TABLE DES MATIÈRES

CHAPITRE IV

CHAPITRE V

LISTE DES FIGURES

LISTE DES TABLEAUX

LISTE DES ABRÉVIATIONS

AD	Anno domini
Cal. year BP	Calibrated years before present
CHAR	Charcoal accumulation rate
CI	Confidence interval
CR	Conservative range
CRS	Constant rate of supply
CSD	Charcoal size distribution
DBH	Diameter at breast height
DC	Drought code
FFI, FRI	Fire free interval, Fire return interval
FO, RegFO	Fire occurrence, Regional fire occurrence
FSL	Fire season length
GCM	Global climate model
GOF	Goodness of fit
KB	Kajak-Brinkhurst
KS	Kolmogorov-Smirnov test
LLP	Lake Loup
LNA	Lake Nano
LOWESS	Locally weighted scatterplot smoothing
MW	Mann-Whitney test
SD	Standard deviation
SFM	Sustainable forest management
SNI	Signal to noise index
UGAMP	Universities Global Atmospheric Modelling Programme

RÉSUMÉ

Suite à la conférence de Rio en 1992, le Québec a adhéré aux principes du développement durable, notamment en adoptant un projet de loi sur les forêts en 1996. C'est aussi dans ce contexte que la limite nordique des forêts commerciales a été créée en 2000. Le climat moins propice au développement de forêts économiquement rentables et la haute fréquence des feux ont été les critères principaux pour déterminer la position de la limite nordique de la forêt commerciale au niveau du 51e parallèle Nord. Au cours des 50 dernières années, des échecs de régénération ont été mis en évidence après le passage d'un feu, transformant la pessière à mousses en pessière à lichens, moins productive. L'objectif général de cette thèse était de mieux comprendre comment les forêts évolueront dans la zone de la limite nordique d'exploitation face aux changements dans le régime des feux en réponse aux changements climatiques en cours. Les travaux ont porté sur la reconstitution des historiques de feux au cours de l'Holocène de onze lacs en Jamésie selon un gradient Sud-Nord du 49e au 53e parallèle Nord.

Une des approches permettant de reconstituer la dynamique des feux de forêts au cours du temps est fondée sur la quantification et l'analyse des charbons de bois préservés dans des dépôts lacustres. Cette méthode s'appuie sur le principe que les feux locaux (dans le bassin versant du lac) peuvent être reconstitués à partir de pics d'accumulation de charbons de bois qui se déposent dans les sédiments lacustres après feux. Pour identifier les feux locaux, les enregistrements de charbons de bois doivent être traités statistiquement, notamment pour en retirer le bruit de fond issu du ruissèlement de surface, de remaniements sédimentaires ou de transport à longue distance. Ces traitements statistiques sont généralement réalisés à l'aide du logiciel CharAnalysis. Malgré une utilisation répandue, des biais restent présents dans l'analyse des charbons pour reconstituer les feux. Premièrement, les résultats dépendent fortement des choix faits au cours du traitement statistique. Des fenêtres temporelles de différentes largeurs peuvent être utilisées dans la reconstitution des épisodes de feu pour modéliser le bruit de fond. Deuxièmement, des transports à longue distance (5-20 km) de charbons ont été rapportés, qui rendent difficile la différenciation des feux locaux et régionaux. Cette thèse comprend ainsi un volet méthodologique visant à évaluer l'impact de ces deux biais dans l'analyse des séries de charbons de bois lacustres pour en améliorer l'interprétation.

Nous avons comparé les historiques de feux des 150 dernières années reconstitués à l'aide de séries de charbons de bois issues de deux lacs avec les reconstitutions dendrochronologiques des feux dans les bassins versants correspondants. L'indice signal-sur-bruit (Signal to Noise Index, SNI) a été utilisé afin d'évaluer la qualité des reconstitutions. Un SNI > 3 permet de considérer positivement les événements de feux reconstitués. Nos résultats ont montré que pour mieux assurer la reconstitution des feux récents, la fenêtre la plus courte pour modéliser le bruit de fond qui permet d'atteindre des SNI > 3 devrait être sélectionnée, plutôt que de chercher à atteindre des valeurs de SNI maximales.

Des trappes lacustres installées dans sept lacs nous ont permis d'étudier la dispersion et la déposition des charbons de bois pendant trois années consécutives. Les pics d'accumulation de charbons étaient liés autant à des feux locaux (dans le bassin versant des lacs) que régionaux (jusqu'à 32 km de distance). Cependant, les feux régionaux étaient caractérisés par une plus grande proportion de petites particules dans les séries de charbons de bois. Nous avons mis en évidence que l'analyse de la distribution de la taille des particules de charbon doit être réalisée sur les pics de charbons détectés par CharAnalysis pour discriminer les feux locaux réels des feux régionaux.

Nous avons reconstitué l'historique des feux de 11 lacs au nord, près et au sud de la limite nordique de la forêt commerciale. Les historiques des feux des forêts au nord et près de la limite nordique de la forêt commerciale montrent les mêmes tendances que pour les forêts plus au sud, avec une augmentation des occurrences de feu à partir de 7000 ans avant nos jours pour atteindre un maximum entre 4000-3000 ans avant nos jours, suivi d'une diminution à la fin de l'Holocène. Cependant, les écosystèmes situés au nord de la limite de la forêt commerciale semblent plus affectés par les changements climatiques. Dans une configuration d'augmentation de l'activité des feux dans les prochaines décennies, il est conseillé de conserver la limite nordique des forêts commerciales à sa position actuelle.

Mots clés : forêt boréale, feux de forêt, charbons de bois, changements climatiques, aménagement forestier durable, limite nordique de la forêt commerciale, distribution de taille de charbons.

CHAPITRE I

INTRODUCTION GÉNÉRALE

Depuis la Conférence des Nations Unies sur l'environnement et le développement en 1992, les principes du développement durable ont intégré les objectifs de l'aménagement des forêts. Cela s'est traduit par l'essor de nombreux concepts, pratiques et politiques axés sur la gestion durable des forêts, tels que la certification forestière et l'adoption de projets de loi sur l'aménagement des forêts (Rist et Moen 2013; Stupak et al. 2011). La gestion durable des forêts exige des conditions minimales à remplir, parmi lesquelles le maintien de la productivité et de la capacité de régénération des forêts (Wilkie et al. 2003). Les forêts doivent être résilientes, c'est-à-dire se régénérer après des perturbations naturelles ou anthropiques, de telle sorte que la densité, la structure, la composition et la productivité des peuplements soient comparables après un certain temps aux conditions avant perturbation. Les écosystèmes forestiers boréaux sont caractérisés par une croissance limitée et par des perturbations naturelles fréquentes (incluant les feux, les épidémies par les insectes, les chablis et les trouées) (Kneeshaw et al. 2011; Payette 1992). De ce fait, y ajouter des perturbations anthropiques peut diminuer leur résilience (Dussart et Payette 2002; Payette et Delwaide 2003) et, *in fine*, leurs fonctionnalités écologiques et les services écosystémiques qu'ils fournissent.

Dans ce contexte, la limite nordique d'exploitation des forêts du Québec a été positionnée en 2000 aux alentours du 51^{e} parallèle Nord, au sein du domaine bioclimatique de la pessière à mousses. Au-delà de cette limite, le climat est moins propice au développement de forêts économiquement rentables, les arbres croissent plus lentement et le cycle de feux est relativement court (Mansuy et al. 2010; MRNF 2000). La densité de la forêt boréale diminue progressivement avec l'augmentation de la latitude et laisse place à la pessière à lichens au-delà du 52° parallèle Nord. Le cycle de feu est plus court près de la limite d'exploitation commerciale (~100 ans) (Mansuy et al. 2010) que plus au sud (~360 ans) (Bergeron et al. 2004), à cause de conditions climatiques particulières impliquant notamment des phénomènes de blocage récurrents de masses d'air au niveau de la troposphère (Girardin et al. 2006; Skinner et al. 2002) qui provoquent un assèchement du combustible et favorisent l'occurrence de grands feux de forêt (Johnson et Wowchuk 1993).

Au regard des prévisions climatiques futures (IPCC 2013), un changement de la fréquence et de l'intensité des perturbations par le feu est attendu. Des études suggèrent que l'augmentation des précipitations ne sera pas suffisante pour compenser la hausse de la température; les épisodes de sécheresse et les feux de forêts seront donc plus fréquents (Bergeron et al. 2010; Girardin et Mudelsee 2008; Hély et al. 2010). Il est important de souligner qu'au cours des 50 dernières années, une partie de la forêt boréale fermée s'est transformée en forêt ouverte à cause de perturbations (naturelles ou/et anthropiques) successives au Québec (Côté et al. 2013; Girard et al. 2008). Quand l'intervalle de temps entre deux feux est trop court, l'épinette noire n'a pas le temps d'atteindre la maturité sexuelle, sachant que la production de graines commence généralement après 30 ans (Viglas et al. 2013). Des échecs de régénération suivant des feux successifs pourraient donc devenir plus fréquents et menacer le développement des pessières à mousses, notamment dans les zones limitrophes. Cependant, le réchauffement climatique pourrait également se traduire par un changement de composition des forêts du nord, dû à un enrichissement en espèces plus typiques des forêts du sud (Burton et Cumming 1995). Cette éventuelle densification du couvert végétal (Gamache et Payette 2005) pourrait donc limiter la perte de résilience des massifs forestiers face à une recrudescence des perturbations.

Ces incertitudes suscitent des interrogations, notamment de la part des compagnies forestières opérant près de la limite nordique de la forêt commerciale, mais aussi des scientifiques, et alimentent la problématique à la base de cette thèse : « Dans un contexte de réchauffement climatique, de quelle manière la forêt évoluera-t-elle dans la zone de la limite nordique d'exploitation forestière? ». Ainsi, un comité scientifique a été créé en 2005 par le Ministère des Ressources naturelles du Québec afin de réévaluer la localisation de la limite nordique de la forêt boréale sur la base d'une étude plus précise du territoire (MRN 2013), avec une attention particulière à l'histoire et au régime des perturbations par le feu à différentes échelles d'espace et de temps.

1.1 S'inspirer du régime des perturbations par le feu pour aménager et gérer la forêt boréale

L'aménagement forestier écosystémique est une approche qui s'inspire des processus écologiques naturels, incluant les perturbations. Ce mode d'aménagement vise le développement de peuplements et de paysages présentant des compositions spécifiques et des structures similaires à celles qui caractérisent les écosystèmes naturels. L'objectif est d'ainsi favoriser le maintien de la diversité biologique et des fonctions écologiques essentielles (Bergeron et al. 2006). Les écosystèmes ont évolué à l'intérieur d'une gamme de conditions naturelles qui peuvent servir de cadre référentiel afin d'assurer l'intégrité écologique des écosystèmes aménagés et maintenir leur résilience (Landres et al. 1999). Dans la mesure où le feu est la perturbation principale contrôlant le fonctionnement des écosystèmes boréaux (Payette 1992), l'aménagement forestier écosystémique doit se baser sur les régimes de feux et leurs variabilités dans le temps et l'espace (Bergeron et al. 2002). Ainsi, l'aménagement des forêts ne doit pas positionner les forêts en dehors de leur gamme de variabilité naturelle (Bergeron et al. 2002; Cyr et al. 2009). Par exemple, pour remplacer les feux par les coupes, il faut que la fréquence des feux actuels additionnée aux coupes ne dépasse pas la fréquence maximale des feux préindustriels. Or, dans la zone d'étude, l'aménagement forestier est « en compétition » avec les feux. Une augmentation de la fréquence future des feux pourrait considérablement réduire la marge de manœuvre disponible à l'aménagement forestier, et ceci devrait être inclus dans les calculs de possibilité forestière.

L'étude de la dynamique des feux de forêt à la limite nordique de la forêt commerciale nous permettra d'établir la gamme de variabilité naturelle et de mieux comprendre comment les forêts à la limite nordique commerciale pourraient évoluer dans le futur face à d'éventuels changements dans le régime des feux en réponse au changement climatique en cours.

1.2 Reconstituer l'historique des feux à partir des charbons de bois lacustres

1.2.1 Dispersion et déposition des charbons

Une des approches permettant de reconstituer la dynamique des feux de forêts au cours du temps est fondée sur la quantification et l'analyse des charbons de bois préservés dans des dépôts lacustres. Cette méthode est fondée sur le principe que des feux locaux (dans le bassin versant du lac) peuvent être reconstitués à partir de pics d'accumulation de charbons de bois qui se déposent dans les sédiments après des incendies. Cependant, cette approche est loin d'être aisée et les enregistrements de charbons de bois doivent être traités pour en retirer le bruit de fond issu du ruissèlement de surface, de remaniements sédimentaires ou de transport à longue distance. Ce bruit de fond obscurcit les enregistrements de feux locaux (Clark et Royall 1996; Long et al. 1998). Le bruit de fond varie spatialement et temporellement en fonction de la topographie, des caractéristiques du lac et de la production de charbons qui dépend de la qualité et de la structuration du combustible (Umbanhowar et Mcgrath 1998; Whitlock et Millspaugh 1996).

Les modèles théoriques prédisent que la distance de dispersion des charbons de bois diminue avec la taille et la densité des particules (Clark 1988). L'analyse de la dispersion des charbons de bois suite à des feux naturels ou dirigés a montré que la région source de larges particules (> 120-150 µm) est inférieure à celle des plus petites particules, ce qui a permis de valider les modèles théoriques (Clark et al. 1998; Gardner et Whitlock 2001; Lynch et al. 2004) qui illustrent la dispersion spatiale des charbons de bois. La communauté scientifique utilise ainsi une maille de tamisage de 120-150 µm pour tamiser les charbons avant de procéder au comptage pour reconstituer l'historique de feux aux abords des lacs échantillonnés.

1.2.2 Quantification des charbons de bois

La reconstitution des paléofeux est fondée sur la quantification en continu des particules carbonisées le long de séquences sédimentaires. Un volume donné est prélevé dans chaque échantillon et trempé dans une solution défloculante d'hexamétaphosphate de sodium ($(NaPO_3)_6$) à 3 % pendant au moins 24 heures sur une plaque chauffante réglée à 100 °C. Le mélange est ensuite tamisé et lavé avec une solution de NaOCl à 10 %, qui permet de blanchir la matière organique noire afin de la distinguer plus aisément des charbons de bois. La quantification des particules de charbon de bois (nombre et surface) est réalisée à l'aide d'une loupe binoculaire (20 ×) équipée d'une caméra digitale et couplée à un logiciel d'analyse d'images. Cette procédure permet de caractériser la concentration en charbons de bois ($mm^2.cm^{-3}$ ou $\#.cm^{-3}$) des séquences lacustres au cours du temps.

1.2.3 Datations et chronologies

Afin d'établir un âge pour chaque niveau des séquences sédimentaires, des datations ^{14}C et ^{210}Pb sont réalisées sur des macrorestes végétaux ou directement sur les sédiments. Les dates ^{14}C sont ensuite calibrées en utilisant le programme CALIB version 6.0.1 (Stuiver et Reimer 1993) et un modèle âge-profondeur est produit à l'aide de modèles numériques tels que MCAgeDepth 0.1 ou le package CLAM développé dans l'environnement statistique R (Higuera 2008).

1.2.4 Reconstitution des évènements de feux

Les concentrations en charbons de bois sont par la suite multipliées par les taux de sédimentation (cm.an^{-1}) pour obtenir des taux d'accumulation de charbons de bois au cours du temps, autrement dit des influx (*charcoal accumulation rates*, CHAR ; # ou mm^{2}.cm^{-2}.an^{-1}). C'est à partir des CHAR que les événements de feu sont reconstitués. L'analyse des CHAR implique la séparation de la composante de haute fréquence (pics de charbons de bois = C_{peak}) correspondant aux évènements de feux, de celle à basse fréquence (bruit de fond = $C_{background}$). Le $C_{background}$ est modélisé et soustrait des séries CHAR en utilisant par exemple une fonction LOWESS (locally weighted scatterplot smoothing) robuste aux valeurs extrêmes avec différentes tailles de fenêtres temporelles. Le signal C_{peak} ainsi obtenu est composé de deux sous-populations: (1) C_{noise}, qui reflète la variabilité due à l'échantillonnage des sites, au bruit inhérent aux analyses statistiques et numériques opérées et à la partie du bruit de fond qui n'aurait pas été enlevée à l'étape précédente; et (2) C_{fire}, qui représente l'occurrence d'un ou plusieurs feux locaux (Gavin et al. 2006; Higuera et al. 2007). La composante C_{fire} est séparée de C_{noise} en appliquant un seuil localement défini, correspondant généralement au 99^{e} percentile de la distribution gaussienne de C_{noise}. Le choix des fenêtres de déplacement pour la modélisation de $C_{background}$ est dicté par l'approche permettant de modéliser et séparer au mieux les deux sous-populations de C_{peak} (Kelly et al. 2011). Ces étapes sont produites à l'aide du logiciel CharAnalysis

1.1 (disponible gratuitement sur http://sites.google.com/site/charanalysis/; Higuera et al. 2009)

1.2.5 Les biais inhérents à l'analyse des charbons pour reconstituer les feux

Les régions sources de charbons dépendent de la hauteur de la colonne de convection qui se forme au-dessus du feu (Peters et Higuera 2007; Pisaric 2002; Tinner et al. 2006). Bien que les modèles théoriques de dispersion produisent de bons résultats pour les distances de dispersion jusqu'à 200 m au-delà de la zone brûlée (Peters et Higuera 2007), la dispersion des charbons de bois à des distances supérieures est moins bien comprise. Des transports à longue distance (5-20 km) ont été rapportés (Pisaric 2002; Tinner et al. 2006) et des pics de charbons de bois ont été enregistrés dans des lacs sans que leurs bassins versants n'aient brûlé (Whitlock et Millspaugh 1996). Kelly et al. (2013) ont d'ailleurs constaté une corrélation significative entre la quantité de charbons déposée dans les lacs et l'aire brûlée autour des lacs sur un rayon allant jusqu'à 20 km. Ceci peut être expliqué par l'élaboration d'une colonne de convection plus haute lors des feux à haute intensité, qui soulève des particules de charbon plus haut, augmentant la probabilité de dispersion à longue distance et le dépôt dans les lacs situés dans l'axe du vent (Peters et Higuera 2007; Pisaric 2002; Tinner et al. 2006).

Les reconstitutions de paléofeux sont fortement influencées par les choix des utilisateurs au cours du traitement statistique des CHAR (Blarquez et al. 2013; Carcaillet et al. 2001; Genries et al. 2012). Pour tenir compte des intervalles d'échantillonnage inégaux résultant de taux d'accumulation de sédiments variables, les CHAR sont interpolés à un intervalle de temps constant, généralement la résolution temporelle médiane de l'ensemble de la séquence (par exemple Ali et al. 2009; Gavin et al. 2006; Higuera et al. 2010), qui peut varier considérablement au sein et entre les lacs (Carcaillet et al. 2001; Genries et al. 2012). Aussi, les fenêtres temporelles de différentes largeurs peuvent être utilisées dans la reconstitution des épisodes de feu pour modéliser le bruit de fond et obtenir des histoires de feux différentes.

Pour résumer, les principaux biais associés à l'analyse des charbons de bois lacustres sont : (1) le transport à longue distance des particules qui rend difficile la différenciation des feux locaux et régionaux et (2) le choix des paramètres lors des traitements statistiques. Cette thèse comprendra ainsi un volet méthodologique visant à évaluer l'impact de ces deux biais dans l'analyse des séries de charbons de bois lacustres et les conséquences dans les reconstitutions des feux.

1.3 Objectifs de la thèse

L'objectif général de cette thèse est d'apporter des éléments d'aide à la décision dans le choix de la localisation de la limite nordique de la forêt commerciale dans un contexte de changements climatiques et sous l'angle des régimes de perturbation par le feu. Nous avons donc reconstitué la dynamique des feux de forêts de part et d'autre de la limite commerciale d'exploitation forestière en Jamésie. La thèse s'articule autour de deux grands volets. Un premier volet constitué de deux chapitres fait référence à des travaux méthodologiques ayant pour objectif l'amélioration de l'interprétation des séries de charbons de bois des dépôts lacustres. Le quatrième chapitre correspond à une reconstitution des régimes d'incendies de part et d'autre de la limite nordique de la forêt commerciale et permet de discuter de la résilience des massifs forestiers dans la zone d'étude. Ci-dessous, une description succincte des objectifs spécifiques des trois chapitres.

- Calibrer la détection des pics d'accumulation de charbons de bois par une comparaison avec des données dendrochronologiques (Chapitre 2). L'influence du choix de deux paramètres fréquemment utilisés dans les analyses de charbons de bois a été étudiée : la résolution temporelle utilisée pour interpoler les enregistrements de charbons de bois et la taille de la fenêtre de lissage utilisée pour modéliser le bruit de fond.

- Evaluer l'influence du transport à longue distance des particules de charbon de bois sur la détection des feux locaux et caractériser les processus taphonomiques contrôlant leur séquestration au cours du temps (Chapitre 3). Des trappes ont été installées dans sept lacs qui nous ont permis d'étudier la dispersion et la déposition des charbons de bois pendant trois années consécutives. Des feux naturels de tailles différentes ont eu lieu pendant le suivi (MRN 2012), incluant notamment un feu qui a atteint le bassin versant d'un des lacs étudiés. Plusieurs grands feux (> 100 000 ha) qui n'ont atteint aucun des bassins versants se sont aussi produits durant le suivi. Cette étude nous a permis de discuter de l'influence de la superficie et de la distance de la zone brûlée sur la déposition et la séquestration des charbons de bois dans les dépôts lacustres.

- Retracer l'historique des feux de part et d'autre de la limite nordique de la forêt commerciale (Chapitre 4). Les variations dans la fréquence des feux ont été discutées au regard des changements climatiques enregistrés au cours de l'Holocène. Van Wagner (1987) a défini l'indice de sécheresse (*drought code*, DC) comme étant un bon indicateur de la teneur en eau des couches organiques profondes et de la sécheresse à long terme au cours de la saison de feux (avril à septembre). Des simulations par un modèle de circulation générale possédant des données paléoclimatiques nous ont permis de calculer les DC au cours de l'Holocène à la limite nordique de la forêt commerciale selon la méthode utilisée par Hély et al. (2010). Les épisodes de sécheresse sont comparés aux fréquences de feux passées, reconstituées à partir des charbons de bois préservés dans des sédiments lacustres. Les données polliniques disponibles au nord et au sud de la région d'étude (Asselin et Payette 2005; Carcaillet et al. 2001; Richard 1979) sont utilisées pour discuter de la résilience des forêts en réponse à la variabilité historique de la fréquence des feux. Ce chapitre fait aussi la synthèse des données afin d'émettre des recommandations aux aménagistes forestiers qui leur permettront de tenir compte des éventuelles configurations de perturbations qui se profilent au regard des changements climatiques en cours. Ces recommandations sont établies selon la différence entre les fréquences de feu passées et futures.

1.4 Région d'étude

La limite nordique de la forêt commerciale québécoise s'étend entre le 50^{e} et le 52^{e} parallèle de latitude Nord. Nous avons centré notre étude en Jamésie, soit dans la partie ouest de la forêt boréale québécoise. La Jamésie occupe un territoire de 350 000 km^2 situé entre le 49^{e} et le 55^{e} parallèle de latitude Nord. Le territoire visé par cette étude est situé le long de la route reliant Matagami à Radisson et de la route reliant Némiscau au barrage Eastmain de Hydro-Québec. La température moyenne (± écart type) annuelle à Matagami et à Radisson était respectivement de -0.7 ± 2.7 °C et de -3.1 ± 1.9 °C entre 1971 et 2000 (Environment Canada 2011). Les précipitations moyennes annuelles étaient de 905 mm à Matagami et de 684 mm à Radisson (Environment Canada 2011). La Jamésie est principalement constituée de forêts résineuses d'épinette noire (*Picea mariana*) et, dans une moindre mesure, de pin gris (*Pinus banksiana*), d'épinette blanche (*Picea glauca*), de mélèze (*Larix laricina*), et de sapin baumier (*Abies basalmea*). Les principales espèces feuillues présentes sur le territoire sont le peuplier faux-tremble (*Populus tremuloides*), le peuplier baumier (*Populus balsamifera*) et le bouleau à papier (*Betula papyrifera*) (Robitaille et Saucier 1998).

CHAPITRE II

USING TREE-RING RECORDS TO CALIBRATE PEAK DETECTION IN FIRE RECONSTRUCTIONS BASED ON SEDIMENTARY CHARCOAL RECORDS

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2.1 Abstract

We compared fire episodes over the past 150 years reconstructed using charcoal particles retrieved from well-dated sediment deposits from two small lakes of the eastern Canadian boreal forest with dendrochronological reconstructions of fire events from the corresponding watersheds. Fire scars and age structure of living trees highlighted three fire events (1890, 1941, and 1989 AD). To explore the ability to detect these fire events based on sedimentary charcoal records, we explored the influence of two user-determined parameters of a widely used peak-detection algorithm (the CharAnalysis software): (1) the temporal resolution used to interpolate charcoal series and (2) the width of the smoothing window used to model background noise. The signal-to-noise index (SNI) is often used to evaluate the ability to detect peaks in sedimentary charcoal records, which can be related to fire events. SNI values > 3 identify records appropriate for peak detection. Selecting standard settings in palaeoecological studies (median temporal resolution of the entire sequence and 500 to 1000-year window width) yielded higher global SNI values but failed to detect most recent fire events. Instead, selecting a shorter reference period (the past ~150-years) to determine the temporal resolution to interpolate the charcoal series, and a narrower smoothing window (100 years) best matched the tree-ring data despite lower SNI values (often < 3.0). However, Holocene fire history (last 7000 years) differed markedly when reconstructed using different smoothing window widths (100-150 years vs. > 300 years). Consequently, we suggest to use the smallest window width yielding a SNI > 3 (here 300 years). Practitioners must not necessarily focus on obtaining the highest possible SNI, usually related to wide smoothing windows. We also suggest that fire history reconstructions should focus on core sections presenting fairly constant sedimentation rates. Alternatively, sediments could be subsampled after age-depth models have been obtained.

2.2 Résumé

Nous avons comparé les historiques de feux des 150 dernières années reconstitués à l'aide de séries de charbons de bois issus de deux petits lacs de la forêt boréale canadienne avec les reconstitutions dendrochronologiques des feux dans les bassins versants correspondant. Les cicatrices de feux et les structures d'âge des arbres vivants ont mis en évidence trois feux (1890, 1941, et 1989 AD). Pour explorer la capacité à détecter ces feux à partir des charbons de bois lacustres, nous avons étudié l'influence des deux paramètres de base utilisés pour reconstituer les événements de feux à l'aide du logiciel CharAnalysis : (1) la résolution temporelle utilisée pour interpoler les séries de charbon de bois et (2) la taille de la fenêtre de lissage utilisée pour modéliser le bruit de fond. L'indice signal-sur-bruit (Signal to Noise Index) permet d'évaluer la qualité des reconstitutions en caractérisant la séparation entre le signal à haute fréquence et le bruit de fond. Un SNI > 3 permet de considérer positivement les événements de feux reconstruits. L'utilisation de paramètres communément employés dans les reconstitutions de feux (résolution temporelle médiane calculée sur l'ensemble de la séquence pour interpoler les CHAR et fenêtre temporelle variant entre 500 et 1000 ans pour modéliser le bruit de fond) permet d'avoir des valeurs de SNI supérieures à 3, mais ne permet pas de détecter les événements de feux récents. Par opposition, l'utilisation d'une résolution temporelle médiane calculée sur les 150 dernières années couplée à une fenêtre temporelle de 100 ans pour modéliser le bruit de fond permet de mieux détecter les feux récents, malgré des valeurs de SNI parfois inférieures à 3. Cependant, les historiques de feux reconstitués à l'échelle de l'Holocène (7000 dernières années) différaient nettement en fonction des tailles de fenêtre temporelle pour modéliser le bruit de fond (100-150 ans vs > 300 ans). À la lumière de ce résultat, nous proposons d'utiliser la plus petite taille de fenêtre qui permet d'obtenir un SNI > 3 (ici 300 ans). Les paléoécologistes

ne doivent pas chercher à obtenir les plus hautes valeurs de SNI, généralement liées à de larges fenêtres temporelles pour modéliser le bruit de fond (> 500 ans). Par ailleurs, les reconstitutions de l'historique des feux devraient se concentrer sur les sections sédimentaires présentant des taux de sédimentation constants. Alternativement, les sédiments pourraient être sous-échantillonnés après que les modèles âge-profondeur aient été obtenus.

2.3 Introduction

In North American boreal forests, wildfires correspond to a key ecological disturbance by controlling vegetation dynamics (Payette, 1992; Senici et al., 2013) and altering the carbon cycle by emitting high quantities of greenhouse gases to the atmosphere (Balshi et al., 2009; Oris et al., 2014). Palaeoecological reconstructions of past wildfire events allow predicting changes in fire regimes in response to climate change and anthropogenic activities. Over the past three decades, lacustrine charcoal records have widely been used to reconstruct past fire activity in diverse ecosystems (Ali et al., 2012; Asselin and Payette, 2005a; Clark, 1990; Power et al., 2008; Tinner et al., 1998). It is increasingly being recognized that such reconstructions must be based on well-dated sequences with clear charcoal signals obtained after statistical treatment (Higuera et al., 2010; Kelly et al., 2011). Moreover, in a best-case scenario, for recent periods (generally < 300 years), charcoal signals must be compared with historical or tree-ring records to refine peak detection (Clark, 1990; Higuera et al., 2011; Long et al., 1998; Pitkänen et al., 1999; Whitlock et al., 2004) and to evaluate reconstruction accuracy. Whereas some “false” fire events are detected or “true” fire events not detected, studies in mountain and subalpine forests of western North America highlight relatively good matches between charcoal signals and dendrochronological data (Higuera et al., 2011; Whitlock et al., 2004). Such calibration procedures are however lacking for eastern Canadian boreal forests.

Fire reconstructions from lake sediments are highly influenced by user choices during statistical treatment (Blarquez et al., 2013; Carcaillet et al., 2001; Genries et al., 2012). To account for uneven sampling intervals resulting from variable sediment accumulation rates, charcoal records are interpolated to a constant temporal interval, typically the median temporal resolution of the entire record (e.g. Ali et al., 2009; Gavin et al., 2006; Higuera et al., 2010), which can vary considerably within and among lakes (Carcaillet et al., 2001; Genries et al., 2012). Additionally, temporal windows of varying widths can be used in the reconstruction of fire episodes by decomposing charcoal series into background noise that represents taphonomical and sampling effects, and high-frequency charcoal peaks that can be related to fire events. To our knowledge, the effect of chosing different temporal resolutions or window widths on fire reconstruction accuracy has not yet been verified with corroborative dendrochronological data in Canadian boreal forests.

In this study we compared recent fire histories inferred from tree-ring and charcoal records for the watersheds of two small lakes located in the eastern Canadian boreal forest. The lakes were less than 5 km apart and were therefore likely to have been equally affected by regional climate. We aimed to (1) evaluate the accuracy of charcoal signals to infer recent local fire events, and (2) discuss the impact of statistical treatment on fire detection in lacustrine charcoal records. Because most wildfires are typically large (> 200 ha) in our study area (Lavoie and Sirois, 1998; Natural Resources Canada, 2013) they should display a clear signal both in tree-ring and sediment records. We hypothesized that for the recent period (i.e., the last 150 years) the two approaches would give comparable results. Nevertheless, the topography of the study area, characterized by flat landscapes covered by large peatlands and lakes that act as natural firebreaks, may induce spatial variability in fire ignition, severity, and propagation (Cyr et al., 2007; Mansuy et al., 2010; Senici et al., 2010) which could reduce the representativeness of fire history reconstructions based on single lacustrine charcoal records (MacDonald et al., 1991). It is also generally admitted that fire history deduced from lacustrine charcoal does not necessarily detect all fire events, as single charcoal peaks could be related to more than one fire (Clark, 1990; Higuera et al., 2007).

2.4 Material and methods

2.4.1 Study area

The study was conducted in the James Bay lowlands of northwestern Quebec. The dominant vegetation cover corresponds to the open boreal forest (lichen woodland) zone. Black spruce (*Picea mariana* (Mill.) B.S.P) and jack pine (*Pinus banksiana* Lamb.), two fire-adapted species, dominate the landscape. Jack pine is often found on dry and sandy soils, while black spruce is more abundant on mesic sites. Lake Nano (LNA) and Lake Loup (LLP) were chosen due to their proximity and similar morphometries (Table 2.1). The study area is recurrently affected by large fires (> 200 ha) (Natural Resources Canada, 2013) with a fire cycle of ~100 years (Le Goff et al., 2007; Mansuy et al., 2010; Payette et al., 1989).

In the study area, deglaciation was followed by the Tyrell Sea invasion ~8000 yrs ago (Dyke and Prest, 1987). After the initial tundra and aspen (*Populus tremuloides* Michx.) parkland phases, open spruce woodlands colonized the area (Richard, 1979). Increased landscape opening occurred over the last 3000 years likely due to postfire regeneration failure (Asselin and Payette, 2005b).

Table 2.1 Location and characteristics of LLP and LNA

	LLP	LNA
Latitude	53°03’18.55”N	53°01’25.54” N
Longitude	77°24’00.38” W	77°21’49.33” W
Elevation (m a.s.l.)	206	206
Local vegetation	*Pinus banksiana, Picea mariana, Larix laricina*	*Pinus banksiana, Picea mariana, Larix laricina*
Topography	Flat	Flat
Lake surface (ha)	1.6	0.4
Maximum water depth (m)	3	3.2
Core length (cm)	106	140
Median deposition time (years/sample)		
entire sequence (~7000 years)	35	22
recent deposits (~ last 150 years)	6	10

2.4.2 Tree-ring records of fire history: sampling and data analysis

Field sampling for dendrochronological analysis was carried out in September 2011. We sampled 36 and 31 cross-sections from scarred living trees around LNA and LLP, respectively. Sampling took place within 200 m from the lakeshores (Figure 2.1). Before sampling, the organic matter and mineral soil were removed from around the base of trees (DesRochers and Gagnon, 1997). We took two cross-sections from each tree: at the root collar to date establishment, and at 1.30 m above ground (breast height) to obtain a master chronology. When fire scars were observed 1.30 m above ground, a third cross-section was collected at the upper limit of the scar. For each sampled tree we recorded diameter at breast height (DBH), height, spatial coordinates, and orientation of the scars. Flame front direction can be inferred from fire scar orientation because scars form on the side of the tree opposite to the origin of fire (Arno et al., 1977; Dickinson and Johnson, 2001). Cross sections were mostly collected from jack pine, with some black spruce and eastern larch (*Larix laricina* (Du Roi) Koch.) (Table 2.3).

Cross-sections were dried and sanded using successively finer grades (80 to 600 grit) until annual growth rings and scars were clearly visible (Schweingruber, 1988). A master chronology was established with tree-ring widths of the DBH cross-sections

(Holmes and Fritts, 1986; Stokes and Smiley, 1968). Tree-ring analysis was made under a binocular microscope according to standard dendrochronological methods (Niklasson et al., 2010; Stokes and Smiley, 1968). Pointer years or marker rings (narrow, wide, and incomplete rings) were identified visually and used for cross-dating (Schweingruber et al., 1990). Tree-ring widths were measured using a Lintab 5 micrometer (Rinn, 2004) with 0.001 mm precision along two radii opposite to the scars and separated by 120°. Cross-dating was achieved using the TsapWin 4.64 software (Rinn, 2003) and validated using the COFECHA 6.06 software (Holmes, 1983). For all scars, calendar date and seasonal position within annual growth-ring were recorded (Arno et al., 1977). Scars and stand age data were analyzed using the dplR package of the R software (Bunn, 2008). Fire history reconstructions based on dendrochronological and lacustrine charcoal records were carried out independently by different researchers in order to avoid any bias.

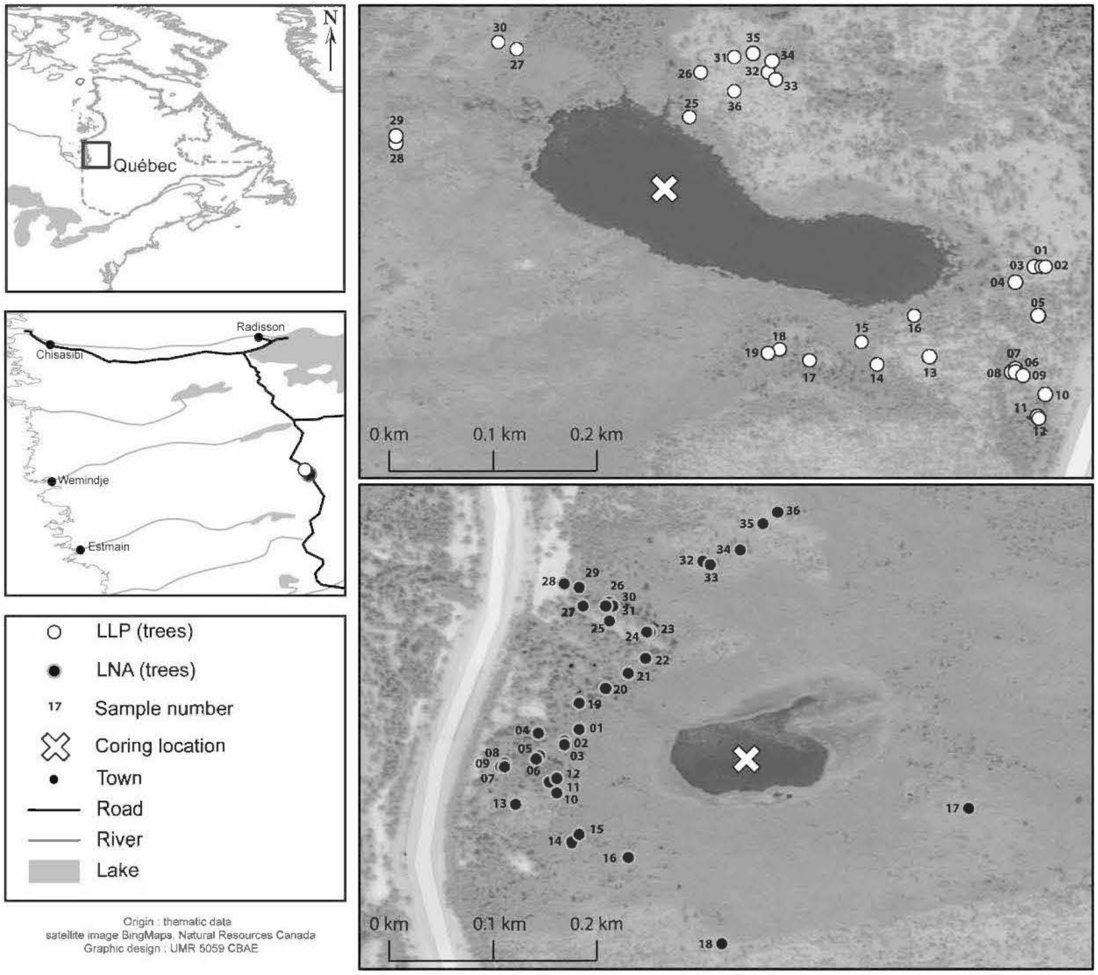

Figure 2.1 Location of the study area, lakes and sampled trees.

2.4.3 Sediment dating and age-depth models

Lake sediments were extracted in March 2011 using a modified Livingstone piston corer (Wright et al., 1984) and the water-sediment interface was collected with a Kajak-Brinkhurst (KB) gravity corer (Glew, 1991).

To obtain an age-depth model for the younger unconsolidated sediments, ^{210}Pb measurements were performed from the uppermost 14 cm of the cores (Table 2.2).

^{210}Pb values were inferred by measuring the activity of the daughter product, i.e. ^{210}Po, by alpha spectrometry assuming an equal concentration of the two isotopes. Fourteen samples, each > 100 mg dry weight, were analyzed for each core (Table 2.2).

Radiocarbon dating of terrestrial plant macroremains and bulk gyttja samples allowed us to extend the chronologies downcore (see Appendice A). The ^{14}C dates were calibrated using the CALIB 7.0 program (Stuiver and Reimer, 1993) based on the IntCal04 dataset (Reimer et al., 2004). Age-depth models (see Appendice B) were obtained using the MCAgeDepth program (Higuera et al., 2008), which applies a Monte Carlo resampling technique to assess median ages and to generate confidence intervals (CI) around the fit, based on the probability distribution of each date.

Table 2.2 ^{210}Pb activity of recent sediments from LLP and LNA. SD = standard deviation.

Sample depth (cm)	LLP			LNA		
	Sample number	^{210}Pb Activity ($Bq.kg^{-1}$)	SD (%)	Sample number	^{210}Pb Activity ($Bq.kg^{-1}$)	SD (%)
0.5	265	798	3.7	251	203	7.8
1.0	266	799	3.0	252	206	7.0
1.5	267	796	3.4	253	135	13.4
2.0	268	800	3.4	254	145	8.8
2.5	269	688	4.2	255	89	7.6
3.5	270	586	3.7	256	49	9.0
4.5	271	447	4.1	257	36	14.2
5.5	272	299	3.7	258	17	15.7
6.5	273	222	3.9	259	16	13.9
7.5	274	80	5.0	260	15	10.7
8.5	275	106	7.1	261	13	10.9
10.0	276	78	8.2	262	10	10.5
11.5	277	41	6.1	263	12	9.9
13.5	278	27	7.6	264	12	11.6

Table 2.3 Characteristics of dendrochronological samples from LLP and LNA watersheds.

	LLP	LNA
Number of trees	31	36
Pinus banksiana	29	27
Larix laricina	1	1
Picea mariana	1	8
Average DBH (cm)	17.45	15.89
Max DBH (cm)	31.35	24.51
Min DBH (cm)	10.00	7.00
Average height (m)	8.79	8.58
Max height (m)	15.20	12.60
Min height (m)	5.30	5.15

2.4.4 From charcoal particles to fire events

The sediment cores were sliced into contiguous 0.5 cm thick samples. For charcoal analysis, a 1 cm^3 sub-sample was removed from each slice and soaked in a 3% $(NaPO_3)_6$ solution before wet-sieving through a 150 µm mesh (Whitlock and Larsen, 2002). Charcoal pieces larger than 150 µm are mostly produced by fire events within 1 km of the lake shores, allowing fire events to be reconstructed at the local scale (Higuera et al., 2007; Lynch et al., 2004). Charcoal pieces were identified under a 20× stereomicroscope and their area was measured with the aid of a digital camera connected to an image-analysis software (Regent Instruments Inc., Canada). Charcoal measurements are reported as charcoal accumulation rates (CHAR, mm^2/cm^2/year) based on age-depth models.

The CHAR series were interpolated to constant time steps ($C_{interpolated}$). We used two different temporal resolutions to explore the effect of the interpolation procedure on the detection of recent fire events: one corresponding to the median temporal resolution of the recent sediments (~ the last 150 years) and one corresponding to the temporal resolution for the entire sequence (~ 7000 years), respectively called Run_{KB} and Run_{All} hereafter. To model the background series (C_{back}), corresponding to low-frequency variations in $C_{interpolated}$, we used a locally weighted regression robust to outliers under several window widths (100-150, 300, 500, 800 and 1000 years). This procedure allowed us to track the incidence of window width on the detection of local fire events. A 100-year smoothing window was used to approximate the temporal resolution of dendrochronological reconstructions. The C_{peak} series was obtained by subtracting C_{back} from $C_{interpolated}$. Global signal-to-noise index (SNI; Kelly et al., 2011) which indicates the suitability of a charcoal record for peak-detection analysis was calculated for each run.

C_{peak} was decomposed into two subpopulations: C_{noise}, representing variability in sediment mixing, sampling, and analytical and naturally occurring noise, and C_{fire}, representing significant charcoal peaks resulting from local fires (Clark et al., 1996; Gavin et al., 2003; Higuera et al., 2010). For each peak, we used a Gaussian mixture model to identify the C_{noise} distribution according to a locally defined threshold. To compare empirical and modelled C_{noise} distributions, we used the p-value from a Kolmogorov-Smirnov test (also called the goodness-of-fit). A p-value > 0.05 suggests that the two populations are from the same distribution. We considered the 95th, 99th and 99.9th percentiles of the C_{noise} distribution as a possible threshold separating C_{peak} into "fire" and "non-fire" events. However, a local 99th percentile threshold of the noise distribution was used to display the Holocene fire histories. A total of 10 runs (5 run_{KB} and 5 run_{All}) by sequence were performed (see Appendice C). To create a smoothed fire frequency, the total number of fires in consecutive 1000-year periods were summed and smoothed using a locally weighted function over 7000 years. All statistical treatments were performed using the CharAnalysis program 1.1 (Higuera, 2009 http://sites.google.com/site/charanalysis/). To compare the fire histories obtained from the different analytical treatments, we examined median Fire Free Intervals (mFFIs) using the nonparametric two-sample Mann-Whitney test (MW), and overall FFIs distributions using the nonparametric two-sample Kolmogorov-Smirnov test (KS) (e.g., Ali et al., 2009; Clark, 1989).

2.5 Results

2.5.1 Tree-ring records of fire history

Stand characteristics around each lake were comparable (Table 2.3). A total of 124 scars were found, from which 104 were identified as fire scars (45 at LNA; 59 at LLP). The 20 other scars (9 at LNA; 11 at LLP) did not have morphological characteristics typical of fire scars (Falk et al., 2011; Smith and Sutherland, 2001) and were thus discarded from analysis. Two and three fires were inferred based on the fire scars during the past 150 years in the LNA and LLP watersheds, respectively (Figure 2.2a and 2.2b). Fire scars and stand age indicated that the two sites were synchronously affected by two fire events in 1941 and 1989. As the eastern part of the LNA watershed was characterized by a large peat bog with few trees, sampling was concentrated in the western part. In the eastern part, only one tree was scarred in 1989 (Figures 2.1, 2.2a and 2.2b). Fire scars were located in the latewood, indicating that wildfires occurred in summer. This was further supported by the orientation of the fire scars indicating that the fire front came from the west, i.e., the direction of prevailing summer winds in the study area (Figure 2.2).

2.5.2 Sediment chronologies

^{210}Pb chronologies allowed us to estimate sediment accumulation rates since *ca.* 1864 AD (Figure 2.3). In LNA, larger standard deviations resulted from less ^{210}Pb excess above the background compared to LLP (with total ^{210}Pb concentration less than 3 times greater than background) (Binford, 1990). ^{210}Pb background was reached at a depth of 7.5 cm at LNA with a value of 12 Bq.kg^{-1} (Figure 2.3). Background was not reached in the LLP sediments. As both lakes were very close to one another, and as background ^{210}Pb concentrations are influenced by regional geology (Robbins and Edgington, 1975), the backgrounds in LNA and LLP were assumed to be the same. Therefore we used the same background value for both sediment sequences. The resulting median temporal resolution of the younger sediments was about 6 and 10 years by sample at LLP and LNA, respectively. Radiocarbon dates allowed us to estimate sediment accumulation rates over ~7000 years (Appendice A and B). Median temporal resolution for the entire sequences were 35 and 22 years per sample at LLP and LNA, respectively.

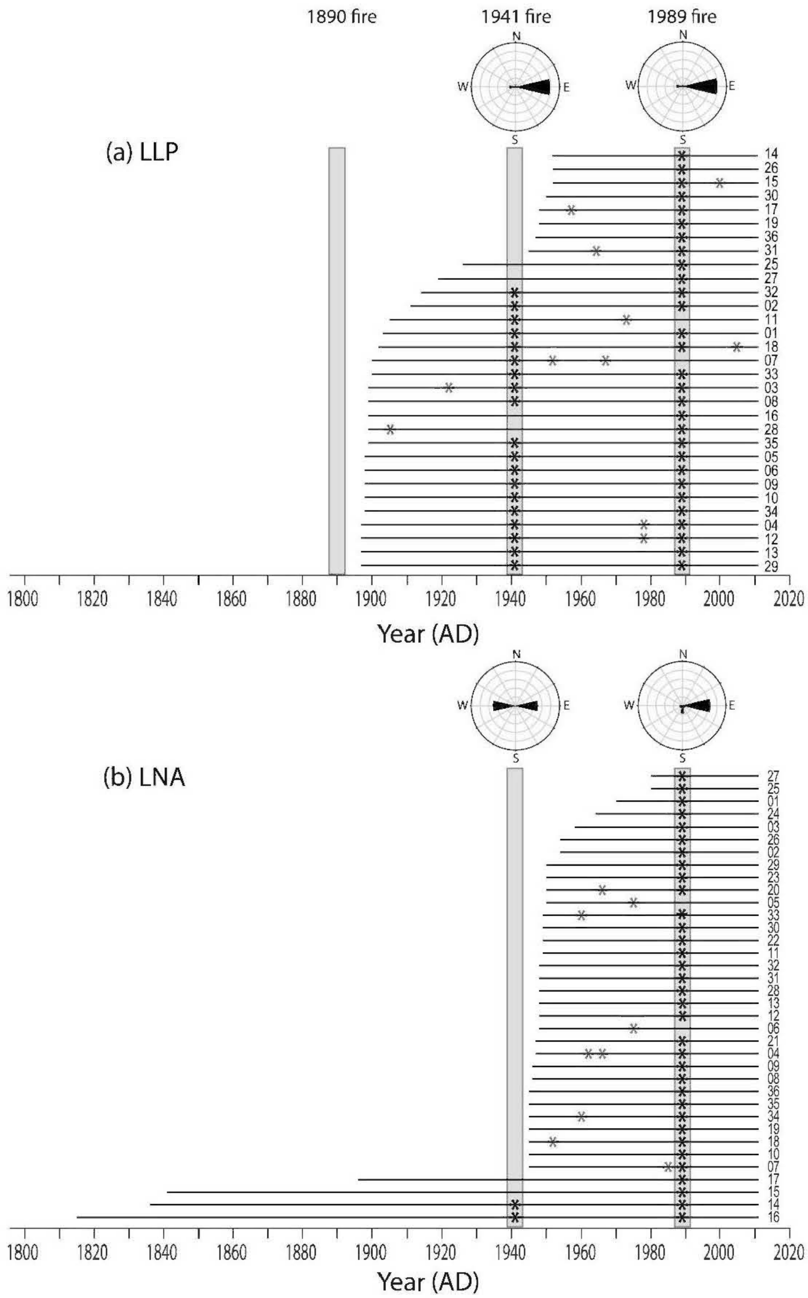

Figure 2.2 Tree-ring records of fire activity for LLP (a) and LNA (b) watersheds. Each horizontal line is an individual tree with sample number at the end, each grey asterisk is a scar (any type) and each black asterisk is a fire scar. Vertical grey bands indicate fire events. Scar orientation is presented in polar plots, each circular graduation corresponding to 20% of the samples.

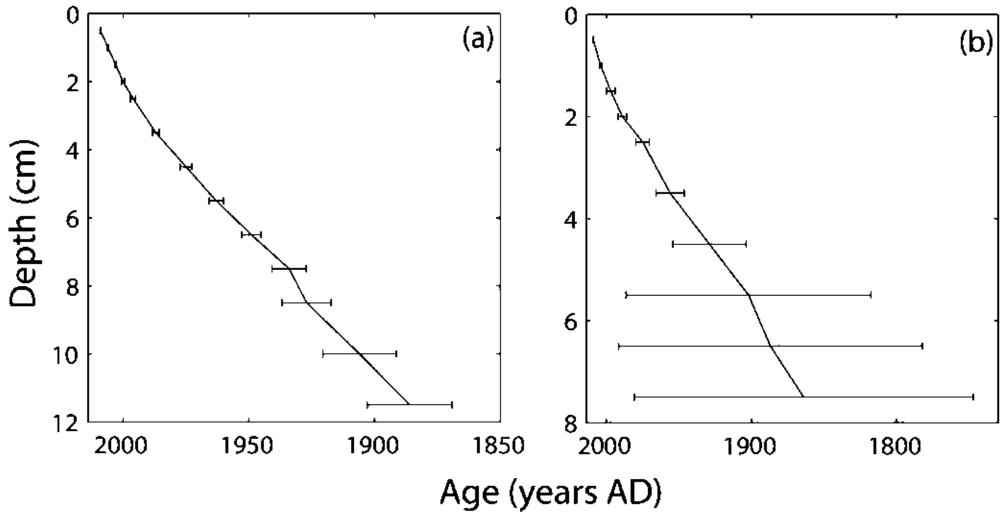

Figure 2.3 ^{210}Pb chronologies for LLP (a) and LNA (b) using the constant rate supply (CRS) model. Error bars represent one standard deviation. Note different scales on X and Y axes.

2.5.3 Recent fire events

The number of detected fire events over the past 150 years changed markedly when different parameters were used (Figure 2.4; for detected fire episodes over 7000 years, see appendices D, E, F and G). Overall, the best concordance between the sedimentary charcoal series and the dendrochronological analysis was reached with Run_{KB} and narrow windows varying between 100 and 300 years (Figure 2.4). A maximum of three and two fires were detected against a minimum of one or no fire in LLP and LNA, respectively. At LLP, all three fires (1890, 1941 and 1989 AD) were detected with Run_{KB} along with a 100-year smoothing window (Figure 2.4a). At LNA, a maximum of two fires (1890 and 1989 AD) were detected when a 100-year smoothing window was used, but with both temporal resolutions (Figure 2.4 c, d). However, these two fires were also detected using a 300-year smoothing window in

Run_{KB} (Figure 2.4c). Using wide windows (> 500 years) in Run_{All} generally failed to detect the recent fire events. For example, when we used a 1000-year smoothing window (Figure 2.4), the 1941 AD and 1989 AD fires were no longer detected in LLP and no fire was detected in LNA (Figure 2.4 c,d). However, the 1989 AD fire was detected in LNA when a local 95^{th} percentile threshold of the noise distribution was used (Figure 2.4 c). Except when a 100-year window was used, local SNI values were generally high (> 3.0).

2.5.4 Fire frequency over the last 7000 years

Except for the fire-episode reconstructions using a 100-year window, the fire frequencies displayed the same general trends (Figure 2.5), according to the different combinations used (window width x temporal resolution). The mFFIs and the distribution of the FFIs were usually not significantly different, except with a 100-year window (Table 2.4; Appendice H), underlining comparable fire histories with most settings. The median and the distribution of FFIs at LNA were not significantly different between Run_{KB} and Run_{All}. At LLP, temporal resolution had an impact when narrow windows were used (100-150 years). Maximum fire frequency occurred at 1000 cal. years BP and 3000 cal. years BP in Run_{KB} and Run_{All}, respectively. Nevertheless all scenarios showed that fires were more frequent between 4000 and 0 cal. years BP (Figure 2.5 a, b). At LNA, all scenarios showed that fire frequencies decreased during the Holocene (Figure 2.5 c, d).

When the window width increased, median SNI also increased (Figure 2.5). Using a 100-year smoothing window did not allow us to reach the SNI threshold (> 3) allowing to accept secure output data. The median goodness-of-fit (GOF) was always higher than 0.05. However, a decrease in GOF values occurred when smoothing window width increased, especially in Run_{KB}.

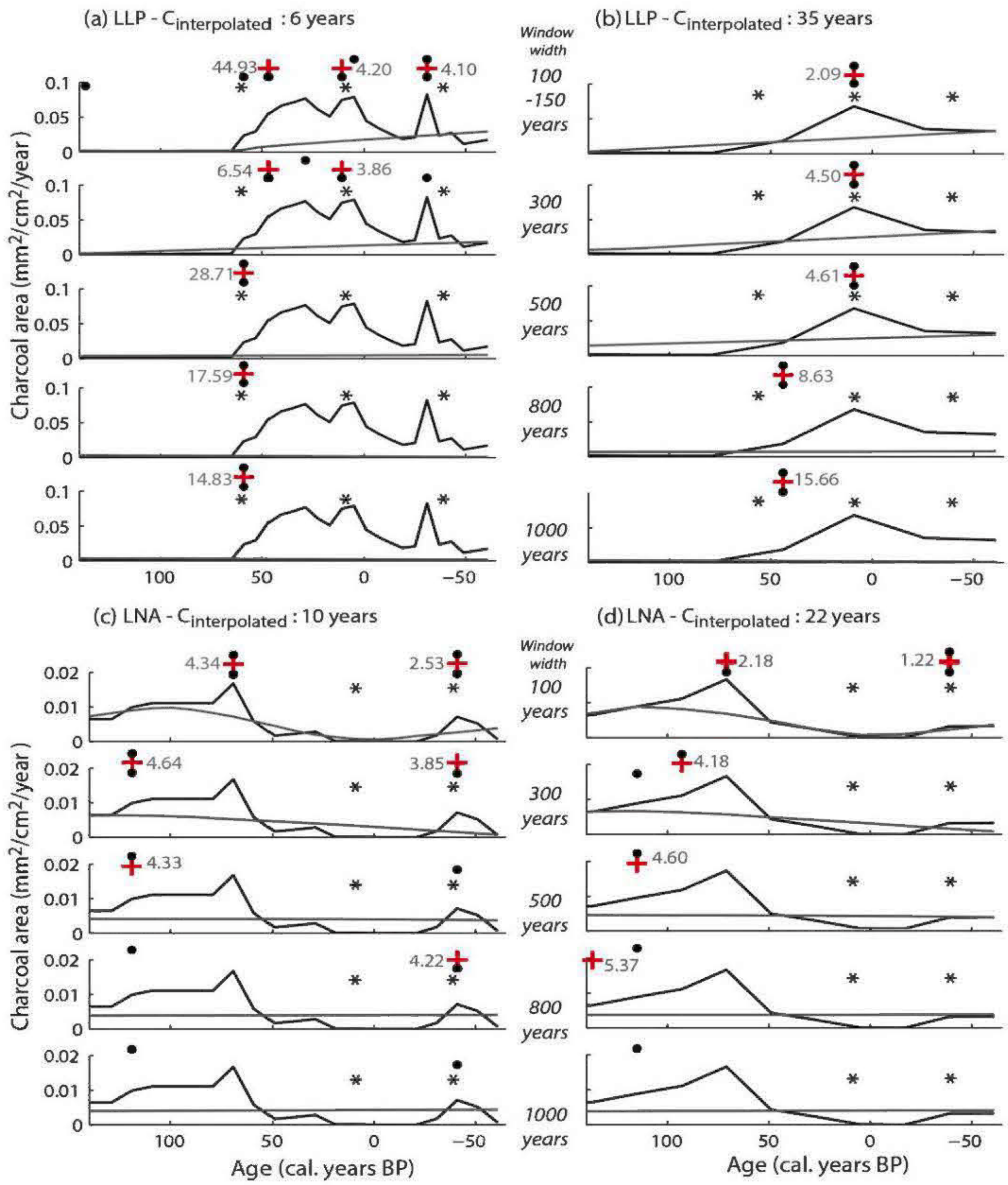

Figure 2.4 Interpolated charcoal accumulation rates ($C_{interpolated}$; black line), background noise (C_{back}; grey line) and detected fire events (+) for recent sediment deposits of LLP (a, b) and LNA (c, d) according to ten model runs. Fires detected by dendrochronology are also shown with asterisks. Numbers above or besides detected fire events represent the local signal-to-noise index. Dots represent detected fires using 95th and 99.9th percentiles of the C_{noise} distribution as possible thresholds separating "fire" and "non-fire" samples. Two temporal resolutions were used for each lake to interpolate the CHAR series: one corresponding to the median temporal resolution of the recent sediments (~ last 150 years; Run_{KB}) (a, c), and one corresponding to the temporal resolution for the entire sequence (~ 7000 years; Run_{All}) (b, d). Low-frequency variations (C_{back}) were computed using a robust lowess regression

with 100-, 300-, 500-, 800- and 1000-year windows, except for LLP where a 150-year window was used instead of 100-year because of the model requirement that the lower value has to be at least 3 times greater than the median temporal resolution (35 years).

Table 2.4 Two-sample comparisons of median fire-free intervals (Mann-Whitney test, MW) and fire-free interval distributions (Kolmogorov-Smirnov test, KS), for LLP and LNA using different smoothing windows for a fixed temporal resolution equivalent to that of the recent deposit (Run_{KB}) (a) and different temporal resolutions for fixed smoothing windows (b). P-values of the tests are reported. KB = recent sediments, ALL = entire sequence.

	LLP		LNA	
(a) Window width	MW test	KS test	MW test	KS test
$Run_{KB\ 100\text{-}300}$	<0.0001	<0.0001	0.0008	0.0002
$Run_{KB\ 100\text{-}500}$	<0.0001	0.0004	0.0001	0.0000
$Run_{KB\ 100\text{-}800}$	<0.0001	0.0001	<0.0001	0.0001
$Run_{KB\ 100\text{-}1000}$	<0.0001	0.0001	<0.0001	0.0001
$Run_{KB\ 300\text{-}500}$	0.5289	0.2401	0.2470	0.6631
$Run_{KB\ 300\text{-}800}$	0.1941	0.0836	0.3435	0.5861
$Run_{KB\ 300\text{-}1000}$	0.0977	0.0607	0.2696	0.3815
$Run_{KB\ 500\text{-}800}$	0.5199	0.9971	0.8541	0.9905
$Run_{KB\ 500\text{-}1000}$	0.3833	0.8511	1.0000	0.9995
$Run_{KB\ 800\text{-}1000}$	0.8730	1.0000	0.8487	1.0000
(b) Temporal resolution	MW test	KS test	MW test	KS test
$100_{KB\text{-}ALL}$	<0.0001	<0.0001	0.3051	0.1896
$300_{KB\text{-}ALL}$	0.0687	0.2795	0.1540	0.3144
$500_{KB\text{-}ALL}$	0.0701	0.1461	0.8204	0.9903
$800_{KB\text{-}ALL}$	0.4191	0.5924	0.3428	0.3398
$1000_{KB\text{-}ALL}$	0.5257	0.7413	0.6376	1.0000

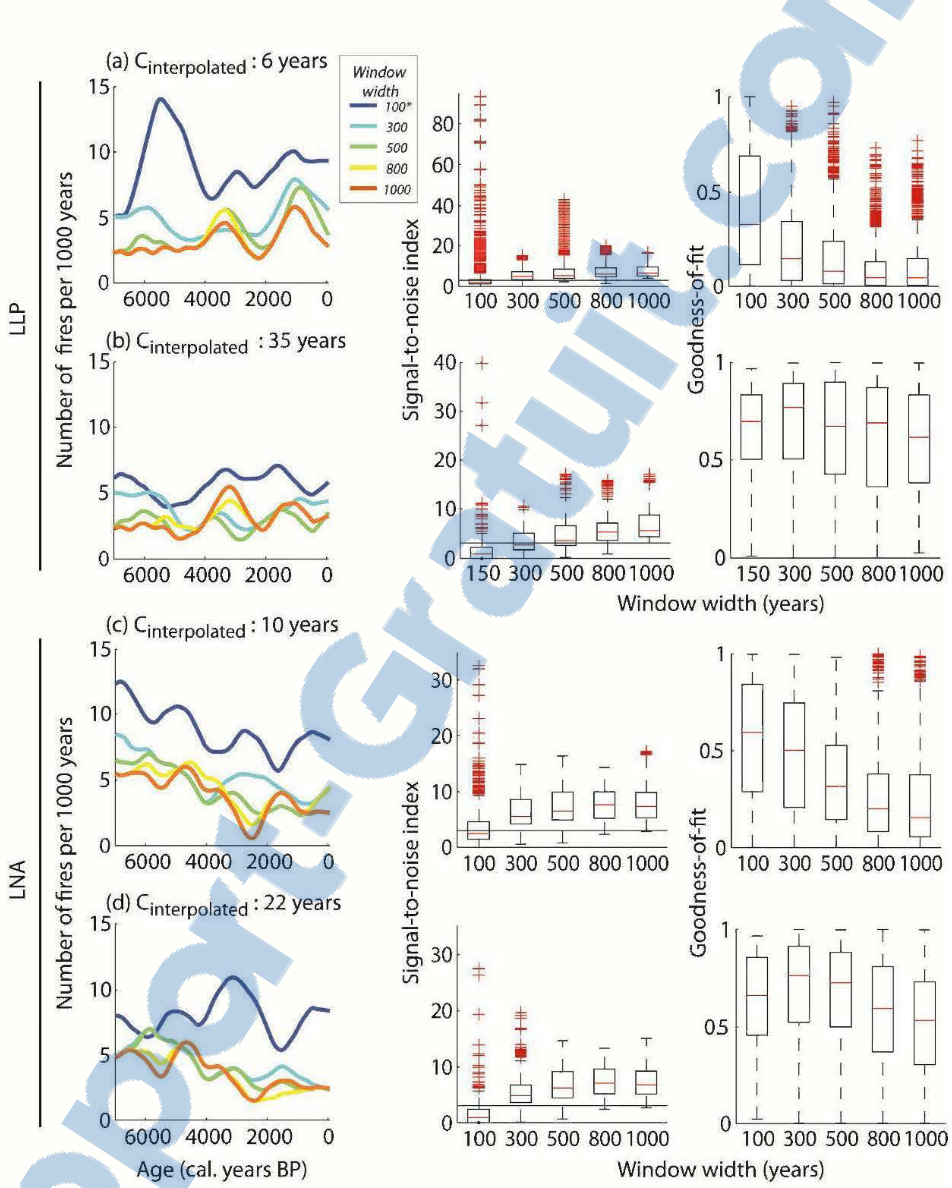

Figure 2.5 Fire frequency, global signal-to-noise index and goodness-of-fit for LLP (a, b) and LNA (c, d) over 7000 years according to ten model runs. Run_{KB} and Run_{All} are displayed in (a, c) and (b, d), respectively. A local 99th percentile threshold of the noise distribution was used. The horizontal bar corresponds to a signal-to-noise index value of 3.0. The goodness-of-fit is a p-value from a Kolmogorov-Smirnov test comparing the empirical and modelled C_{noise} distributions. A large p-value suggests that the two populations are from the same distribution. *A 150-year window for LLP

was used instead of 100-year because of the model requirement that the lower value has to be at least 3 times greater than the median temporal resolution (35 years).

2.6 Discussion

Our study compared fire episodes over the past 150 years reconstructed using charcoal pieces retrieved from lacustrine deposits from two sites of the eastern Canadian boreal forest with three fire events detected in the watersheds using dendrochronology. To explore the ability of the widely used CharAnalysis software to detect these fires, we explored the influence of the temporal resolution used to interpolate the CHAR series and the window width used to model background noise. As the dendrochronologically-dated fire events could only be detected using specific combinations of methods and sites, the following discussion first focuses on the usefullness of a multi-site and multi-proxy approach to fire history reconstruction. Then, we discuss the influence of using various values of the different parameters central to the reconstructions.

2.6.1 Multi-site and multi-proxy reconstructions

The fire event that occurred in 1890 AD at LNA was clearly identified in the charcoal record, but not in the tree-ring record. This oversight may be due, on the one hand, to the fact that cross sections were sampled from scarred living trees. Dendrochronological analyses indicated that the 1941 AD fire was likely severe in that particular area (Héon, 2010), which resulted in the establishment of a new cohort of trees (Agee, 1996; Smirnova et al., 2008). Thus, even if some trees survived the 1890 AD fire, they likely burned later during the 1941 AD fire. In the boreal forest, large fires include a mosaic of stands that have burned at different degrees of severity (Madoui et al., 2010). Such variation could explain why the 1890 AD fire was detected at LLP, where the 1941 AD fire was likely not severe enough to erase traces from the preceding event. However, we cannot exclude that the 1890 AD fire did not reach the lakeshore at LNA. Indeed, charcoal fragments can travel up to tens of kilometers from the flame front (Gardner and Whitlock, 2001; Whitlock and Millspaugh, 1996).

At LNA, the 1941 AD fire could not be detected in any model run, although it was likely a severe stand-replacing fire (Héon, 2010). According to the chronological setting of LNA, this fire should have been recorded at a depth of 4-5 cm in the KB core, where no charcoal was counted. We first interpreted this absence of charcoal particles as a result of an important spatial variability in charcoal deposition into the lake (Gardner and Whitlock, 2001; Whitlock and Millspaugh, 1996). However, a second attempt to extract charcoal from this level was successful. Unfortunately, samples accidentally dried between the first and second counts, thus preventing us to include the results of the second count into the series. We concluded that the charcoal detected in the second count could be due to increased concentration of particles after water loss, but we cannot exclude the above-mentioned sample effect .

The only way we could clearly identify all fire events was using when it is possible two proxies (dendrochronology and sedimentary charcoal) and a minimun of two sites. Hence, whenever possible multi-proxy and multi-site studies should be favored.

2.6.2 Temporal resolution

Using the temporal resolution of the recent sediments (Run_{KB}) allowed us to detect almost all of the fire events recorded by dendrochronological analysis (Figure 2.4). Re-sampling the records to a constant sedimentation rate allowed us to minimize the influence of changes in sediment accumulation through time, a technique frequently used to analyze time series (Carcaillet et al., 2001; Genries et al., 2012). However, the usual procedure of using the median temporal resolution of the entire sequence (Ali et al., 2009; Gavin et al., 2006) generally failed to detect recent fire events (Run_{All}). The important difference in temporal resolution between the entire sequence and the upper part, 29 and 12 years in LLP and LNA respectively, could explain the difficulty to detect recent fire events when using the median temporal resolution from the entire sequence to interpolate the CHAR series. This also confirms that the optimal sampling interval for detecting individual fires should be < 0.12-0.20 times the mFFI (Clark, 1988; Higuera et al., 2007). Indeed, the mFFI of the recent fire events in our study area is 49.5 years, corresponding to an optimal sampling interval < 5.9-9.9 years, which matched the Run_{KB} ones. A solution to minimize the problem of changing sedimentation rates through time could be to separate the sediment sequences according to changes in temporal resolution, and to analyse the sections separately, being cautious in the interpretation of low-resolution sections. However, that would imply to use more sequence extremities in the statistical treatment, which are admitted to introduce a bias, as each level in the analysis depends on the preceding ones. An alternative subsampling procedure could be to take into account changes in sediment accumulation rates along the core. To do this, more efforts should be made to establish at which resolution a sediment core should be subsampled. For example, sediment records are increasingly being subsampled after the age-depth models are established, and each sediment slice may represent as close as possible to a defined sediment accumulation threshold (Finsinger et al., 2013; Hicks et al., 2004; Joosten and Klerk, 2007). Such a procedure, although being potentially more time-consuming and expensive, should be used when subsampling lacustrine sediment cores if the resolution of the proxy records is deemed to be critical.

Our analyses underlined that if the main goal is to obtain a general trend in fire activity, using a temporal resolution equivalent to the entire sequence does not seem problematic (Figure 2.5). Nevertheless, when the difference in median temporal resolution per sample between recent and complete sequence is high, discrepancies appear between fire reconstructions. At LLP, the highest fire frequency was recorded at 1000 cal. year BP and at 4000 cal. BP in Run_{KB} and Run_{All} respectively (corresponding to 6- and 35-year temporal resolutions respectively) (Figure 2.5a, b). However, the general trend in fire history was preserved, with more fire activity after 4000 cal. BP, regardless of the temporal resolution used.

2.6.3 Window width

The temporal window used to model C_{back} strongly affected the number of fire events detected. The C_{back} component can vary over time (from centennial to millennial timescales) because of changes in overall charcoal production, sedimentation, mixing, and sampling (Long et al., 1998). The estimation of the C_{back} component is generally guided by maximizing the SNI and the GOF. Usually, the wider the temporal window (500-1000 years), the higher the SNI (Ali et al., 2009; Gavin et al., 2006). Our results displayed the same trend. However, wide windows (500, 800 and 1000 years) failed to detected the recent fires. In addition, narrow windows (100-150 years) displayed a completely different Holocene fire history, and had low global SNI (< 3). Low SNI could be explained by the fact that the smoothing window used to model the background noise should be 2-5 times the mean to fully separate C_{back} from C_{peak} (Higuera et al., 2007).

2.7 Conclusion

Fire history reconstructions based on lacustrine sedimentary charcoal is made difficult by the various taphonomical processes involved in charcoal deposition into lakes. The use of rigorous and up-to-date numerical techniques may not prevent the underestimation of fire occurrence, notably for recent periods, even when maximizing the SNI. Hence, only considering settings with the highest SNI should not necessarily be the standard procedure. Variation in sample resolution (sedimentation rate) is the main impairment that practitioners must carefully consider when analysing and interpreting CHAR series. Reconstructions of fire events should ideally focus on core sections presenting fairly constant sedimentation rates and resampling CHAR series to a constant sedimentation rate must be conducted with caution. Several combinations of smoothing windows and temporal resolutions can be used to draw a consensual fire history. We showed that using wide smoothing windows (> 300 years) under various temporal resolutions (6-10 versus 22-35 years per sample) yielded comparable fire histories. Nevertheless, we cannot totaly rule out the possibility that the fire history based on the narrowest smoothing window (100-150 years) was false, even if the median SNI over the last 7000 years was low. Here the best compromise was obtained when using a 300-year smoothing window, that provided relatively good SNI values (> 3), allowed us to detect most recent fire events, and displayed a fire history similar to those obtained with wider smoothing windows (500, 800 and 1000 years). Thus, using the widest smoothing window which allows to detect the recent fire events and satisfy the statistical needs (maximizing SNI and GOF) must be the ultimate goal. Consequently, fire reconstructions based on lacustrine sedimentary charcoal analysis must be coupled with dendrochronological reconstructions to minimize false fire identification, notably for the recent period.

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CHAPITRE III

CHARCOAL DISPERSION AND DEPOSITION IN BOREAL LAKES FROM 3 YEARS OF MONITORING: DIFFERENCES BETWEEN LOCAL AND REGIONAL FIRES

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3.1 Abstract

To evaluate the influence of long-distance transport of charcoal particles on the detection of local wildfires from lake sediment sequences, we tracked 3 consecutive years of charcoal deposition into traps set within 7 boreal lakes in northeastern Canada. Peaks in macroscopic charcoal accumulation (> 150 µm) were linked to both local (inside the watershed) and regional wildfires. However, regional fires were characterized by higher proportions of small particles (< $0.1 mm^2$) in charcoal assemblages. We conclude that the analysis of particle size distribution is useful to discriminate 'true' local fires from regional wildfires.

3.2 Résumé

Pour évaluer l'influence du transport à longue distance des particules de charbon de bois sur la détection des feux locaux à partir de séquences sédimentaires, nous avons suivi durant trois années consécutives la déposition et la séquestration de particules dans des trappes lacustres à l'intérieur de sept lacs dans le nord-est du Canada. Les pics d'accumulation de charbons de bois (>150 µm) étaient liés à des feux locaux (à l'intérieur du bassin versant) et à de grands feux régionaux. Cependant, les feux régionaux étaient caractérisés par une plus grande proportion de petites particules (< $0.1mm^2$) dans les séries de charbons de bois. Nous concluons que l'analyse de la distribution de la taille des particules doit être conduite sur les pics de charbons pour discriminer les feux locaux des feux régionaux.

3.3 Introduction

Sediment-based fire history reconstructions can inform on long-term fire-climate-vegetation interactions in diverse ecosystems [Aleman et al., 2013; Ali et al., 2012; Mooney et al., 2011]. This information is useful to guide future management decisions [Bergeron et al., 2006; Oris et al., 2014] or to understand biogeochemical cycles [Bremond et al., 2010; van Bellen et al., 2012]. An oft-used method to reconstruct spatially-explicit fire histories involves the numerical analysis of continuous macroscopic charcoal (>120-150 µm) accumulation records (CHAR) with the so-called 'decomposition approach' that aims at separating charcoal records into a 'peak component' and a 'background component' [Clark and Royall, 1996; Long et al., 1998]. This method is based on the assumption that fire events can be inferred from the peak component because of the rapid settlement of wind-dispersed charcoal particles in lake sediments during a fire (primary deposition). However, the sediment charcoal record can be obscured by inputs from regional fires [Clark and Royall, 1996], as well as from secondary deposition as a result of surface run-off, sediment mixing and re-deposition within the lake [Whitlock and Millspaugh, 1996; Whitlock and Anderson, 2003] ('background' charcoal). The background component can vary spatially according to topography, lake characteristics, and differences in overall charcoal production between vegetation types, as well as temporally because of vegetation changes [Umbanhowar and Mcgrath, 1998; Whitlock and Millspaugh, 1996].

Theoretical models predict that charcoal dispersal distance decreases with increasing particle size and density [Clark, 1988; Higuera et al., 2007]. The models have been validated by few empirical studies that have measured charcoal deposition following natural fires or prescribed burns, showing that the source area of large charcoal particles (>120-150 µm) is smaller than that of smaller particles [Clark et al., 1998; Gardner and Whitlock, 2001; Lynch et al., 2004]. Source areas strongly depend on injection height (i.e., the height of the smoke plume), which is influenced by fire intensity and size of the area burned [Peters and Higuera, 2007; Pisaric, 2002; Tinner et al., 2006].

Although theoretical dispersal models perform well for dispersal distances up to 200 m from the burn edge [Peters and Higuera, 2007], charcoal dispersal at distances >200 m is less well understood. Long-distance transport (5-20 km) has been reported [Pisaric, 2002; Tinner et al., 2006] and charcoal peaks were recorded in lakes without their watersheds having burned [Whitlock and Millspaugh, 1996], suggesting that charcoal-source areas may be larger than previously assumed. In agreement with this, Kelly et al. [2013] found that although the maximum agreement between macroscopic charcoal-inferred fire frequency and area burned was reached for distances up to 1 km from lakeshore, it was robust up to 10 km. This can be explained by high-intensity fires developing a convection plume which lifts charcoal particles higher, increasing the probability of long-distance dispersal and deposition in lakes downwind of the fire [Peters and Higuera, 2007; Pisaric, 2002; Tinner et al., 2006].

An attempt to identify charcoal assemblages created by local fires was proposed by Asselin and Payette [2005], who suggested fitting a linear regression of the proportion of charcoal particle size against size classes (the charcoal size distribution (CSD) method). This method was based on previous observations that assemblages deposited nearer to burn edges contained higher proportions of large-sized charcoal particles than assemblages collected farther from burn edges [Clark et al., 1998; Lynch et al., 2004]. The slope of the linear regression could thus be used as an index of the site proximity from burn edge and should be less steep for a local fire compared to a regional fire or a non-fire year. Empirical studies would place the slope value threshold allowing to separate local fires from regional fires in circumboreal forests between -1.58 and -2.0 [Asselin and Payette, 2005; Clark et al., 1998; Lynch et al., 2004]. A further attempt to distinguish peaks caused by local and regional fires involves screening previously identified charcoal-area peaks using bootstrap resampling of charcoal-particle areas from samples around previously identified peaks [Finsinger et al., 2014]. Peaks with total area significantly greater than expected by chance are deemed robust indicators of past local fire events. A stronger empirical basis is needed to fine-tune these methods and to determine their potential for the detection of past local fire events.

Here, we present results of 3-year long charcoal accumulation records (2011 to 2013) from traps located within seven boreal lakes in northeastern Canada. Large wildfires occurred in the study area during the monitoring period [MRN, 2012], including a fire that burned within the watershed of one of the studied lakes up to lakeshore (Appendice I), and several very large fires (>100 000 ha) that did not reach any of the studied watersheds (Appendice J). We aimed at investigating the influence of area burned and distance to burn edge on annual charcoal deposition. We expected that charcoal size distribution would differ for local and regional fires, with the latter having a higher proportion of smaller particles. We then applied the CSD method [Asselin and Payette, 2005] and the charcoal-area peak-screening method [Finsinger et al., 2014] to Holocene charcoal records available for two of the studied lakes for which information on 20th century local fires was available from a previous dendrochronological study [Brossier et al., 2014].

3.4 Study area and methods

3.4.1 Study area

The seven study sites are aligned along a south-north transect that spans a vegetation gradient from the spruce–moss to the spruce–lichen bioclimatic domains across the James Bay Lowlands (northern Quebec, Canada) (Figure 3.1, Appendice K and Appendice L). Data from the Matagami (49°46'N, 77°49'W; 281 m above sea level (a.s.l.)) and the La Grande Rivière (53°38'N, 77°42'W; 194 m a.s.l.) weather stations respectively recorded mean (±SD) annual temperatures of -0.7 ± 2.7 °C and -3.1 ± 1.9 °C and mean annual precipitations of 905 mm and 684 mm, with approximately one third falling as snow [Series 1971–2000; Environment Canada, 2011]. Dominant winds are from the west in the study area [Mansuy et al., 2014]. Black spruce (*Picea mariana* (Mill.) B.S.P) dominates the regional land cover, along with jack pine (*Pinus banksiana* Lamb.) on drier sites. Specific surface-weather conditions related to anomalous circulation patterns in the upper atmosphere decrease fuel moisture and promote the occurrence of large wildfires > 200 ha [Canadian Forest Service, 2011; Johnson and Wowchuk, 1993], with a ~100 years period of time needed to burn an area equivalent to the study area [Mansuy et al., 2010; Payette et al., 1989]. Area burned is also related to rainfall frequency, temperature, relative humidity, and to the passage of cold fronts characterized by a surface wind shift from southwest to northwest [Flannigan and Harrington, 1988].

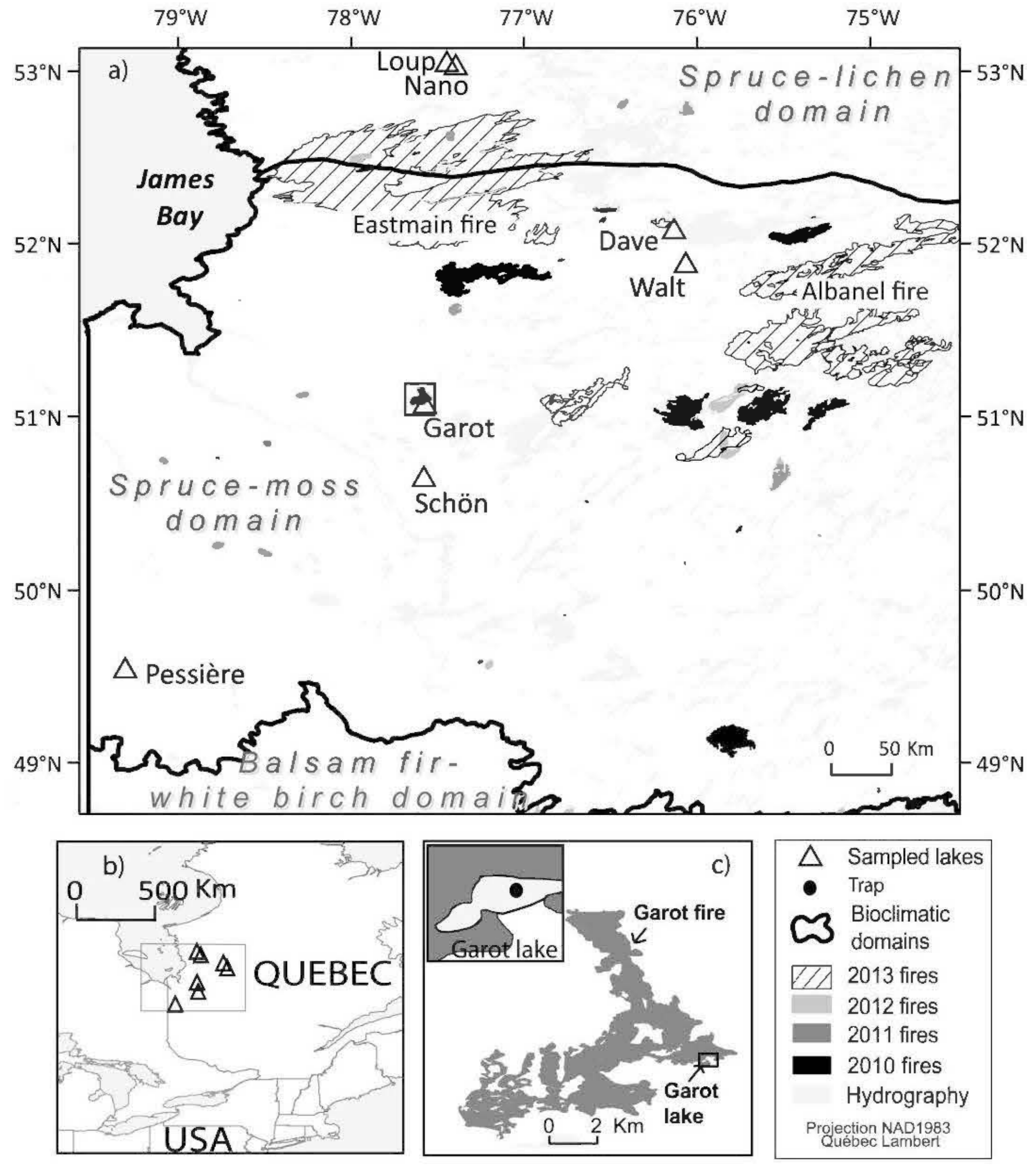

Figure 3.1 Location of the studied lakes and of the fires having occurred in 2010-2013 (a). The location of the studied lakes in eastern North America is also presented (b). A close-up of the Garot fire is also displayed (c).

3.4.2 Recent fire history

We obtained area burned by fires that occurred in 2010-2012 from the GIS fire database of the Ministry of Natural Resources [MRN, 2012]. This database is available for fires with an area ≥ 14 ha and is derived from air photos and satellite imagery. Only 3% of all boreal Canadian wildfires exceed 200 ha in size, yet these fires account for 97% of the total area burned [Stocks, 1991]. We measured the perimeters of the 2013 fires on a composite of Landsat8 images [available from U.S. Geological Survey at http://glovis.usgs.gov/] taken on July 15 and 22 and on September 25 and 26, 2013. We also calculated the shortest distance between the studied lakes and the edges of the 2010-2013 fires (Appendice M and Appendice N). We calculated yearly area burned within areas defined by various radii (ranging from 1 to 100 km) around all study sites (Appendice K and Appendice O).

3.4.3 Sampling design

Our sampling design was inspired by that of Giesecke and Fontana [2008]. Lacustrine traps were installed in the center of the 7 study lakes in September 2010 and trap content was collected once a year in September 2011, 2012, and 2013. Lacustrine traps consisted of two vertical plastic cylinders (length = 70 cm; diameter = 9 cm) inserted into two sampling bottles anchored to a weighted PVC plate (Uwitec Sampling Equipments), itself anchored at the lake's bottom (Appendice P). Trap opening was placed about 1 m above the sediment-water interface and at least 1m below the water surface to prevent the traps to be stuck in ice in winter. Once collected, trap contents were kept in a refrigerator at 4°C until analysis.

3.4.4 Macroscopic charcoal analysis

Trap contents were first gently sieved through a 150-µm mesh and then immersed in a 10% NaOCl aqueous solution to bleach organic matter and ease charcoal identification. The number and area of charcoal particles were measured under a binocular microscope (at 20× magnification) equipped with a camera and connected to a computer with an image-analysis software (WinSeedle 2009, Regent Instruments Canada Inc.). We expressed charcoal particle abundance as accumulation rates by number or by area (CHAR, i.e. number of particles cm^{-2} yr^{-1} or mm^2 cm^{-2} yr^{-1}).

We transformed particle surface area into geometric mean diameters of charcoal particles by calculating the square root of particle surface area as suggested by Clark and Hussey [1996]. We then fitted a linear regression to the charcoal particle size distribution using a maximum of 5 evenly spaced classes ranging from -0.9 to 0.1 log mm (i.e., every 0.2 log mm). Thus the model predicted the proportion of charcoal particles (response variable) for each size class. We expected the slope of the regression to be less steep for local fires, that produce charcoal particle assemblages with a higher proportion of large particles [Asselin and Payette, 2005; Clark et al., 1998; Lynch et al., 2004].

We retrieved particle-size distributions from previously published Holocene charcoal records available for two of the studied lakes (Loup and Nano lakes; Appendice B) [Brossier et al., 2014; Oris et al., 2014]. Charcoal accumulation rates (# cm^{-2} yr^{-1} or mm^2 cm^{-2} yr^{-1}) were analyzed with the CharAnalysis v1.1 software [available via http://sites.google.com/site/charanalysis/; Higuera et al., 2009] (Appendice K). Following the above-mentioned method, we computed the slope of linear regressions of charcoal size distributions for samples that: (i) were identified as fire events with the CharAnalysis software, and (ii) contained more than 10 charcoal particles belonging to at least three size classes [Clark et al., 1998]. We then used different slope values obtained from the charcoal assemblages recovered from the lacustrine traps to determine the appropriate threshold to identify local fire events. Specifically, a charcoal peak was rejected (i.e., considered not to be a "true" local fire) if the slopes of the charcoal size distributions of all the samples having contributed to that peak were steeper than the threshold used.

We also compared results based on different parameters of the charcoal-area peak-screening method [Finsinger et al., 2014]. To screen the peaks, a bootstrap resampling of charcoal particle areas observed within a 900-year window centered on each charcoal area peak identified by CharAnalysis was used, to obtain the range of likely charcoal areas for different counts. Significant charcoal area peaks were then defined as those that had a charcoal area significantly higher than the pth percentile threshold of the bootstrapped values. To test the sensitivity of the area screening method, we used two different pth percentile thresholds $p = 0.95$ and $p = 0.90$.

To evaluate the sensitivity of the CSD and area-screening methods to changes in parameters, we focused our attention on local fire events (1890, 1941 and 1989 AD) identified by dendrochronological analysis [Brossier et al., 2014]. We finally compared fire histories obtained from all methods by calculating fire return intervals (FRI).

3.5 Results

3.5.1 Recent fire occurrence

During the 3-year monitoring period, only one fire burned within the watershed of one of the study lakes (the 2011 fire at Garot lake; Figure 3.1c, Appendice I and Appendice M). The distance from this fire's edge to other study lakes was 54-212 km (Appendice M). In 2010, 2011, 2012 and 2013, shortest distances from burn to lake edge varied between 27-67 km, 0-157 km, 12-88 km and 4-236 km, respectively (Appendice N). Although the 2013 Albanel fire burned only 4 km away from Dave lake (Appendice M), it did not burn within the watershed. The large Eastmain fire was 32-57 km away from the shores of lakes Nano, Loup, Dave and Walt (Appendice J and Appendice M). During the monitoring period, most of the areas burned were >40 km from the study lakes (Appendice O).

3.5.2 Macroscopic charcoal

Macroscopic charcoal accumulation rates displayed comparable trends when computed with particle number or area (Figure 3.2a and Figure 3.2b; Spearman correlation coefficient R^2=0.93, p<0.0001). At Garot lake, CHAR values peaked one year after the local fire event. Whereas no fire occurred in the Nano lake watershed during the monitoring period, macroscopic CHAR in 2013 was higher than peak CHAR values at Garot lake (Figure 3.2a and Figure 3.2b). In 2013, CHAR was also higher than in previous years at Schön, Walt, Dave and Loup lakes, but to a lesser extent than at Nano lake (Figure 3.2a and Figure 3.2b).

Charcoal particle areas varied from 0.023 mm^2 to 1.55 mm^2 but most were smaller than 0.4 mm^2 (Figure 3.2c). The distribution of particle areas at Garot lake had a longer tail and higher median than at Nano lake (Appendice Q). Due to the higher proportion of larger charcoal particles, the slope of the linear regression of particle size distribution was less steep for Garot lake (slope = -0.90, R^2= 0.76) than for Nano lake (slope = -1.88, R^2= 0.86) (Figure 3.2d).

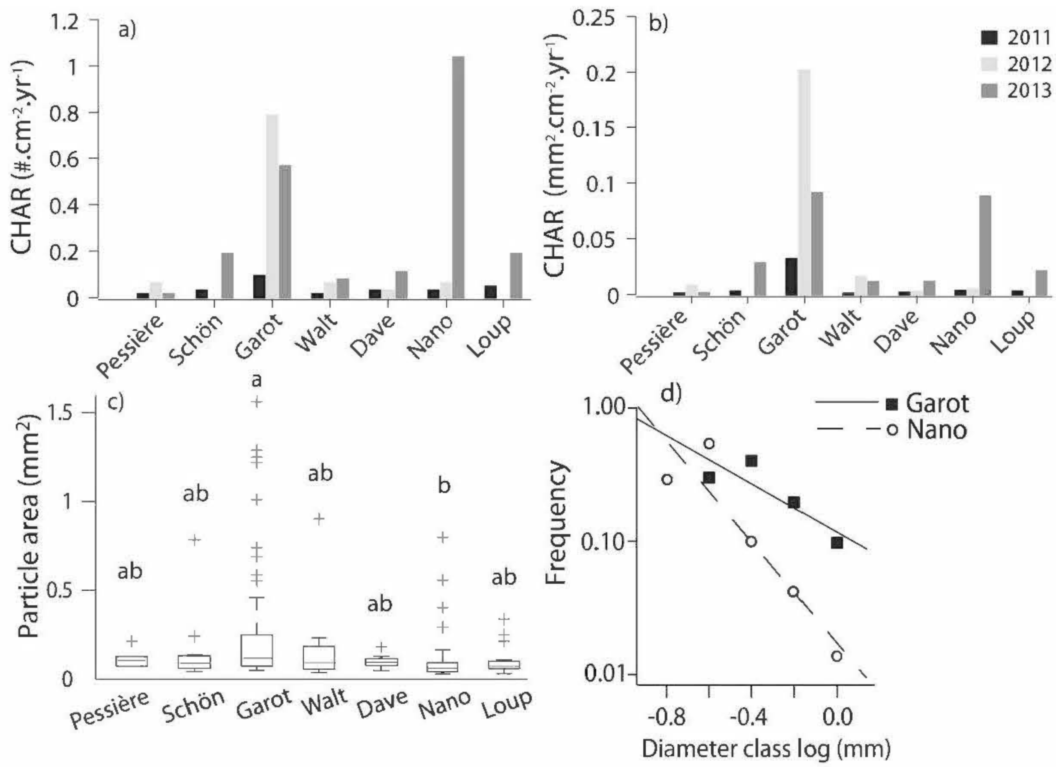

Figure 3.2 Number (a) and total area (b) of macroscopic charcoal particles deposited in lacustrine traps for each sampling year. Box-plots (c) show the summed area of charcoal particles deposited in each lake during the 3 sampling years. Significant differences (Kruskall-Wallis test, d.f.=6, H=42.88, $p<0.0001$) between lakes are shown by different letters. Only Garot and Nano lakes have significantly different medians. Linear regressions of the size distributions of macroscopic charcoal particles (sum of the 3 sampling years) for Nano (white circles, dashed line) and Garot (squares, straight line) lakes (d) are also shown.

3.5.3 Holocene macroscopic charcoal records

The slope of the regression of macroscopic charcoal size distribution was calculated for samples corresponding to fire events recorded over 7000 years at Nano and Loup lakes using CharAnalysis [Figure 3.3 and Appendice R; Brossier et al., 2014]. To apply the CSD method, we used slope values obtained from charcoal assemblages recovered from traps, and from local fire events (1890, 1941 and 1989 AD) detected by dendrochronological analysis [Brossier et al., 2014]. At Nano and Loup lakes, CharAnalysis detected two dendrochronological fires. We compared three different slope values as potential thresholds to detect 'true' local fire events: (1) the slope of the charcoal size distribution at Garot lake (-0.9), known to represent a local fire; (2) the slope of the charcoal size distribution at Nano lake (-1.88), known to represent a regional fire; and (3) the median slope of the samples corresponding to the 1890 AD local fire detected by charcoal and dendrochronological analysis at Loup lake (-1.77).

Only 4 and 6 fire events passed the -0.9 slope screening test at Nano and Loup lakes, respectively. With this threshold, only one fire detected by dendrochronology (at 60 cal. yr BP) was detected at Nano lake and none at Loup lake. With a slope threshold of -1.77, 23 and 20 fire events were identified at Nano and Loup lakes, respectively. With the -1.88 slope threshold, 25 and 20 fire events were identified at Nano and Loup lakes, respectively. The -1.77 and -1.88 slope threshold values screened one (out of two) and two (out of two) fire events detected by CharAnalysis and dendrochronology at Nano and Loup lakes, respectively. With the p=0.95 area screening test, 13 and 10 fire events were detected at Nano and Loup lakes, respectively. With p=0.90, 11 and 2 more peaks were identified at Nano and Loup lakes, respectively. One and two of the CharAnalysis/dendrochronological fire events were respectively detected at Nano Lake using the p=0.95 and p=0.90 area screening thresholds, while none was detected at Loup lake.

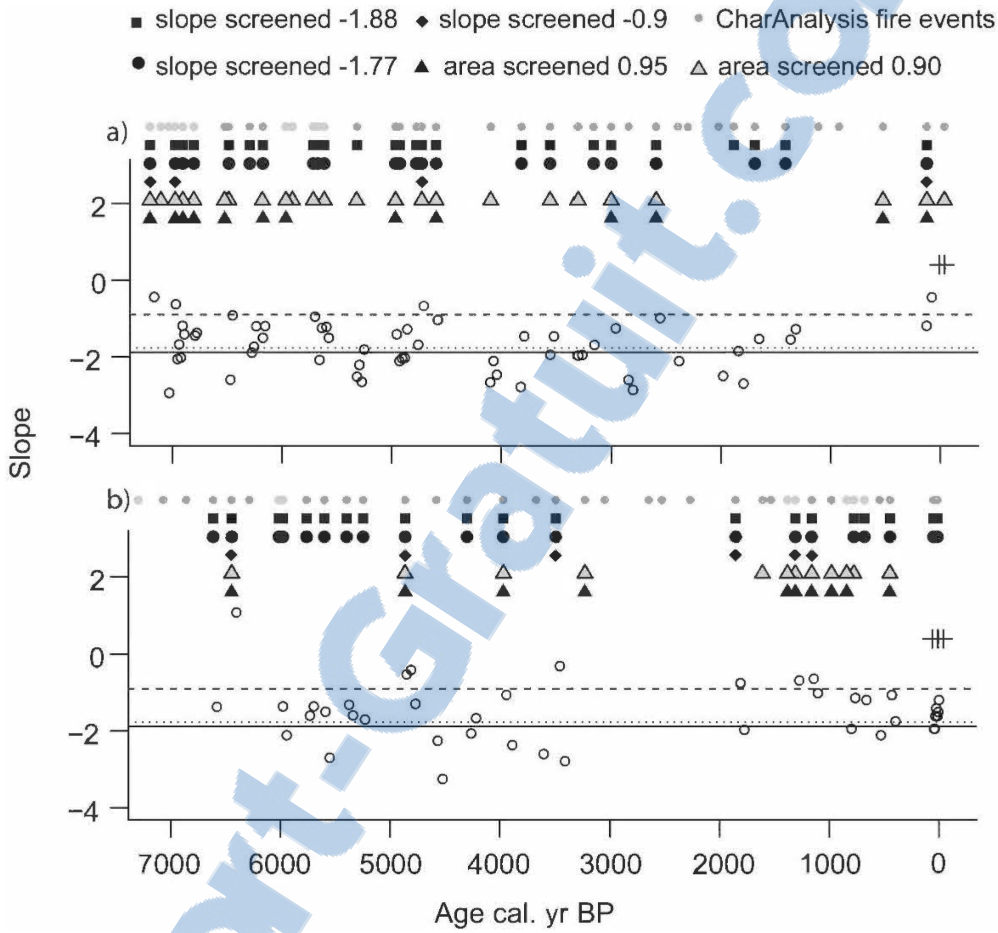

Figure 3.3 Slope values of linear regressions of charcoal size distributions obtained from each sample identified as a charcoal peak with CharAnalysis in Nano (a) and Loup (b) sediment sequences. Fires detected by dendrochronology are shown with crosses. Five different peak-screening methods were used to identify 'true' local fire events. The straight, dotted and dashed horizontal lines represented slope thresholds of -1.88,-1.77 and -0.9, respectively.

Generally, all methods displayed the same trends at Nano lake, with more frequent fire events detected between 7000 and 2500 cal. yr BP (Figure 3.3a). At Loup lake (Figure 3.3b), the -0.9 slope screening test and both area screening tests (p=0.95 and p=0.90) detected only a few fire events, leading to very long fire return intervals

(Appendice S). In summary, the -0.9 slope screening and the p=0.95 area-screening tests failed to detect most fires identified by dendrochronological analysis and yielded unrealistic (too long) FRI values. The -1.88 and -1.77 slope screening tests and the p=0.90 area-screening test retained similar numbers of fires and successfully detected most fires identified by dendrochronology. However, the p=0.90 area-screening test produced longer FRI values for Loup lake.

3.6 Discussion

We presented charcoal accumulation data in lakes from a region submitted to a regime of large, high-severity, stand-replacing wildfires [MRN, 2012]. The originality of our study resides in the monitoring of charcoal accumulation in lakes during natural fires (i.e., traps were installed prior to fires) and collected during three consecutive years. Variability in size and distance of wildfires in our study area allowed us to discuss implications for the detection of local fire events in sediment records. The occurrence of particles with larger diameters in macroscopic charcoal assemblages was a good indicator of short dispersal distances, and could be used to detect 'true' local fire events as was previously assumed based on theoretical models and empirical studies [Asselin and Payette, 2005; Clark, 1988; Clark et al., 1998; Lynch et al., 2004].

3.6.1 Identifying 'true' local fire events from macroscopic charcoal assemblages

Charcoal accumulation rates reported here were comparable to those recorded over the Holocene period in boreal lakes located south of our study area [Ali et al., 2012; Hély et al., 2010]. At Garot lake, maximum macroscopic CHAR occurred one year after a 1684-ha local fire (2011), and high CHAR were also recorded during the following year (2013). A similar delay was observed after the 1988 Yellowstone fire, with a significant increase of charcoal accumulation during the five years following the fire [Whitlock and Millspaugh, 1996]. This could possibly be explained by a stronger influence of secondary deposition from surface run-off after the spring snowmelt, wind erosion of burned snags, or redeposition at lake bottom [Bradbury, 1996; Whitlock and Millspaugh, 1996].

A 2387-ha fire occurred in 2013, only 4 km away from Dave lake, but outside the watershed. Studies have shown a relationship between macroscopic charcoal accumulation and the relative position of lakes with respect to fire (downwind versus upwind) [Gardner and Whitlock, 2001; Whitlock and Millspaugh, 1996]. Although Dave lake was downwind of this fire, no macroscopic charcoal peak was recorded. Other parameters such as fire intensity or severity, wind strength, and lake area can influence the deposition of charcoal particles into a lake [Gardner and Whitlock, 2001]. Thus, even if the fire was close to the watershed, conditions were not reached to allow its detection from lake sediments.

Interestingly, a macroscopic charcoal peak was recorded at Nano lake in 2013 although the distance to the closest fire (the large Eastmain fire) was 32 km (Appendice M and Appendice N). Long-distance dispersal can occur because of the formation of a high convection plume above a fire, with intense and turbulent winds [Clark, 1988; Peters and Higuera, 2007]. Our data thus support theoretical modelling indicating that the contribution of long-distance dispersal to CHAR peaks increases with fire size [Peters and Higuera, 2007]. Previous studies also evidenced long-distance (>5-20 km) transport of macroscopic charcoal particles [Pisaric, 2002; Tinner et al., 2006]. Whitlock and Millspaugh [1996] noted a charcoal peak in lakes located 7 km downwind of the 1988 Yellowstone fire, but charcoal accumulation decreased beyond 13 km from the burn edge. However, both the Yellowstone area [Whitlock and Millspaugh, 1996] and the Swiss Alps [Tinner et al., 2006] display higher topographic heterogeneity than the eastern Canadian boreal forest and may thus not provide the best analogs for comparing charcoal dispersal distance. Our data show that long-distance transport is possible up to 32 km, but maybe not much further as no charcoal peak was recorded at Loup lake, only 4 km north of Nano lake.

Macroscopic charcoal peaks in lacustrine deposits could thus represent fire events having occurred several kilometers outside the watershed (extra-local to regional scales), consequently inflating the local-scale fire history. Hence, identifying charcoal peaks based on common peak-identification methods is not sufficient to guard against the occurrence of peaks produced by extra-local or regional fires. Distinguishing local from regional fires is especially important for studies aiming at describing the incidence of fires on local vegetation dynamics as inferred from plant macrofossils [Genries et al., 2012; Senici et al., 2013]. If the goal is to obtain a regional fire frequency to compare with climatic data, the distinction between local and regional fires could be thought of as being less problematic as all fires having occurred within a region have to be included in this kind of analysis. However, if the same regional fire is recorded in several lake sediment profiles, the regional fire frequency can be overestimated.

Previous studies have suggested that peak magnitude could be used as an indicator of fire proximity [Duffin et al., 2008; Pitkänen and Huttunen, 1999]. However, peak magnitude has also been related to other parameters such as fire size, intensity, and severity [Colombaroli and Gavin, 2010; Duffin et al., 2008; Higuera et al., 2005; Pitkänen and Huttunen, 1999]. Comparing CHAR at Nano and Garot lakes indicated that the sum of particles was higher at Nano (regional fire) than at Garot (local fire) the year of the fire (2013 for Nano and 2011 for Garot). Hence, peak magnitude could not be used as a proxy to infer fire proximity to the lakeshores. Large and severe regional wildfires could produce higher peaks than local fire events, underlining the difficulty to interpret peak magnitude data in palaeofire reconstructions.

More than 80% of the macrocharcoal particles in the trap installed at Nano lake were <0.1mm^2 compared to ~50% at Garot lake. Large charcoal particles are usually dispersed at shorter distances compared to smaller ones [Clark, 1988; Patterson et al., 1987; Radke et al., 1991]. Analyzing charcoal size distributions may help differentiate local and regional fire peaks. Previous studies on charcoal size distribution reported that distributions with a slope less steep than -1.58 to -2.0 could indicate local fires [Asselin and Payette, 2005; Clark et al., 1998; Lynch et al., 2004]. Here we showed that fires detected by dendrochronological analysis at Loup and Nano lakes were also identified using slope thresholds of -1.88 and -1.77. These thresholds allowed us to remove from our Holocene sequences fire events initially detected by CharAnalysis, which may correspond to wildfires having occurred outside the watersheds. The -0.9 threshold failed to detect local fires recorded by dendrochronological analysis and lead to FRIs (median = 2250 and 1374 years at Nano and Loup lakes respectively), considerably longer than current FRIs in our study area [about 100 years; Payette et al., 1989]. Consequently, the optimal slope threshold to identify local fire events probably lies between -1.88 and -1.77.

The area peak-screening method with p=0.90 allowed us to detect local fire events detected by dendrochronological analysis at Nano lake, and yielded results similar to those obtained with the -1.77 and -1.88 slope threshold. However, at Loup lake, the area peak-screening method displayed FRIs considerably longer than current FRIs in our study area (somehow like the -0.9 slope threshold), and failed to detect the local fires detected by dendrochronological analysis.

Charcoal-area peak-screening methods remove fire events initially detected by CharAnalysis that may correspond to distant wildfires. The two methods (CSD and area screening) strongly depend on the proportion of large particles in the charcoal assemblages. Therefore, local fires could go unnoticed if (1) a wildfire failed to produce high proportions of large particles due to in situ biomass structuring, (2) large charcoal particles were not included in lake sediments because of taphonomical processes and bathymetric characteristics of the lake, or (3) charcoal counts were too low. This is illustrated by the fact that the local fires identified by dendrochronological analysis at Loup lake (1890 AD fire) produced charcoal distributions with a median slope of -1.77, compared to -0.9 at Garot lake. The area peak-screening method seems to be more sensitive to variability in the proportion of large charcoal particles, but could better account for changes in local vegetation as it uses variable thresholds instead of a fixed threshold as for the slope screening method.

3.6.2 Implications for fire history reconstructions

Our study displayed long-distance dispersal of macroscopic charcoal particles (>150 µm) in boreal ecosystems during large and severe fire events. Consequently, macroscopic charcoal peaks recorded in lacustrine deposits could be related to both local and regional fire events. For studies aiming to reconstruct local fire events, a particular effort must be done to characterize particle size distributions, knowing that low proportions of larger particles (> $0.1 mm^2$) indicate regional wildfires. We showed that screening area-based CHAR peaks using either the slope of the particle size distribution [Asselin and Payette, 2005] or the peak-screening test [Finsinger et al., 2014] can help identify 'true' local fire events. The slope threshold we identified (between -1.88 and -1.77) is in line with those reported in previous studies conducted in the circumboreal forest (between -2.00 and -1.58 [Asselin and Payette, 2005; Clark and Hussey, 1996; Clark et al., 1998; Lynch et al., 2004]). Among the two percentile thresholds for the area-screening test, the p=0.90 value seems preferable. Few studies have empirically validated theoretical models of charcoal transport and deposition [Clark et al., 1998; Gardner and Whitlock, 2001; Lynch et al., 2004; Ohlson and Tryterud, 2000; Whitlock and Millspaugh, 1996]. Validation studies from a variety of biome/fuel types are highly needed. Also, as charcoal production could vary according to forest type or fire type [Duffin et al., 2008; Umbanhowar and Mcgrath, 1998], studies in other forest ecosystems would allow to fine-tune the charcoal-area screening tests.

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CHAPITRE IV

LONG-TERM FIRE HISTORY IN NORTHERN QUEBEC: IMPLICATIONS FOR THE NORTHERN LIMIT OF COMMERCIAL FORESTS

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4.1 Summary

1. Fire frequency is expected to increase in boreal forests over the next century owing to climate change. In Quebec (Canada), the location of the northern limit of commercial forests (~51 °N) was established in 2000 taking into account mainly forest productivity and fire risk. The location of the limit is currently under debate and is being re-evaluated based on a more extensive survey of the territory. We characterized the natural variability of fire occurrence (FO) in the area surrounding the northern limit and these results are a useful contribution to discussions on the re-evaluation of its location.

2. Regional FO over the last 7000 years was reconstructed from sedimentary charcoal records from 11 lakes located in three regions surrounding the northern limit (i.e. south, north, and near the limit). Holocene simulated precipitation and temperature from a general circulation model (GCM) were used to identify the long-term interactions between climate and fire.

3. Fire histories displayed similar trends in all three regions, with FO increasing from 7000 calibrated years before the present (cal. years BP) to reach a maximum at 4000–3000 cal. years BP, before decreasing during the late Holocene. This trend matches the simulated changes in climate, characterized by drier and warmer conditions between 7000–3500 cal. years BP and cooler and moister conditions between 3500–0 cal. years BP.

4. Northern ecosystems displayed higher sensitivity to climate change. The natural variability of FO was narrower in the southern region compared to the limit and northern regions. An abrupt decrease in FO was recorded close to and north of the limit at 3000 cal. years BP, whereas the decrease was more gradual in the south.

5. *Synthesis and applications.* We reconstructed the natural variability in fire activity over the last 7000 years near the current location of the northern limit of

commercial forests in Quebec. FOs were more sensitive to climate change near to and north of the limit of commercial forestry. In the context of predicted increase in fire activity, the lower resilience of northern forests advocates against a northern repositioning of the limit of commercial forests.

4.2 Résumé

1. Les changements climatiques devraient augmenter la fréquence des feux boréaux au cours du XXIe siècle. Au Québec (Canada), la position de la limite nordique des forêts commerciales (~51 °N) a été établie en 2000 en prenant en compte principalement la productivité de la forêt et les risques de feu. Cette position est actuellement débattue et doit être réévaluée à partir d'une étude plus précise du territoire. Nous avons caractérisé la variabilité naturelle de l'occurrence des feux de part et d'autre de la limite nordique de la forêt commerciale afin de contribuer aux discussions sur la réévaluation de sa position.

2. Les occurrences de feux régionaux sur les 7000 dernières années ont été reconstituées à partir de séquences sédimentaires de 11 lacs dans trois régions localisées de part et d'autres de la limite nordique de la forêt commerciale (au sud, au nord et au niveau de la limite). Les précipitations et les températures simulées à partir d'un modèle de circulation générale ont été utilisées pour identifier les interactions entre le climat et le feu au cours du temps.

3. Les occurrences de feu montrent les mêmes tendances dans les trois régions, avec une augmentation des occurrences de feux à partir de 7000 avant nos jours pour atteindre un maximum entre 4000 et 3000 avant nos jours, et de diminuer à l'Holocène supérieur. Cette tendance correspond aux changements du climat simulés, caractérisés par des conditions plus chaudes et sèches entre 7000 et 3500 avant nos jours et plus froides et humides ensuite.

4. Les résultats mettent en évidence que les écosystèmes localisés au nord de la limite de la forêt commerciale semblent plus affectés par les changements climatiques. La variabilité naturelle de l'occurrence des feux était moins importante dans le sud comparée à celles observées dans le nord et au niveau de la limite. Une diminution abrupte de l'occurrence des feux a été observée dans les régions près et au nord de la limite il y a 3000 ans, alors qu'elle a été plus graduelle dans le sud.

5. Synthèse et applications. Nous avons reconstitué la variabilité naturelle de l'occurrence des feux au cours des 7000 dernières années près de la limite nordique des forêts commerciales au Québec. Les écosystèmes au nord et au niveau de la limite semblent réagir plus abruptement aux changements climatiques. Dans une configuration d'augmentation de l'activité des feux dans les prochaines décennies, nos résultats ne permettent pas d'appuyer un repositionnement vers le nord de la limite des forêts commerciales.

4.3 Introduction

Since the United Nations Conference on Environment and Development (UNCED) in 1992, many forestry policies focused on sustainable forest management (SFM) have been proposed, such as forest certification (Stupak et al. 2011; Rist & Moen 2013). Sustainability requires some minimum conditions to be fulfilled, among which are minimum forest productivity and regeneration capacity. Forests need to be resilient, i.e. to regenerate after natural or anthropogenic disturbances in such a way that stand density and productivity are comparable to pre-disturbance conditions. As boreal ecosystems are characterized by limited growing conditions and regular natural disturbances (Kneeshaw, Bergeron & Kuuluvainen 2011), adding anthropogenic disturbances may decrease resilience and create unsustainable conditions (Dussart & Payette 2002; Payette & Delwaide 2003).

In this context, since 2000 the northern limit of commercial forests in Quebec (Canada) has been established around 51 °N in the black spruce *Picea mariana* – feather moss bioclimatic domain. This limit was mainly determined by taking into account the economic value of forests according to their productivity and fire cycle (MRNF 2000). North of the limit, productivity was deemed too low and fire cycles too short (< 150 years) to allow for sustainable wood harvesting (MRNF 2000). The density of the boreal forest cover progressively decreases with increasing latitude, and gives way to lichen woodlands beyond 52 °N. The fire cycle is shorter near the limit of commercial forests (~100 years) (Mansuy et al. 2010) than further south in the boreal forest (~360 years) (Bergeron et al. 2004), because climatic conditions, including recurrent blocking of air masses in the troposphere close to the limit of commercial forests (Skinner et al. 2002; Girardin et al. 2006), decrease surface fuel moisture and promote the occurrence of large wildfires (Johnson & Wowchuk 1993).

Over the last 50 years, 9% of the area occupied by closed-canopy spruce–moss forests in boreal Quebec has shifted to open lichen woodlands because of successive fires (Girard, Payette & Gagnon 2008). When the interval between successive fires is too short, black spruce trees do not have time to reach sexual maturity, as seed production usually begins after 30 years (Viglas, Brown & Johnstone 2013). Moreover, 50–150 years are needed before enough seedlings are produced to restock northern black spruce forests after fire (Viglas, Brown & Johnstone 2013). Climate change is likely to cause fire frequency to increase in Quebec's boreal forest (Bergeron et al. 2010), and thus regeneration failure following successive fires could become more common. Therefore, the current location of the northern limit of commercial forests might be put into question with regards to the potential lack of resilience of the northern boreal forest under climate change.

Natural ecosystems have evolved within ranges of conditions that can serve as references to assess the current ecological integrity of managed ecosystems and maintain their resilience (Landres, Morgan & Swanson 1999). As wildfire is the main disturbance controlling terrestrial boreal ecosystem functioning (Payette 1992), ecosystem-based forest management needs to be based on natural fire regimes (Bergeron et al. 2002). It has been suggested that management should not push forest ecosystems outside their natural range of variability (Bergeron et al. 2002; Cyr et al. 2009).

To assess the long-term stability of the current northern limit of commercial forests and its sensitivity to predicted increased fire activity, we investigated the long-term natural variability of the fire regime. More specifically, we compared fire histories recorded in the sediments of six lakes located near and north of the northern limit of commercial forests with similar data from five previously published records from lakes located further south in the boreal forest (Ali, Carcaillet & Bergeron 2009; Hély et al. 2010; Ali et al. 2012). Because northern ecosystems are known to change more rapidly under climate modifications (Payette, Fortin & Gamache 2001; Thuiller, Lavorel & Araújo 2005; Alsos et al. 2012), we expected that forests north of 51 °N would be more sensitive to climate change with, for instance, delayed, earlier, or more abrupt decreases in fire occurrence observed north compared to south of 51 °N. We compared predicted fire frequencies (Bergeron et al. 2010) with the long-term Holocene variability to evaluate whether future wildfire activity could exceed the natural range of variability.

4.4 Material and methods

4.4.1 Study area

We examined the climate–fire relationship north, near and south of the northern limit of commercial forests in the James Bay Lowlands of northern Quebec (Canada) (Figure 4.1). Eleven lakes were sampled along a vegetation gradient that extended from the black spruce – feather moss bioclimatic domain in the south to the spruce – lichen woodlands in the north. Four lakes were located north of the limit of commercial forests, five lakes were south of it, and two lakes were close to the limit. Dominant tree species along the transect were black spruce and jack pine *Pinus banksiana*. Climate averages recorded from the closest meteorological stations to the southern lakes (Matagami, 49°46'N, 77°49'W; 281 m above sea level (a.s.l.)) and to the northern lakes (La Grande Rivière, 53°38'N, 77°42'W; 194 m a.s.l.) are -0.7 ± 2.7 °C and -3.1 ± 1.9 °C (mean ± SE) respectively for annual temperature. Annual precipitation averaged 905 in the south and 684 mm in the north, with 38% and 36% falling as snow, respectively (Series 1971-2000; Environment Canada, 2011).

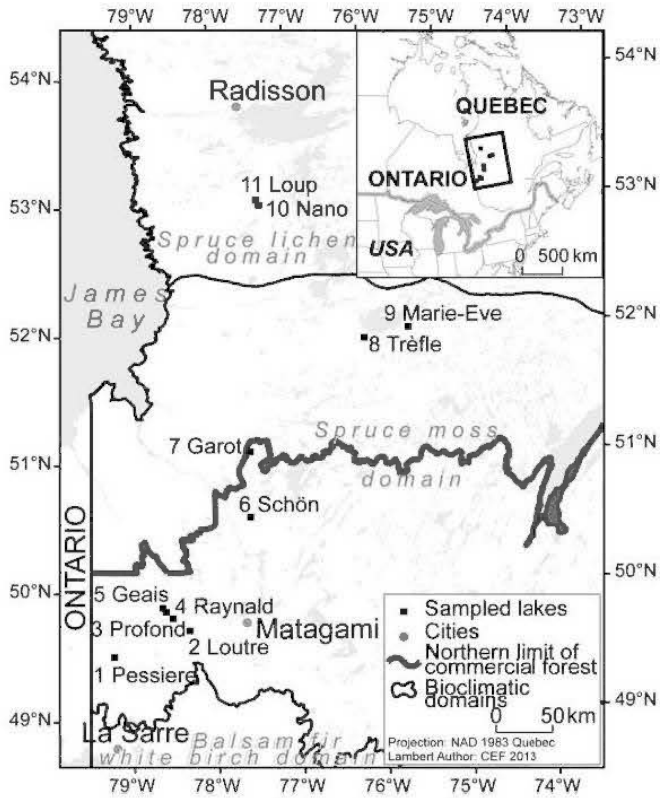

Figure 4.1 Location of the study sites in northern Quebec.

4.4.2 Sediment sampling

Lacustrine sediment cores were extracted between March 2007 and March 2011 using a Livingstone corer, except for Lac à la Pessière where a Mackereth corer was used. The water-sediment interface was collected using a Kajak-Brinkhurst gravity corer, except for Lake Marie-Eve (named L-40 in Ferland et al. (2012)). Sedimentary sequences from the five southernmost lakes have already been published (Carcaillet et al. 2001; Ali, Carcaillet & Bergeron 2009; Hély et al. 2010). All sequences were composed of gyttja and their lengths ranged from 100 cm (Lake Garot) to 600 cm (Lake Geais) (Table 4.1).

Table 4.1 Main characteristics of the sampled lakes

Region	Lake	Latitude	Longitude	Elevation (m a.s.l.)	Lake area (ha)	Water depth (m)	Core length (cm)	Mean deposition time ± SE (yr cm^{-1})
North	Loup	53°03'18.1" N	77°24'01.9" W	206	1·6	3·0	106	69·0 ± 1·49
	Nano	53°01'25.5" N	77°21'51.3" W	206	0·4	3·2	140	54·0 ± 1·63
	Marie-Eve	52°01'47.4" N	75°31'14.6" W	296	16·5	8·7	290	24·0 ± 0·71
	Trèfle	51°57'54.7" N	76°04'52.0" W	270	6·8	5·4	150	48·0 ± 1·10
Limit	Garot	51°05'58.7" N	77°33'12.9" W	248	5·1	6·9	100	74·7 ± 3·00
	Schön	50°35'41.7" N	77°34'06.1" W	291	2·8	7·0	133	55·0 ± 0·12
South	Geais	49°53'32.2" N	78°39'18.4" W	280	3·6	10·2	603	13·2 ± 0·35
	Profond	49°51'40.1" N	78°36'47.9" W	270	0·6	>20	223	18·3 ± 0·50
	Raynald	49°48'33.4" N	78°32'09.0" W	250	1·5	10·3	472	15·2 ± 0·30
	Loutre	49°42'42.1" N	78°20'09.0" W	274	2·1	10·6	227	36·6 ± 0·76
	Pessière	49°30'11.5" N	79°14'22.2" W	305	4·0	16·0	302	13·0 ± 0·11

Sediment accumulation chronologies were obtained from radiocarbon measurements of terrestrial plant macroremains and gyttja samples (Appendice T). The ^{14}C dates were calibrated using the CALIB program (Stuiver & Reimer 1993) based on the IntCal04 dataset (Reimer et al. 2004). The age–depth models (Appendice U) were obtained using the MCAgeDepth program (Higuera 2008), which applies a Monte Carlo resampling technique to assess median ages and to generate confidence intervals around the fit, based on the probability distribution of each date that was provided by the CALIB program.

Three age–depth models displayed substantial sediment accumulation (~50 cm) over short periods of time (~ 100 years) (Appendice U). This could be explained by peat and/or soil erosion from the shores into the lakes caused by major flooding events that have been observed elsewhere in boreal and subarctic Quebec (Payette & Delwaide 2004; Asselin & Payette 2006; Ali et al. 2008). Rapid changes in sedimentation accumulation rates represent an impairment for accurate charcoal analysis (Higuera et al. 2010), therefore sections of the cores showing disruptions in sediment accumulation were not used in the analyses.

4.4.3 Charcoal quantification

To obtain fine-scale temporal resolution, sedimentary sequences were cut into 0.5 to 1 cm thick slices, depending on total sequence length. Sediment samples (1 cm^3) taken from each slice were heated for 24 hours in an aqueous 3 % $(NaPO_3)_6$ solution to facilitate deflocculation, and then sieved through a 150-µm mesh. Peaks in charcoal particles larger than 150 µm were likely to represent local fire events (Higuera et al. 2007). Sieved samples were immersed in an aqueous 10% NaOCl solution to ease distinction of charcoal from bleached organic matter. The calculation of the number and size of charcoal particles was performed under a binocular microscope (× 20) equipped with a camera and connected to a computer with image analysis software (WinSeedle 2009, Regent Instruments Canada Inc.). Charcoal area was transformed to a charcoal accumulation rate (CHAR; mm^2 cm^{-2} $year^{-1}$) using the age–depth models.

4.4.4 Fire histories reconstuctions

Fire-history reconstructions were performed with the CharAnalysis 1.1 software (Higuera et al. 2009, freely available at https://sites.google.com/site/charanalysis/). To remove bias induced by the different sedimentation rates (median sample resolution varied between 12 and 37 years, with a mean of 20 years), a constant resolution of 20 years was used to interpolate the CHAR series into $CHAR_{interpolated}$

series for further charcoal analyses. The $CHAR_{interpolated}$ series were then decomposed by removing the low-frequency background signals ($CHAR_{back}$), corresponding to variation in charcoal production, the sedimentation process, mixing and sampling, to obtain residual high-frequency series ($CHAR_{peak}$). Finally, the $CHAR_{peak}$ series were separated into two sub-populations, which are referred to as $CHAR_{noise}$ and $CHAR_{fire}$, using a Gaussian mixture model according to a locally defined threshold. Each $CHAR_{peak}$ that exceeded the 99th percentile threshold was considered a local fire episode. The signal-to-noise index (SNI; Kelly et al. 2011) and goodness-of-fit (GOF) were respectively 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.

The $CHAR_{interpolated}$ series can be decomposed using several filtering methods (e.g. moving mode, moving median, moving average, lowess, robust lowess) and using various smoothing-window widths. The choice is generally guided by maximizing the SNI and GOF. To obtain a robust fire reconstruction for each lake and to minimize potential bias related to the choice of a given filter, we used the method developed by Blarquez et al. (2013), which automatically produces several iterations of the numerical analysis, changing the filtering method and the smoothing-window width (t =100, 135, 170, …, 1500 years). As a result, 205 reconstructions were obtained for each lake (41 smoothing-window widths x 5 filtering methods). A kernel density function (Mudelsee et al. 2004) was then applied to the 100 best reconstructions, i.e. those with the greatest SNI and GOF, to calculate 100 fire occurrence (FO) scenarios for each lake. Finally, the median FO was calculated for each lake.

Regional fire occurrence (RegFO) was obtained by averaging the local median FO values for three regions: southern (49 to 50 °N); limit (~51 °N); and northern (52 to 53 °N). These were composed respectively of lakes 1–5, 6–7, and 8–11 (Figure 4.1). Bootstrap confidence intervals (90%) were computed around the RegFO for each region, except for sites at the limit, which included only two lakes. A nonparametric Kruskal-Wallis test among 1000-year periods and Wilcoxon rank-sum tests among period pairs were used to identify significant changes in the RegFOs. The RegFOs were also inverted to estimate mean fire interval (MFI). To determine if RegFOs of sites near the limit were more similar to those north or south of it, dissimilarity between RegFOs was calculated as 1 minus the samples' Spearman rank correlation between observations and used to conduct a hierarchical clustering.

4.4.5 Climate data

We applied the method developed by Hély et al. (2010) on climate simulations from the UK Universities Global Atmospheric Modelling Programme GCM (thereafter UGAMP) for each millennium throughout the Holocene (Hall & Valdes 1997; Singarayer & Valdes 2010). To increase the spatial resolution of the GCM simulation to ease comparison with our local proxy records, a downscaling method was used by applying the UGAMP temperature and precipitation anomalies to the Climate Research Unit climatology data set TS 2.1 with time series at 0.5° (Mitchell & Jones 2005). Within each 0.5° pixel, we used a normal distribution for temperature and a gamma distribution for precipitation (New et al. 2002) to obtain a 30-year time series where each specific monthly distribution was parameterized with the reconstructed monthly mean (Ramstein et al. 2007).

From climate simulations, the Drought Code (DC) index of the Canadian Forest Fire Weather Index System was calculated. The DC is a component of the Fire Weather Index (FWI; van Wagner 1987) that is used to assess fire risk based on weather conditions (de Groot et al. 2007). Richardson's weather generator (Richardson 1981) was applied to the simulated 30-year monthly temperature and precipitation time series to derive daily values needed to compute the DC.

A DC value of zero is indicative of water saturation and values higher than 400 are indicative of extreme dryness that could result in deep burning of sub-surface heavy fuels. We calculated the fire-season length (FSL) under moderate fire danger, which is the cumulative number of days during the fire season with a DC value greater than 80 units (Hély et al. 2010).

Departure from the mean Holocene FSL under moderate fire danger was also determined for spring (April–June) and summer (July–September). Simulated precipitation and temperature models are displayed as anomalies relative to the control period (0 cal. years BP) that was assumed to be representative of the present-day conditions. Climate averages used in this study came from a twelve-pixel grid corresponding to the area encompassing 70–80 °W and 47–55 °N. A Kruskal-Wallis test among 1000-year periods was also used to identify significant changes in the climate data.

4.5 Results

4.5.1 Fire occurrence reconstructions

The RegFOs displayed the same Holocene trend for all regions, with highest fire occurrence around 4000–3000 cal. years BP, relative to periods before and after (Figure 4.2a,b,c) (see Appendice V for details of the 11 local FOs). The RegFO for the northern region gradually increased from ca. four fires per millennium at 7000 cal. years BP to ca. five fires per millennium at 4000 cal. years BP (Figure 4.2a). It then significantly decreased to a low of ca. three fires per millennium around 2500 cal. years BP (Wilcoxon test, $Z = -8.6673$, $P < 0.0001$), before slightly increasing to present values close to those recorded 7000 cal. years BP. The RegFO near the commercial forest limit was stable at ca. four fires per millennium from 7000 to 5000 cal. years BP (Figure 4.2b). It then increased to a maximum of ca. six fires per millennium around 3500 cal. years BP, before significantly decreasing to a low of ca. three fires per millennium around 1500 cal. years BP (Wilcoxon test, $Z = 16.1420$, $P < 0.0001$), and increasing again to present values close to those recorded at 7000 cal. years BP. The southern RegFO displayed relative stability between 7000 and 4000 cal. years BP at ca. five fires per millennium (Figure 4.2c), before slightly increasing to a maximum of ca. six fires per millennium at 3000 cal. years BP. A significant decrease in RegFO subsequently occurred from 3000 cal. years BP to the present value of ca. four fires per millennium (Wilcoxon test, $Z = 10.9447$, $P < 0.0001$). The significant decrease in RegFO lasted 1500 years near or north of the limit of commercial forests, compared to 3000 years south of it.

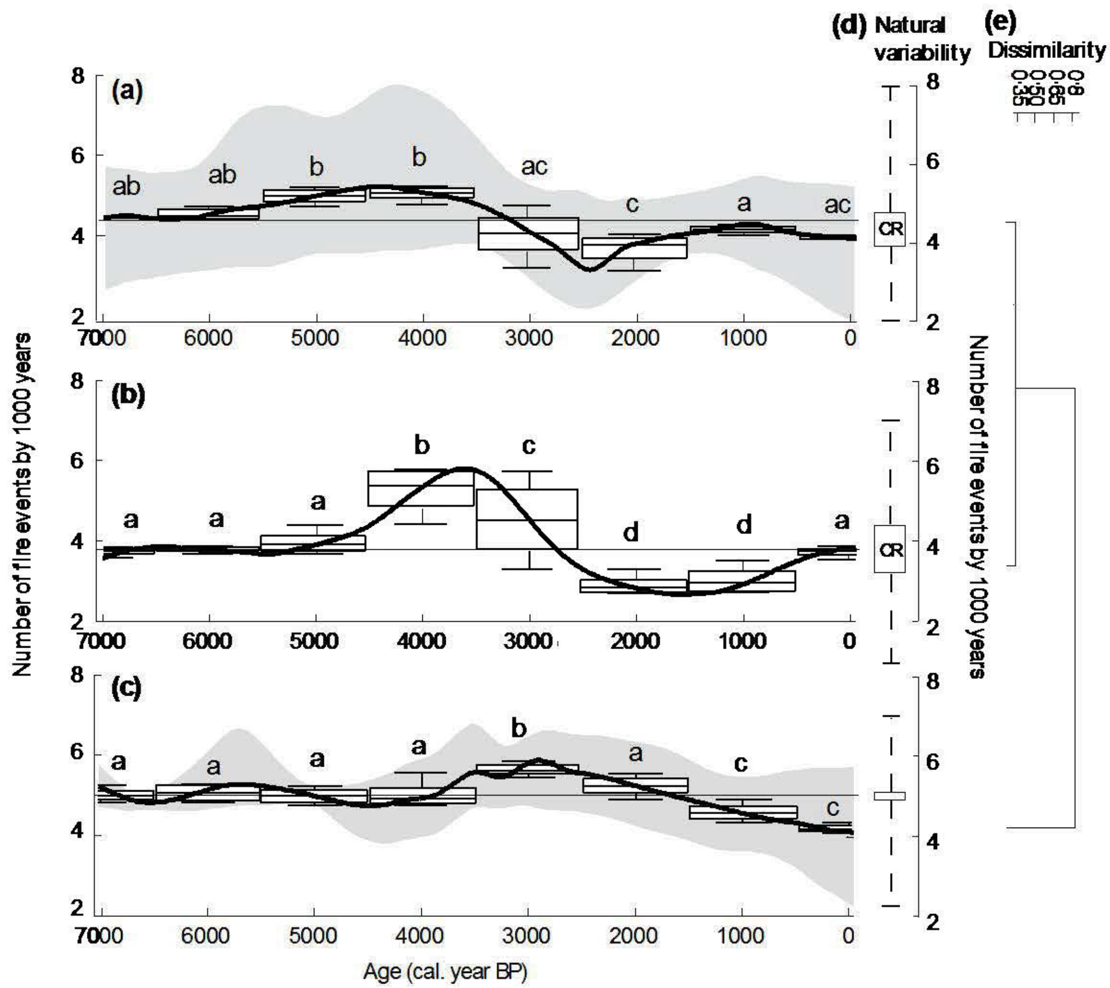

Figure 4.2 Reconstructed fire occurrence based on the analysis of lacustrine charcoal deposits. RegFOs represent the average of median FOs from sampled lakes in the northern (a), limit (b), and southern (c) regions. Thick black lines correspond to smoothed values obtained using a LOWESS function (500-year window). Grey areas correspond to 90% bootstrap confidence intervals. The median value for each sequence is represented by a horizontal black line. Box-plots are shown for each millennium and significant differences between millennia are shown by different letters. Two ranges of natural variability in fire occurrence are presented (d). The conservative range (CR) corresponds to the range between mean RegFOs for the periods 3000–0 and 7000–3000 cal. years BP and is represented by a white box. The extended range corresponds to the minimal and maximal values of the 90% confidence interval for the northern and southern regions, and corresponds to the minimal

and maximal values of all local FOs in the limit region over the last 7000 years. It is represented by dashed lines below and above the CR. Hierarchical clustering of the three regional fire histories based on dissimilarity coefficients is also shown (e).

Over the last 7000 years, median RegFOs were 4.4, 3.9 and 5.0 fires per millennium for the northern, limit, and southern regions, respectively, and these values were significantly different (Kruskal Wallis test, H = 722.57, d.f. = 2, $P < 0.0001$). RegFOs for all regions were higher than (or close to) the median until ~3000 cal. years BP and lower afterwards. Using these periods [3000–0 and 7000–3000 cal. BP] of relatively stable fire regimes, the conservative ranges of variability in RegFO are 3.9–4.8, 3.2–4.4, 4.9–5.1 fires by millennium for the northern, limit, and southern regions, respectively (Figure 4.2d). These values correspond to MFI ranges of 256–208, 312–227 and 204–196 years for the northern, limit, and southern regions, respectively. The extended range of natural variability that corresponds to the minimal and maximal values of the 90% confidence interval for the northern and southern regions and to the minimal and maximal values of all local FOs in the limit region over the last 7000 years, are 1.8–7.8, 1.5–7.0, 1.8–7.0 fires per millennium for the northern, limit, and southern regions, respectively. Hierarchical clustering based on dissimilarity indices established two groups of RegFOs: the northern and limit regions versus the southern region (Figure 4.2e).

4.5.2 Climate reconstructions

Whereas summer temperature displayed relative stability, a gradual increase in spring temperature occurred from 7000 to 1000 cal. years BP (Figure 4.3a). Temperature anomalies were positive from 7000 to 1000 cal. years BP in summer and from 3000 to 1000 cal. years BP in spring. A ~0.7 °C decrease in annual and seasonal temperatures occurred between 1000 and 0 cal. years BP.

A general increase in precipitation anomalies occurred from 7000 to 1000 cal. years BP, before decreasing to present-day values (Figure 4.3b). Summer precipitation anomalies were positive throughout the Holocene, whereas spring anomalies were negative between 7000–6000 and at 3000 cal. years BP.

The fire season length (FSL) was shorter between 5000–4000 cal. years BP and between 2000–1000 cal. years BP (Figure 4.3c). The longest FSL was recorded at 7000–6000 cal. years BP and significantly differed from the minimum value reached at 1000 cal. years BP (Kruskal Wallis test, $H = 29.11$, d.f. = 7, $P = 0.0001$). A slight, although not significant, increase in FSL occurred between 4000 and 3000 cal. years BP. FSL anomalies in spring and summer displayed the same trend during the Holocene (Figure 4.3c), although spring anomalies were always lower than summer anomalies.

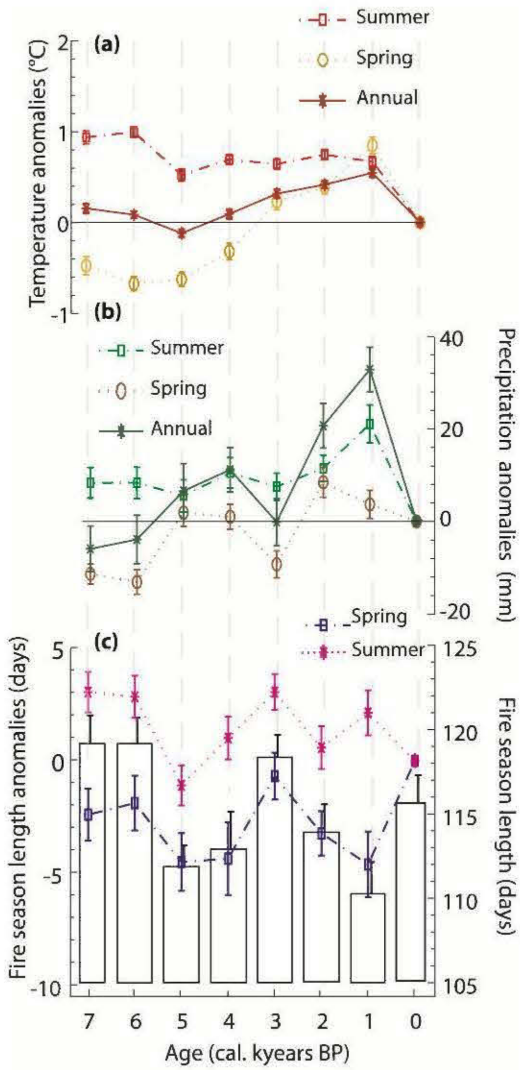

Figure 4.3 Simulated annual and seasonal temperature (a) and precipitation (b) with standard error, obtained from the UGAMP model (anomalies relative to 0 cal. years BP) for the area encompassing 70–80°W and 47–55°N. Fire season length with standard error (c) over the last 7000 years assessed on the basis of the number of days with simulated monthly means of daily Drought Code higher than 80 (bars, scale on the right hand side). The lines correspond to fire season length anomalies in spring and summer (scale on the left hand side).

4.6 Discussion

4.6.1 Climate forcing on fire occurences

RegFOs peaked in the Mid-Holocene (4000–3000 cal. years BP), subsequently decreasing during the late Holocene in all regions. Peatland fires in northern Quebec also have indicated a late-Holocene decrease in frequency (van Bellen et al. 2012). These trends match the regional simulated long-term decrease in FSL over the last 7000 years (Figure 4.3c). The decrease in FSL resulted from an increase in annual precipitation (Figure 4.2b) together with a decrease in summer insolation (Hély et al. 2010; Ali et al. 2012). This Holocene climate corresponds to the July mean temperature and total annual precipitation reconstructions from pollen data for northern Quebec (50–70°N, 65–80°W) published by Viau and Gajewski (2009).

Maximum RegFO occurred earlier in the northern region than in the southern region (4000 vs. 3000 cal. years BP) (Figure 4.2). Such a 1000-year time lag has already been observed between boreal mixedwood and coniferous forests (Carcaillet et al. 2001). It could be interpreted as earlier establishment of drought conditions in the north. However, no significant simulated climate change occurred at 4000 cal. years BP. Nevertheless, annual precipitation anomalies reconstructed from pollen data in northern Quebec (Viau & Gajewski 2009) suggest a period at 4000 cal. years BP that was drier than that exhibited in our simulations.

4.6.2 Variability in Holocene fire activity north and south of the northern limit of commercial forests

Over the last 7000 years, RegFO has been more variable north and near, than south of the northern limit of commercial forests. Higher variability in the northern region compared to the southern region underscores a greater sensitivity to climate. Moreover, whereas a gradual monotonous decrease in RegFO occurred between 3000 and 0 cal. years BP in the southern region, the shift towards lower RegFO was more rapid in the northern region, and it was followed by another shift to intermediate

RegFO ca. 2000 cal. years BP (Figure 4.2ab). These last modifications in fire occurrence were not related to a significant change in simulated climate (Figure 4.3), suggesting possible influence of other regional mechanisms. First, changes in the Pacific Decadal Oscillation and the mean position of the Arctic Front have previously been invoked as explanations for discrepancies in fire activity and tree-growth between the northern and southern regions in the last few centuries (Hofgaard, Tardif & Bergeron 1999; Le Goff et al. 2007). Although a decrease in fire activity in the southern region since ca. 3000 cal. years BP is likely to correspond to the Neoglacial period onset characterized by incursions of humid air masses from subtropical North Atlantic regions, northern sites could still be more strongly influenced by dry cold arctic air masses that favour fire ignition (Girardin et al. 2006). Second, changes in fire regimes could also lead to shifts in vegetation composition and structure, which could feedback on fire activity, thereby leading to a decrease in fire occurrence. Palynological investigations in the James Bay region, north of 53°N, indicated an opening of the forest cover since the late Holocene (Richard 1979; Asselin & Payette 2005). A possible explanation for this modification in forest structure could be the combined effect of higher fire occurrence and cooler climate, which would have inhibited post-fire regeneration (Payette et al. 1989). The inability of black spruce to regenerate under such environmental conditions could explain the transformation of some sites from spruce woodlands to lichen heath (Payette & Gagnon 1985; Asselin & Payette 2006). No such change in pollen-inferred vegetation history occurred in the southern studied region, where the forest cover seems more resilient to fire and climate changes than in the northern region (Carcaillet et al. 2001; Carcaillet et al. 2010).

4.6.3 Implications for the location of the northern limit of commercial forests

A scientific committee was created in 2005 by the Quebec Ministry of Natural Resources to reevaluate the location of the northern limit of commercial forests based on a more extensive survey of the territory (MRN 2013).

Simulations of future climate from GCMs with various forcing scenarios (Meehl et al. 2007) have indicated that a warmer climate is expected in the study area, with a mean summer temperature increase of 4°C between 1961–1999 and 2081–2100. The pattern of future summer precipitation is not as clear, with predicted increases and decreases (between -18% and +11%). All scenarios simulated an increase in spring precipitation, ranging from 8 to 41% (Bergeron et al. 2010). Climate change in the boreal zone of northeastern North America could thus trigger fire-weather conditions more favourable to forest fire in the summer but not necessarily in the spring (Le Goff, Flannigan & Bergeron 2009; Bergeron et al. 2010; Ali et al. 2012). A warmer climate would favour seed viability, leading to denser stands (Gamache & Payette 2005; Meunier, Sirois & Begin 2007). Nevertheless, seedling mortality is sensitive to episodic, prolonged and/or repeated drought (Moss & Hermanutz 2009) and forest recovery is slower during dry postfire years or on dry surface deposits (Mansuy et al. 2012). The CO_2 fertilization effect would increase plant productivity until a concentration threshold (Amthor 1995), wheareas the increased temperature effect on productivity is still debated (Way & Sage 2008; Girardin et al. 2012).

To determine if the current location of the northern limit of commercial forests could be sustained in the future under the ongoing climate change, we have presented the long-term natural variability of the fire regime, as it is increasingly used as a target to maintain resilience in managed forests (Landres, Morgan & Swanson 1999; Bergeron et al. 2002; Kuuluvainen 2002). The future mean fire interval inferred from the monthly drought code computed using GCM-scenario simulations is predicted to decrease from 500 to 222 years [95% confidence interval: 169, 313] by the end of the

21st century in the study area (Bergeron et al. 2010). This estimate lies within the natural range of variability of fire occurrence that has been recorded over the last 7000 years in all regions (Fig. 3.2d). However, higher fire occurrence in the northern region between 4000–3000 cal. years BP was followed by forest opening (Richard 1979; Arseneault & Sirois 2004; Asselin & Payette 2005), implying that northern forests are more sensitive to climate change and fire disturbance. Despite a potential global increase in productivity due to both CO_2 fertilization as well as warmer and longer growing season, landscape opening will likely continue in northern forests, even if future fire occurrence does not exceed the natural range of variability. Adding logging to fire could exacerbate the opening phenomenon (Payette & Delwaide 2003). To prevent jeopardizing ecosystem integrity, and thus the possibility of sustainable ecosystem management, the northern limit should remain in its current position. Moreover, the Holocene fire regime near the current limit was more comparable to that in the northern region than in the southern region, suggesting that mitigation strategies would be best targeted around 51°N, including lengthening of harvest rotations and increasing fire protection measures (Mansuy, Gauthier & Bergeron 2013). Although formal limits to commercial forestry might not exist elsewhere in the boreal zone, the transition from closed-crown forests to open woodlands is a circumboreal phenomenon (Payette, Eronen & Jasinski 2002). Fire history reconstructions along south–north gradients such as the present one could help determine the potential northern extent of forest harvesting activities in other boreal ecosystems.

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CHAPITRE V

CONCLUSION

L'objectif général de cette thèse était d'apporter des éléments d'aide à la décision dans le choix de la localisation de la limite nordique de la forêt commerciale dans un contexte de changements climatiques. Afin de mieux comprendre comment la forêt pourrait évoluer dans le futur face à une augmentation des feux, nous avons utilisé comme référentiel une reconstitution de l'historique des feux pendant les 7000 dernières années de part et d'autre de la limite nordique d'exploitation commerciale de la forêt boréale. Cette thèse montre cependant que les reconstitutions de l'historique des feux restent biaisées par plusieurs problèmes méthodologiques. Le premier volet de la thèse propose ainsi plusieurs recommandations afin d'améliorer l'analyse et l'interprétation des charbons de bois dans les séquences de sédiment pour reconstituer les paléofeux. La thèse s'est donc focalisée sur « comment mieux détecter et caractériser les pics de charbons de bois dans les séquences sédimentaires? » (Chapitre 2), et sur « comment distinguer les pics de charbons de bois formés par des feux locaux de ceux issus de feux régionaux? » (Chapitre 3).

Les analyses dendrochronologiques nous ont permis de distinguer l'occurrence de trois feux (1890, 1941 et 1989 AD) dans le bassin versant de deux petits lacs dont les séquences sédimentaires avaient été prélevées en mars 2011 (Chapitre 2). L'objectif était de vérifier si ces mêmes feux étaient détectés dans les séries de charbons de bois en faisant varier deux paramètres de base du traitement statistique des séries de charbons de bois. En effet, les reconstitutions sont fortement influencées par les choix de l'analyste (Carcaillet et al. 2001; Genries et al. 2012), souvent seulement guidés par la maximisation du rapport signal-sur-bruit (SNI). Les résultats ont montré que les feux récents étaient davantage détectés lorsque la largeur de la fenêtre temporelle pour modéliser le bruit de fond était <300 ans. Cependant, en utilisant ces paramètres, les rapports signal-sur-bruit (SNI) étaient faibles et l'historique des feux à l'échelle de l'Holocène pouvait varier considérablement. L'utilisation d'une résolution temporelle correspondant à celle des dépôts récents (KB) pour interpoler la série de charbons de bois a permis de mieux détecter les feux récents. La tendance des historiques des feux à l'échelle de l'Holocène ne changeait pas par rapport à celle reconstituée avec une interpolation fondée sur la résolution médiane calculée sur toute la séquence. Cependant, la tendance pouvait changer si les taux de sédimentation (de résolution temporelle) variaient beaucoup le long des séquences. Afin de mieux assurer la reconstitution des feux récents, la fenêtre la plus courte pour modéliser le bruit de fond qui permet d'atteindre des SNI supérieurs à 3 devrait être sélectionnée plutôt que de chercher à atteindre des valeurs de SNI maximales.

Afin de mieux connaître les processus taphonomiques impliqués dans la dispersion des charbons de bois lors d'un feu, un réseau de trappes lacustres a été installé dans sept lacs en Jamésie pendant trois ans (Chapitre 3). La formation d'un pic de charbons de bois par un feu qui s'est produit à 32 km de notre réseau de trappes a été mise en évidence. Cette dispersion à longue distance peut être expliquée par la formation d'une haute colonne de convection accompagnée de vents forts (Peters et Higuera 2007). Ce phénomène dépend de l'intensité et de la taille du feu, sachant que la taille du feu responsable de ce pic de charbons (feu de Eastmain) était de plus de 500 000 ha. Un autre pic de charbons de bois a été observé dans un de nos sites d'étude suite à un feu qui s'est produit dans le bassin versant du lac. Le pic de charbons de bois formé par ce feu local était à son maximum la première année après feu, soulignant l'importance du ruissellement dans la formation des pics de charbons de bois. Des régressions linéaires développées sur les distributions des tailles des charbons de bois ont mis en évidence une pente plus abrupte pour le feu régional (-1,88) comparé au feu local (-0,9) soulignant qu'un pic de charbons formé par un feu local est composé d'une plus grande proportion de gros charbons. La pente de ces régressions a été aussi calculée dans les assemblages de charbons contribuant aux feux locaux identifiés autour de deux lacs par la dendrochronologie (cf. chapitre 2). Dans un des deux lacs, la pente était supérieure à -0,9 mais dans le deuxième la pente médiane était égale à -1,77, mettant en évidence une variabilité dans la présence de gros charbons lors d'un feu local. Nous avons ensuite utilisé ces valeurs comme seuil afin de distinguer les pics de charbons produits par un feu local de ceux produits par un feu régional. Nous avons ainsi calculé les pentes de chacun des échantillons fossiles qui ont contribué aux événements de feu détectés au cours des 7000 dernières années autour de ces deux lacs. Nous avons par la suite effectué un filtrage avec trois valeurs seuils (-1.88, -1.77 et -0.9). Cette approche permet d'affiner les reconstitutions des feux qui se sont réellement produits dans les bassins versants. Nos résultats font écho à d'autres travaux du même genre réalisés dans d'autres écosystèmes boréaux et suggèrent que le seuil (pente) pour identifier des feux locaux en zone boréale par l'étude de la distribution des tailles des charbons de bois serait entre -1,77 et -1,88.

Finalement, la deuxième partie de cette thèse offre une meilleure compréhension de la dynamique de la forêt boréale à sa limite nordique d'exploitation commerciale (Chapitre 4). Peu d'études paléoenvironnementales ont été réalisées dans cette région (Arseneault et Sirois 2004; Gajewski et Garralla 1992; Magnan 2009; Richard 1979) et une grande partie de ces études concernait la paléohydrologie (Beaulieu-Audy et al. 2009; Brosseau 2008; Loisel et Garneau 2010) ou ne remontaient que quelques siècles en arrière (Lavoie et Sirois 1998; Le Goff et al. 2009). Six lacs positionnés selon un gradient sud-nord en Jamésie ont ainsi été sélectionnés afin de reconstituer l'historique des feux sur une plus longue période (les 7000 dernières années). Leurs historiques de feux ont été comparés à ceux de plusieurs lacs positionnés plus au sud, dans la forêt commerciale. Les épisodes de sécheresse ont aussi été modélisés, afin de mettre en évidence une trajectoire écologique potentielle de la forêt boréale au regard des données paléoclimatiques. Les résultats montrent une augmentation des occurrences de feu dans le nord et le sud à partir de 7000 avant nos jours pour atteindre un maximum entre 4000 et 3000 ans avant nos jours, et de diminuer ensuite. Cette tendance correspond aux changements climatiques simulés, caractérisés par des conditions plus chaudes et sèches entre 7000 et 3500 avant nos jours et plus froides et humides par la suite. Une diminution abrupte de l'occurrence des feux a été observée dans les régions près et au nord de la limite 3000 ans avant nos jours, alors qu'elle a été plus graduelle dans le sud. Les données palynologiques au-delà du 53^{e} parallèle Nord mettent en évidence une ouverture du milieu à partir de 3000 ans avant nos jours (Asselin et Payette 2005; Richard 1979). Une fréquence de feu élevée aux alentours de 3000 ans avant nos jours, associée à un climat plus froid dans le nord auraient ainsi contribué à cette ouverture du milieu, qui en retour aurait agi négativement par une diminution abrupte sur la fréquence de feu. Ainsi, le climat et la végétation auraient influencé la fréquence des feux au Nord alors qu'au Sud la forêt semble plus résiliente (Carcaillet et al. 2001; Carcaillet et al. 2010) avec une diminution progressive de la fréquence des feux au cours des 3000 dernières années.

Les occurrences de feu régionales présentées au chapitre 4 ne tiennent pas compte des recommandations faites aux chapitres 2 et 3 puisque, dans les faits, le chapitre 4 a été réalisé en premier. Les occurrences de feu régionales ont été recalculées en fonction des recommandations faites aux chapitres 2 et 3 (Figure 5.1). Les tendances sont les mêmes que celles présentées au chapitre 4, soulignant la cohérence de notre précédente interprétation.

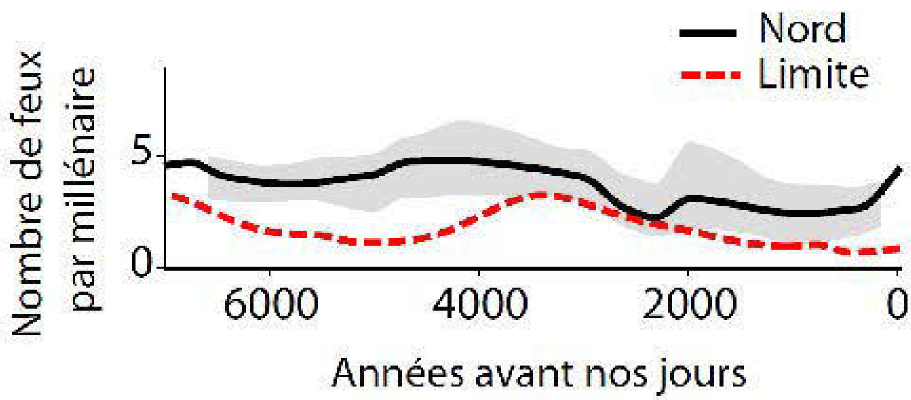


Figure 5.1 Occurrences régionales de feux de la région au nord (trait noir) et proche (trait pointillé rouge) de la limite nordique commerciale reconstituées à partir des dépôts de charbons dans les séquences sédimentaires selon les recommandations méthodologiques faites aux chapitres 2 et 3. Les occurrences régionales de feu représentent la moyenne des occurrences de feu locales (lacs Marie-Eve, Nano, Trèfle et Loup pour le nord et lacs Schön et Garot pour la limite) lissées à partir d'une fonction lowess avec une fenêtre de 500 ans. Les aires grises représentent les intervalles de confiance à 90% autour de la moyenne régionale au nord de la limite nordique de la forêt commerciale. La plus petite fenêtre (300 ans) atteignant une médiane de l'indice du signal sur bruit supérieure à 3,0 (SNI <3,0) a été utilisée pour modéliser le bruit de fond et une résolution d'interpolation des séries de charbons à 20 ans. Les pentes de distribution des tailles de charbons de bois ont par la suite été calculées afin d'épurer les fréquences de feu en utilisant une pente seuil de -1,77.

La position de la limite nordique de la forêt commerciale dépend majoritairement de deux critères : la productivité forestière et l'occurrence des feux, tous deux dépendant du climat. Plus la forêt est au nord, plus il fait froid, et plus la croissance des arbres est lente. De même, une fréquence de feux plus importante est observée, laissant place à la pessière à lichens au-delà du 52^e^ parallèle Nord. Cette transformation est principalement expliquée par l'intervalle de temps entre les feux. Avec un intervalle court, la pessière à mousses n'a pas le temps nécessaire pour atteindre la maturité et pour produire des graines avant le prochain feu (Brown et Johnstone 2012), dans la mesure où la production de graines commence habituellement à 30 ans (Viglas et al. 2013). De plus, la viabilité et la masse des graines dépendent fortement du climat, plus froid au nord (Lavoie et Sirois 1998; Liu et al. 2013; Meunier et al. 2007; Sirois et Payette 1991).

Les changements climatiques entrent alors en jeu et modifient les régimes de feux et la productivité forestière. Un climat plus chaud devrait augmenter la proportion de graines viables, menant ainsi à de peuplements plus denses (Meunier et al. 2007). Néanmoins, la mortalité des graines est plus grande lorsqu'elles sont exposées à des sécheresses épisodiques, prolongées ou répétées (Moss et Hermanutz 2009). La fertilisation par l'augmentation du CO_2 devrait augmenter la productivité des arbres jusqu'à un certain seuil (Amthor 1995). L'augmentation des températures devrait améliorer l'activité photosynthétique, et ainsi la productivité, mais les sécheresses en été peuvent annuler cet effet (Angert et al. 2005; Way et Sage 2008).

En Jamésie, les modèles de circulation planétaires utilisant différents scénarios de forçage des gaz à effet de serre ont permis de simuler une diminution de l'intervalle de temps entre les feux de 500 à 222 ans (intervalle de confiance à 95%: 169, 313) d'ici 2100 (Bergeron et al. 2010). Cet intervalle de temps est compris dans la gamme de variabilité naturelle au nord et près de la limite nordique de la forêt commerciale (chapitre 4). Cependant, ceci ne garantit pas que les forêts du nord seront résilientes face à l'augmentation de la fréquence des feux. En effet, sachant que l'ouverture du milieu s'est effectuée sous de hautes fréquences de feu, il est possible qu'une augmentation de la fréquence des feux contribuera à exacerber l'ouverture du milieu, même si l'augmentation des températures aura un effet positif sur la productivité/densité des forêts au nord. Cependant, il reste possible qu'une recrudescence en espèces feuillues se produise. En effet, l'augmentation des feux de forêts en Alaska ces dernières années a entraîné une augmentation de la proportion de peuplier faux-tremble (*Populus tremuloides*) dans le paysage (Johnstone et Chapin 2006). Sachant que les espèces feuillues représentent un combustible moins inflammable (Hély et al. 2000), la perte de résilience locale engendrerait une augmentation de la résilience des forêts au niveau du paysage (Johnstone et al. 2010; Terrier et al. 2013). Ce phénomène reste à prouver au Québec, où une augmentation des feuillus a surtout été observée après des coupes forestières (Laquerre et al. 2009) et où on observe généralement une augmentation du pin gris (*Pinus banksiana*) avec une diminution de l'intervalle de temps entre les feux dans les forêts du nord (Arseneault et Sirois 2004; Boiffin et Munson 2013; Lavoie et Sirois 1998) ou une ouverture du milieu (Boiffin et Munson 2013; Côté et al. 2013; Girard et al. 2008; Veilleux-Nolin et Payette 2012).

Rajouter des coupes forestières aux perturbations par le feu amplifierait le phénomène d'ouverture (Payette et Delwaide 2003) déjà observé depuis 50 ans (Boiffin et Munson 2013; Côté et al. 2013; Girard et al. 2008; Veilleux-Nolin et Payette 2012). Au-delà du risque pour l'intégrité écologique des massifs forestiers, exploiter les forêts au nord de la limite nordique de la forêt commerciale comprend des risques de pertes économiques. Les unités d'aménagement seraient alors dans des zones peu accessibles et éloignées des scieries. Il n'est pas sûr que de créer des routes afin d'accéder aux ressources puisse être rentabilisé (Bourgeois et al. 2005) dans une région à haut risque de feu. De plus, les forêts au nord restent celles qui présentent les grands massifs forestiers les moins fragmentés par les routes et constituent de bonnes occasions à la création d'aires protégées et à la conservation d'espèces à grand domaine vital (dont le caribou forestier *Rangifer tarandus*). Le Québec s'est engagé à porter le réseau d'aires protégées à 12% du territoire d'ici 2015, étant actuellement à 9,11% (MDDELCC 2014).

Il est ainsi conseillé de conserver la limite nordique des forêts commerciales à sa position actuelle. Enfin, certaines stratégies d'aménagement qui comprennent le haut risque de feu devraient être davantage utilisées dans les forêts près de la limite telles que l'allongement de la période entre les récoltes de bois. A des fins de prévention, planter des espèces feuillues pourrait permettre de diminuer la fréquence des feux (Hély et al. 2000; Terrier et al. 2013). Protéger ces forêts face aux feux semble une tâche difficile, puisqu'elles sont difficilement accessibles. De plus, l'accumulation de biomasse au cours du temps par la suppression des feux constitue une augmentation de combustible et peut contribuer à une augmentation de la sévérité des feux (Miller et al. 2009; Tilman et al. 2000). Les unités d'aménagement présentes dans des zones à haut risque de feu devraient pratiquer prioritairement des coupes de récupération par prélèvement de bois mort. Cependant, au moins 30% de la superficie brûlée depuis les cinq dernières années devrait être conservée dans une unité d'aménagement, afin de maintenir la diversité biologique présente dans ces forêts (Nappi et al. 2011). De plus, les échecs de régénération ont davantage lieu lorsque les feux sont peu sévères et qu'une épaisse couche de matière organique est laissée après feu (Veilleux-Nolin et Payette 2012). Dans de tels cas, une scarification du sol pendant les coupes de récupération permettrait d'assurer une meilleure régénération des forêts après les feux.

Cette thèse montre l'importance d'étudier l'historique des feux afin de mieux comprendre dans quelle variabilité naturelle de l'occurrence des feux les forêts ont évolué et comment elles pourraient évoluer face aux changements climatiques. Bien qu'une limite nordique de la forêt commerciale n'existe pas formellement ailleurs dans la zone boréale, une Entente sur la forêt boréale canadienne signée en 2010 cherche à mettre en œuvre les meilleures pratiques d'aménagement forestier durable (EFBC 2010). Cette entente a notamment permis la création de zones de restriction d'exploitation des forêts pour la conservation des espèces et de leur habitat, notamment pour le caribou forestier. Comme la transformation de la pessière en mousses en pessière à lichens est un phénomène circumboréal (Payette et al. 2002), d'autres études de ce genre pourraient aider à prendre des mesures en matière de changements climatiques en lien avec la conservation des forêts.

APPENDICE A

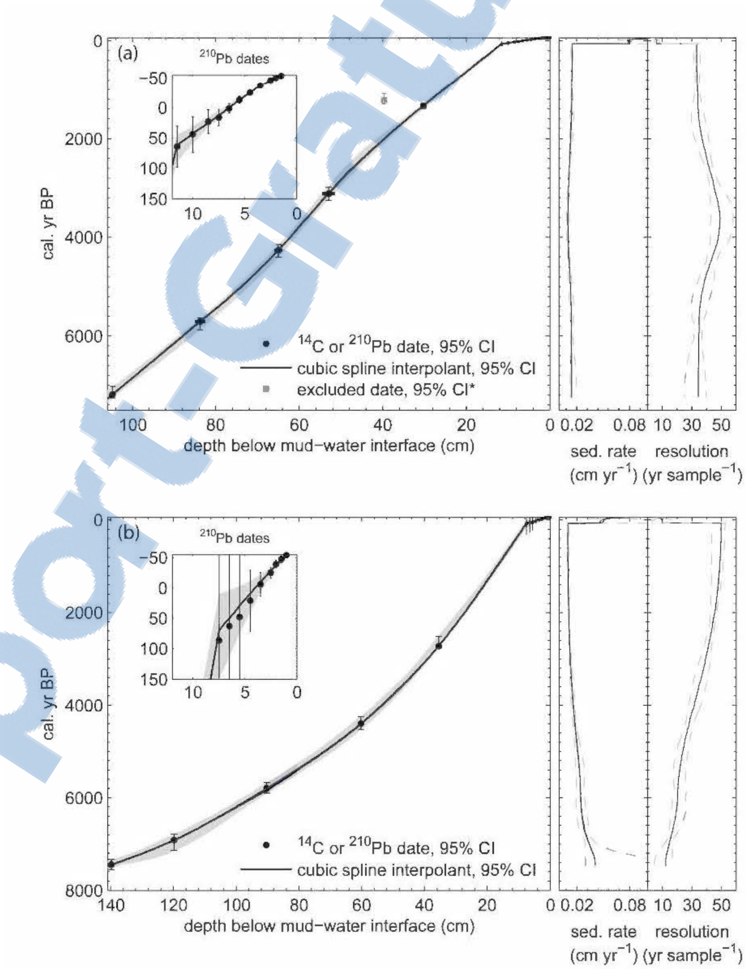
RADIOCARBON DATES OBTAINED FROM SEDIMENTS SAMPLED IN LAKES LNA AND LLP

Sample depth (cm)	Dated material	Sample number	^{14}C dates (years BP)
LLP			
30-30.5	Gyttja	Poz-44888	1430 ± 30
39.5-40*	Macroremains	Poz-44887	1290 ± 50
51.5-54.5	Macroremains	Poz-48072	2950 ± 40
64.5-65	Macroremains	Poz-44885	3845 ± 35
83.5-84	Macroremains	Poz-44884	4990 ± 35
104.5-105	Macroremains	Poz-44883	6250 ± 40
LNA			
35-35.5	Gyttja	Poz-44893	2575 ± 35
60-60.5	Gyttja	Poz-44892	3950 ± 50
90-90.5	Gyttja	Poz-44891	5025 ± 35
119.5-120	Macroremains	Poz-44890	6060 ± 50
139.5-140	Macroremains	Poz-44889	6530 ± 50

* Excluded from the age/depth model because of low carbon content

APPENDICE B

AGE-DEPTH MODEL, SEDIMENTATION RATE AND SAMPLE RESOLUTION FOR LAKES LNA (A) AND LLP (B)



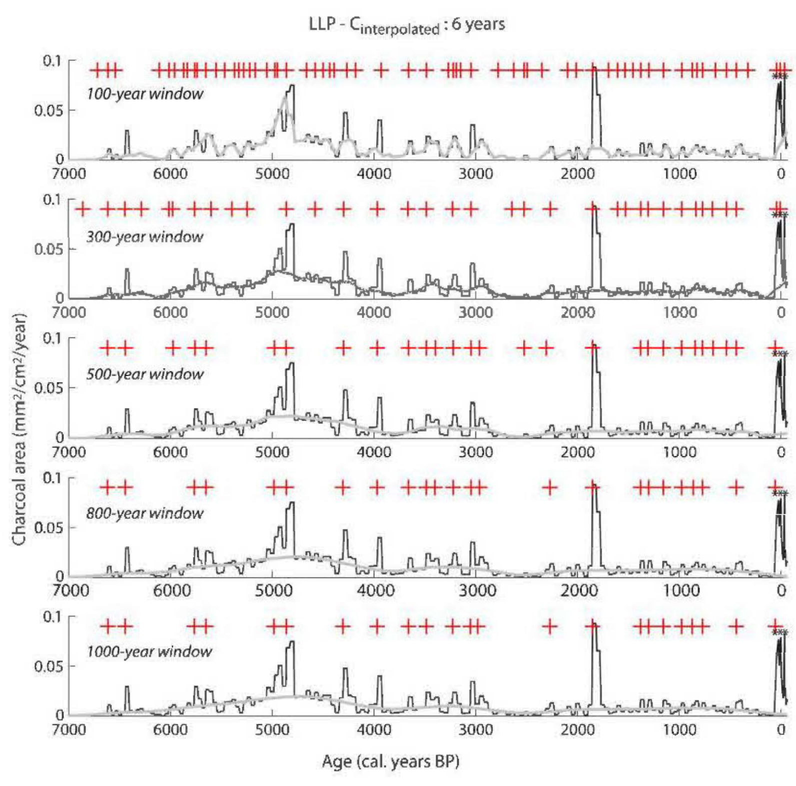
APPENDICE C

PARAMETIZATION IN CHARANALYSIS

Beginning of the record (cal. year BP)	Time-resolution to interpolate $CHAR_i$ series (years)	Transformation of the $CHAR_i$ series?	Estimation of $C_{background}$	Windows size to model $C_{background}$ (years)	Calculation of High-Frequencies in CHAR (C_{peak})	Determination of the noise distribution (C_{noise})
-61	Recent part	No	Lowess robust to outliers	100	residuals (C_{peak}= $C_{interpolated}$ - $C_{background}$)	99th percentile cutt-off of a noise distribution using a gaussian mixture model according to a locally defined threshold
	LLP 6			300		
End of the record	LNA 10			500		
	All sequence:			800		
LLP 7500	LLP 35			1000		
LNA 7500	LNA 22					

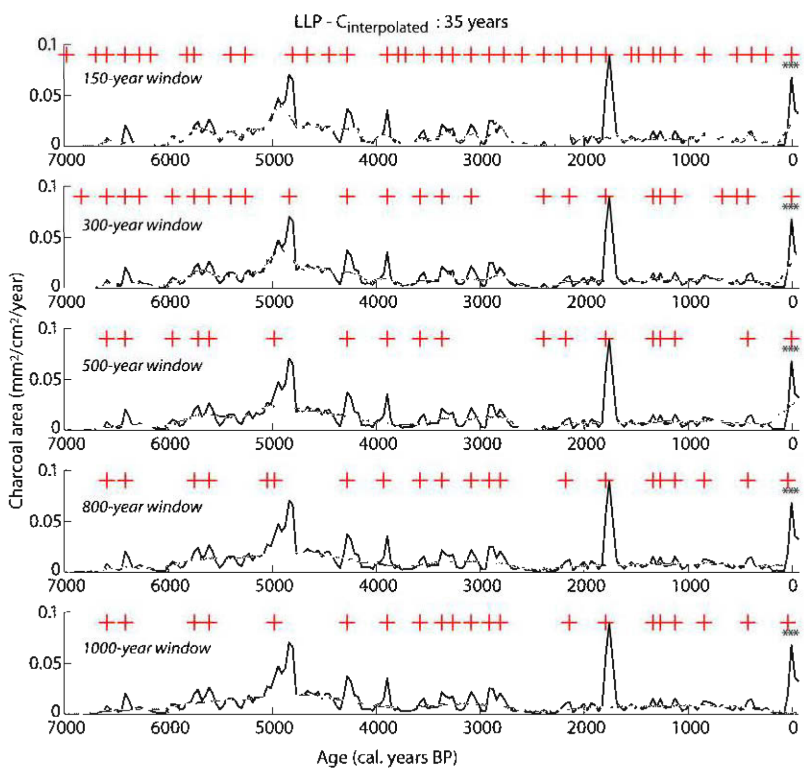
APPENDICE D

INTERPOLATED CHARCOAL ACCUMULATION RATES (*CHAR*$_I$; BLACK LINE), $C_{BACKGROUND}$ (GREY LINE) AND DETECTED FIRE EVENTS (+) ESTABLISHED USING CHARANALYSIS IN THE SEDIMENT DEPOSITS OF LLP SEDIMENT CORES ACCORDING TO FIVE MODEL RUNS. *CHAR* SERIES WAS INTERPOLATED WITH A CONSTANT STEP CORRESPONDING TO THE MEDIAN TIME-RESOLUTION PER SAMPLE OF THE RECENT SEDIMENTS (~ THE LAST 150 YEARS; 6 YEARS). LOW-FREQUENCY VARIATIONS ($C_{BACKGROUND}$) IN *CHAR*$_I$ WERE COMPUTED USING A ROBUST LOWESS REGRESSION WITH A 100, 300, 500, 800 AND 1000 YEARS WINDOW. FIRES (*) ESTABLISHED BY DENDROECOLOGY ARE ALSO SHOWN



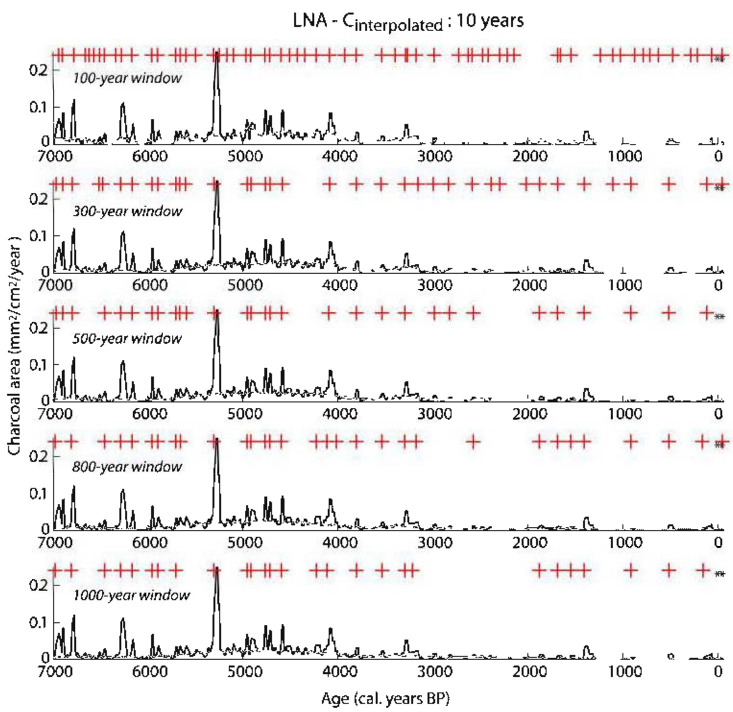
APPENDICE E

INTERPOLATED CHARCOAL ACCUMULATION RATES (*CHAR*$_I$; BLACK LINE), $C_{BACKGROUND}$ (GREY LINE) AND DETECTED FIRE EVENTS (+) ESTABLISHED USING CHARANALYSIS IN THE SEDIMENT DEPOSITS OF LLP SEDIMENT CORES ACCORDING TO FIVE MODEL RUNS. CHAR SERIES WAS INTERPOLATED WITH A CONSTANT STEP CORRESPONDING TO THE MEDIAN TIME-RESOLUTION PER SAMPLE OF TOTAL SEQUENCE LENGTH (~ 7000 YEARS; 35 YEARS). LOW-FREQUENCY VARIATIONS ($C_{BACKGROUND}$) IN *CHAR*$_I$ WERE COMPUTED USING A ROBUST LOWESS REGRESSION WITH A 150, 300, 500, 800 AND 1000 YEARS WINDOW. FIRES (*) ESTABLISHED BY DENDROECOLOGY ARE ALSO SHOWN



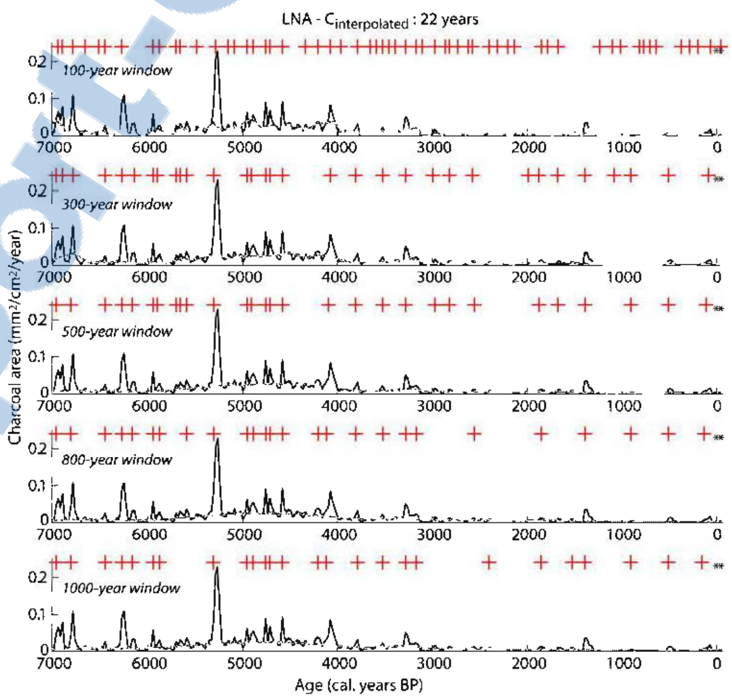
APPENDICE F

INTERPOLATED CHARCOAL ACCUMULATION RATES (*CHAR*$_I$; BLACK LINE), $C_{BACKGROUND}$ (GREY LINE) AND DETECTED FIRE EVENTS (+) ESTABLISHED USING CHARANALYSIS IN THE SEDIMENT DEPOSITS OF LNA SEDIMENT CORES ACCORDING TO FIVE MODEL RUNS. *CHAR* SERIES WAS INTERPOLATED WITH A CONSTANT STEP CORRESPONDING TO THE MEDIAN TIME-RESOLUTION PER SAMPLE OF THE RECENT SEDIMENTS (~ THE LAST 150 YEARS; 10 YEARS). LOW-FREQUENCY VARIATIONS ($C_{BACKGROUND}$) IN *CHAR*$_I$ WERE COMPUTED USING A ROBUST LOWESS REGRESSION WITH A 100, 300, 500, 800 AND 1000 YEARS WINDOW. FIRES (*) ESTABLISHED BY DENDROECOLOGY ARE ALSO SHOWN



APPENDICE G

INTERPOLATED CHARCOAL ACCUMULATION RATES (*CHAR*$_I$; BLACK LINE), $C_{BACKGROUND}$ (GREY LINE) AND DETECTED FIRE EVENTS (+) ESTABLISHED USING CHARANALYSIS IN THE SEDIMENT DEPOSITS OF LLP SEDIMENT CORES ACCORDING TO FIVE MODEL RUNS. *CHAR* SERIES WAS INTERPOLATED WITH A CONSTANT STEP CORRESPONDING TO THE MEDIAN TIME-RESOLUTION PER SAMPLE OF TOTAL SEQUENCE LENGTH (~ 7000 YEARS; 22 YEARS). LOW-FREQUENCY VARIATIONS ($C_{BACKGROUND}$) IN *CHAR*$_I$ WERE COMPUTED USING A ROBUST LOWESS REGRESSION WITH A 100, 300, 500, 800 AND 1000 YEARS WINDOW. FIRES (*) ESTABLISHED BY DENDROECOLOGY ARE ALSO SHOWN



APPENDICE H

TWO-SAMPLES MW AND KS-TEST COMPARISONS OF MEDIAN FIRE-FREE INTERVALS (MFFIS) AND FIRE-FREE INTERVAL DISTRIBUTIONS, RESPECTIVELY FOR LLP AND LNA USING DIFFERENT SMOOTHING WINDOWS, UNDER MEDIAN TIME-RESOLUTION OF THE ENTIRE SEQUENCE LENGTH TO INTERPOLATE THE *CHAR* SERIES

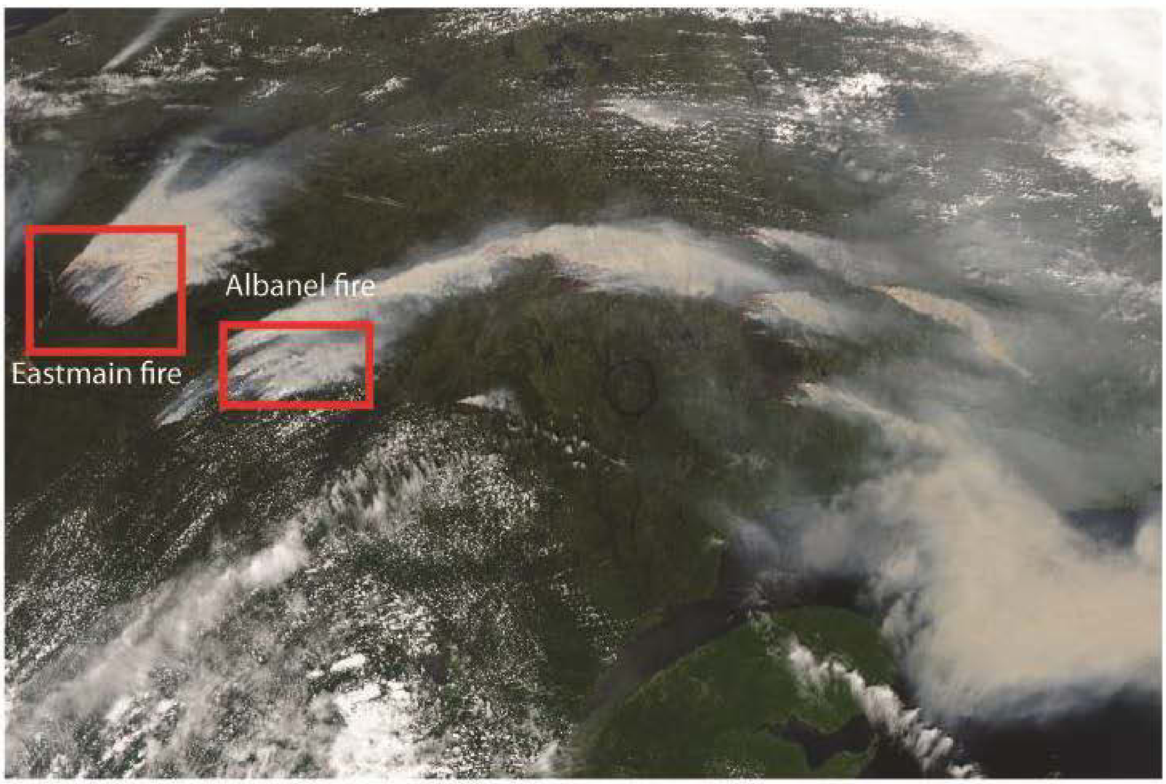
Smoothing window comparisons	MW-test	KS-test
LLP_{100}- LLP_{300}	0.0063	0.0154
LLP_{100}- LLP_{500}	0.0007	0.0035
LLP_{100}- LLP_{800}	0.0023	0.0056
LLP_{100}- LLP_{1000}	0.0031	0.0175
LLP_{300}- LLP_{500}	0.1879	0.4050
LLP_{300}- LLP_{800}	0.3556	0.5944
LLP_{300}- LLP_{1000}	0.4392	0.6931
LLP_{500}- LLP_{800}	0.6251	0.9993
LLP_{500}- LLP_{1000}	0.5870	0.9981
LLP_{800}- LLP_{1000}	1.0000	1.0000
LNA_{100}-LNA_{300}	0.0002	0.0001
LNA_{100}-LNA_{500}	0.0002	<0.0001
LNA_{100}-LNA_{800}	0.0001	0.0002
LNA_{100}-LNA_{1000}	0.0001	0.0008
LNA_{300}-LNA_{500}	0.7926	1.0000
LNA_{300}-LNA_{800}	0.4205	0.7336
LNA_{300}-LNA_{1000}	0.5377	0.4613
LNA_{500}-LNA_{800}	0.6099	0.9977
LNA_{500}-LNA_{1000}	0.7321	0.7675
LNA_{800}-LNA_{1000}	0.9150	1.0000

APPENDICE I

THE 2011 GAROT BURN

APPENDICE J

MODERATE RESOLUTION IMAGING SPECTRORADIOMETER (MODIS) PICTURES CAPTURED ON JULY 4, 2013, ON NASA'S AQUA SATELLITE OF WILDFIRES BURNING IN NORTHERN QUEBEC. THE IMAGE IS CENTERED AT 65° WEST LONGITUDE AND 55° NORTH LATITUDE [NASA, 2013]



APPENDICE K

MATERIAL AND METHODS FOR CHARCOAL DISPERSION AND DEPOSITION IN BOREAL LAKES FROM 3 YEARS OF MONITORING: DIFFERENCES BETWEEN LOCAL AND REGIONAL FIRES

Watershed area for each lake, Garot fire and 2013 fires:

We calculated watershed areas using Arcinfo v.10 (Spatial Analyst / Hydrologic Tool). We used the polygon shapefile of each lake and the Canada3D digital elevation model (DEM) produced by the Canadian Forest Service (http://geogratis.gc.ca) (Appendice L). The Garot fire reached the shore of Garot lake in July 2011 [MRN, 2012] (Appendice I). The very large 2013 forest fires had wide and high convectional plumes (Appendice J), but none reached any of the lake shores (Appendice M).

Recent fire history:

The western and northern parts of the Garot lake watershed experienced a 1684-ha fire in July 2011 [MRN, 2012] (Appendice I). Very large forest fires (>100 000 ha) that spanned several days occurred in June-July 2013 in the study area, but did not reach any of the study lakes' watersheds (Appendice J). The two largest fires (the Eastmain and Albanel fires) burned areas estimated at 583 260 ha and 312 381 ha. Wind direction during these wildfires was from the west. However, satellite images [unpublished, 2013] available from the University of Wisconsin-Madison [http://go.wisc.edu/9n3t19] showed evidences of winds also blowing from the northeast. The Canadian Wildland Information System has estimated a head fire intensity > 30,000 kW/m [Natural Resources Canada, 2013]. Satellite images [unpublished, 2013] available from NASA [http://earthobservatory.nasa.gov/] showed smoke drifting over Europe.

We also measured the shortest distance between lakeshores and edges of the 2010-2013 fires (Appendice N). By creating buffer zones around the lakes' centers using ArcInfo v.10, we calculated the area burned (ha) for zones delimited by eight different radii: 0-1,000 m; 0-5,000 m; 0-10,000 m; 0-15,000 m; 0-20,000 m; 0-40,000 m; 0-80,000 m and 0-100,000 m (Appendice O).

Sediment analysis :

Sediment sequences of Nano and Loup lakes were obtained in March 2011 using a modified Livingstone piston corer and a Kajak–Brinkhurst (KB) gravity corer. Their fire histories, reconstructed using the CharAnalysis program and macroscopic charcoal data, were previously published [Oris et al., 2014]. Dendrochronological data highlighted three recent local fires (1890, 1941 and 1989 AD) [Brossier et al., 2014]. Core chronologies were based on radiocarbon dating of terrestrial plant macroremains and bulk gyttja samples, and ^{210}Pb measurements. Age-depth models were obtained using the MCAgeDepth program, which applies a Monte Carlo resampling technique to assess median ages and to generate confidence intervals (CIs) around the fit, based on the probability distribution of each date (Appendice B).

For charcoal analysis, we removed a 1 cm^3 sub-sample from each 0.5 cm-thick slice of the sediment cores, and soaked it in a 3% $(NaPO_3)_6$ solution before wet-sieving through a 150 µm mesh [Whitlock and Larsen, 2002]. We identified and sorted charcoal particles under a stereomicroscope, and reported data as charcoal accumulation rates (CHAR, $mm^2/cm^2/year$) based on age-depth models.

Following recommendations provided in Brossier et al. [2014], CHAR series were interpolated to constant time steps ($C_{interpolated}$), corresponding to the median temporal resolution of the recent deposit (10 and 6 years for Nano and Loup lake, respectively) and we used a locally-weighted regression robust to outliers under a 300-year time window to produce the C_{back} series, representing background noise due to changes in charcoal production, transport, sedimentation, mixing, and sampling. We then obtained the C_{peak} series by subtracting C_{back} from $C_{interpolated}$. C_{peak} was decomposed into two subpopulations: C_{noise}, representing variability in sediment mixing, sampling, and analytical and naturally occurring noise, and C_{fire}, representing significant charcoal peaks assumed to result from local fires [Clark et al., 1996; Gavin et al., 2003; Higuera et al., 2010]. For each peak, we used a Gaussian mixture model to identify the C_{noise} distribution according to a locally-defined threshold. We considered the 99th percentile of the C_{noise} distribution as a possible threshold separating C_{peak} into “fire” and “non-fire” events.

We screened charcoal-area peaks as in Finsinger et al. [2014]. For each charcoal-area peak, we thus simulated 10,000 bootstrapped charcoal-area values with the same charcoal count but with different particle areas taken from a 900-year window around each peak. Significant charcoal-area peaks were then defined as those that had a charcoal area significantly higher than the *p*th percentile threshold of the bootstrapped values. To test the sensitivity of the area screening method, we used p=0.95 and p=0.90.

Linear regression on charcoal size distributions:

We computed linear regressions on charcoal size distributions as in Clark et al. [1998], Lynch et al. [2004] and Asselin and Payette [2005]. We transformed the area of each particles (mm^2 ; Appendice Q) in diameters (mm) by assuming diameter to be equal to the square root of particle surface area as determined by Clark and Hussey [1996]. We then log-transformed diameter as this transformation reduced the influence of outlying observations and allowed for a direct comparison with previous studies. Particle-size distributions were calculated for the sum of the three trap monitoring years, using classes ranging from -0.9 to 0.1 log mm (i.e., every 0.2 log mm). The same procedure was used on samples from Loup and Nano lakes' sedimentary charcoal records identified as local fire events with CharAnalysis (Appendice R). We did not analyze samples with less than three size classes and less than 10 charcoal particles in their macroscopic charcoal distribution. We screened fire events detected by CharAnalysis using three different slope thresholds: (1) the slope from the Garot lake charcoal trap data (-0.9) representing a local fire; (2) the median slope from samples corresponding to one of the two local fires identified by dendrochronological analysis at Loup lake (-1.77; median slope of samples from 8.5 to 10 cm); and (3) the slope from the Nano lake charcoal trap data (-1.88) representing a regional fire. A peak was identified as a “true” local fire if the slope was less steep than the threshold in one of the samples which contribute to the charcoal peak.

We compared fire histories obtained from all methods by calculating fire return intervals (FRI) (Appendice S). By screening the charcoal peaks, the median FRI increases over the Holocene. The difference was greater with the -0.9 slope screening test and both area screening tests.

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APPENDICE L

CHARACTERISTICS OF THE STUDIED LAKES: LATITUDE, LONGITUDE, ELEVATION, LAKE AREA (HA), WATER DEPTH (M), WATERSHED AREA (HA), SLOPE, AND DATE OF THE LAST LOCAL FIRE.

Name	Latitude	Longitude	Elevation (m a.s.l.)	Area (ha)	Water depth (m)	Slope	Watershed area (ha)	Date of the last local fire
Pessière	49°30'11.5" N	79°14'22.2" W	305	4.0	16.0	flat	56.02	<1924
Schön	50°35'41.7" N	77°34'06.1" W	291	2.8	7.0	flat	54.70	1997
Garot	51°05'58.7" N	77°33'12.9" W	248	5.1	6.9	flat	108.23	2011
Walt	51°51'06.5" N	76°02'33.4" W	288	2.2	4.5	flat	53.20	1996
Dave	52°03'42.1" N	76°09'08.2" W	294	5.9	7.5	Moderate	105.92	1995
Nano	53°01'25.5" N	77°21'51.3" W	206	0.4	3.2	flat	51.84	1989
Loup	53°03'18.1" N	77°24'01.9" W	206	1.6	3.0	flat	51.81	1989

APPENDICE M

YEAR OF THE GAROT, EASTMAIN AND ALBANEL FIRES, AREA BURNED (HA), AND SHORTEST DISTANCE (KM) AND ORIENTATION (NORTH, SOUTH, WEST, EAST) FROM THE STUDIED LAKES.

Name	Year	Area (ha)	Shortest distance (km) and orientation from lake						
			Pessière	Schön	Garot	Walt	Dave	Nano	Loup
Garot	2011	1684	208 NE	54 N	0 NW	133 W	142 W	209 S	212 S
Eastmain	2013	583 260	295 NE	153 N/NW	96 N/NW	57 W	44 W	32 S/SW	36 S/SW
Albanel	2013	312 381	236 NE	141 NE	124 E	24 SE	4 NW	178 SE	186 SE

APPENDICE N

DISTANCE TO THE CLOSEST FIRE FOR EACH OF THE STUDIED LAKES FOR YEARS 2010-2013, AND RELATIVE POSITION AND AREA BURNED.

Lake	Distance to the closest fire and its area burned and orientation from lake											
	2010			2011			2012			2013		
	Distance (km)	Relative position	Area burned (ha)	Distance (km)	Relative position	Area burned (ha)	Distance (km)	Relative position	Area burned (ha)	Distance (km)	Relative position	Area burned (ha)
Pessière	50	S	51.6	157	N	92	88	NE	366	236	NE	30427
Schön	66	SE	60	54	N	1684	76	NW	309	66	NE	30427
Garot	67	N	27881	0	N	1684	50	W	309	45	E	30427
Walt	40	NE	10647	49	NW	710	37	N	28	24	SE	312381
Dave	27	NW	271	28	NW	710	12	N	28	4	NW	2387
Nano	58	S	127	37	N	1325	66	SE	359	32	S/SE	583260
Loup	61	S	127	32	N	1325	70	SW	1154	36	S/SE	583260

APPENDICE O

AREA BURNED (HA) IN THE 2010 (A), 2011 (B), 2012 (C), AND 2013 (D) FIRES FOR RADII OF INCREASING WIDTH (KM) AROUND THE SEVEN STUDIED LAKES. DATA FOR LAKES THAT RECORDED A CHARCOAL SIGNAL ARE PRESENTED IN BOLD CHARACTERS.

a) 2010

Lake	Area burned in a radius of (km)							
	0-1	0-5	0-10	0-15	0-20	0-40	0-80	0-100
Pessière	0	0	0	0	0	0	52	52
Schön	0	0	0	0	0	0	60	96
Garot	0	0	0	0	0	0	8510	32153
Walt	0	0	0	0	0	569	20944	76951
Dave	0	0	0	0	0	449	22679	40010
Nano	0	0	0	0	0	0	1387	1427
Loup	0	0	0	0	0	0	1270	1427

b) 2011

Lake	Area burned in a radius of (km)							
	0-1	0-5	0-10	0-15	0-20	0-40	0-80	0-100
Pessière	0	0	0	0	0	0	0	0
Schön	0	0	0	0	0	0	1776	1776
Garot	**111**	**1196**	**1684**	1684	1684	1684	2518	2518
Walt	0	0	0	0	0	0	710	1452
Dave	0	0	0	0	0	710	710	1207
Nano	0	0	0	0	0	1312	1922	1922
Loup	0	0	0	0	0	1325	1922	1922

c) 2012

Lake	Area burned in a radius of (km)							
	0-1	0-5	0-10	0-15	0-20	0-40	0-80	0-100
Pessière	0	0	0	0	0	0	0	646

Schön	0	0	0	0	0	0	587	955
Garot	0	0	0	0	0	0	309	329
Walt	0	0	0	0	0	28	625	5958
Dave	0	0	0	28	28	28	707	1402
Nano	0	0	0	0	0	0	1513	2529
Loup	0	0	0	0	0	0	1513	2529

d) 2013

Lake	Area burned in a radius of (km)							
	0-1	0-5	0-10	0-15	0-20	0-40	0-80	0-100
Pessière	0	0	0	0	0	0	0	0
Schön	0	0	0	0	0	0	14390	27221
Garot	0	0	0	0	0	0	28869	474336
Walt	0	0	0	0	0	23615	220038	409634
Dave	0	261	2271	2387	2387	2387	215270	474335
Nano	0	0	0	0	0	**13612**	288457	470681
Loup	0	0	0	0	0	4213	261615	445195

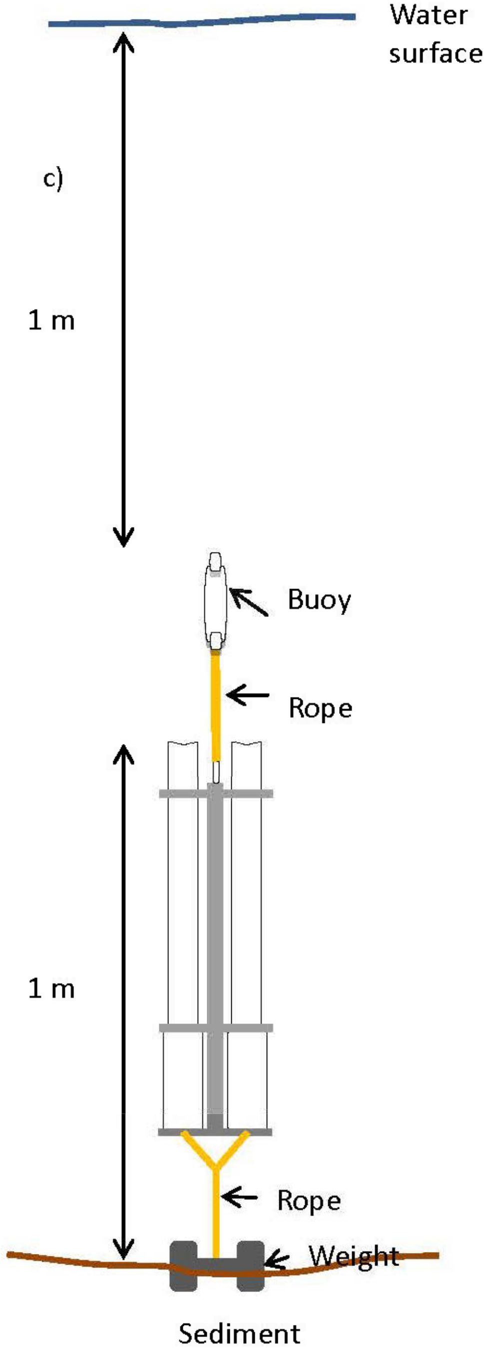
APPENDICE P

LACUSTRINE TRAPS (A-B) AND SCHEMATIC VIEW OF HOW THEY WERE INSTALLED IN THE LAKES (C).

a)

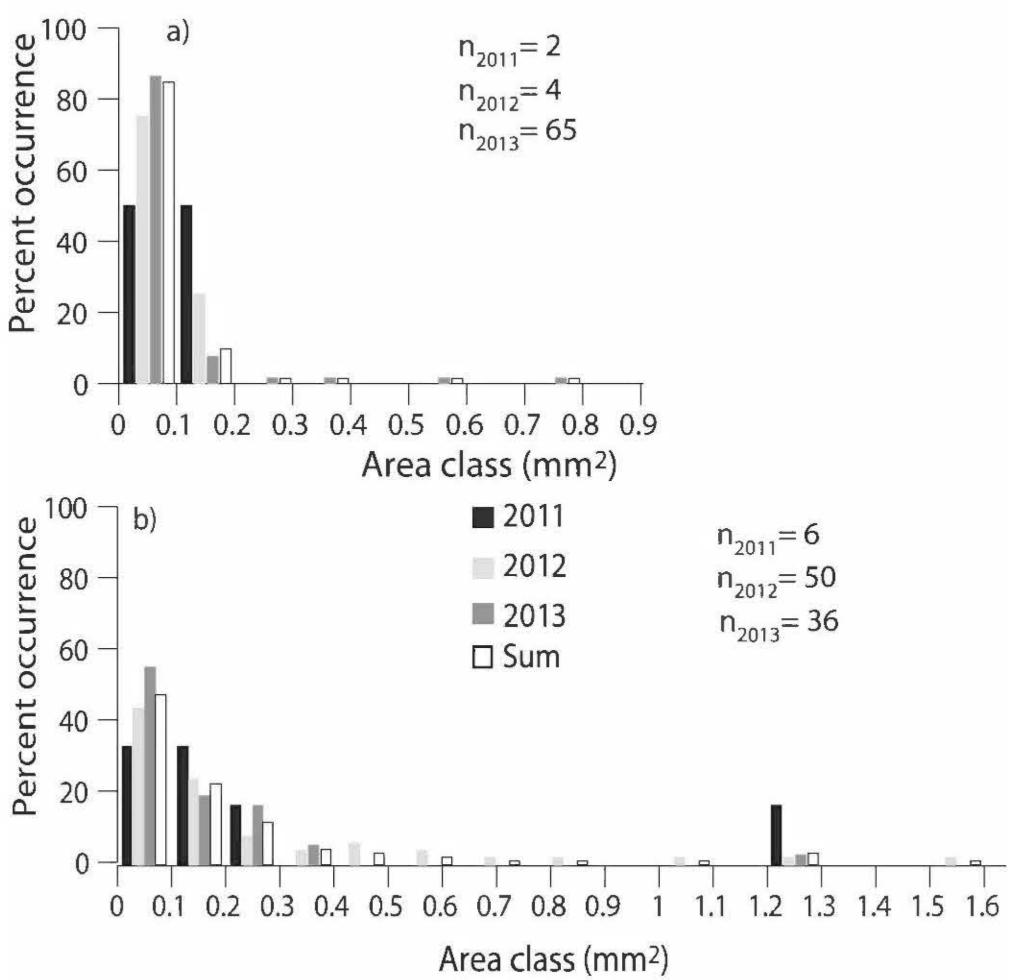
b)

c)



APPENDICE Q

SIZE DISTRIBUTION OF MACROSCOPIC CHARCOAL PARTICLES RETRIEVED FROM TRAPS IN NANO (A) AND GAROT (B) LAKES.



APPENDICE R

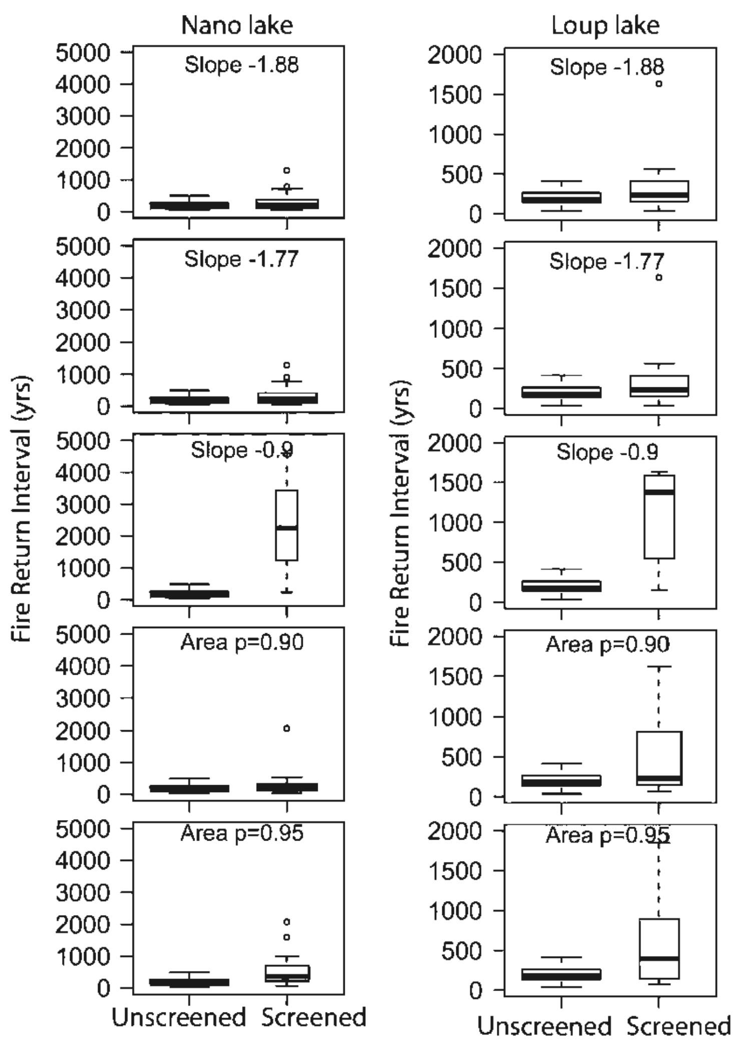
SLOPE AND R^2 VALUES OF THE LINEAR REGRESSIONS ON CHARCOAL SIZE DISTRIBUTIONS FOR SAMPLES OF NANO AND LOUP LAKE SEDIMENT SEQUENCES PREVIOUSLY IDENTIFIED AS PEAKS USING CHARANALYSIS.

Nano				Loup			
Depth (cm)	Age (cal. year BP)	Slope	R^2	Depth (cm)	Age (cal. year BP)	Slope	R^2
7.5	76	-0.452	0.600	6.5	0	-1.193	0.370
8	126	-1.193	0.978	7	6	-1.505	0.687
20	1319	-1.280	0.955	7.5	13	-1.613	0.995
20.5	1367	-1.551	0.984	8.5	25	-1.411	0.906
23.5	1654	-1.534	0.964	9	32	-1.613	0.995
25	1795	-2.698	0.996	9.5	38	-1.945	0.909
25.5	1842	-1.851	0.792	10	44	-1.945	0.632
27	1981	-2.500	0.986	16.5	396	-1.747	0.906
31.5	2384	-2.113	0.750	17	429	-1.065	0.473
33.5	2556	-0.991	0.961	18.5	529	-2.113	0.994
36.5	2804	-2.865	0.959	20.5	663	-1.193	0.978
37	2845	-2.603	0.944	22	764	-1.138	0.726
38.5	2964	-1.255	0.990	22.5	798	-1.945	0.983
41	3156	-1.692	0.929	27	1104	-1.017	0.510
42.5	3267	-1.952	0.950	27.5	1138	-0.638	0.150
43	3304	-1.970	0.991	29.5	1277	-0.682	0.571
46	3518	-1.467	0.973	36.5	1775	-1.971	0.954
46.5	3552	-1.945	0.488	37	1811	-0.753	0.212
50	3787	-1.460	0.822	56	3404	-2.785	0.993
50.5	3819	-2.785	0.998	56.5	3452	-0.312	0.750

54	4039	-2.468	0.981	58	3597	-2.603	0.944
54.5	4069	-2.108	0.907	61	3887	-2.373	0.916
55	4099	-2.667	0.995	61.5	3935	-1.065	0.473
63.5	4577	-1.039	0.945	64.5	4215	-1.667	0.928
66	4706	-0.671	0.632	65	4260	-2.065	0.944
67	4756	-1.687	0.959	68	4523	-3.253	0.952
69	4855	-1.280	0.886	68.5	4565	-2.252	0.983
69.5	4879	-2.032	0.928	71	4769	-1.289	0.748
70	4903	-2.040	0.851	71.5	4809	-0.411	0.133
70.5	4927	-2.113	0.875	72	4849	-0.526	0.357
71	4951	-1.418	0.999	77	5229	-1.703	0.947
77.5	5249	-1.811	0.933	78.5	5338	-1.595	0.827
78	5271	-2.654	0.922	79	5374	-1.318	0.987
78.5	5293	-2.215	0.975	81.5	5554	-2.698	0.939
79	5315	-2.519	0.900	82	5589	-1.500	0.980
85	5572	-1.505	0.977	83.5	5696	-1.360	0.750
85.5	5593	-1.221	0.884	84	5731	-1.602	0.840
86.5	5636	-1.248	0.893	87	5943	-2.113	0.809
87	5656	-2.082	0.981	87.5	5978	-1.363	0.571
88	5698	-0.954	0.467	93.5	6401	1.065	0.299
99	6153	-1.199	0.941	96	6577	-1.378	0.987
99.5	6174	-1.505	0.544				
101	6234	-1.204	0.737				
101.5	6254	-1.738	0.873				
102	6274	-1.893	0.917				
106.5	6450	-0.920	0.967				
107	6469	-2.603	0.944				
115.5	6776	-1.375	0.954				
116	6793	-1.448	0.693				
119	6891	-1.415	0.986				
119.5	6907	-1.193	0.750				
120	6922	-2.020	0.973				
120.5	6938	-1.678	0.999				
121	6953	-2.060	0.892				
121.5	6968	-0.631	0.936				
123.5	7027	-2.940	0.988				
128.5	7165	-0.440	0.997				

APPENDICE S

FIRE RETURN INTERVALS (FRI) FOR NANO AND LOUP LAKES ACCORDING TO DIFFERENT FIRE HISTORIES, WITH OR WITHOUT PEAK-SCREENING TESTS



APPENDICE T

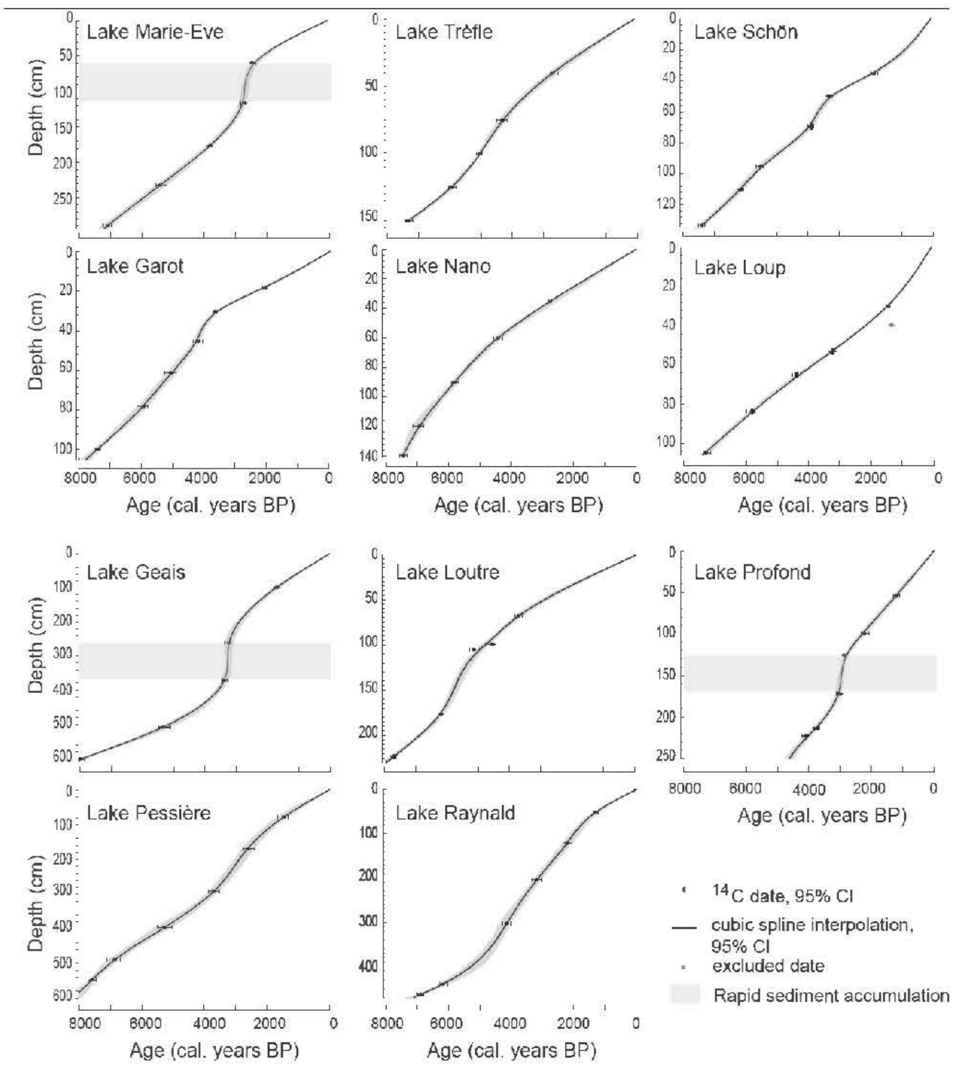
RADIOCARBON DATES FROM LAKE SEDIMENTS IN THE REGIONS NORTH AND CLOSE TO THE LIMIT

Sample depth (cm)	Sampled material	Labelling number	^{14}C date (years BP)	Calibration range (cal. years BP; Two sigma ranges)
Lake Loup				
30-30.5	Gyttja	Poz-44888	1430 ± 30	1290 - 1386
39.5-40*	Macroremains	Poz-44887	1290 ± 50	1121 - 1298
51.5-54.5	Macroremains	Poz-48072	2950 ± 40	2975 - 3247
64.5-65	Macroremains	Poz-44885	3845 ± 35	4153 - 4360
83.5-84	Macroremains	Poz-44884	4990 ± 35	5642 - 5761
104.5-105	Macroremains	Poz-44883	6250 ± 40	7151 - 7264
Lake Nano				
35-35.5	Gyttja	Poz-44893	2575 ± 35	2696 - 2761
60-60.5	Gyttja	Poz-44892	3950 ± 50	4245 - 4524
90-90.5	Gyttja	Poz-44891	5025 ± 35	5803 - 5892
119.5-120	Macroremains	Poz-44890	6060 ± 50	6777 - 7027
139.5-140	Macroremains	Poz-44889	6530 ± 50	7410 - 7514
Lake Marie-Eve				
59.5-60	Gyttja	Poz-44877	2330 ± 30	2309 - 2369
116-116.5	Gyttja	Poz-44875	2500 ± 30	2468 - 2730
176-176.5	Gyttja	Poz-44874	3440 ± 30	3631 - 3780
232-232.5	Gyttja	Poz-44873	4595 ± 35	5275 - 5331
289-289.5	Gyttja	Poz-45252	6110 ± 40	6890 - 7034
Lake Garot				
18-18.5	Gyttja	Poz-48071	2060 ± 30	1948 - 2118
30-30.5	Gyttja	Poz-44882	3390 ± 30	3562 - 3703

45-45.5	Gyttja	Poz-44881	3795 ± 35	4083 - 4295
61-61.5	Gyttja	Poz-44880	4445 ± 35	4956 - 5085
78-78.5	Gyttja	Poz-44879	5200 ± 50	5890 - 6031
99.5-100	Gyttja	Poz-44878	6510 ± 40	7323 - 7494
Lake Schön				
35-35.5	Gyttja	Poz-44899	1820 ± 30	1694 - 1825
49.5-50	Gyttja	Poz-44898	3010 ± 35	3136 - 3275
67-71.5	Macroremains	Poz-44897	3515 ± 35	3696 - 3881
95-95.5	Gyttja	Poz-44895	4675 ± 35	5315 - 5473
110-110.5	Gyttja	Poz-44894	5280 ± 40	5983 - 6183
133-133.5	Gyttja	Poz-48073	6370 ± 40	7247 - 7420
Lake Trèfle				
40-40.5	Gyttja	Poz-44904	2480 ± 35	2435 - 2718
75.5-76	Gyttja	Poz-44903	3790 ± 40	4075 - 4296
100-100.5	Gyttja	Poz-44902	4325 ± 35	4837 - 4972
125-125.5	Gyttja	Poz-44901	5040 ± 35	5710- 5901
150-150.5	Gyttja	Poz-44900	6280 ± 40	7156 - 7308

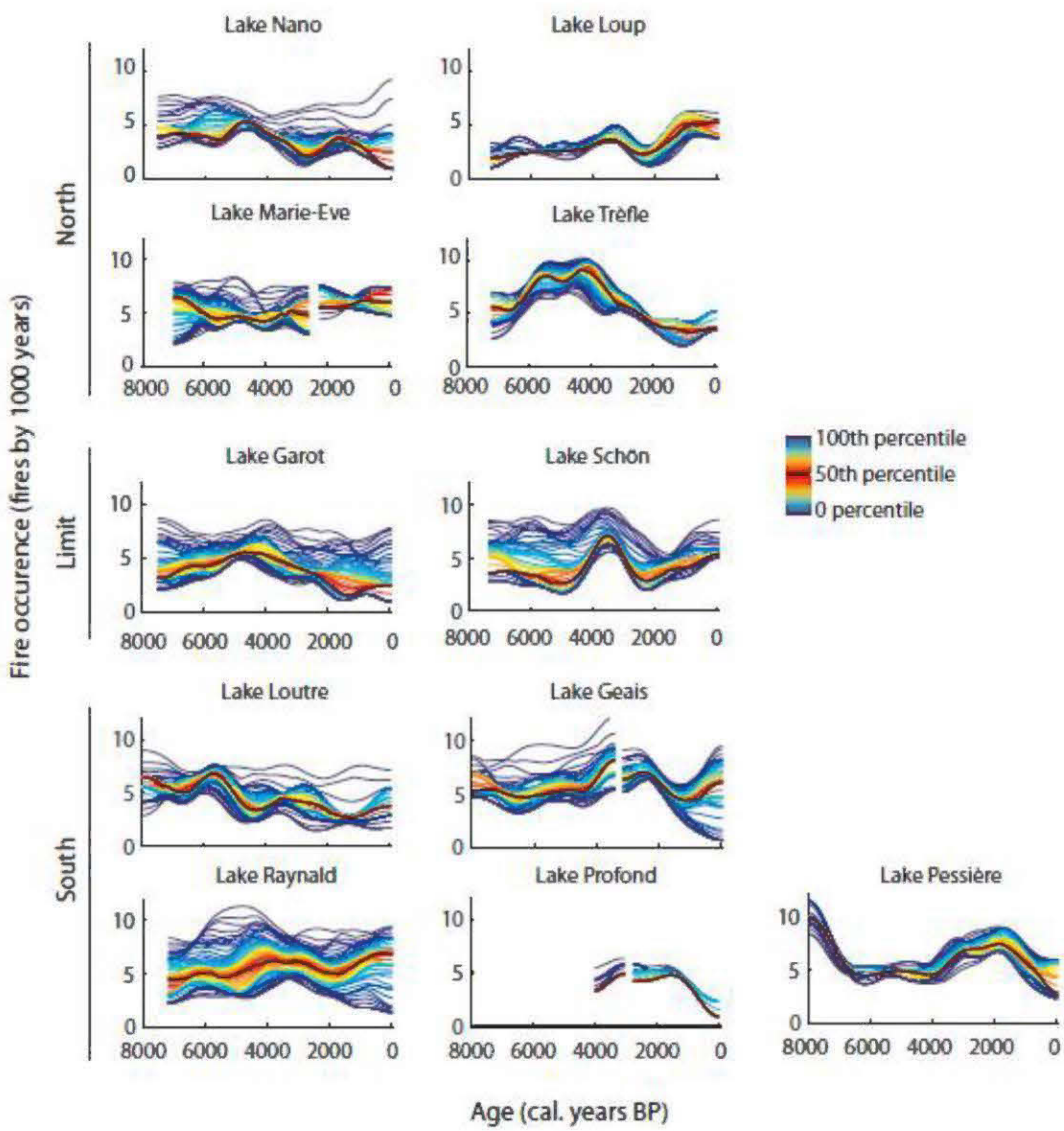
APPENDICE U

AGE-DEPTH MODELS OF THE SAMPLED LAKES



APPENDICE V

FIRE OCCURRENCE RECORDED IN THE SAMPLED LAKES



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