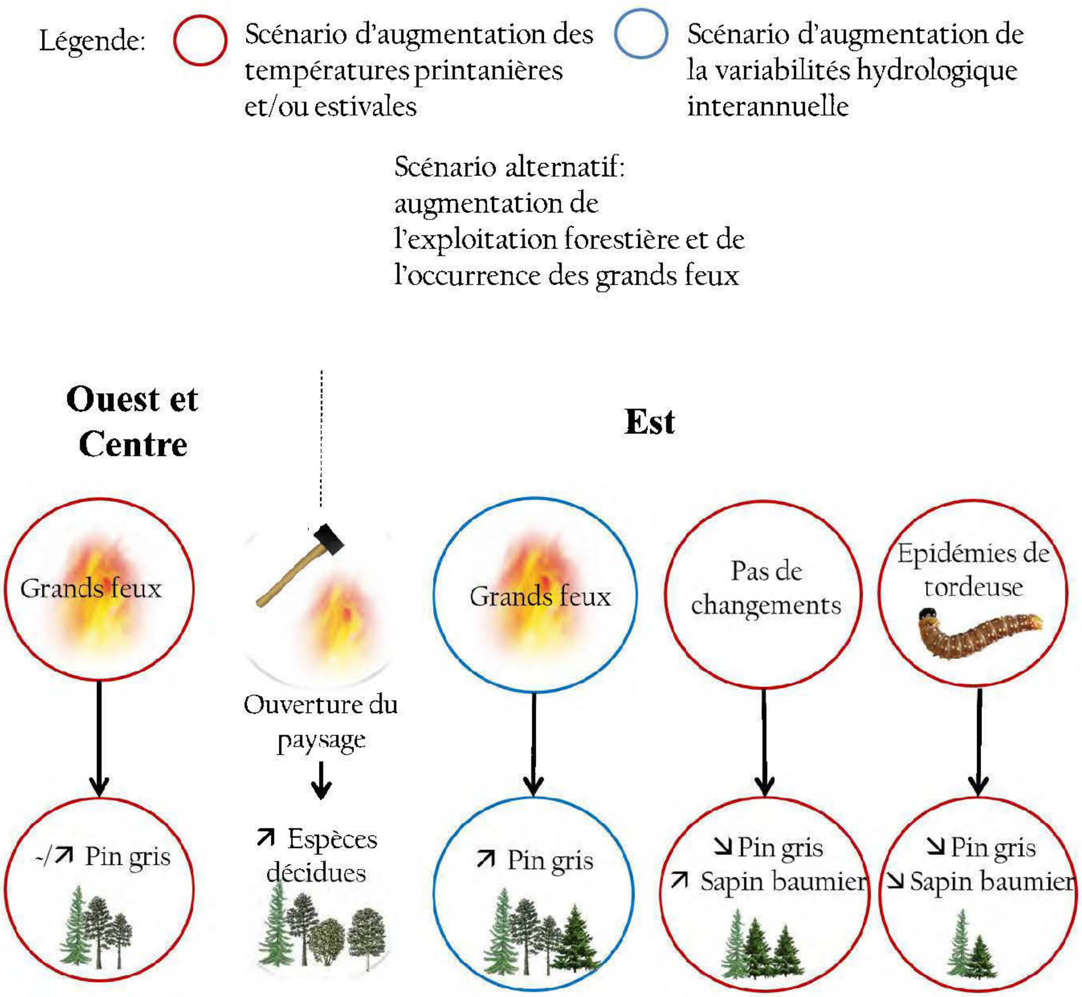


Figure 5.1 Schéma récapitulatif des conséquences envisagées des scénarios climatiques futurs sur les trajectoires de végétation dans les trois régions d'étude

La profondeur temporelle des causes associées aux grands feux et leurs impacts dorénavant connus sur la dynamique de végétation (Chapitre 3) nous permet d'établir des hypothèses sur les trajectoires futures au sein des trois régions étudiées (Figure 5.1).

Au regard de nos résultats, l'augmentation des températures adossée au réchauffement climatique, sans augmentation nette des précipitations annoncée pour le siècle en cours (Ressources naturelles Canada, 2009), pourrait augmenter l'occurrence de grands feux dans les régions ouest et centre des forêts conifériennes du Québec. Cette étude conforte donc les précédents résultats issus de simulations de taille de feux futurs dans cette zone (Amiro *et al.*, 2009 ; Boulanger et al., 2014 ; Flannigan *et al.*, 2005 ; Gillett, 2004 ; Stocks *et al.*, 1998). Néanmoins, cette intensification des grands feux ne devrait pas avoir de conséquence significative sur la composition des forêts, si ce n'est peut-être une légère augmentation du pin gris. En effet, la végétation de ces régions s'est principalement modifiée entre 7000 et 3000 ans avant aujourd'hui (ci-après: années A.A.) avant de montrer ensuite une relative stabilité (Chapitre 2; Garralla et Gajewski, 1992; Carcaillet *et al.*, 2001). Les grands feux qui ont eu lieu jusque vers 3000 ans A.A. semblent avoir permis une augmentation de l'abondance du pin gris qui, malgré une diminution de la taille des feux au cours des trois derniers millénaires, s'est maintenu en tant qu'espèce co-dominante avec l'épinette (Chapitre 2).

À l'est du Québec-Labrador, les projections futures restent plus incertaines car les causes des grands feux passés dans cette région n'ont pas été totalement élucidées (Chapitre 3). Nous avons émis l'hypothèse que les fluctuations interannuelles d'humidité induisant des années de sécheresse potentiellement à leurs origines aux alentours de 1500 ans A.A. semblaient avoir été induites par des blocages de crêtes de haute pression liés à un régime de circulation atmosphérique particulier à l'échelle régionale. Cependant, les connaissances actuelles sur les mécanismes et la périodicité de ces circulations sont encore trop fragmentaires pour pouvoir les associer aux variations d'humidité passées (Fauria et Johnson, 2008 ; Girardin *et al.*, 2006 ; Skinner *et al.*, 1999). De la même façon, la résolution des données de variabilité hydrologique dans les tourbières et de charbons de bois dans les sédiments lacustres ne permet pas d'observer un synchronisme entre une ou plusieurs années successives de sécheresse et l'éclosion des grands feux. Malgré ces incertitudes, il est possible d'établir différents scénarios de dynamique de végétation future. Si cette région n'est pas confrontée à une forte variabilité hydrologique dans le futur, il est probable que les paysages forestiers demeurent tels qu'ils le sont actuellement, c'est-à-dire dominés par les épinettes (noire et blanche) et le sapin baumier avec une présence marquée de bouleau à papier et très peu de pin gris (Chapitre 2). Il est toutefois envisageable que, comme ce fut le cas entre 8000 et 7000 ans A.A., une longue période (pluricentenaire) de feux de faibles tailles entraîne progressivement une raréfaction du pin gris. Parallèlement, une augmentation des températures pourrait entraîner une densification du sapin baumier vers de plus hautes latitudes (Bouchard *et al.*, 2008 ; Messaoud *et al.*, 2007). Au contraire, si la taille des feux venait à augmenter, le couvert végétal pourrait alors favoriser le pin gris dans le paysage comme cela a été le cas suite aux grands feux enregistrés vers 1500 ans A.A. (Chapitre 2). Le pin gris aurait alors tendance à se multiplier principalement dans les habitats fréquemment affectés par le feu, sur sol sec, sableux et pauvres en nutriments (Desponts et Payette, 1992 ; Payette, 1993). En revanche, bien que moins adapté aux feux, rien ne présage que le sapin baumier verrait son abondance décliner sur le long-terme (Chapitre 2 ; Couillard *et al.*, 2013) même si des études ont précédemment montré que son abondance dans les territoires plus au sud de notre région d'étude et dans la région de l'ouest est majoritairement contrôlée par le régime de feux (Ali *et al.*, 2008 ; Messaoud, 2007). Son maintien dans le paysage après la période de grands feux pourrait résulter d'un effet indirect du relief vallonné offrant des zones refuges aux vieilles forêts et donc à cette espèce (Cyr *et al.*, 2007 ; De Grandpré *et al.*, 2000). Une augmentation des températures estivales favorisant les épidémies de tordeuse des bourgeons de l'épinette (*Choristoneura fumiferana* (Clemens)) pourrait cependant contrebalancer l'effet positif probable du relief sur l'abondance du sapin baumier quelle que soit la taille des feux (Bergeron et Leduc, 1998 ; Gray, 2007). Le degré d'importance des facteurs locaux vis-à-vis du régime de feu sur la dynamique du sapin baumier dans l'est du Québec-Labrador reste donc à déterminer.

Deux autres paramètres doivent être ajoutés dans tous ces scénarios futurs proposés pour les forêts conifériennes du territoire québécois. Le réchauffement climatique comme l'ouverture du milieu par des grands feux pourraient augmenter la vitesse de croissance des arbres ainsi que la proportion d'espèces décidues peu inflammables dans le paysage, ayant une rétroaction négative sur la propagation des feux (Hély *et al.*, 2001 ; Johnstone et Chapin, 2006 ; Terrier *et al.*, 2013). À cela s'ajoute finalement l'impact croissant de la fragmentation paysagère d'origine anthropique introduite par le biais du développement du réseau routier, des villes et villages, des infrastructures hydro-électriques et surtout des parcelles exploitées (Bowman *et al.*, 2011 ; Niklasson et Granstrom, 2000).

En attendant de pouvoir mieux appréhender les futurs patrons et processus de perturbations spécifiques aux différentes régions, nous sommes tout de même en capacité de réfléchir à de nouvelles stratégies d'aménagement permettant le maintien de la résilience des forêts. Au Québec, la structure d'âge et la composition des forêts naturelles observées antérieurement aux début des activités anthropiques servent de références pour définir les objectifs des aménagements écosystémiques (Boucher et al., 2011 ; Gauthier et al., 2009 ; Long, 2009). Le cadre temporelle préindustriel utilisée pour définir la dynamique des forêt naturelle doit être assez étendu pour décrire le plus exactement possible la variabilité des attributs forestiers. D'après nos résultats (chapitre 2), la végétation à l'est du Québec-Labrador n'a pas beaucoup changé entre la fin de la période de reboisement post-déglaciation (avant 7000 ans A.A.) et 2000 ans A.A. mais semble adoptée progressivement une nouvelle dynamique depuis 1500 ans, époque marqué par une augmentation de la taille des feux. Dans la région de l'ouest, la composition de la végétation a varié entre 7000 et 2500 ans A.A. du fait d'une plus forte activité de feux qu'à l'est avant de se stabiliser au cours des 2500 dernières années. Afin de prendre en compte le maximum de variabilité dans la composition forestière liée aux changements du régime de feux, les périodes choisies pour définir la dynamique naturelle des forêts devraient couvrir au minimum les 2000 dernières années dans la région est et les 3000 dernières années dans la région ouest.

5.3 Une nouvelle façon d'appréhender les recherches sur les paléofeux et les paléovégétations

Au vu de la complexité des interactions et de la diversité des facteurs pouvant intervenir sur les dynamiques de végétation en forêt boréale coniférienne, l'étude tridimensionnelle 'standard' climat-feux-végétation des interactions gouvernant la structure et la composition des paysages semble inappropriée pour rendre compte des faits réels dans certaines régions. En ce sens, la région de l'est du Québec-Labrador en est le parfait exemple. Par déduction, cela implique aussi que les résultats des études effectuées à une échelle spatiale supra-régionale, voire supra-locale, ne peuvent pas être systématiquement généralisables à plus grande échelle et réciproquement. En effet, dans notre cas, la généralisation des processus pour les régions de l'ouest et du centre du Québec semble cohérente compte-tenu de leurs similitudes, mais ne l'est pas pour celle de l'est du Québec-Labrador. Or, à l'heure actuelle, les dynamiques à long terme des perturbations et des compositions végétales sont loin d'avoir été étudiées dans toutes les régions circumboréales (de Groot *et al.*, 2013 ; Global Fire Monitoring Center, 2013). Les processus impliqués ne sont pas encore suffisamment compris pour pouvoir prétendre les simuler pour l'horizon 2100 à des fins de planification d'aménagement forestier et de projections de bilan carbone à l'échelle du biome (Bremond *et al.*, 2010 ; Oris *et al.*, 2014). Cela implique que nous avons encore besoin d'alimenter les modèles numériques en données paléoécologiques. Cependant, il est inconcevable d'imaginer que l'intégralité des régions circumboréales puisse être étudiée dans les prochaines années. De nouveaux outils, stratégies et améliorations méthodologiques doivent donc être exploités afin d'optimiser les prochains travaux de recherche.

Avant tout chose, il semble désormais indispensable de privilégier le développement des modèles climatiques régionaux (MCR ; Eden *et al.*, 2014 ; Giorgi, 1990 ; Sousa *et al.*, 2015) en parallèle des globaux (MCG) pour étudier les dynamiques de perturbations et de végétations en forêt boréale. De plus, compte-tenu de l'urgence des besoins en simulations associée aux changements climatiques en cours, il serait préférable de privilégier l'étude de zones d'intérêt en termes de biodiversité, d'exploitation ou celles proches de zones urbaines. La généralisation des résultats associés à l'étude de seulement quelques sites devrait se faire prudemment, en fonction des caractéristiques locales à régionales (topographie, végétation, type de sol, climat, fragmentation anthropique). Prenons l'exemple du nord-est du Canada. La région de la Côte-Nord regroupe toutes les caractéristiques citées précédemment. En effet, en plus de représenter environ 30 % du bois récolté à l'échelle provinciale (Ministère des Forêts, de la Faune et des Parcs, 2015), elle se caractérise par une mosaïque paysagère très diversifiée et un pourcentage très élevé de vieilles forêts (environ 60% des forêts sont âgées de plus de 90 ans) qui jouent un rôle prépondérant dans la conservation de certaines espèces fauniques telles que le caribou forestier considéré comme une espèce vulnérable au Québec (De Grandpré *et al.*, 2008 ; Hins *et al.*, 2009). Des conséquences socio-économiques et écologiques négatives seraient attendues si de grands feux venaient à éclore régulièrement dans cette région. Ces mêmes feux pourraient, à travers les panaches successifs de fumée, constituer un risque sanitaire non négligeable dans les zones urbaines sises à proximité, plus particulièrement celles situées le long de la route 389 allant à Fermont et de la route 138 longeant l'estuaire du Saint-Laurent (Naeher *et al.*, 2007). Cependant, les processus impliqués dans les dynamiques de perturbation et de végétation mis en évidence dans l'est du Québec-Labrador ne peuvent être généralisés à l'ensemble de la région. Le long de la côte, de Forestville à Blanc-Sablon et sur le plateau de la Basse-Côte-Nord, la topographie est plus plane, les dépôts de surface moins épais, le climat plus humide et plus froid et la végétation plus abondante en sapin baumier et bouleau blanc que dans les secteurs immédiats des sites étudiés dans cette thèse (Ministère des Forêts, de la Faune et des Parcs, 2016). Les prochaines recherches paléoenvironnementales au Québec devraient donc privilégier ces territoires encore peu étudiés à l'échelle plurimillénaire.

Les processus liés aux dynamiques de perturbation et de végétation devraient être prioritairement étudiés à l'échelle d'une zone la plus homogène possible en termes de composition végétale, de topographie et de climat. Cette homogénéité permettrait de cibler plus précisément les facteurs impliqués, leurs interactions et leur importance. C'est dans cette optique que la nouvelle méthode de détection des feux locaux survenus au sein du bassin versant d'un lac à l'échelle plurimillénaire à partir des charbons lacustres a été développée (méthode LCC ; Chapitre 4). Afin de détecter ces feux à partir des sédiments lacustres, nous préconisons d'utiliser le nombre de charbons et non leur aire à partir du programme CharAnalysis en utilisant la méthode du 'Minimum Count Test' (Gavin *et al.*, 2006 ; Higuera *et al.*, 2010) avant d'appliquer la méthode LCC en elle-même. Cette amélioration méthodologique conjuguée à l'étude de bio-indicateurs locaux tel que les macrorestes végétaux (Senici *et al.*, 2013), les grains de pollen (Carcaillet *et al.*, 2001 ; Fréchette *et al.*, 2008; Appendice S), les chironomides (Larocque *et al.*, 2006), la composition chimique des sédiments (Colombaroli et Gavin, 2010; Engstrom et Hansen, 1985) ou encore la granulométrie et le contenu en matière minérale et organique des sédiments d'un même lac (Campbell *et al.*, 2000) devrait nous permettre de mieux comprendre les causes et conséquences des variations de taille des feux au regard des différentes combinaisons observées de facteurs environnementaux. Elle pourrait par exemple nous permettre de savoir autour de quels lacs les événements de grands feux ont eu lieu dans les régions étudiées au chapitres 2 et 3. Cette information, couplée à l'étude de bio-indicateurs locaux nous apporterait de plus amples connaissances sur les causes et conséquences des grands feux. Cependant, deux lacunes méthodologiques persistent au niveau de la reconstruction de la fréquence des feux, qu'elle soit régionale ou locale. La première est liée à un plateau observé dans les modèles âge-profondeur de la majorité des lacs sur les 1000 à 3000 dernières années (Lehman, 1975). Ce plateau traduit une accélération du taux d'accumulation sédimentaire dû à la plus faible compaction du matériel sédimentaire de surface comparativement aux niveaux plus profonds, ou potentiellement liée à une augmentation des précipitations. Nous ne sommes actuellement pas en mesure de savoir si ce changement taphonomique induit ou non une plus faible fragmentation des charbons et donc un biais dans la détection des feux. Pour cela, il faudrait faire des comparaisons fines les dates des feux reconstruits à partir des archives sédimentaires lacustres avec d'autres archives issues d'un autre matériel non affecté par ce même changement de taux de sédimentation, et ce, sur une période à l'échelle millénaire voire plurimillénaire. Les étalonnages à partir de cicatrices de feux analysées sur des troncs aux alentours d'un lac ne couvrent bien souvent que les 300 dernières années au maximum (Brossier *et al.*, 2014 ; Niklasson et Granstrom, 2000). L'analyse des restes d'arbres tombés dans les lacs pourrait offrir une plus longue couverture temporelle permettant de tester cette hypothèse (Arseneault *et al.*, 2013 ; Gennaretti *et al.*, 2014 ; Payette et Delwaide, 2004). La deuxième lacune méthodologique concerne le calcul de la fréquence de feux durant la période séparant le dernier feu détecté à aujourd'hui. Plusieurs corrections mathématiques ont été proposées dans le passé (Blarquez *et al.*, 2014 ; Mann, 2004 ; Minckley *et al.*, 2007). Pourtant, il est maintenant possible de connaître la fréquence de feux actuelle grâce aux données satellitaires (Goetz *et al.*, 2006 ; Kasischke et Turetsky, 2006). Il serait alors intéressant de corriger les reconstructions sur la période récente à partir des données dendrochronologiques (cicatrices de feux), permettant ainsi d'obtenir des fréquences plus proches de la réalité sur les derniers siècles après lissage.

Compte-tenu de l'importance des grands feux sur la dynamique de végétation mise en évidence dans cette thèse, il serait aussi nécessaire d'apporter des améliorations à la récente méthode de calcul de la taille des feux (Ali *et al.*, 2012). La taille des feux calculée est actuellement relative et ne fournit pas de résultat en unité de surface. Une calibration avec la taille des feux actuels à partir de données satellitaires semble impérative dans le développement futur de cette méthode. Malgré tous les efforts apportés pour améliorer les reconstructions d'activité de feux à partir des sédiments lacustres, la trop faible résolution temporelle des données ne pourra cependant pas nous permettre d'observer les mécanismes sous-tendant l'éclosion des grands feux à l'échelle interannuelle à interdécennale pour toute la période de l'Holocène. Un effort de recherche doit donc être réalisé pour mieux comprendre ces phénomènes à plus petite échelle temporelle (derniers siècles) afin de comprendre les dynamiques de circulations atmosphériques et océaniques en lien avec les variations d'activité de feux.

Au-delà du travail descriptif réalisé sur les causes et conséquences des feux en forêt boréale coniférienne, cette thèse montre également l'importance, bien souvent sous-estimée, des facteurs régionaux et locaux dans la caractérisation des processus de dynamique de perturbations et de végétation. La prise de conscience de la complexité de ces processus rend la tâche difficile mais néanmoins stimulante pour les prochaines recherches dans ce domaine. Une nouvelle façon d'aborder et d'optimiser ces recherches dans le temps et dans l'espace est donc proposée ici en vue d'améliorer les outils décisionnels en termes de gestion forestière et de lutte contre le réchauffement climatique en cours.

APPENDICE A

AMS ^{14}C DATING FROM LAKES AYLA, STEEVE AND INNU

Site and depth (cm)	^{14}C year BP ($\pm \sigma$)	Material dated	Laboratory code
Lake Ayla			
14-14.5	990 ± 15	Gyttja	UCIAMS-137791
34-35	1205 ± 15	Gyttja	UCIAMS-137792
112-113	1620 ± 15	Gyttja	UCIAMS-137794
162-163	2280 ± 15	Gyttja	UCIAMS-137795
211-212	3015 ± 15	Gyttja	UCIAMS-137796
261.5-262.5	3930 ± 15	Gyttja	UCIAMS-137797
312-313.5	4455 ± 15	Gyttja	UCIAMS-137798
362-362.5	6045 ± 15	Gyttja	UCIAMS-137799
Lake Steeve			
20.5-21	1080 ± 25	Gyttja	UCIAMS-138428
60.5-61	1240 ± 15	Gyttja	UCIAMS-137800
110-111	2195 ± 15	Gyttja	UCIAMS-137801
160-161	3825 ± 25	Gyttja	UCIAMS-137802
209.5-210.5	4415 ± 15	Gyttja	UCIAMS-137803
260-261	5990 ± 15	Gyttja	UCIAMS-137804
300-300.5	7485 ± 20	Gyttja	UCIAMS-137805
Lake Innu			
21-22.5	500 ± 30	Gyttja	Beta-377380
70.5-72.5	1750 ± 30	Gyttja	Beta-377381
121-122	2745 ± 25	Gyttja	UCIAMS-138423
171-172	3750 ± 25	Gyttja	UCIAMS-138422
221-221.5	4705 ± 25	Gyttja	UCIAMS-138421
271-271.5	6300 ± 25	Gyttja	UCIAMS-138420
324-324.5	6555 ± 25	Gyttja	UCIAMS-138419
361-361.5	7925 ± 30	Gyttja	UCIAMS-138418

APPENDICE B

CHAR SERIES USING CHARANALYSIS, FIRE FREQUENCY AND BIOMASS BURNING SIMULATED FOR EACH LAKE

To remove the bias induced by the different sedimentation rates, CHAR series were interpolated ($CHAR_{interpolated}$) using a constant time-resolution of 20 years per sample, corresponding approximately to the mean of median time-resolution of all records. $CHAR_{interpolated}$ series were decomposed into a low-frequency component ($CHAR_{background}$) and a high-frequency component (CHARpeak; Figure S2). $CHAR_{background}$ results from long-distance burning and/or redeposition processes of charcoal particles that are unrelated to local fire occurrences. $CHAR_{background}$ was estimated by applying the LOWESS-smoother robust technique to outliers and removing $CHAR_{interpolated}$ to isolate the $CHAR_{peak}$ component. $CHAR_{peak}$ was decomposed into two subpopulations: $CHAR_{noise}$, representing variability in sediment mixing and sampling as well as analytical and naturally occurring noise, and $CHAR_{fire}$, representing significant charcoal peaks that are considered to originate from local fire events (Gavin *et al.*, 2006; Higuera *et al.*, 2010). For each peak, we used a Gaussian mixture model to identify the $CHAR_{noise}$ distribution according to a locally-defined threshold. Signal-to-noise index (Kelly *et al.*, 2011) and goodness-of-fit (Brossier *et al.*, 2014) were used to evaluate the effectiveness of the discrimination between $CHAR_{fire}$ and $CHAR_{noise}$ and to assess peak detection accuracy by comparing the empirical and fitted noise distributions, respectively. Each $CHAR_{peak}$ that exceeded the 99th percentile threshold was assumed to be a local fire event, but could actually include one or more fires (Gavin *et al.*, 2006).

References

Brossier, B., Oris, F., Finsinger, W., Asselin, H., Bergeron, Y. & Ali, A.A. (2014) Using tree-ring records to calibrate peak detection in fire reconstructions based on sedimentary charcoal records. The Holocene, 24, 635–645.

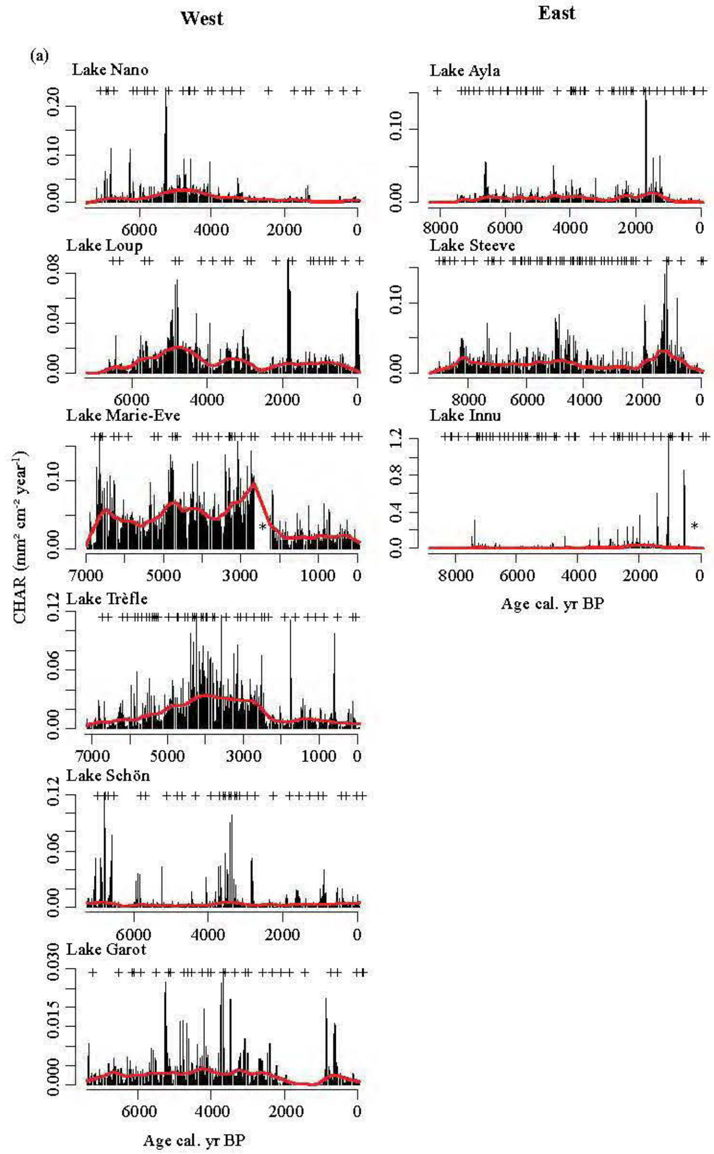
Gavin, D.G., Hu, F.S., Lertzman, K. & Corbett, P. (2006) Weak climatic control of stand-scale fire history during the late Holocene. Ecology, 87, 1722–1732.

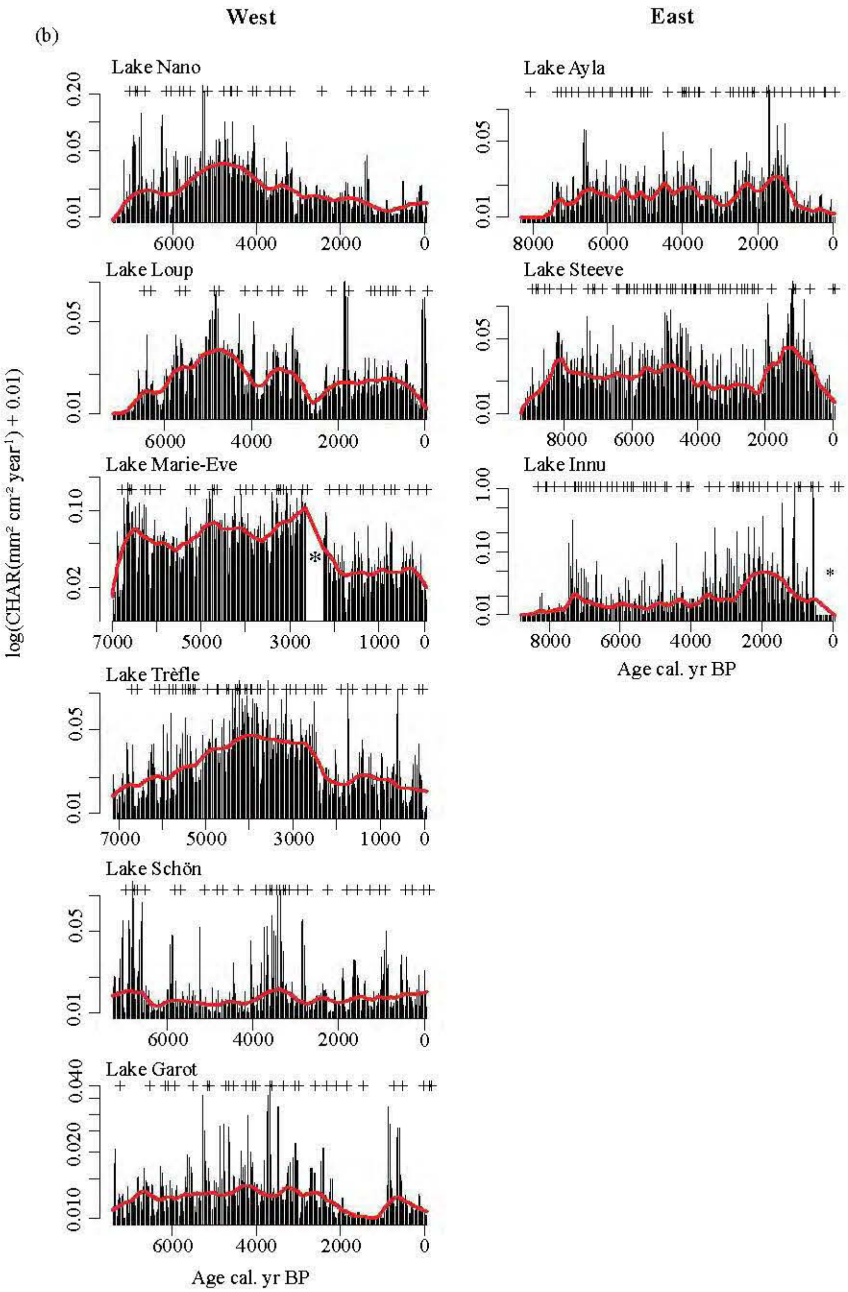
Higuera, P.E., Gavin, D.G., Bartlein, P.J. & Hallett, D.J. (2010) Peak detection in sediment–charcoal records: impacts of alternative data analysis methods on fire-history interpretations. International Journal of Wildland Fire, 19, 996–1014.

Kelly, R.F., Higuera, P.E., Barrett, C.M. & Hu, F.S. (2011) A signal-to-noise index to quantify the potential for peak detection in sediment–charcoal records. Quaternary Research, 75, 11–17.

APPENDICE C

CHARCOAL AREA SERIES IN (A) CHAR AND (B) LOG(CHAR)+0.01 FROM SEDIMENT SEQUENCES OF LAKES IN WESTERN AND EASTERN QUEBEC.

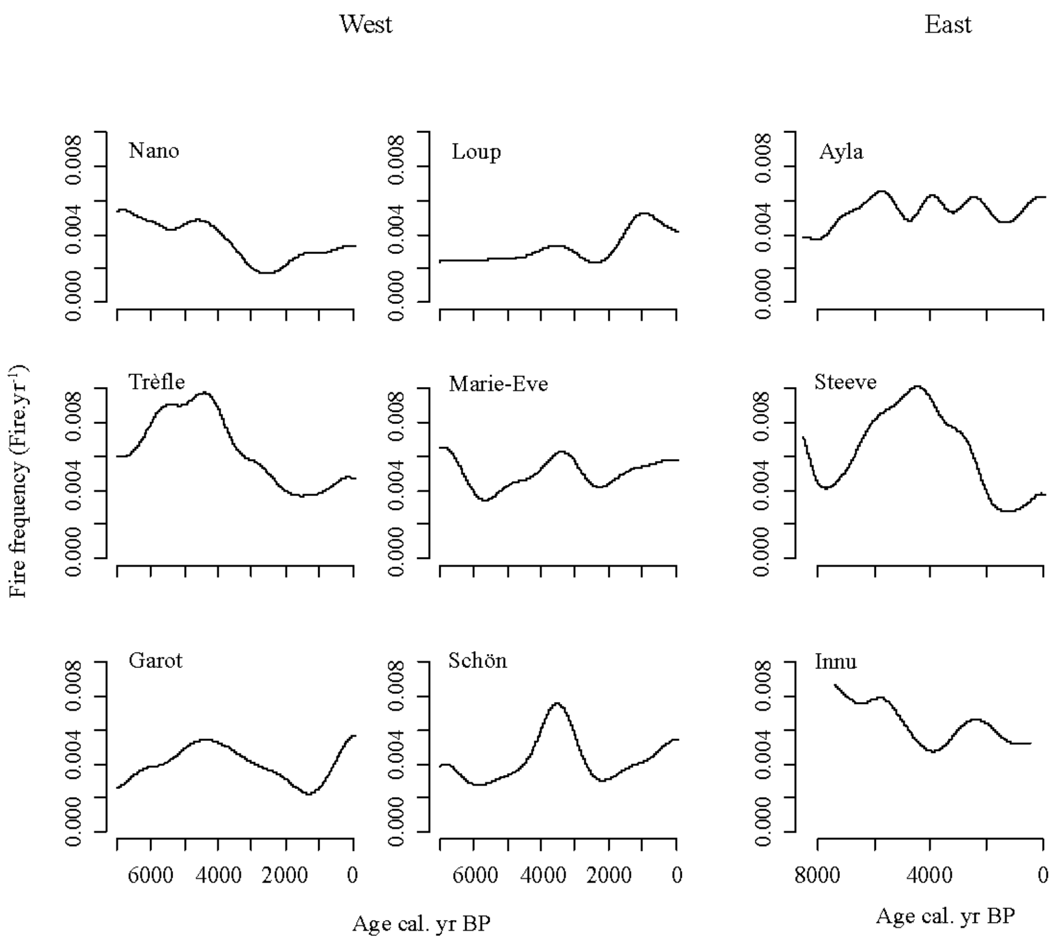




$CHAR_{background}$ is represented by values that do not significantly exceed the threshold curve (red line). $CHAR_{peak}$ corresponds to values (fire events) that significantly exceed the threshold curve and is identified by crosses. Asterisks indicate missing data in the sediments records of Lake Marie-Eve and Lake Innu.

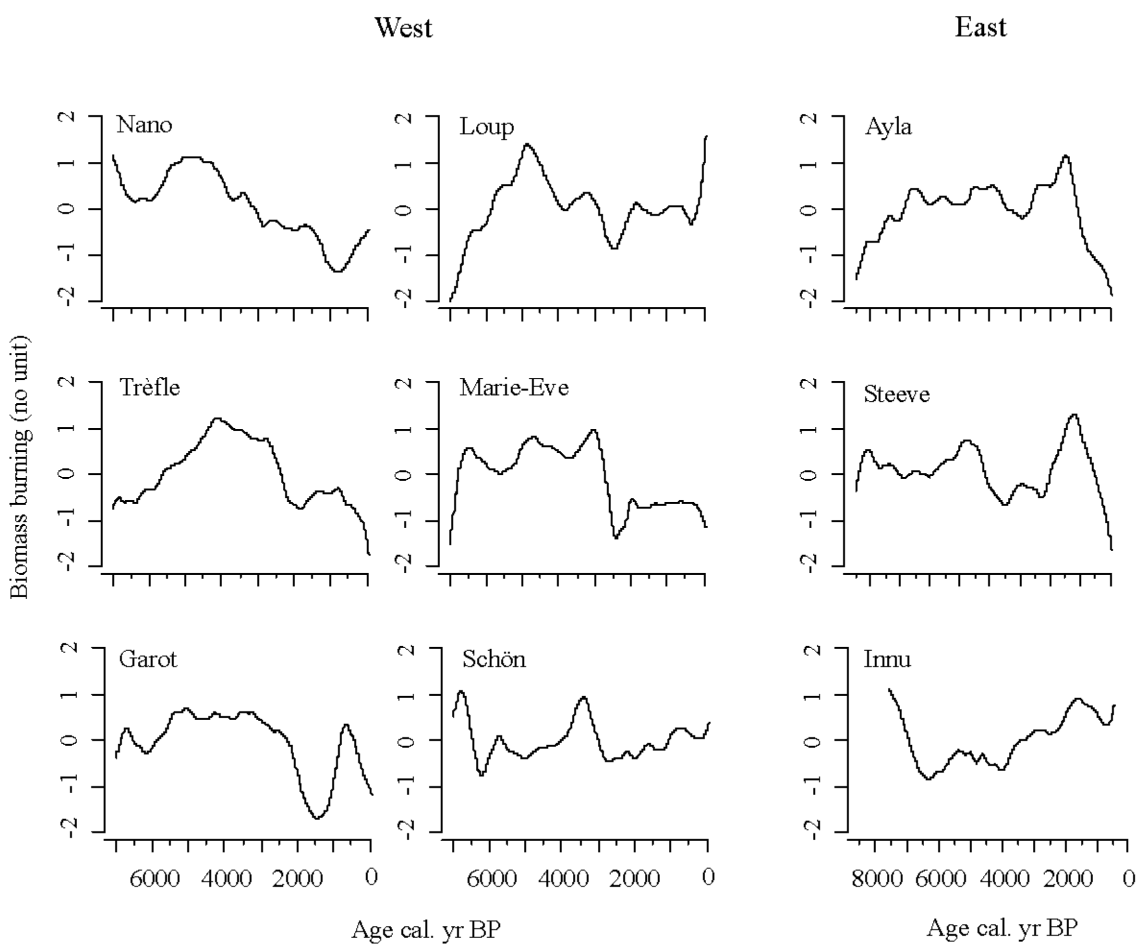
APPENDICE D

FIRE FREQUENCY SIMULATED FOR THE 500-YEAR BANDWIDTH FROM LAKES IN THE WESTERN AND EASTERN REGIONS OF QUEBEC-LABRADOR



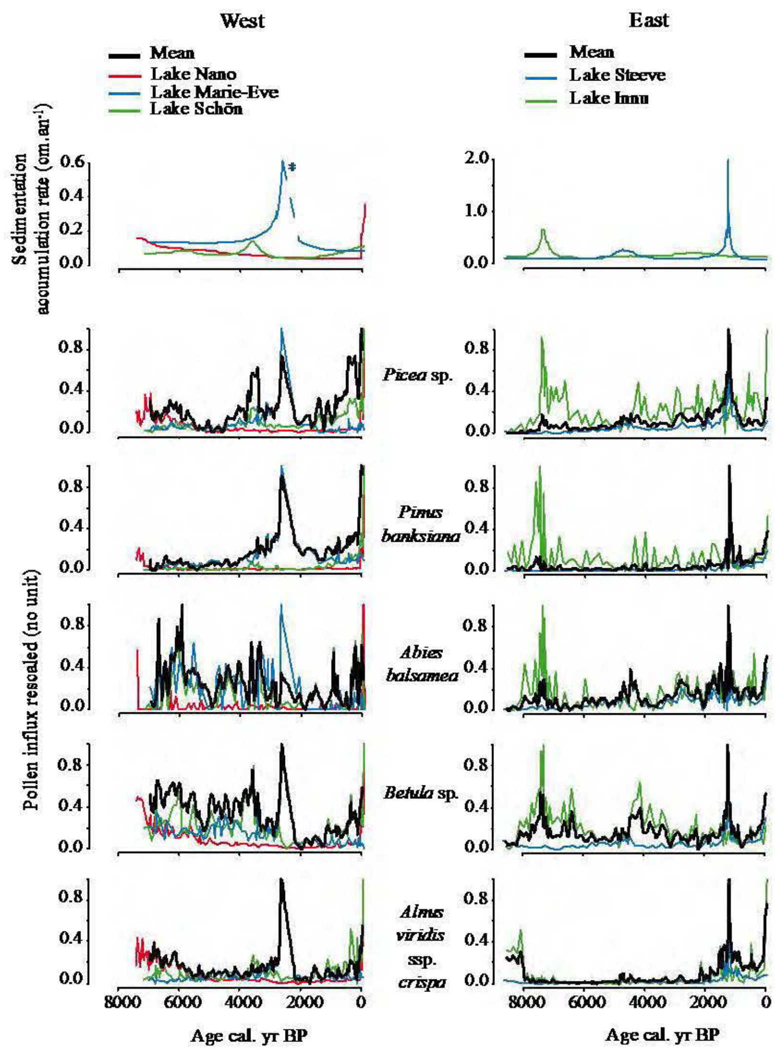
APPENDICE E

BIOMASS BURNING SIMULATED FOR THE 500-YEAR BANDWIDTH FROM LAKES IN THE WESTERN AND EASTERN REGIONS OF QUEBEC-LABRADOR



APPENDICE F

SEDIMENTATION ACCUMULATION RATE AND STANDARDIZED POLLEN ACCUMULATION RATES FROM LAKES IN THE WESTERN AND THE EASTERN REGIONS OF QUEBEC-LABRADOR.



The asterisk indicates missing data in the sediments records of Lake Marie-Eve.

APPENDICE G

ANALYSIS OF CHAR SERIES USING CHARANALYSIS

To remove the bias induced by differences in sedimentation rates, CHAR series were interpolated (CHARinterpolated) using a constant time-resolution of 20 years per sample, corresponding approximately to the mean of the median time-resolution of all records. CHARinterpolated series were decomposed into a low-frequency component (CHARbackground) and a high-frequency component (CHARpeak; Appendice I). CHARbackground results from long-distance burning and/or redeposition processes of charcoal particles that are unrelated to local fire occurrences. CHARbackground was estimated by applying the LOWESS-smoother robust technique to outliers and removing CHARinterpolated to isolate the CHARpeak component. CHARpeak was decomposed into two subpopulations: CHARnoise, representing variability in sediment mixing and sampling as well as analytical and naturally occurring noise, and CHARfire, representing significant charcoal peaks considered to originate from local fire events (Gavin *et al.*, 2006; Higuera *et al.*, 2010). For each peak, we used a Gaussian mixture model to identify the CHARnoise distribution according to a locally-defined threshold. Signal-to-noise index (Kelly *et al.*, 2011) and goodness-of-fit (Brossier *et al.*, 2014) were used to evaluate the effectiveness of the discrimination between CHARfire and CHARnoise and to assess peak detection accuracy by comparing the empirical and fitted noise distributions, respectively. Each CHARpeak that exceeded the 99th percentile threshold was assumed to originate from a local fire event, but could actually have originated from more than one fire (Gavin *et al.*, 2006).

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Brossier, B., Oris, F., Finsinger, W., Asselin, H., Bergeron, Y. & Ali, A.A. (2014) Using tree-ring records to calibrate peak detection in fire reconstructions based on sedimentary charcoal records. *The Holocene*, **24**, 635–645.

Gavin, D.G., Hu, F.S., Lertzman, K. & Corbett, P. (2006) Weak climatic control of stand-scale fire history during the late Holocene. *Ecology*, **87**, 1722–1732.

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APPENDICE H

MAIN CHARACTERISTICS OF LAKES

Sedimentary sequences for lakes in the Eastern, Central and Western regions have been published by Remy *et al.* (2016), El Guellab *et al.* (2015) and Oris *et al.* (2014), respectively.

El Guellab, A., Asselin, H., Gauthier, S., Bergeron, Y., Ali, A.A. (2015) Holocene variations of wildfire occurrence as a guide for sustainable management of the northeastern Canadian boreal forest. *Forest Ecosystems,* **2**:15.

Oris, F., Asselin, H., Finsinger, W., Hély, C., Blarquez, O., Ferland, M.-E., Bergeron, Y. & Ali, A.A. (2014) Long-term fire history in northern Quebec: implications for the northern limit of commercial forests. *Journal of Applied Ecology*, **51**, 675–683.

Remy, C.C., Lavoie, M., Girardin, M.P., Hély, C., Bergeron, Y., Grondin, P., Oris, F., Asselin, H. & Ali, A.A. (accepted) Wildfire size alters long-term vegetation trajectories in boreal forests of eastern North America.

Region	Lake	Coordinates	Elevation (m a.s.l.)	Current local vegetation	Lake surface (ha)	Water depth (m)	Length of organic core (cm)	Mean sediment accumulation rate (cm $year^{-1}$)	Median time-resolution (year per sample)
Eastern	Ayla	52°53'39.3" N 67°02'27.3" W	582	*Picea mariana, Picea glauca, Abies balsamea*	10.8	10.2	408	0.0499	10
	Steeve	51°56'23.9" N 68°09'19.2" W	548	*Picea mariana*	3.4	3.5	327	0.0349	17
	Innu	50°04'10.9" N 68°48'40.7" W	399	*Picea mariana, Abies balsamea*	1.4	7.7	370	0.0415	13
Central	Twin	50°56'68.9" N 74°33'91.2" W	376	*Picea mariana, Pinus banksiana*	2.9	5.7	189	0.0317	21
	Richard	50°36'69.9" N 74°40'69.9" W	432	*Picea mariana, Pinus banksiana*	4.0	5.3	160	0.0234	25
	Aurelie	50°25'06.6" N 74°13'67.6" W	428	*Picea mariana, Pinus banksiana*	0.18	5.7	355	0.0731	10
	Nans	50°22'07.1" N 74°18'21.32" W	431	*Picea mariana*		5.0	213	0.0494	18
Western	Loup	53°03'18.1" N 77°24'01.9" W	206	Picea mariana, *Pinus banksiana*	1.6	3.0	106	0.0145	37
	Nano	53°01'25.5" N 77°21'51.3" W	206	*Picea mariana, Pinus banksiana*	0.4	3.2	140	0.0185	22
	Marie-Eve	52°01'47.4" N 75°31'14.6" W	296	*Picea mariana, Pinus banksiana*	16.5	8.7	290	0.0416	15
	Trèfle	51°57'54.7" N 76°04'52.0" W	270	*Picea mariana, Pinus banksiana*	6.8	5.4	150	0.0208	24
	Garot	51°05'58.7" N 77°33'12.9" W	291	*Picea mariana, Pinus banksiana*	2.8	7.0	133	0.0181	26
	Schön	50°35'41.7" N 77°34'06.1" W	248	*Picea mariana, Pinus banksiana*	5.1	6.9	100	0.0133	37

APPENDICE I

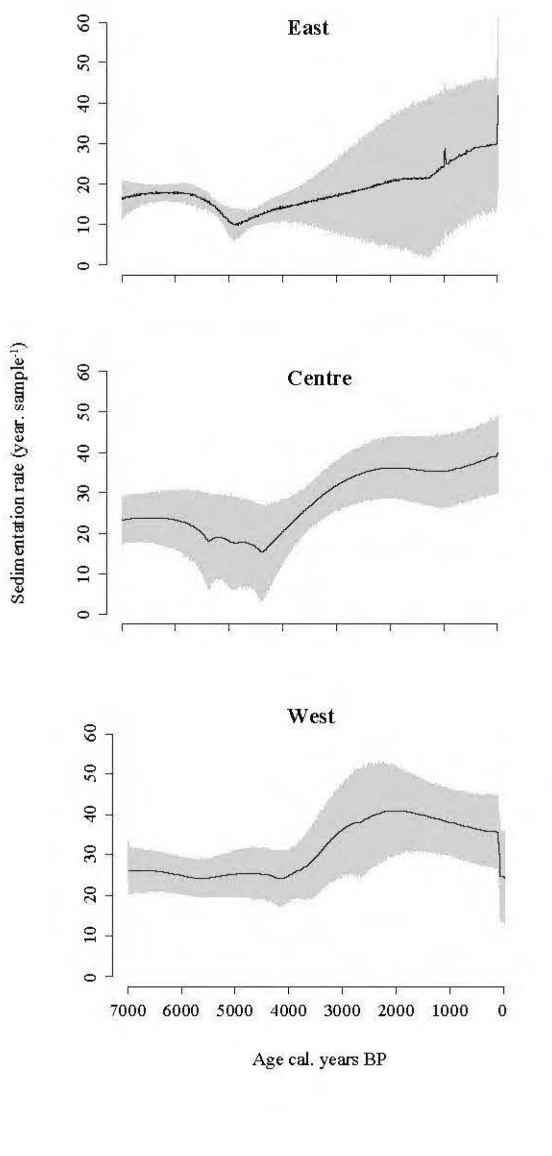
PEARSON'S CORRELATION COEFFICIENTS BETWEEN RECONSTRUCTED *RegFF* AND *RegBB* HISTORY AND MAIN CLIMATIC VARIABLES

		West		Centre		East	
		RegBB	*RegFF*	*RegBB*	*RegFF*	*RegBB*	*RegFF*
Temperature	spring	0.003	**-0.440*** **	**-0.267*** **	**-0.437*** **	-0.081	**-0.335*** **
	summer	**0.481*** **	0.027	**0.418*** **	**0.215*** **	**0.634*** **	**0.607*** **
	spring + summer	**0.375*** **	**-0.431*** **	0.052	**-0.234*** **	**0.346*** **	0.101
Precipitation	spring	**0.124** **	**-0.411*** **	0.002	-0.054	**0.380*** **	**0.230*** **
	summer	**-0.094** **	**-0.647*** **	**0.340*** **	**0.343*** **	**0.888*** **	**-0.232*** **
	spring + summer	-0.024	**-0.645*** **	**0.288*** **	**0.249** **	**0.846*** **	**-0.096* **
Fire season length	spring	**-0.321*** **	**-0.460*** **	0.105	-0.037	**-0.214*** **	**-0.149** **
	summer	-0.003	0.114	**-0.227*** **	**-0.322*** **	**-0.563*** **	**0.167*** **
	spring + summer	**-0.164*** **	**-0.128** **	**-0.191*** **	**-0.440*** **	**-0.569*** **	**0.103** **

Fire season is split into two periods: "spring" from April to June and "summer" from July to September. Significant correlation coefficients are marked in boldface type and asterisks indicate *P* values (* $P < 0.1$, ** $P < 0.05$, *** $P < 0.01$) determined by permutation tests (sample size: n= 8 millennia).

APPENDICE J

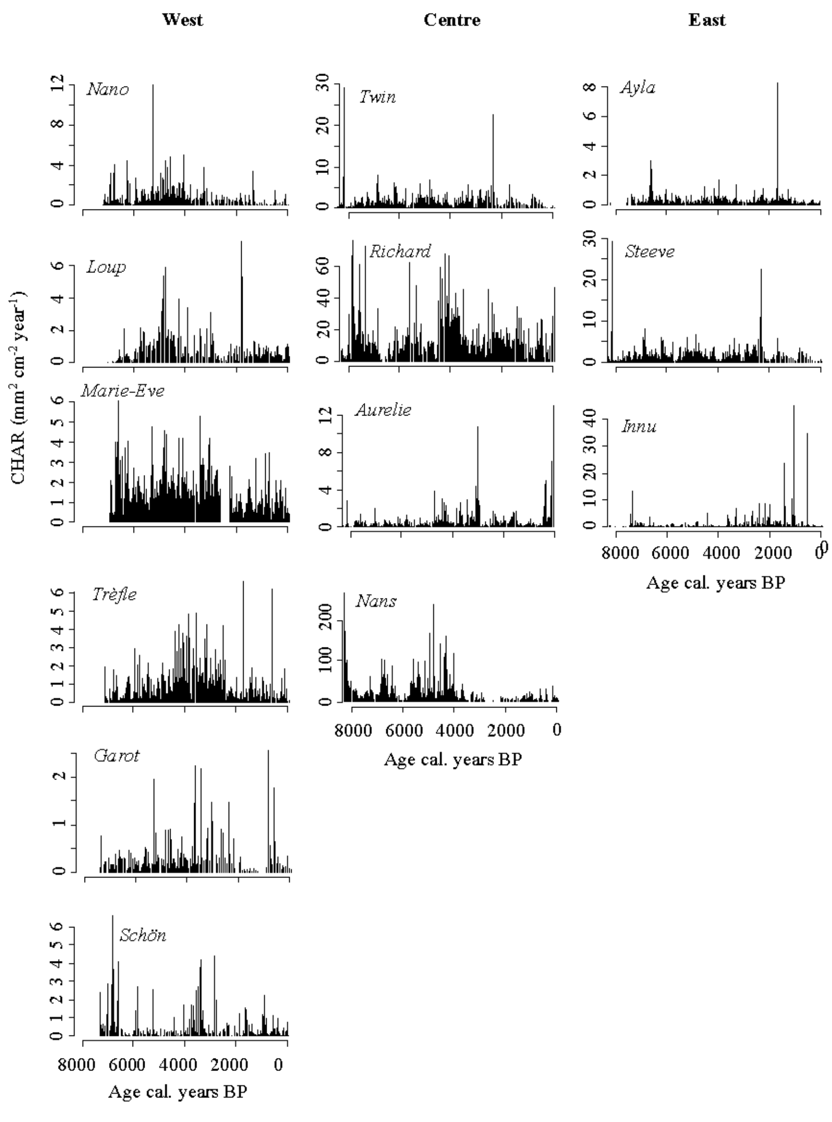
SEDIMENTATION RATES FROM SEDIMENT SEQUENCES OF LAKES



The black lines indicate the average sedimentation rate in lakes located in the corresponding regions. The grey areas indicate 90% bootstrap confidence intervals.

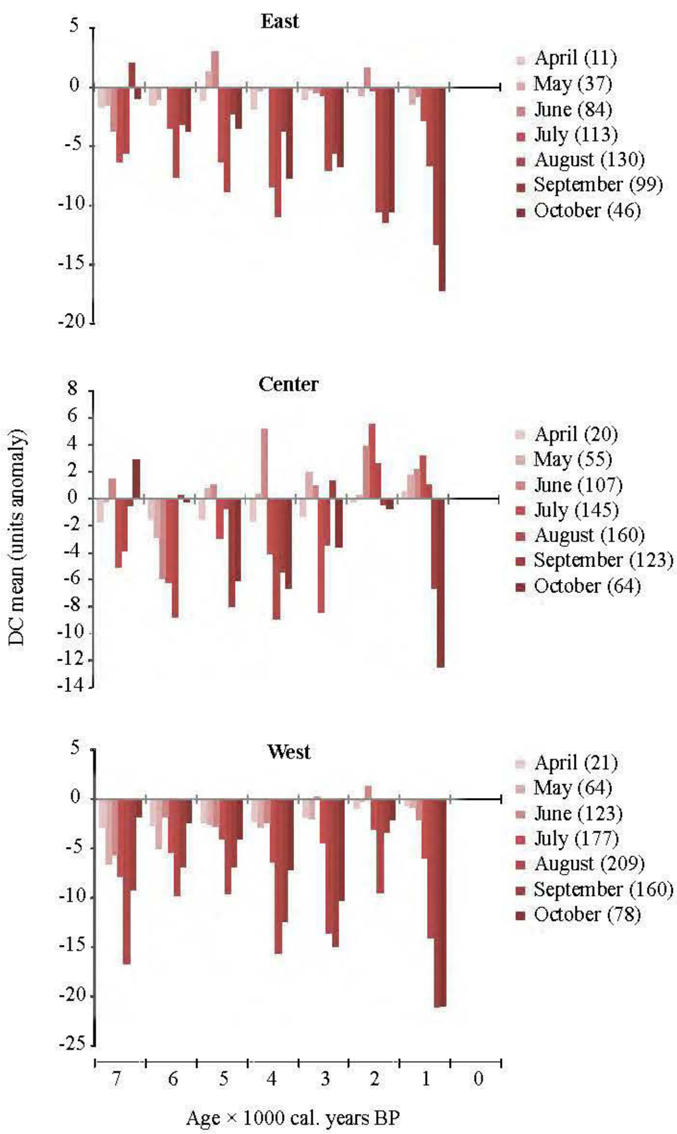
APPENDICE K

CHARCOAL AREA SERIES FROM SEDIMENT SEQUENCES OF LAKES



APPENDICE L

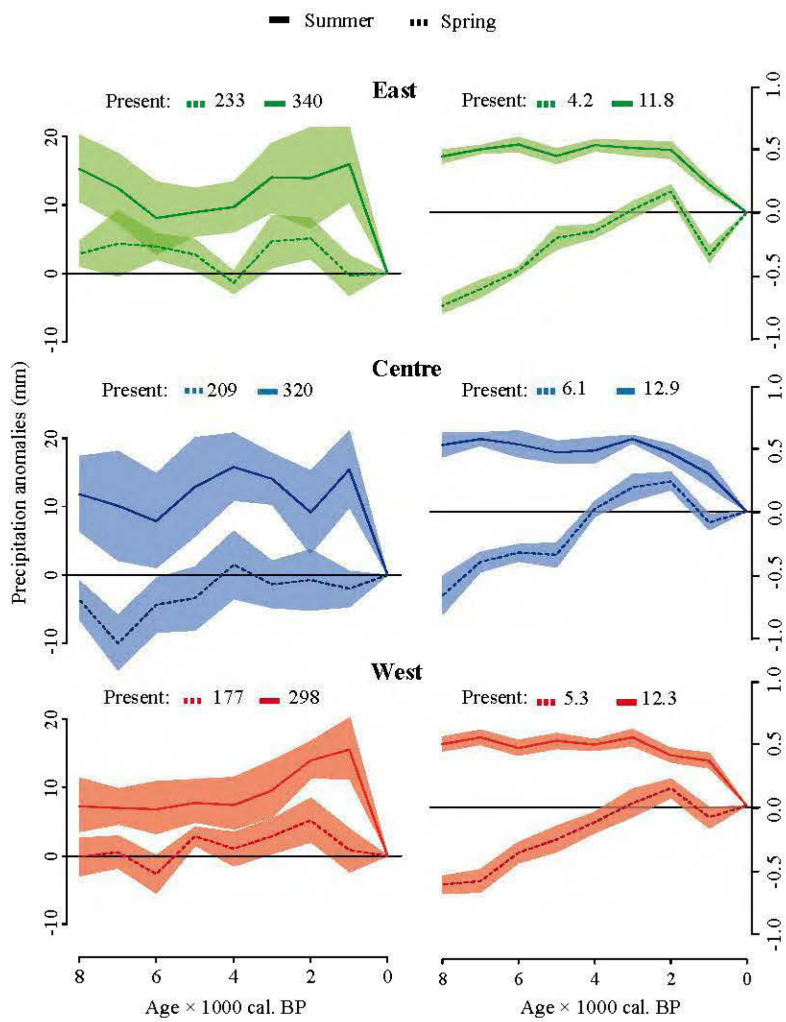
RECONSTRUCTIONS OF MONTHLY MEANS OF DAILY DROUGHT CODE (DC) DURING THE HOLOCENE FROM UGAMP SIMULATIONS



Numbers in parentheses are monthly means of DC at present-day.

APPENDICE M

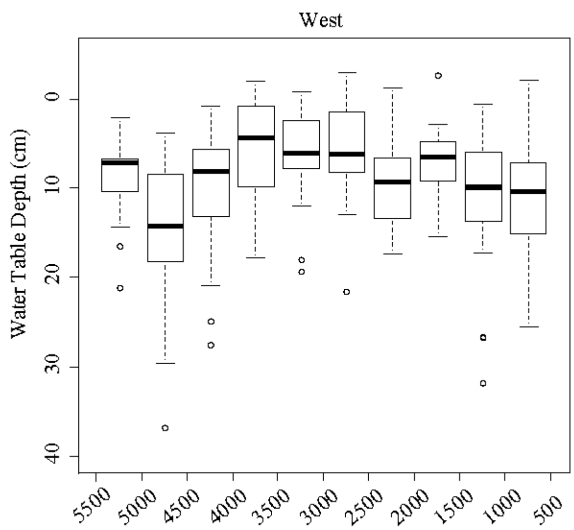
SIMULATED SEASONAL PRECIPITATION (LEFT) AND TEMPERATURE (RIGHT) WITH STANDARD ERRORS

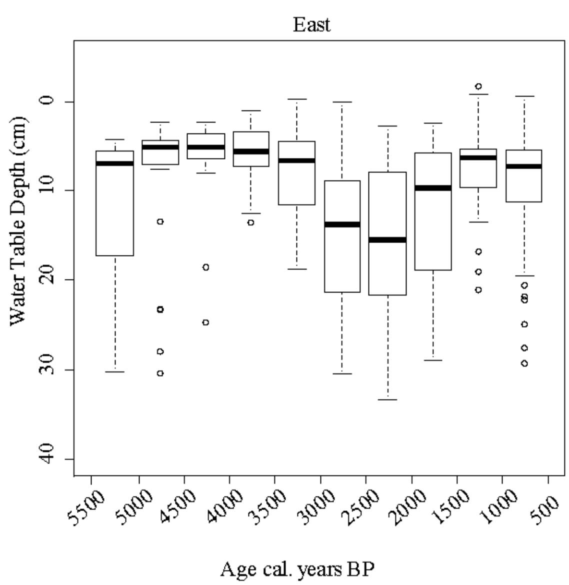


Results are obtained from the HadCM3 model (anomalies relative to 0 cal. years BP) for the three regions of the study area (East, Centre and West) during the fire season (spring from April to June and summer from July to September). The temperature and precipitation at present-day are indicated for each of the three regions.

APPENDICE N

RECONSTRUCTIONS OF WATER TABLE DEPTH FROM REPORTED VALUES FOR THREE PEATLANDS IN THE WESTERN REGION OF THE STUDY AREA (VAN BELLEN *ET AL*. 2011) AND FOUR IN THE EASTERN REGION (MAGNAN *ET AL*. 2014).





Water table depths are negatively linked to atmospheric humidity.

Magnan, G. & Garneau, M. (2014) Evaluating long-term regional climate variability in the maritime region of the St. Lawrence North Shore (eastern Canada) using a multi-site comparison of peat-based paleohydrological records. Journal of Quaternary Science, 29, 209–220.

van Bellen, S., Garneau, M. & Booth, R.K. (2011) Holocene carbon accumulation rates from three ombrotrophic peatlands in boreal Quebec, Canada: Impact of climate-driven ecohydrological change. The Holocene, 27, 1217-1231.

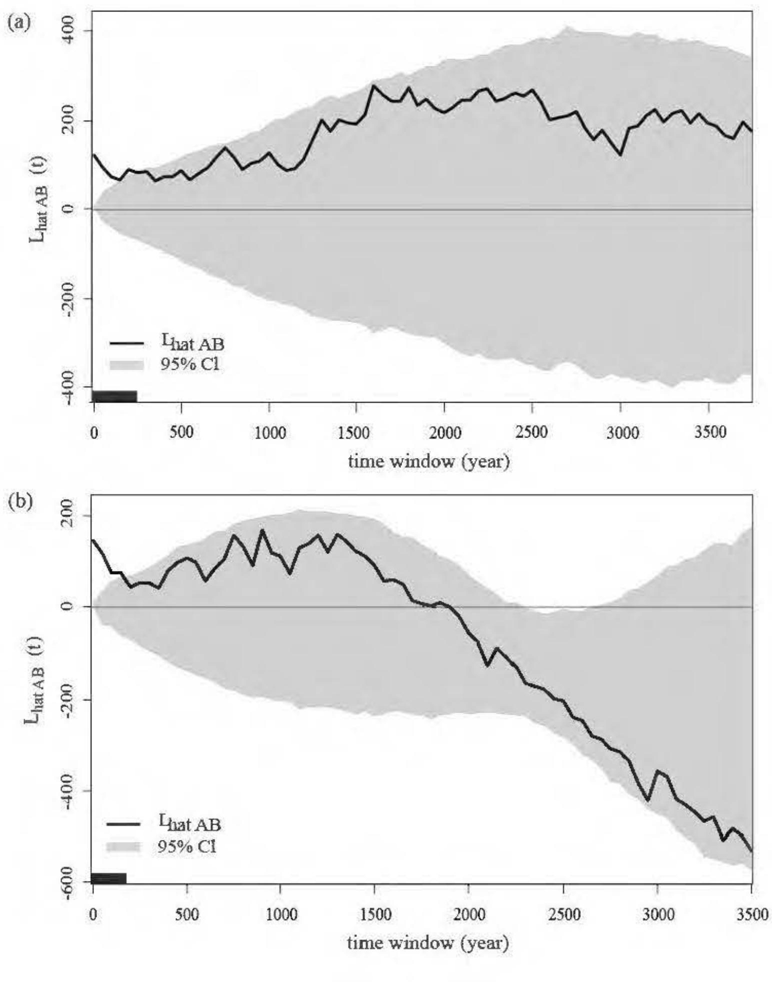
APPENDICE O

CHARANALYSIS METHOD

The CHAR series were interpolated ($CHAR_{interpolated}$) using the median time-resolution (year. sample^{-1}) of the records. The $CHAR_{interpolated}$ series were decomposed into a low-frequency component ($CHAR_{background}$) and a high-frequency component ($CHAR_{peak}$). The $CHAR_{background}$ is considered to consist of charcoal particles from long-distance burning and/or re-deposition processes, unrelated to local fire occurrences. $CHAR_{background}$ was estimated by lowess-smoother robust to outliers and removed from the $CHAR_{interpolated}$ to isolate the $CHAR_{peak}$ component. $CHAR_{peak}$ was decomposed into two subpopulations: $CHAR_{noise}$, representing variability in sediment mixing and sampling, and analytical and naturally occurring noise, and $CHAR_{fire}$, representing significant charcoal peaks considered to originate from local fire events [Clark and Royall, 1996; Gavin *et al.*, 2006; Higuera *et al.*, 2010]. For each peak, we used a Gaussian mixture model to identify the $CHAR_{noise}$ distribution according to a locally defined threshold. Each $CHAR_{peak}$ that exceeded the 99th percentile threshold was considered a local fire event. Signal-to-noise index [SNI; Kelly *et al.*, 2011] and goodness-of-fit (GOF) were used to evaluate the effectiveness of the discrimination between $CHAR_{fire}$ and $CHAR_{noise}$ and to assess peak detection accuracy by comparing the empirical and fitted noise distributions, respectively. To estimate $CHAR_{background}$, we used the widest smoothing window that satisfied statistical needs (SNI > 3 and GOF) detected fire events [Brossier *et al.*, 2014].

APPENDICE P

BIVARIATE L-FUNCTION (BLACK LINE) FOR TESTING THE SYNCHRONY BETWEEN FIRE EVENTS RECONSTRUCTED WITH PEAKS RETAINED BY CSD AND LCC METHODS FROM (A) NANO AND (B) LOUP LACUSTRINE SEDIMENT SEQUENCES, RESPECTIVELY



Grey areas correspond to 95% confidence intervals (CI) around L_{hat} AB = 0 (i.e. independence) and black line not included in grey areas and greater than 0 corresponds to L_{hat} AB indicating synchrony at time window of ± *time window* (length of black boxes).

APPENDICE Q

MAIN CHARACTERISTICS OF STUDY LAKES

Latitude	50°40'10.9" N	51°56'23.9" N	53°01'25.5" N	53°03'18.1" N
Longitude	68°48'40.7" W	68°90'19.2" W	77°21'51.3" W	77°24'01.9" W
Elevation (m asl)	399	548	206	206
Current local vegetation	*Picea mariana* (Mill.), *Abies balsamea* (L.) Mill., *Betula papyrifera* Marshall	*Picea mariana* (Mill.), *Betula glandulosa* Michx.	*Picea mariana* (Mill.), *Pinus banksiana* Lamb.	*Picea mariana* (Mill.), *Pinus banksiana* Lamb.
Hill slopes	Moderate	Moderate	Flat	Flat
Lake surface (ha)	1.4	3.4	0.4	1.6
Water depth (m)	7.7	3.5	3.2	3.0
Length of organic core (cm)	370	327	140	106
Mean sediment accumulation rate (cm. year^{-1})	0.0415	0.0349	0.0185	0.0145
Median time-resolution (year. sample^{-1})	13	17	22	37

APPENDICE R

AMS ^{14}C DATING FROM INUK AND STEEVE LAKES

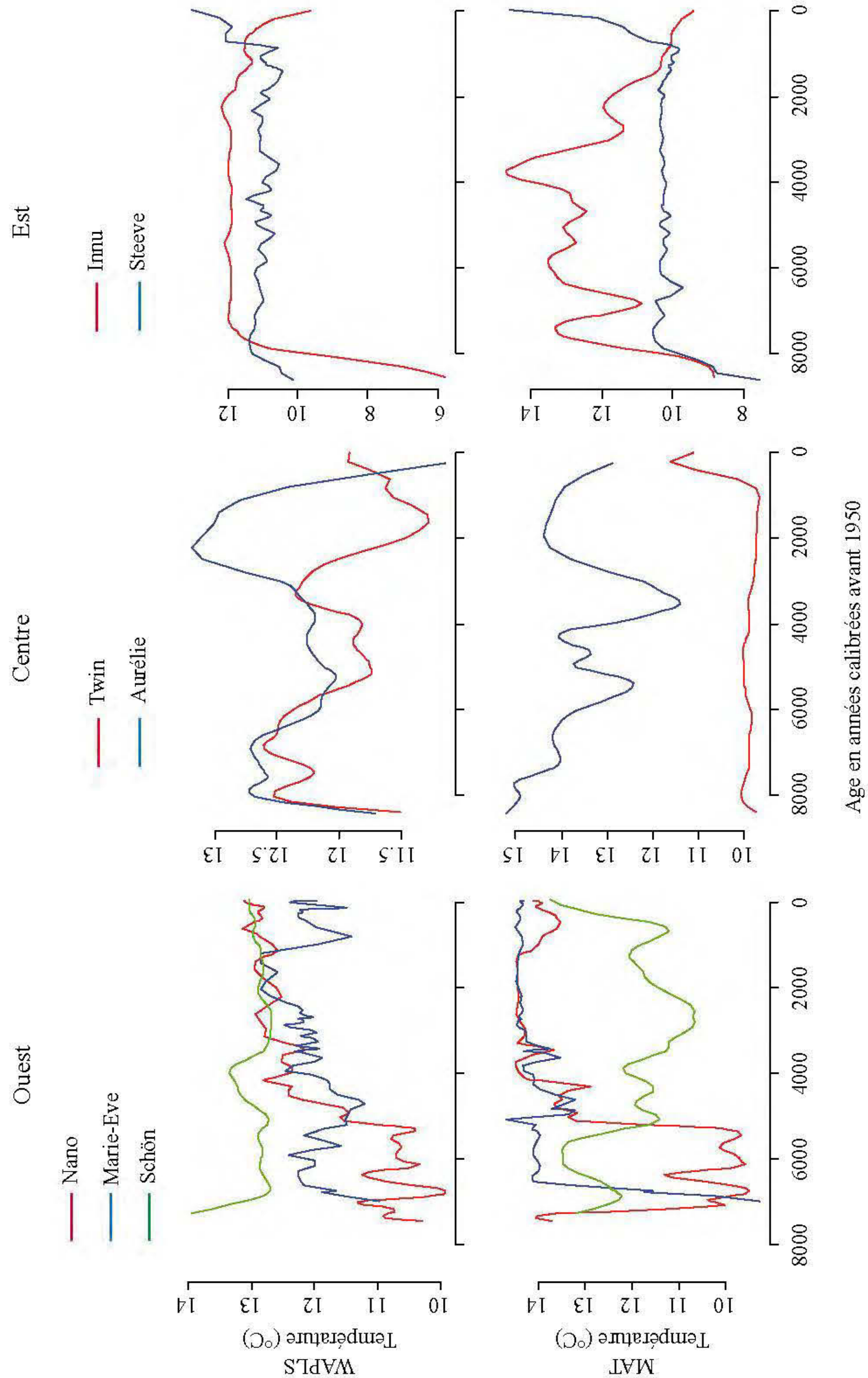
Site and depth (cm)	^{14}C year BP ($\pm \sigma$)	Materials dated	Laboratory code
Steeve Lake			
20.5-21	1080 ± 25	Gyttja	UCIAMS-138428
60.5-61	1240 ± 15	Gyttja	UCIAMS-137800
110-111	2195 ± 15	Gyttja	UCIAMS-137801
160-161	3825 ± 25	Gyttja	UCIAMS-137802
209.5-210.5	4415 ± 15	Gyttja	UCIAMS-137803
260-261	5990 ± 15	Gyttja	UCIAMS-137804
300-300.5	7485 ± 20	Gyttja	UCIAMS-137805
Inuk Lake			
21-22	340 ± 15	Charcoal	* UCIAMS-137812
21-22.5	500 ± 30	Gyttja	Beta-377380
71.5-72	1575 ± 15	Plant macroremains	* UCIAMS-137815
58-58.5	1645 ± 15	Plant macroremains	UCIAMS-137813
70.5-72.5	1750 ± 30	Gyttja	Beta-377381
121-122	2745 ± 25	Gyttja	UCIAMS-138423
171-172	3750 ± 25	Gyttja	UCIAMS-138422
221-221.5	4705 ± 25	Gyttja	UCIAMS-138421
271-271.5	6300 ± 25	Gyttja	UCIAMS-138420
342-342.5	6555 ± 25	Gyttja	UCIAMS-138419
361-361.5	7925 ± 30	Gyttja	UCIAMS-138418

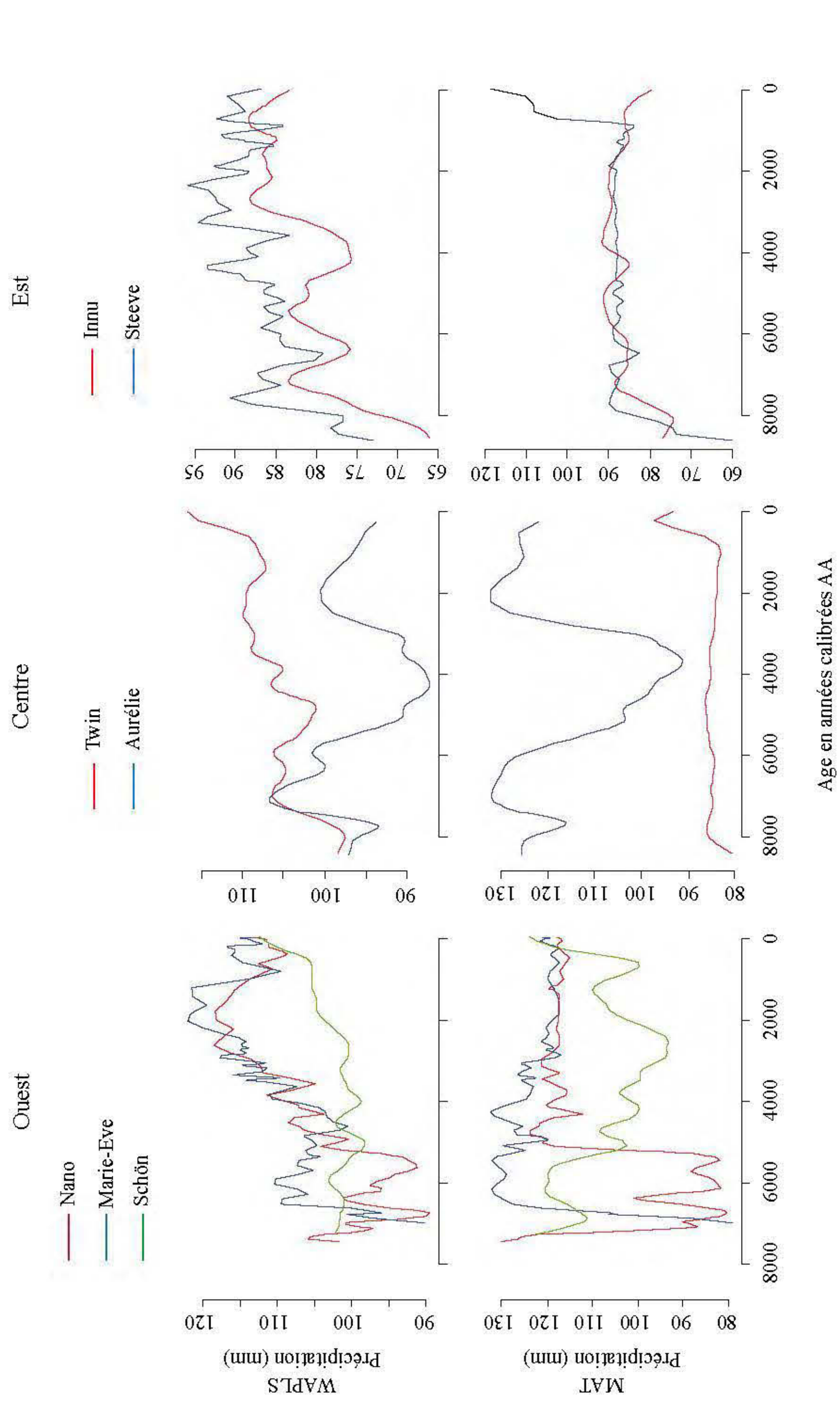
* Rejected dates

APPENDICE S

RESULATS PRELIMINAIRES DE RECONSTRUCTIONS DE LA TEMPERATURE ET DES PRECIPITATIONS A PARTIR DES DONNEES POLLINIQUES DES LACS ETUDIES

La méthode utilisée est entièrement basée sur les travaux de Fréchette *et al.* (2015). La base de données de polliniques modernes utilisée a été fournie par Bianca Fréchette et la base de données climatiques actuelle a été tirée de Whitmore *et al.* (2005). Les reconstructions ont été effectuées à partir du package *rioja* sur R (Juggins, 2016). Les données polliniques utilisées pour faire les reconstructions sont celles qui ont été présentées dans le chapitre 2 de cette thèse, ainsi que les données polliniques non publiées des lacs Twin et Aurélie analysés par Verushka Valsecchi, post-doctorante (2010-2011) sous la supervision de Adam A. Ali. Deux types de reconstructions ont été utilisés : la technique des analogues modernes (MAT) et la méthode des moindres carrés partiels pondérée par la moyenne (WAPLS) sur la période juillet-août-septembre. Les degrés de fiabilité utilisés sont l'erreur quadratique moyenne (RMSE) et le coefficient de détermination (r^2). Le RMSE de la température est de ±0.83°C (r^2 = 0.97) pour la MAT et ±2.00°C (r^2 = 0.83. Le RMSE des précipitations est de ±10 mm (r^2 = 0.90) pour la MAT et ±17 mm (r^2 = 0.73) pour la WAPLS.


Ouest
Centre
Est
Nano
Marie-Eve
Schön
Twin
Aurélie
Innu
Steeve
WAPLS
Température (°C)
MAT
Température (°C)
Age en années calibrées avant 1950


Ouest
Centre
Est
Nano
Marie-Eve
Schön
Twin
Aurélie
Innu
Steeve
WAPLS
MAT
Précipitation (mm)
Précipitation (mm)
Age en années calibrées AA

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