UNIVERSITÉ DU QUÉBEC À MONTRÉAL

EFFETS DE LA COMPOSITION FORESTIÈRE INITIALE ET DU TEMPS DEPUIS LE DERNIER FEU SUR LA DYNAMIQUE DES COMBUSTIBLES ET DU COMPORTEMENT DU FEU DANS LA PESSIÈRE À MOUSSE DE LA CEINTURE D'ARGILE DU QUÉBEC

MÉMOIRE
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ANCOVA – Analyse de la covariance

ANOVA - Analyse de la variance (Analysis of variance)

AREA - Aire brûlée (ha)

BUI - Buildup index

CFBPM - Canadian fire behavior prediction model

DC - Drought code

DMC - Duff moisture code

FBP - Fire behavior prediction system

FFMC - Fine fuel moisture code

FWI - Fire weather index

HFI - Head fire intensity (kW/m)

LFDB - Large fire database

MCPCI - Méthode canadienne de prédiction du comportement des incendies

PBA - Composition initiale débutant par le pin gris (*Pinus banksiana*)

PMA-N - Composition initiale débutant par l'épinette noire issue d'un feu non-sévère (*Picea mariana*)

PMA-S - Composition initiale débutant par l'épinette noire issue d'un feu sévère (*Picea mariana*)

PTR - Composition initiale débutant par le peuplier faux-tremble (*Populus tremuloides*)

ROS - Rate of spread (m/min.)

SA/V - Surface area to volume ratio (cm^{-1})

SOPFEU – Société de protection contre les incendies de forêt

TDF - Temps depuis feu (années)

TSF - Time since fire (years)

WAF - Wind adjustement factor

RÉSUMÉ GÉNÉRAL

Très peu d'études concernant la dynamique des combustibles dans la forêt boréale existent; et encore moins dans les peuplements à fort potentiel de paludification comme dans la pessière à mousse de la ceinture d'argile de l'est du Canada. L'objectif général de ce mémoire est donc d'étudier les interactions entre le TDF, les compositions initiales et plusieurs caractéristiques des combustibles, et de vérifier leurs effets potentiels sur le comportement des feux. Plus précisément, le chapitre 1 vise à comprendre comment s'accumulent et/ou s'arrangent les différentes catégories de combustibles selon le TDF et la composition initiale. De son côté, le chapitre 2 concerne l'analyse du comportement des feux potentiels reliés à ces combustibles avec deux logiciels de prévision des incendies forestiers (FBP - Fire Behavior Prediction et BehavePlus 5.0). Pour atteindre ces objectifs, nous avons inventorié les caractéristiques des combustibles dans 61 sites âgés de 11 à 356 ans et catégorisés dans 4 compositions initiales différentes étant dominées en début de succession par: 1) le peuplier faux-tremble (PTR), 2) le pin gris (PBA), 3) l'épinette issue d'un feu sévère (PMA-S) et issue d'un feu non sévère (PMA-N).

Dans le premier chapitre, il est démontré que la composition initiale a un effet important sur les caractéristiques des combustibles, alors que le TDF en a que très peu. Les plus grandes différences sont observées entre les chronoséquences de PTR et de PMA-N. En effet, contrairement à la composition initiale de PTR, celle de PMA-N tend à avoir une charge de matière morte au sol moindre, tout en ayant une meilleure continuité entre les différentes strates de combustibles. Nous montrons aussi, qu'à l'inverse de certains autres biomes forestiers, il y a peu d'accumulation de combustibles avec le TDF. Dans le deuxième chapitre, les résultats se rapportant au comportement du feu associés avec les valeurs de combustibles sont différents selon le modèle de comportement du feu utilisé. Étonnamment, dans les deux modèles, la composition initiale de PMA-N possède la plus grande vitesse de propagation. Dans FBP, l'intensité y était même maximale. De plus, les différences significatives au niveau de la charge en combustible entre les compositions initiales de PTR et des autres compositions initiales se sont traduites en comportements très différents dans les deux modèles.

Nos conclusions sont donc que la paludification a un effet indirect sur la dynamique des combustibles en pessière à mousse. Cet effet s'opère lors de la transformation de la composition des forêts avec le TDF, qui elle, a un effet direct sur plusieurs caractéristiques des combustibles. Néanmoins, nous soulignons le fait que les résultats portant sur le comportement du feu proviennent d'outils de prévision qui ne sont pas adaptés à la pessière à mousse en ceinture d'argile et qu'il serait important de les améliorer en implantant un nouveau module de prévision de la combustion lente au sol et/ou un nouveau type de combustible incorporant les modifications en structure des peuplements paludifiés pour le FBP.

INTRODUCTION GÉNÉRALE

PROBLÉMATIQUE

L'aménagement écosystémique est en processus de devenir la stratégie utilisée par la plupart des aménagistes forestiers pour faire un compromis entre la préservation de la biodiversité, le maintien de l'intégrité des écosystèmes forestiers, et l'exploitation régulière de la ressource pour l'industrie des bois et papiers. Le précepte général de cette stratégie d'aménagement est de réduire les différences entre les régimes de perturbations naturelles et de l'aménagement, en assumant que ces perturbations ont "préservé" la biodiversité pour une très longue période de temps. Dans la forêt boréale de l'Amérique du Nord, le feu est l'une des perturbations les plus importantes pour la régulation des dynamiques forestières (Johnson 1992). La compréhension des mécanismes du feu devient alors un élément clé pour atteindre un tel objectif.

Le régime de feu, défini par le patron global des fréquences, intensités, sévérités et dimensions de tous les feux sur la végétation, a des influences sur plusieurs attributs de la forêt. Par exemple, le feu peut amorcer des successions végétales importantes ou y mettre fin; contrôler la structure d'âges et la composition en espèces de la végétation; créer une mosaïque végétale à l'échelle du paysage et de la communauté végétale; modifier la distribution et la diversité des insectes et des maladies; influencer le cycle des nutriments, le coefficient d'humidité et le flux d'énergie; régulariser la productivité, la diversité et la stabilité des systèmes; déterminer la diversité des habitats fauniques; régulariser le type de biomasse (combustibles), sa distribution et sa charge (Gauthier, 2006). De plus, le feu est un important créateur de diversité, car son importante variabilité opère à plusieurs échelles, autant continentales, que locales (Keane *et al.* 2004).

Dans la forêt boréale, la majorité des feux de forêts sont des feux de grande envergure, très intenses et très sévères (mortalité des arbres) alors qu'un feu d'une superficie de 100 000 hectares est commun (Johnson 1992). Par exemple, durant la période entre 1980 et 1989, les grands feux (> 200 ha) représentaient 3% des feux survenus, mais 97% de l'aire brûlée au Canada (Stocks et al. 2003). Un régime des feux de cycle court (101 ans) et de forte intensité assurerait la pérennité de ces écosystèmes. Toutefois, depuis 1850 nous observons une importante baisse du cycle des feux dans plusieurs systèmes de la forêt boréale. Par exemple, dans la forêt de conifères, le cycle des feux est passé de 101 ans en 1850 à 398 ans depuis 1920 (Bergeron *et al.* 2004a). Cette différence est expliquée par une modification plutôt abrupte du climat depuis 1850 qui a engendré un climat plus humide, moins propice à l'allumage d'un feu naturel.

Avec le climat et la topographie, le combustible fait partie des paramètres importants de l'environnement du feu (Agee 1997). Les combustibles forestiers comprennent tous les matériaux organiques, vivants ou morts, qui se trouvent sur le sol forestier, jonchent les parterres de coupes ou qui composent toutes les strates des peuplements forestiers. Un combustible de qualité, de quantité et d'arrangement convenable est un pré requis nécessaire pour un feu de forêt (Brown et Davis 1973). Comme le combustible en forêt résulte des interactions entre la production de la biomasse et sa décomposition, la forêt boréale, avec une productivité faible et une décomposition lente, est susceptible à une accumulation du combustible tout au long de la succession (Schimmel & Granström 1997). Une meilleure compréhension des mécanismes d'accumulation ou de diminution de la charge, ainsi que des propriétés structurelles des combustibles est donc nécessaire pour bien comprendre les dynamiques structurelles et de productivité dans la forêt boréale, et donc, le comportement d'un feu de forêt potentiel.

Étonnamment, très peu d'études ont évalué les dynamiques d'accumulation du combustible au long de la succession dans la forêt boréale. Alors que certaines études se sont penchées sur la dynamique du bois mort (*e.g.* Freedman *et al.* 1996, Schimmel & Granström 1997, Hély *et al.* 2000, Harper *et al.* 2005, Ter-Mikaelian 2008), aucune étude à notre connaissance n'a décrit comment s'accumule, s'arrange, et se transforme le combustible en fonction du temps depuis le dernier feu (TDF) et des différentes compositions initiales dominantes après feu en forêt boréale résineuse, en considérant le comportement du feu potentiel s'y rattachant au fil du temps. Cette situation devient problématique non seulement en considérant le manque au niveau du savoir scientifique, mais aussi en évaluant notre capacité actuelle à prédire les incendies forestiers dans notre aire d'étude. En effet, les outils actuels de prévision du comportement du feu (Méthode canadienne de prévision du comportement des incendies - MCPCI, Forestry Canada Fire Danger Group 1992) dont disposent les autorités canadiennes en matière de feu de forêt (ex. Société de protection des forêts contre le feu - SOPFEU) ne permettent pas d'attribuer un type de combustible qui convient parfaitement à toutes les situations rencontrées sur le terrain. Par exemple, Pelletier *et al.* (2009) ont dû décrire environ 77% de l'aire totale qui aurait dû être décrite comme C2 ("épinette boréale"), en C-2a, décrit par les auteurs comme un type de combustible utilisé pour des sites qui ne respectaient ni la structure ni la densité d'un C2, mais qui s'en rapprochaient le plus, comparativement aux autres types de combustible. L'expérience du spécialiste entre alors en jeu afin de raffiner la prévision du comportement du feu en fonction de la situation, des autres données disponibles et de son expérience (Lavoie, N., *comm. pers.*). De plus, comme dans le cas de Pelletier *et al.* (2009), certaines configurations de combustible sont impossibles à reproduire dans la MCPCI.

ÉTAT DES CONNAISSANCES

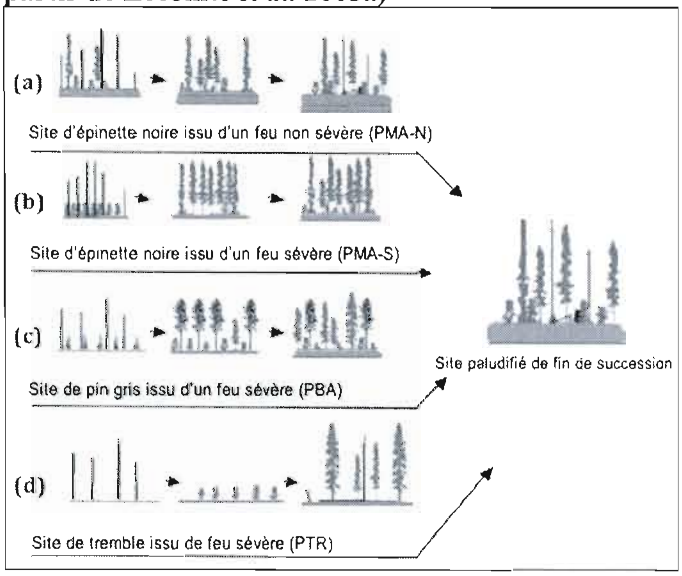
Compositions initiales possibles et sévérité du feu à l'origine des peuplements dans la pessière à mousse

Notre aire d'étude est située dans la pessière à mousse du Nord-Ouest du Québec et au Nord-est de l'Ontario. Les sites étudiés reposent sur la ceinture d'argile, une zone située à quelques 200 km au sud de la Baie James, où les sols sont composés presque exclusivement d'argile. Ces dépôts ont été laissés à la suite du retrait du lac pro-glaciaire Barlow-Ojibway il y a quelques 9000 ans vers la mer Tyrell (Veillette 1994). La majorité de notre aire d'étude est incorporée dans la ceinture d'argile qui possède un effet prédominant sur la végétation et les processus écologiques. Par exemple, outre les landes permanentes (Jasinski et Payette 2005), il existe trois grandes compositions initiales possibles dans la pessière à mousse de la ceinture d'argile. Après le passage d'un feu, les peuplements peuvent être dominés par de l'épinette noire (*Picea mariana*), du pin gris (*Pinus banksiana*) ou du peuplier faux-tremble (*Populus tremuloides*). Toutefois, en absence de feu sur une longue période, les compositions initiales possibles dans ces régions mènent toutes à des sites peuplés majoritairement par de l'épinette noire et à des sites paludifiés (Gauthier *et al.* 2000). Cette convergence successionelle est causée par l'accumulation de tourbe (*Sphagnum spp.*), qui agît comme une éponge, en retenant une grande quantité d'eau et donc, en augmentant le niveau de la nappe phréatique. Cette élévation du niveau de l'eau souterraine entraine alors une migration des racines des arbres de seconde cohorte du sol minéral plus riche, vers un sol organique peu fertile. Des pertes de productivité de 80% ont même été observées à certains endroits dès la 2e cohorte d'arbres (Simard *et al.* 2007). Avec le temps, seule l'épinette noire peut s'installer dans ce type de sol. L'entourbement crée alors une convergence des conditions de croissance des arbres et des attributs structuraux des sites, peu importe la composition initiale, ou la sévérité du dernier feu (Fenton *et al.* 2005).

Toutefois, plusieurs études (Lecomte 2005a, Lecomte et Bergeron 2005b, Lecomte *et al.* 2006a, Lecomte *et al.* 2006b, Simard *et al.* 2007, Bergeron *et al.* 2007) confirment que la sévérité (au niveau du sol) du dernier feu pourrait avoir un effet sur la vitesse à laquelle les changements causés par la paludification ont lieu. En effet, ces études démontrent qu'un feu sévère (qui brûle la quasi totalité de la matière organique au sol) permettrait l'exposition du sol minéral et favoriserait donc l'établissement d'espèces végétales requérant un sol plus productif (ex. peuplier faux-tremble). L'effet bénéfique du peuplier faux-tremble sur la productivité des sols a été démontré (Légaré 2005), alors qu'il permettrait de retarder l'établissement de certaines espèces du genre *Sphagnum spp.* responsables de l'élévation du niveau de la nappe phréatique, et donc, de retarder la paludification. À l'opposé, il a été observé que les peuplements issus de feux non sévères sont beaucoup plus hétérogènes dans la quantité de matière organique résiduelle après le passage d'un feu, que les sites issus de feux sévères qui brulent de façon égale une grande partie de la matière organique, ce qui crée une mosaïque de croissance à l'intérieur d'un même site (Lecomte *et al.* 2006b). Les feux non sévères diminuent la productivité en affectant le taux de croissance des arbres et le recrutement des jeunes pousses après le feu. Aussi, les sites issus de feux non sévères ont une voute ouverte laissant passer une grande quantité de lumière au sol, ce qui favorise l'établissement de plantes telles les éricacées (*i.e. Rhododendron Groenlandicum*) et les *Sphagnum spp.*, qui nuisent à la croissance des épinettes (Inderjit & Mallik 1996). Les feux non sévères diminuent donc la productivité en affectant le taux de croissance des arbres et le recrutement des jeunes pousses après le feu.

Lors de cette étude, nous tenterons de comparer les effets du TDF, les attributs des combustibles entre compositions initiales, et les comportements du feu potentiels s'y rattachant, entre quatre compositions initiales principales; soit, celles commençant par une dominance en 1) peuplier faux-tremble, 2) pin gris et 3) épinette noire, tous issues d'un feu ayant brulé la majorité de la matière organique au sol. De plus, vu les effets décrits plus haut, nous ajouterons une 4^{e} composition initiale en tenant compte de la distinction entre les sites dominés initialement par de l'épinette noire issus de feu non sévères (Figure 1).

Figure 1 - Compositions initiales possibles dans la pessière à mousse (modifié à partir de Lecomte *et al.* 2005a)



Dynamiques structurelles dans la ceinture d'argile

La dynamique de la biomasse forestière dans notre aire d'étude semble suivre le modèle du développement d'une forêt en 4 étapes d'Oliver (1981). Ce modèle est le plus familier et celui qui représente le plus adéquatement les réalités de la forêt boréale (Harper *et al.* 2005). Les 4 stades décrits par l'auteur sont: 1) l'initiation du peuplement par établissement de la régénération, où il y a une abondance de bois mort résultant de la dernière perturbation; 2) l'éclaircie naturelle lors duquel les arbres les moins compétitifs sont exclus et où la matière ligneuse morte est décomposée; 3) la réinitialisation d'une nouvelle cohorte d'arbres lorsque les vieux arbres de la première cohorte meurent et font place à des trouées où la lumière peut passer et se rendre au sol; et finalement, 4) l'état de vieille forêt, caractérisée par une grande diversité structurelle. Le temps de passage des stades de développement est toutefois dépendant de la productivité et de la composition du peuplement (Harper *et al.* 2005). Par exemple, il a été démontré (Harper *et al.* 2005) que dans la pessière à mousse, le stade d'initiation du peuplement est plus long lorsque les arbres poussent sur un sol organique à faible productivité que sur un site d'argile plus productif, d'où notre intérêt à faire une distinction entre les sites d'épinette noire issus d'un feu sévère et non sévère. Aussi, il est clair que les rythmes d'accumulation du combustible en forêt sont corrélés avec le remplacement des espèces, mais un lien peut aussi être établi avec le remplacement par cohortes de la même espèce (Johnson 1992). La compréhension des stades de développement de la forêt peut alors faciliter la prédiction des courbes d'accumulation du combustible.

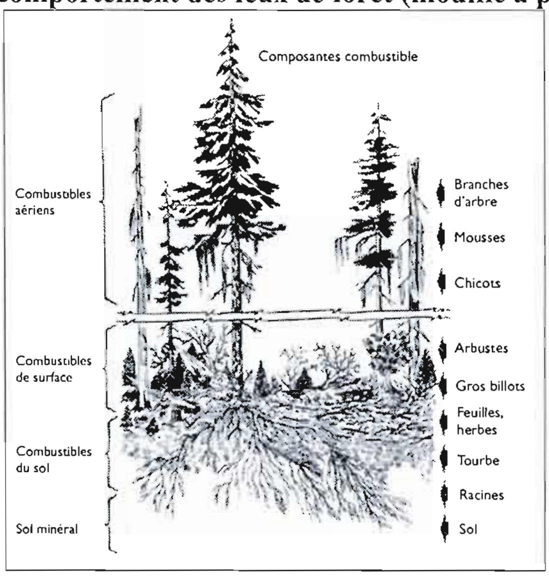
Comportement du feu

Propriétés des combustibles et effets sur le feu

Trois types de feux peuvent résulter de complexes de combustible différents : un feu de cime actif, de cime passif ou intermittent et un feu de surface. Les feux de cime actifs sont présents dans le cas où les combustibles dans la cîme des arbres sont suffisamment abondants pour permettre au feu de demeurer dans la partie aérienne des arbres. Dans le cas des feux de cime intermittents, le combustible présent dans la cime des arbres n'est pas assez dense pour soutenir le feu dans la partie aérienne des arbres, mais les combustibles étagés permettent au feu d'y grimper de façon intermittente. Finalement, pour les feux de surface, l'intensité du feu ne lui permet pas de grimper jusque dans la cime des arbres ou le combustible étagé est absent. Pyne *et al.* (1996) soulignent que la combustion de la matière végétale dépend de son contenu en eau; l'humidité du combustible serait donc le principal facteur régissant le type de feu résultant d'un certain complexe de combustible. Selon les auteurs, comme l'eau modifie l'inflammabilité des combustibles, le contenu en eau est fondamental dans la compréhension du comportement du feu. Le contenu en eau peut varier si le combustible est vivant ou mort. Par exemple, un combustible vivant possède des processus physiologiques travaillant pour activer ou retarder le gain ou la perte d'eau; chez les combustibles morts, la réponse est passive. Les combustibles vivants peuvent être ligneux (arbustes, arbres) ou non (herbacées, graminées), et chaque catégorie possède une structure cellulaire différente une fois le combustible mort, pouvant avoir un impact sur la facilité avec laquelle l'eau qu'elle contient peut être diffusée dans l'atmosphère. Aussi, la taille des combustibles peut avoir un impact important sur leur teneur en eau et leur vitesse de séchage. En effet, les petits morceaux de bois mort au sol réagissent plus rapidement aux variations d'humidité (Valette 1990); plus le combustible est petit, plus sa dessiccation est rapide (Johnson 1992).

Nous savons aussi que l'arrangement spatial des combustibles aura des impacts sur leur disponibilité pour le feu et sur son comportement au cours de l'incendie (McRae *et al.* 1979). Un complexe de combustibles peut contenir plusieurs couches (Figure 2). Les strates connues incluent les combustibles aériens (canopée, mousses sur les troncs, chicots), les combustibles de surface (arbustes, débris ligneux) et les combustibles au sol (la litière ou la tourbe, racines). Si les combustibles de surface sont en quantité suffisante, un feu pourra s'allumer et se propager horizontalement pour atteindre une intensité minimale nécessaire à la combustion des autres couches de combustible. Une autre façon qu'a le feu d'atteindre les strates de combustibles aériens peut aussi être par l'utilisation des combustibles étagés qui offrent une bonne continuité verticale. Ces combustibles permettent alors à un feu moins intense de rejoindre les strates plus élevées et se transformer en feu de cime. En résumé, les caractéristiques des combustibles ayant un impact sur le comportement du feu sont donc leur quantité (charge), leur configuration (compacité, densité, continuité, profondeur, ratio mort/vivant) et leur composition (la taille, la forme et la chimie). Il est aussi important de noter que les combustibles évoluent avec le TDF; généralement depuis la dernière grande perturbation, dans notre cas, le dernier feu. Les combustibles changent en charge, mais aussi en caractère, notamment: par la taille de leur particules, par leur statut de vivant à mort et par leur place dans le complexe des combustibles en changeant de strate (*i.e.* en passant de surface à aérien et de retour à surface). Néanmoins, peu d'études à ce jour ont visé à analyser les processus d'arrangement du combustible en pessière à mousse au fil du temps et les différences pouvant exister entre les complexes de combustible de peuplements composés d'espèces différentes, sur le comportement d'un incendie de forêt potentiel.

Figure 2 - Différentes catégories de combustibles ayant un impact sur le comportement des feux de forêt (modifié à partir de Pyne *et al.* 1996).



Mesures du comportement du feu

Les deux composantes primaires du comportement du feu sont la vitesse de propagation et l'intensité de l'incendie au front. La propagation d'un feu résulte d'une suite d'ignition de flammes par convection et par radiation (Johnson 1992). Lorsque modélisée, c'est la vitesse prévue d'un incendie au front ou à la tête d'un feu (en surface ou en cime), là où le feu progresse le plus rapidement. Elle est mesurée en mètre par minute (m/min.) et est basée sur le type de combustible, l'indice de propagation initiale, l'indice du combustible disponible ainsi que sur de nombreux paramètres spécifiques aux combustibles tels que l'état phénologique (aphylle ou vert) chez les feuillus, la hauteur à la base de la cime chez les conifères, ainsi que le taux d'humidité des herbacées. L'intensité de l'incendie au front est l'intensité prédite, ou la production d'énergie, d'un incendie au front ou à la tête d'un feu. Cet aspect est devenu un des indicateurs standard en vertu duquel les gestionnaires d'incendies de forêt estiment la difficulté de contrôler un incendie et choisissent des méthodes appropriées de suppression. Elle est mesurée en kilowatts par mètre (kW/m) et est modélisée en tenant compte de la vitesse de propagation ainsi que la combustion du combustible total. Il est important de comprendre qu'un feu très intense peut être issu d'un combustible moindre, mais avec une très haute vitesse de propagation et vice versa. Ces trois facteurs sont donc inter-reliés.

Pour vérifier que l'effet des différentes caractéristiques du combustible a un effet significatif sur le comportement d'un feu potentiel, il aurait été préférable de faire des brûlages expérimentaux tout en mesurant certains paramètres du combustible, de noter les effets sur le feu et de comparer avec nos résultats. Cependant au Québec, un moratoire sur l'utilisation du brûlage dirigé en milieu naturel nous empêchait d'utiliser une telle méthode, et en Ontario, où ces brûlages sont légaux, la météo était beaucoup trop humide pendant l'été où l'inventaire a eu lieu. L'utilisation de modèles de comportement du feu devint alors notre seule alternative. Ces logiciels permettent d'utiliser des données combustibles empiriques pour calculer les comportements théoriques d'un feu potentiel associés avec plusieurs scénarios de météo. Ils nous permettront aussi de vérifier l'impact des différentes caractéristiques des combustibles sur le comportement d'un feu de forêt potentiel, tout en analysant les effets des différentes compositions initiales et du TDF sur le comportement d'un feu potentiel.

Cette étude tentera donc de décrire la dynamique d'accumulation et d'arrangement de plusieurs catégories de combustibles, dans la pessière à mousse de la ceinture d'argile du nord-ouest du Québec pour remplir deux objectifs. Premièrement, aucune étude n'a déjà analysé les effets respectifs du TDF et des différentes compositions initiales possibles dans notre région sur les caractéristiques des combustibles. Nous comblerons ainsi un manque empirique. Le deuxième objectif sera d'utiliser les données combustibles récoltées et de les utiliser avec des modèles de prévision du comportement du feu pour vérifier si les différences observées entre les compositions initiales au niveau des caractéristiques des combustibles et en fonction du TDF, à l'intérieur d'une même composition, sont toujours significatives lorsqu'elles sont inclues dans les modèles de prévision du comportement des incendies. De façon générale, ces deux objectifs nous permettront peut-être de mieux comprendre les effets de la paludification sur le comportement du feu. Ultimement, ces observations pourraient renforcer le fait qu'un raffinement des outils canadiens pour la prédiction d'éventuels incendies situés dans la pessière à mousse de la ceinture d'argile du nord-ouest du Québec est nécessaire.

CHAPITRE I

EFFECTS OF INITIAL FOREST COMPOSITION AND TIME SINCE FIRE ON FUEL DYNAMICS IN THE BLACK SPRUCE FORESTS OF QUEBEC LOCATED ON THE CLAY BELT

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Contribution des auteurs:

Mathieu Paquette: Recherche, méthodes et protocole statistique, inventaire forestier, base de donnée, rédaction.
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RÉSUMÉ

Dans la forêt boréale, peu d'études ont porté sur la dynamique des combustibles en termes de qualité, de quantité et d'arrangement en fonction des différentes compositions initiales ou du temps depuis feu (TDF). Dans la pessière à mousse de la ceinture d'argile du Québec et de l'Ontario, lorsque le TDF est long, nous observons une convergence successionelle où les peuplements tendent tous à devenir des peuplements d'épinette noire ouverts et non productifs, peu importe la composition arborescente initiale. L'objectif principal de cet article est donc l'étude des effets de la composition initiale et du TDF sur plusieurs caractéristiques des combustibles forestiers. Nous avons inventorié ces caractéristiques dans une chronoséquence de 61 sites, âgés de 11 à 356 ans en les classant dans l'une des 4 compositions initiales possibles, soit lorsque dominée initialement par: le peuplier faux-tremble, le pin gris ou l'épinette noire, cette dernière chronoséquence étant subdivisée selon l'origine à la suite d'un feu sévère ou non au niveau du sol. L'ANCOVA a ensuite été utilisée pour tester l'effet de la composition initiale et du TDF sur les caractéristiques des combustibles. De façon générale, les chronoséquences d'épinette noire ont toujours une charge de matière ligneuse morte moindre, mais une meilleure continuité entre les différentes strates de combustible tandis que la composition initiale du peuplier a une charge plus élevée et une distance plus grande entre les différentes couches de combustible. Pour leur part, les compositions initiales d'épinette issue d'un feu sévère et du pin gris sont intermédiaires quant à leur charge en combustible et à la connectivité entre les différentes strates de combustibles. L'effet du temps depuis feu se manifeste dans les peuplements de pin gris, où nous assistons à une diminution significative de la charge de débris ligneux au cours du temps, tandis que pour certaines classe de débris on observe un augmentation légère au cours du temps dans les deux compositions initiale d'épinette noires. Au niveau de la continuité du combustible, les peuplements d'épinette affichent une meilleure connexion entre les différentes couches de combustible. Nous pensons donc qu'il y a une grande différence entre les compositions initiales au niveau du combustible mais un léger effet du temps.

Mots clés: *combustible, chronoséquence, composition, temps depuis feu, paludification*

ABSTRACT

In the boreal forest of Canada, few studies have examined the links between the modification of the forest structure with time since fire (TSF), initial composition, and fuel. In the black spruce-feathermoss domain of northwestern Quebec, when the TSF is long, we observe a successional convergence transforming every type of stand in low density and low productivity black spruce stands. The main objective of this study is then to understand the effects of initial compositions and TSF on fuel characteristics. To achieve this goal, we inventoried 61 plots and categorized them in a chronosequence of stands aged between 11 and 356 years old and within 4 different initial compositions based upon initial composition (aspen, jack pine, black spruce from a non-severe fire and black spruce from a severe fire). ANCOVAs were then performed to understand the effect of TSF and initial compositions on fuel characteristics. In general, the two black spruce chronosequences always have a lower DWD load but a better connectivity of fuel layers, while trembling aspen stands have a higher load, with less connectivity. The effect of time since fire is noticeable in Jack pine stands, where we see a significant decrease of the downed woody debris load with time, while in both black spruce chronosequences some downed woody debris diameter classes will increase very lightly. Therefore, we think there is a strong difference between initial compositions with a slight effect of time since fire.

Keywords: *Fuel accumulation, initial composition, time since fire, chronosequence, paludification*

INTRODUCTION

Wildfires are recognized as one of the major natural disturbances that shape boreal forests over large regions in terms of stand composition, age, and spatial distribution (Johnson 1992, Shugart *et al.* 1992). Fuel is, with weather and topography, one of the most important factors influencing forest fire behavior (Countryman 1972, Agee 1997). Forest fuels can be described as all the organic material, live or dead, available to burn or not, lying on the forest floor, covering harvested or natural landscapes and composing stand layers, that can propagate a fire. A fuel composition of quality (*e.g.* continuity between fuel layers, fuel moisture, compactness, mixture of dead and live, arrangement and size of fuel particles) and quantity (loads of different fuel layers) is a pre requisite necessary for a forest fire ignition and propagation (Schimmel and Granström 1997).

The idea of fuel accumulation was first described for *Pinus ponderosa* ecosystems in the interior West of the United States (Brown 1983, Johnson & Miyanishi 2001). In this region, during most of the 20th century, the policy of total fire exclusion has created a situation where dead fuels can accumulate with time since fire (TSF). However, in the boreal forest, very few studies have examined dead fuel dynamics. Although some studies have looked at coarse woody debris (CWD, >7.6 cm in diameter) characteristics and accumulation in boreal ecosystems (e.g. Clark *et al.* 1998, Hély *et al.* 2000, Chojnacky and Heath 2002, Ferguson and Archibald 2002, Harper *et al.* 2005, Ter-Mikaelian *et al.* 2008), most of them have neglected the fine fuel component. Rather, the central objective of these studies was to describe, in different regions (sub-boreal spruce forest of west-central British Columbia, Quebec mixedwood boreal, Ontario coniferous-boreal, Quebec western black spruce forest), the pattern of CWD accumulation with TSF. However, in the Black spruce (*Picea mariana*) – Feathermoss domain of the northwestern Quebec clay belt, only few studies have looked at this aspect (Brais *et al.* 2005, Harper *et al.* 2005), and none about fuel dynamics as a whole, including finer DWD (downed woody debris) and other fuel layers. Fine fuel, as defined by *Pyne et al.* (1996), is composed of dead grass, needles and small twigs up to 7.6 cm in diameter. The interest for the fine fuel component lies in the fact that it is believed to be the fuel category that burns entirely when the fire front passes, and thus, the main driver of fire behavior.

Studying fuel characteristics in the clay belt is also interesting because the prolonged absence of fire leads to a convergence of stand structure characteristics (*e.g.* tree composition, density, height of trees, litter type), irrespective of the initial composition of the stands (Harper *et al.* 2002, DeGrandpré *et al.* 2000, Gauthier *et al.* 2000). Indeed, what we observe in these forests is a convergent structural and compositional development of forests initially composed of 1) trembling aspen (*Populus tremuloides*), 2) jack pine (*Pinus banksiana*) or 3) dense, closed black spruce (*Picea mariana*) stands, towards paludified, unproductive, low density, pure black spruce stands after 150 years (Lecomte 2005a). Paludification is defined as the process by which a poor drainage, caused by lacustrine (clay) deposits, and the presence of *Sphagnum* spp. plants cause a rise of the water table, often associated with a drop in productivity of the sites (Simard *et al.* 2007). The effect of the accumulation of peat, and, the consequent change in forest structure on fuel characteristics is then poorly understood.

The particular successional trends of this region are also interesting for studying fuel dynamics as it is possible to associate fuel characteristics with structural changes found amongst forest with similar climate and soil properties. For example, few studies have been found that compare the volume of dead downed logs in young, intermediate and old coniferous and deciduous forests (Brassard and Chen 2006), and to fuel characteristics in general. Interestingly, one study (Stewart *et al.* 2003) has shown that the volume of CWD was higher in old coniferous forests, than in old deciduous forests in Nova Scotia. This has been explained by the fact that deciduous species generally have faster decomposition rates of CWD than coniferous species (Yatskov *et al.* 2003), and that CWD could persist longer on the forest floor in coniferous forests (Brassard and Chen 2006). In this example, although some knowledge pertaining to the differences in fuel characteristics between deciduous and coniferous forests has been acquired, we still don't know much about the differences that could exist between coniferous forests that started off with different dominant species (*e.g.* jack pine vs. black spruce). Moreover, we are faced with the particular case of the clay belt: common knowledge of other boreal forests might not be applicable to this special region.

Therefore, the main objective of this study is to characterize the dynamics of fuel (all fuel strata) in forests found in the Black spruce – Feathermoss domain located on the clay belt of Northwestern Quebec. Primarily, we want to analyze the impacts of 1) stand initial composition and 2) TSF on the characteristics of the different fuel categories, in order to assess if there is a significant change with TSF, and if the fuel characteristics converge to similar patterns as the stands get paludified. Generally speaking, we think that both effects should have a significant effect on fuel characteristics through the process of structural change consequent of succession. Without proposing hypotheses on how should react each fuel parameter in each of the four initial compositions studied, we think that fuel characteristics of black spruce stands initiated from a low severity fire should reflect the drop in productivity found in highly paludified stands. For example, there should be less DWD while *Sphagnum* sp. percent cover should be higher. On the other hand, ericaceous shrubs and small trees should be more abundant offering a good continuity for a potential surface fire.

METHODOLOGY

Study area

The study area (Figure 1.1, 49°00' – 50°00' N, 78°30' – 80°00' W) is located in the eastern North American coniferous boreal forest and is within the *Picea* *mariana* - feathermoss bioclimatic domain (Robitaille and Saucier, 1998), just north of La Sarre in Abitibi. This area is located in the Clay Belt of northeastern Ontario and northwestern Québec, a physiographic unit composed mostly of clay deposits left by pro-glacial Lake Ojibway (Veillette, 1994). This area covers 125 025 km^2 and spans on both sides of the Quebec-Ontario border. The topography of the region is mostly flat with a mean elevation of 250m above sea level. Average annual temperature (1971-2000) recorded at the closest weather station to the north (Matagami, 49°46' N, 77°49' W) and to the south (La Sarre, 48°46' N, 79°13' W) are respectively -0.7°C and 0.7°C with an average of 906 and 890 mm of precipitation annually (Environment Canada). The area is dominated by *Picea mariana*, which tends to form monospecific, structurally diverse stands (Harper *et al.*, 2002; 2005) with a forest floor dominated either by *Sphagnum spp.* or *Pleurozium schreberi* (Boudreault *et al.*, 2002). Occasional deciduous (*Populus tremuloides* Michx. *and Betula papyrifera* Marsh.) and pine dominated stands are dispersed across the landscape. Caused by the cold climate and the impermeable deposits, important organic material accumulations of more than 60 cm on half the territory are observed. Wetlands types like bogs and fens are also common in the region. The fire cycle (time necessary to burn an area similar to the study area) has also quite changed in the last 150 years as it has increased from 101 years before 1850 to 398 years since 1920; mean stand age is 148 years (Bergeron *et al.*, 2004a).

Structural dynamics of the study area

The regional vegetation is composed in vast majority of coniferous stands (Bergeron *et al.* 1998), the most abundant specie being black spruce. Other species found are jack pine, balsam fir (*Abies balsamea*), trembling aspen and white birch (*Betula papyrifera*). Structural changes occurring with TSF in the west Black spruce – Feathermoss forests are strongly associated with paludification (Simard *et al.* 2007, Lecomte 2005a). Paludification is triggered by succession, where cold climate and the absence of fire favor the accumulation of organic material with TSF

(Lecomte N. and Y. Bergeron, 2005c; Harper *et al.* 2002). Sites prone to paludification can be rich and productive, but lose this characteristic with TSF, as the tree roots change positions as soon as the second tree cohort, when they follow the water in the organic material rather than installing themselves in the mineral soil. Productivity declines of up to 80% have been observed in some of these sites (Simard *et al.* 2007). Consequently, low-fertility, cold climate and shade tolerant species will be advantaged with TSF in this type of successional paludification.

In the clay belt region, when a fire has passed, three main dominant species can colonize the post fire site: jack pine, trembling aspen and black spruce. Interestingly, some studies (Gauthier *et al.* 2000, Lecomte *et al.* 2006) have confirmed that whatever the initial composition of the sites, most sites transform, with different timings, to low-productivity, opened, pure black spruce sites (Figure 1.2). Moreover, the same authors have shown that the severity (quantity of organic material burned on the ground) of the last fire has a direct effect on the structure of the stands very early in succession. For this paper, we used a residual organic matter depth threshold of 5 cm to distinguish between a severe and a non-severe fire. We used this limit to classify plots, because past this depth in organic material on the ground, the establishment of many species of trees becomes very difficult (Greene *et al.* 2007). Only black spruce can proliferate mainly by layering (as seeding is also common) from residual stems in these types of forests. Therefore, paludification having a head start, we can recognize that a young low-severity black spruce stand will, structurally speaking, look alike an older high-severity site becoming paludified. We then assume that only black spruce can colonize a soil with more than 5 cm. However, after high-severity fires, trembling aspen or jack pine could colonize the stands, depending on the pre-fire composition or the proximity of the seed source to the burn area. Thus, in this study, we will compare fuel characteristics of 4 different initial compositions (trembling aspen; PTR, jack pine; PBA, severe black spruce; PMA-S and non-severe black spruce; PMA-N) and describe fuel properties transformations that take place with TSF for each different initial composition.

Plot Inventory

Plot selection and dendrometric information

For each age class/initial composition category, we inventoried a certain number of plots (Table 1.1). However, it has been impossible to find PTR sites older than 200 years. Out of the 61 plots inventoried (Figure 1.1), 43 plots were part of the study of Nicolas Lecomte sampled during the summers of 1999 to 2002 (Lecomte, 2005a). Revisiting these sites had the advantage that many variables like: TSF, initial composition, the organic layer depth, the basal area and the density by species were already known. Obviously, we adjusted TSF values to the actual date. These sites originating from 43 spatially distinct fires (does not necessarily mean 43 different fire years). When sampling in the summer of 2008, many of N. Lecomte's stands had been harvested. To complete the sampling, a total of 18 plots were added (plots sampled in other studies or new ones). For 7 plots, we made a replicate just next (100m) to plots of N. Lecomte, as we assumed that the variability within a fire is very important (Leduc *et al.* 2007), so that we could consider two plots close to each other (minimum of 100m) as two different sites. In theses plots, we performed all standard fuel inventories, but we also added basal area measurements (see methods further). When selecting new sites, we applied the same criteria used by Lecomte *et al.* (2005a); the plots needed to be located less than 2km away from a road, on a very slight incline, on fine material (clay), and the last disturbance had to be fire. Sites where anthropogenic signs of disturbance were found were rejected. We are aware that selecting new plots next to others might be considered as pseudo-replication. We assume that these results might lose some significance from this situation but we preferred a higher number of plots. All pseudo-replicated plots are marked in Appendix 1.

For all sites the same sampling procedure was applied based on the method of Lecomte *et al.* (2006). On each site, one or more 10x10m (100m^2) quadrat(s) were installed, in which a thorough dendroecological analysis was performed where they recorded the DBH and height of all live and dead stems > 2m. Also, dead trees buried under the organic matter were exhumed for analysis of species based on bark and branch morphology. Stand age was assessed in young stands (<100 yrs) with the stand initiation map (Bergeron *et al.* 2004b) and by counting the number of rings on tree cross-sections. In older stands, cross sections of the dominant trees were finely sanded and crossdated. In stands where no fire scars were visible, or when trees were older than 200 years, samples of carbonized plant remains found in the uppermost charcoal layer were dated by AMS (accelerator mass spectrometry) carbon dating.

Inventory of ground and surface fuels (duff, litter, herbs, shrubs and DWD loads)

On site, we used a variant of the line-intersect method (Van Wagner, 1968) described by McRae *et al.* (1979), by establishing, at a location chosen randomly, a graduated triangle of 30m sides around which diverse information were measured (Appendix 2). The triangle method was used to reduce bias when counting woody pieces crossing the line that could have fallen in the same angle with the wind. The bias linked to the fact that one piece could cross two different lines was also taken into consideration during inventory, but never happened.

All dead woody pieces crossing the line were counted according to 6 diameter size classes suggested by the method of McRae *et al.* (1979) (class D1 - 0 to 0.49 cm, class D2 - 0.5 to 0.99 cm, class D3 – 1.0 to 2.99 cm, class D4 – 3.0 to 4.99 cm, class D5 – 5.0 to 6.99 cm and class D6 – 7.0 cm and +). Woody pieces of 7.0 cm and more were counted along the 30 m transects, but, by each 5 m, we stopped counting the smallest class. Therefore, for the last 5m only the logs of the 6th diameter class were counted. We used a “go-no-go” gauge to be sure we put woody pieces in the good diameter class. Woody pieces equal to or larger than 7 cm (CWD) in diameter were measured with a caliper, taking care to measure the diameter of the pieces at the point of intersection with the line, like suggested in McRae *et al.* (1979). The proportion of each species of DWD on the ground was estimated by sight for the <7 cm and for the ≥7 cm for later use in the load extrapolation formulas provided in the method of McRae *et al.* (1979).

Woody shrubs were measured in nine 1m^2 plots at the 7, 14 and 21m marks on each sides of the triangle using the method described by Brown *et al.* (1982). In each of these quadrats we ocularly determined the number of stems for each species per height (± 1cm) and stem diameter category (± 0.1cm: 1: 0 to 10 stems, 2: 10 to 20 stems, 3: 20 to 30 stems, 4: 30 to 40 stems). In addition, in order to get allometric equations for the main species present, we took approximately 30 samples of different height and diameter categories of the following species: *Chamaedaphne calyculata, Kalmia angustifolia, Rhododendron groenlandicum and Vaccinium myrtilloides.* We then built formulas using the diameter at soil height and the full height (Appendix 3). Allometric equations were already provided by Hély *et al.* (*unpublished data*) for *Lonicera canadensis*, *Ribes sp.*, *Rosa acicularis* and *Viburnum edule.*

In addition, at each of these 1m^2 plots (n=9), for PMA-S, PMA-N and PBA sites growing on peat duff, we noted the species on top *Sphagnum spp.* or *Pleurozium spp.*), duff depth (surface up to mineral layer, max. of 20 cm), and Von post (decomposition index) measurements were performed. We have established the maximum depth at 20 cm because it is the value recommended by McRae *et al.* (1979), where it becomes very rare for a fire to burn that deep. If the organic layer did not go down to 20 cm, we simply noted the maximum depth down to the mineral soil. For PTR stands not growing on peat, soil layers L, F and H were measured up to 20 cm or less when the mineral soil was higher, at 3 locations around the triangle (15, 45 and 75m marks). We used a woody square of 20x20 cm to cut the soil and marked the knife at 20 cm to respect the depth needed, which resulted in samples measuring 20x20 cm and with varying depths (depending on the mineral soil depth). Afterwards, we put the LFH volume collected in a oven at 50°C for 5 days for complete dehydration. For later litter load (ton/ha) extrapolation, dry weight (g) was measured when the soil was completely dry. We used this dichotomy in inventory procedures for peat and non peat soils because for peat soils, we had load extrapolation formulas using bulk density by species and depth provided by Fransen (1997) that allowed us to calculate duff load, without having to weight it precisely.

Finally, for herb load calculations, we used the method provided by Brown *et al.* (1982). In this paper, we will use the term "herb" to define all surface vegetation that is not woody (*e.g.* forbs and graminoids). First, 4 rectangles of $0.5m^2$ were installed at the 15m marks of each side of the triangle and one in the middle of it. The 4 rectangles were examined visually, and the one with the highest herbs cover was harvested, the sample put in a bag, and oven dried at 95°C for 24h for dry weight measurements. This sample was given a code 8 (100%). The three other quadrats were given a code from 1 to 7 pertaining to the relative abundance of herbs compared to the one harvested (1:0-5%, 2: 6-20%, 3: 21-40%, 4: 41-60%, 5: 61-80%, 6: 81-95%, 7: 96-100%). With these numbers we were able to extrapolate the herbaceous load (ton/ha).

Description of fuel structure and arrangement

To characterize fuels, load is insufficient. Fire behavior also depends on how the different fuel layers are organized spatially together, as this arrangement can have important effects on the rate of spread, head fire intensity or crown fire initiation (transition from surface fire to crown fire) of a fire (Pyne *et al.* 1996). To explain why a surface fire transforms into a crowning fire, Van Wagner (1977) proposes that crowning depends ultimately on a surface fire of above critical crowning intensity, but other factors have been proposed like the height of the lowest continuous branches of the tree canopy (CBH) or the height of the lowest live or dead branch material that could carry fire into the crown (Ottmar *et al.* 1998). According to the last author, bridge fuels like shrubs, small trees, lichen, lower dead branches of trees and dead bark could help a fire move to the crown with a lower surface fire intensity. Therefore, we inventoried some "bridge fuels" and measured the distances between the different fuel layers to understand the crowning potential. However, we inventoried only the variables that needed to be inserted in the fire behavior prediction system *BehavePlus* for later fire behavior predictions. Hence, we are totally aware that the following variables are only some of the factors influencing the potential fire behavior and crowning potential, but we felt they were the most important and they were sufficient for use in fire behavior prediction systems (chapter 2). For the basal area of trees, we only needed an approximation. Like explained earlier, we did not have the time nor the means to perform 10m x 10m quadrats in which all trees were inventoried.

For the 18 added sites, to rapidly assess commercial basal area, we used the prism (factor 2, metric) method. We counted each "good" tree (alive and ≥9 cm in diameter) and noted the species. Basal area values from 43 plots of the 2002 database were calculated from the data provided by Lecomte et al. 2005). For large trees (DBH ≥9 cm), we used the 2002 dataset to extract only live standing trees that had been calculated on a 100m^2 surface. Total and "by species" basal area values for each plot can be found in appendix 1.

Cruz *et al.* (2003) describe Crown Base Height as being one of the most important factor explaining crown fire phenomenology as it influences the likelihood of fire initiation and the interaction between the surface and canopy fuel layer. To give us a good idea of the vertical continuity of fuels, or the crowning potential, we inventoried all small trees (< 3m height) in three plots of 4m^2 each (radius 1.13m), on each corner of the triangle. We noted the species, basal diameter and height for each tree that was in the sub-plot. Furthermore, we assessed the vertical gap distance, defined in this case as the distance between the mean live crown base height of dominant trees and the mean maximum height of shrubs, to better understand the continuity of the fuels for a fire in the vertical fashion. This distance was assessed visually (approximate precision of 1m) at four different places around the inventory triangle: looking towards the exterior of the triangle at the three corners, and when looking parallel to the first triangle side, when standing in the middle of the triangle. Beforehand, to ensure precise and consistent lectures, we visually got use to estimate tree height using a vertex with a number of different trees.

Likewise, we were also interested in understanding how well a fire could move horizontally in the stands (surface spread). Hence, we took different measures of horizontal continuity; one for the shrubs layer and one for ground species. With regard to shrub continuity, we were interested in the horizontal length of gaps that occur between patches of small woody species. Therefore, we measured the length of cover around the triangle's 90m transect occupied by each species of shrubs. We did the same for ground species surface (litter species in peat soils), noting how long each species was covering the ground, and noting also the blank spots (*i.e.* rock patches), where fire could have difficulties to propagate.

Fuel Calculations

Fuel load

In order to analyze and compare the relative abundance of DWD by diameter class category, we needed to transform the number of intersections counted on the line-intersect in load as ton/ha. For the DWD with a diameter < 7cm, we used the procedure and formula (a) taken from McRae *et al.* (1979). First, the number of intersections per diameter class (D1-5: 0 to 6.99 cm) per species on the 90m triangular transect was calculated. Afterwards, this number was multiplied by a correction factor (CF), specific to each species as specified by the authors. No slope correction factor was used, because all the sites were on flat slopes. This number was then multiplied by 10 to transform kg/m^2 in ton/ha.

$$\text{(a) biomass (ton/ha)} = 10 * \sum(\text{nb. intersections/per species/diameter class}) * \text{CF} * \text{slope factor}$$

To calculate the fuel load in ton/ha of the pieces ≥7.0 cm in diameter for each site, we also used the formula found in McRae *et al.* (1979) (b). We added all the diameter square values per species and multiplied by a species' specific CF. We then added the species values.

$$\text{(b) biomass (ton/ha)} = 10 * \sum(\sum(\text{diameter square values per species} * \text{CF}))$$

We also transformed DWD diameter classes recorded in the McRae *et al.* (1979) manner to the American diameter classes following the method of Hély *et al.* (2001). The classes 1h (0-0.25 in.), 10h (0.25-1 in.) and 100h (1-3 in.) refer to the timelag principle. A timelag is the time required for a fuel particle to reach 63% of the difference between the initial moisture content and the equilibrium moisture content (or equilibrium with changed atmospheric conditions). The categories are named for the "midpoint" of the response time of each fuel category: 1-hour fuels respond in less than 2 hours, 10-hour fuels respond in 2 to 20 hours, 100-hour fuels respond in 20 to 200 hours. We used the following linear interpolation formulas (c, d and e) to split the D1 to D5 diameter class loads into the three American classes. We added 31% of the amount of the D5 weight to the 100h because the D5 category stops at 7 cm, while 3 inches equals 7.62 cm.

Formulas used to transform McRae diameter classes to American classes (modified from Hély *et al.* 2001):

c) 1h: 100% D1 + 27% D2

d) 10h: 73% D2 + 77% D3

e) 100h: 23% D3 + 100% D4 + 100% D5 + 31% D5

For shrubs, we used formulas incorporating species height and diameter at soil level to extrapolate total weight. We used the formulas found by C. Hély (unpublished data) for the following species: *Lonicera Canadensis, Ribes spp., Rosa acicularis,* and *Viburnum edule*. For the remaining species (*Ledum groenlandicum, Kalmia angustifolia, Vaccinium angustifolium, Chamaedaphne calyculata*), we used the allometric formulas we calculated from the samples (Appendix 3).

Also, to estimate the load of herbs per hectare, we used the formulas provided in Brown *et al.* (1982). Like described earlier, the relative abundance (%) of herbs was ocularly described in 4 quadrats. One served as a reference and the three others were compared to this one. The reference quadrat was always the one with the highest abundance of herbs and was attributed an herb abundance of 100%. The three other quadrats were then attributed a percentage of the abundance found in the reference quadrat. The herbs from the reference quadrat (quadrat 1 in equation *f*) were harvested and weighted. Afterwards, the total weight was found with the formula (f). We then transformed in ton/ha.

$$\text{(f) Herb biomass } (g/0.16m^2) = \text{wt. quadrat } 1 + \sum_{i=2}^{4} \%\text{ of quadrat } 1 * \text{quadrat}_i$$

To estimate the duff load (ton/ha) of everything above the mineral soil, we used a combination of the data, and the species bulk density values from Fransen (1997). The author describes bulk densities by species and certain depth brackets. We adapted his values to represent the 20 cm depth we measured. Therefore, we used a value of 42.7 kg/m^3 for *Pleurozium schreberi*, 82.55 kg/m^3 for *Sphagnum spp.*, 46.10 kg/m^3 for *Cladina sp./Pleurozium schreberi*. For dry leaves and the underneath LFH horizons, we used the measures of bulk density we have calculated, making an average bulk density from all soil samples we had taken (n=21). The mean bulk density for dry leaves type of litter we found was 66.02 kg/m^3. From these numbers, we calculated the relative abundance of each litter type per sub-plot and computed the relative bulk density for each plot. For example, if the sub-plot was composed purely of *Sphagnum spp.* the bulk density of the plot would then be 82.55 kg/m^3.

However, if 7 points out of 9 were covered with *Sphagnum spp.* and 2 were covered with *Pleurozium schreberi*, than the plot corresponding bulk density calculated with equation (g).

$$(g)\ \left[(7X82,55)+(2X42,7)\right]/9 = 73,69\ kg/m^3$$

Statistical Analyses

To determine if there was a link between the different fuel characteristics (load and arrangement), TSF and initial compositions, we proceeded mainly through ANCOVAs since we had to incorporate continuous data (TSF) with class data (initial compositions). For all variables, ANCOVA models were done by incorporating three effects: interaction, TSF and initial composition. Before each ANCOVA analysis, we determined the homoscedasticity of the residuals with a *Shapiro-Wilk* test. If a normal distribution of the residuals could not be obtained with transformations such as log, square root, squared, and ultimately, the *Box Cox* transformation, we transformed values to averaged ranks (weighted values from 0-61) and performed and ANCOVA on these values. If none of these techniques helped us reach a normal distribution of the residuals, we kept results of the untransformed model but indicated in the figures and tables that residuals were not normally distributed. When the interaction was not significant a reduced model was applied to assess the effects of single factors. When drawing regression lines (Figure 1.3), we looked for coefficient values indicating if the slope was different than zero. If so, a trend line was drawn. If not, only points were shown. All ANCOVAs were performed with the JMP 7.0 statistical software.

RESULTS

The methodologies explained before have allowed the calculation of the load (ton/ha) for the following fuel categories: DWD load, herbs, shrubs and duff load. We have also estimated some structural characteristics of the fuel such as litter species % cover, shrub % cover, small tree height and basal area. The presentation of all results of the ANCOVAs will be done in the same sequence for all categories: 1) the effects of the interaction between TSF and initial composition, where TSF has a significant effect but different in each of the 4 initial compositions, 2) effects of TSF similar in all compositions and 3) significant differences between initial compositions independent of TSF.

Fuel Load

Fine and coarse downed woody debris (DWD, 0 to >7cm in diameter)

The sum of all diameter classes load values for small woody debris (diameter classes D1 to D5) ranged from 0.48 to 21.14 ton/ha among the 61 plots inventoried. CWD (diameter class D6) load values ranged from 0 to 84.65 ton/ha (data not shown). We found that for diameter classes D1, D4, D5, 1h, and the sum of all DWD loads (Figure 1.3), there was a significant interaction between TSF and initial composition. Interestingly, within all graphs, we note a significant decrease in load for all previously mentioned diameter classes in PBA. The same trend was observed for PTR but was non-significant. PMA-S showed a significant but slight increase with TSF in D4 and DWD total and PMA-N showed one in the D1 and 1h classes although their loads were lower than PBA or PTR (Figure 1.3 and Table 1.2).

For the initial composition effect, we found a strong significance level ($p= <0.0001$) in diameter classes D2, D3 and D6, where PMA-N was significantly different from the other three successions with the smallest mean load (Table 1.2). The same pattern was also found in 10h and 100h diameter classes (Table 1.2).

Generally for these variables, the initial composition of PMA-N is always the lowest fuel load, whereas PTR had the highest load. Consequently, PBA and PMA-S were often found to be intermediates between these two extremes. Interestingly, even though there was an effect of the interaction in diameter classes D1, D4, D5, total DWD and 1h, the same pattern is observed for these variables where PTR has the highest loads, PBA and PMA-S are intermediates and PMA-N has lower loads (Table 1.2).

Low stratum load

For duff load (ton/ha), a test on the ranks revealed that it tends to increase in PBA and PMA-S (Figure 1.3). Within PTR a lot of variability is present on the graph, whereas in PMA-N the points tend to remain more or less constant with TSF. Stands classified in the chronosequence of PBA also appear to have the highest duff load (Table 1.2).

The test on the ranks has shown that the herb load tends to decrease with TSF in PBA, but increase in PMA-S and PMA-N. Predictably, the mean load values were more important in the PTR initial composition than in the three other compositional types: PTR has a mean load of 2.79 ton/ha versus 0.13 ton/ha for PBA, 0.08 ton/ha for PMA-S and 0.11 ton/ha PMA-N (Table 1.3). Also, surprisingly, even at advanced ages (150-200 years), it appears that there is still herbs growing in the older PTR colonized sites.

Although PTR appears to have a higher average shrub biomass than PBA, PMA-S and PMA-N, the effect of initial compositions and TSF on the shrub load was not significant (Table 1.2).

Structure and continuity

In this section we present the results pertaining to the general structure of the different fuel categories, keeping in mind the effects of these structural aspects on fire behavior. The presentation of the results is done from the lowest point on the forest floor, going up; thus in order: litter type % cover (*Sphagnum spp., Pleurozium sp., dry leaves, Cladina sp.*), shrubs (height and horizontal continuity, vertical continuity), small trees (< 3m) “height importance” (defined later) and basal area.

Ground species abundance

In general, there is no significant trend with TSF explaining length of cover, for any species and compositional type. *Cladina spp.* and dry leaves litter were rare, so it was impossible to extract a significant effect of initial compositions or TSF (Table 1.2). However, the analyses revealed that initial compositions were a significant element in explaining the percent cover for *Sphagnum spp.* and for *Pleurozium schreberi* (Table 1.2). For *Pleurozium schreberi*, PTR had the lowest cover, but differences among PBA and the two PMA chronosequences was less evident, maybe reflecting the fact that *Pleurozium schreberi* has the ability to colonize more productive *Pinus* sites than *Sphagnum spp.*. For *Sphagnum spp.* cover, PTR had the lowest length of cover, PBA was intermediate, and the two black spruce successional types had the highest cover.

Shrub continuity

For the horizontal and vertical gap distance, ANCOVA results suggest that initial compositions would be the only explaining factor as no effects of TSF were found (Table 1.2). The initial compositions of PTR and PBA are the ones with the longest gaps between shrub patches while the black spruce (PMA-S and PMA-N) are the ones with the smallest gaps. For vertical gap distance, the ANCOVA (Table

1.2) revealed strong effects of initial compositions, where PTR has a higher distance between shrubs and tree branches.

Small trees (< 3m in height)

To analyze the behavior of small trees among the plots, we tested for 1) basal area at ground level and 2) "importance of height". For the "importance of height" parameter, we used the sum of all tree heights, since we wanted to take account of the density effect of the small trees on the propagation of a fire.

The analyses revealed that initial compositions and TSF were significant in explaining the sum of heights of small trees and their basal area (Figure 1.3). With time, we see that both the sum of height and the basal area tend to increase equally in all compositions. Also, for both variables, the mean values by initial composition are lower in PTR than in the three other chronosequences (Table 1.2), PMA-N has the most small trees and PBA and PMA-S are intermediates.

DISCUSSION

Effects of initial compositions on fuel characteristics

First, for what pertains to DWD load, although the trend is not significant in all diameter categories, there is generally more dead wood in PTR stands than in the other three initial compositions where PMA tend to be lower. This could be explained by two factors. First, we think that the higher productivity of these stands (Légaré *et al.* 2005) might be responsible for a greater load of pre-fire woody fuels that persist after the fire and a higher post-fire production. Second, in coniferous stands, woody debris are included in peat, whereas the higher productivity of deciduous stands limits the accumulation of peat on the ground and thus the including of woody pieces. However, like in this actual research, a lot of variability seems to exist in the literature pertaining to the DWD load in different boreal ecosystems. For example, the DWD load results are different from the study of Hély *et al.* (2000) in the boreal mixedwood forest just south of the study area, where the authors found an average DWD load of 51 ton/ha (total of the diameter classes D1 to D6), which is more than 2 times the mean value of 24.00 ton/ha. This difference should be mostly explained by the fact that Hély *et al.* have inventoried their plots after a spruce budworm outbreak having killed about 80% of the balsam firs. Another reason could be that our value is a mean incorporating coniferous stands of lower productivity. However, the PTR CWD (D6, >7.0 cm in diameter) load results (16.71 ton/ha) are similar to the results of Ter-Mikaelian *et al.* (2008) who have found, in a chronosequence similar to ours, a mean CWD load value of 15.9 ton/ha for softwood dominated stands (age span 19-156 years old) and 16.5 ton/ha (age span 8-245 years old) for hardwood stands in boreal forests of Ontario of various latitudes.

Second, the distance between the surface fuels and the canopy of trees was significantly longer for PTR plots and the sum of heights of small trees was the smallest. This suggests that the continuity between the lower fuel layers and the canopy of trees would potentially be less adequate to promote the transition from a surface fire to a crown fire by increasing the critical crown fire intensity required to initiate a crown fire. This situation is also reinforced by the herb component, which is most important in PTR plots; further decreasing the fire intensity potential during the summer, when the moisture content of leaves and herbs are at a maximum. Supporting this idea, DeByle *et al.* (1987) even suggest that wildfires burning in coniferous and shrubland fuel complexes under extreme weather conditions in the western U.S. seldom penetrate pure aspen stands by more than 30 m. In fact, trembling aspen stands in Canada have traditionally been considered as fire-spread barriers during the summer (Alexander 2010). This seasonal effect, where the moisture content of leaves [and herbs] is so high as to overwhelm environmental conditions and preclude fire occurrence, has been documented in some studies (*e.g.* Wright and Beall 1938), and is thought to be a responsible factor for the lack of fire in summer aspen stands. We suggest here that the lack of vertical continuity between fuel layers in deciduous stands might also be important, contributing to this fire barrier effect.

Testing for *Sphagnum spp.* and *Pleurozium schreberi* cover % was pertinent for the study, since it was proven that the saturation point in water for *Sphagnum spp.* in example, is from 2100-2700% of its dry weight, whereas *Pleurozium schreberi* can hold up to 500-1700% (Silvola, 1992); a major difference for fire ignition probability. Knowing how much of the stands are covered by these two litter types can help us understand the chances that a fire ignites on these sites. Plots initiated by trembling aspen had less *Sphagnum spp.* and *Pleurozium schreberi* on the ground. These results go accordingly with the results of Fenton *et al.* (2005), who have shown that the presence of trembling aspen diminished the cover of *Sphagnum spp.* It has been suggested to explain this fact that deciduous leaves have a negative impact on the growth of forest floor mosses, either through a chemical interaction or through smothering (Saetre *et al.* 1997, Frego and Carleton 1995). This discontinuous hypnaceous cover was also mentioned in Van Wagner *et al.* (1992) for the fuel complex described for mixed forests (M1 and M2). As we assume that mosses (*Pleurozium spp.* and *Sphagnum spp.*) have a higher water retention capacity (Silvola, 1992), we could suspect that fire ignition could be easier to achieve in mixed forest, as dead leaves have a poor water retention capacity, dry faster and thus, offer a better ignition substrate.

Also, with respect to *Sphagnum spp.* % cover, the PBA chronosequence was an intermediary between PTR and the two black spruce initial compositions. The higher productivities of PTR and PBA might have delayed the establishment of *Sphagnum spp.*, who prefer less productive, very humid soils, with lots of light reaching the ground. These results go in accordance with Lecomte *et al.* (2006) who have found that among plots that came from a low severity fire, there was a more important *Sphagnum* spp. and ericaceous shrub (*Rhododendron groenlandicum* and *Kalmia spp.*) cover sooner after the fire than after a high severity fire. These groups of plants are known to degrade growing conditions for trees (Inderjit and Mallik 1996).

Concerning DWD, we found similar results, where PMA-N has always the smallest load of DWD and PMA-S and PBA are intermediates. On the other hand, the mean load values for both PMA-S and PMA-N initial compositions (12.51 and 4.29 (ton/ha) are lower than the mean value of 15.9 ton/ha found by Ter-Mikaelian *et al.* (2008) for softwood dominated stands in boreal ecosystems of Ontario, whereas the PBA value of 24.60 ton/ha is above their findings. We suggest that this might be the result of the inclusion of DWD within the peat layer and the reflection of the slower colonization of *Sphagnum spp.* in PBA stands due to the higher productivity.

Finally, PMA-N exhibits a higher level of proximity between fuel layers than PTR, PMA-S and PBA. This initial composition has more small trees, and the connection between the shrub layer and the crown of trees is better. The proximity of the different layers of fuels: litter, herbs, shrubs, little trees and larger trees is very important for the transfer of heat, and help a fire move through the different categories/layers of fuels. With litter and herbs, a fire can propagate on the soil surface, whereas little trees (<3m) and shrubs help a fire move from a surface fire to a higher intensity crown fire. Therefore, aside from stand density and canopy continuity, we think that black spruce forests originating from low severity fires in the region have similar chances of burning with high intensity, as forests having burned severely in the past.

TSF effects on fuel characteristics (and convergence due to paludification)

Litter

For what pertains to ground species cover variations with TSF, surprisingly, no significant result was found with respect to *Sphagnum spp.* cover % in all initial compositions. These results do not meet our expectations, as the initial hypothesis was that *Sphagnum spp.* cover would increase with TSF within all initial compositions, following the successional convergence explained by Lecomte *et al.* (2006) and the results of Fenton *et al.* (2007) for the forests in this region. From the findings of the authors, we should have noted an increase in *Sphagnum spp.* cover with TSF for PTR, PBA, PMA-S and PMA-N, with a lower rate of increase in cover for PMA-N, as the initial post fire cover % should have been already important. We could explain this by the fact that the increase in *Sphagnum* spp. cover % is not linear and the changes happen suddenly, when black spruce is sufficiently abundant to trigger the change. Also, another reason why this trend might not be visible for PTR and PBA plots, and non-significant in the other chronosequences might be attributable to the difficulties of assigning initial composition to older sites. One of the problems with the chronosequence approach for disturbance dynamics studies is that information about the history of the studied stands (other secondary disturbances) is unavailable, making it hard to guess if TSF had a significant role or not (Ter-Mikaelian *et al.* 2008).

Surface fuels

For PTR and PBA, there is a trend in fuel load with TSF, which suggests that there is a lot of woody debris early after a fire, but that they decrease with time. For PBA, this tendency was significant for four of the dead woody pieces diameter classes (D1, D4, D5 and total) and for the herb load, whereas for PTR a non-significant trend was also oberserved. Interestingly, we expected a reduction in DWD debris load with TSF due to a slow degradation of the post fire residual DWD in all 4 initial compositions. To explain this situation, we propose that the inundation of DWD by peat starts off very soon in the succession for the two initial compositions of black spruce, whereas the *Sphagnum spp.* cover is limited by the higher productivity of deciduous and pine stands (Lecomte *et al.* 2005b), and thus this process is slower. It might also be attributable to the fact that black spruce has branches with a smaller diameter than the branches of trembling aspen and jack pine, which take longer to decompose or get inundated in peat.

For all initial compositions, significant increases with TSF in small trees presence (sum of heights and basal area) were observed. This is logical, since aging stands have a wider range of tree ages added to the fact that highly paludified stands have more small trees due to productivity issues. However, some other lightly positive trends in PMA-S and PMA-N were found among fuel components like D1, D4, DWD total, 1h, herb load and duff load. For duff load and herbs, we need to take caution in the interpretation of these results as they were performed on the ranks rather than real values. In reality, few herbs were found in black spruce stands. Concerning the increase with TSF in DWD in PMA-S, note that the natural variation is relatively minor as compared to the loads observed in PBA and PTR.

CONCLUSION

The main objectives of this study were reached. The goals were to better understand the effects of initial compositions and TSF on different aspects of forest fuels like: DWD, live shrub loadings, herb and duff loadings, but also structural components like the surface area of small and large trees plus vertical (distance between shrub and CBH) and horizontal continuity (length of cover of shrubs and % cover of ground species). We have observed a decrease in several fuel loads with TSF in PBA and some slight increase in fuel loads in the PMA-S initial composition. We have learned that initial composition was a better descriptor of forest fuel characteristics than TSF. The starting hypothesis was that we should have found a convergence in fuel characteristics in stands showing advanced paludification issues. This idea started from the fact that other studies (*e.g.* Lecomte *et al.* 2005b) have described and showed a convergence in stand structure in the clay belt region with respect to the density, height and surface area of large trees. However, another way to look at this could be that TSF still has an indirect effect on fuel characteristics.

Previous studies have demonstrated that stands transform with time (Lecomte *et al.* 2005a, Gauthier *et al.* 2000) and we showed that the initial composition is a significant factor controlling fuel characteristics. Therefore, we propose that it is more the change in composition with time, rather than the change due to time, that is the most important for fuel loading and structure dynamics.

Finally, some might argue that this approach is inadequate as a small difference that is not significant in fuel characteristics in the data might turn out to make an important difference in the behavior of a potential fire. The next step is then to build theoretical fire scenarios using empirical weather and fuel data for the region, and test the potential fire behavior with fire behavior modeling systems. This way, minor differences in fuel characteristics might turn out significative fire behavior predictions and vice versa. We also think that further ignition and propagation tests should be done on organic soil types to better understand what are the ignition probabilities of the different litter types. Coniferous stands had more peat than deciduous types, and even though a potential fire could have more ease propagating in their continuous fuel layers, we have no information about the weather conditions needed for a fire to ignite or propagate in peat soils. The model Canfire (Canadian fire), which is the new modification of the old model Borfire (Boreal fire - De Groot *et al. 2003*) is a new model in preparation that allows the user to calculate the depth of burn in peat material. This new tool could prove useful in the understanding of the effects of paludification on fire behavior.

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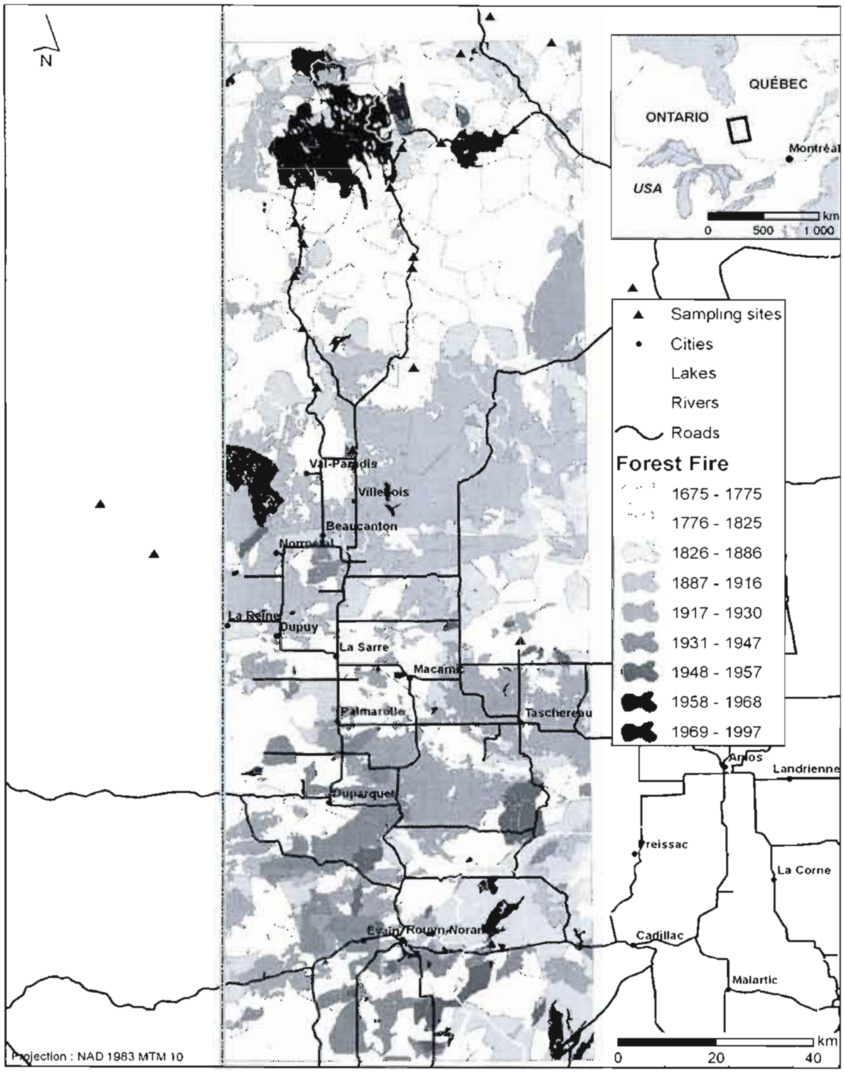
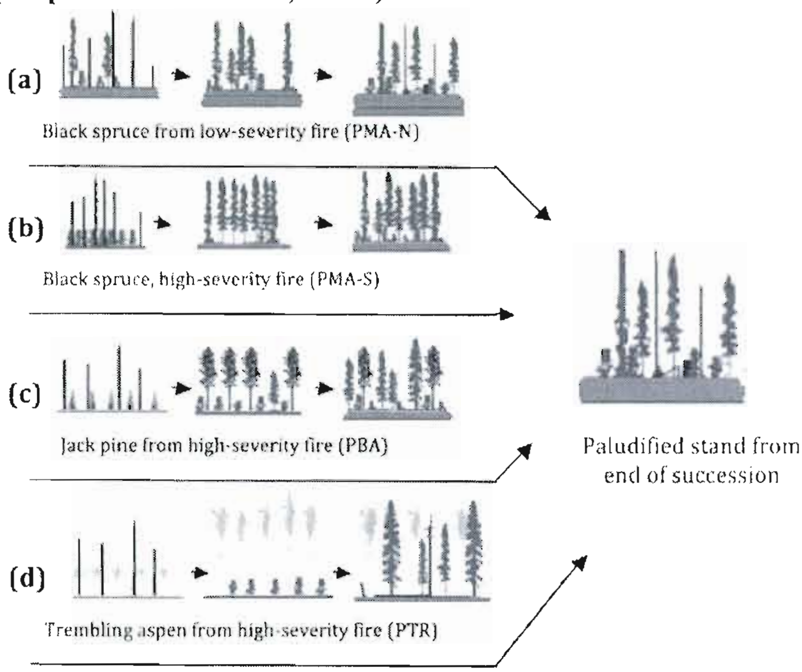
FIGURES

Figure 1.1 – Study area and sites location (*some sites overlap and are therefore invisible)



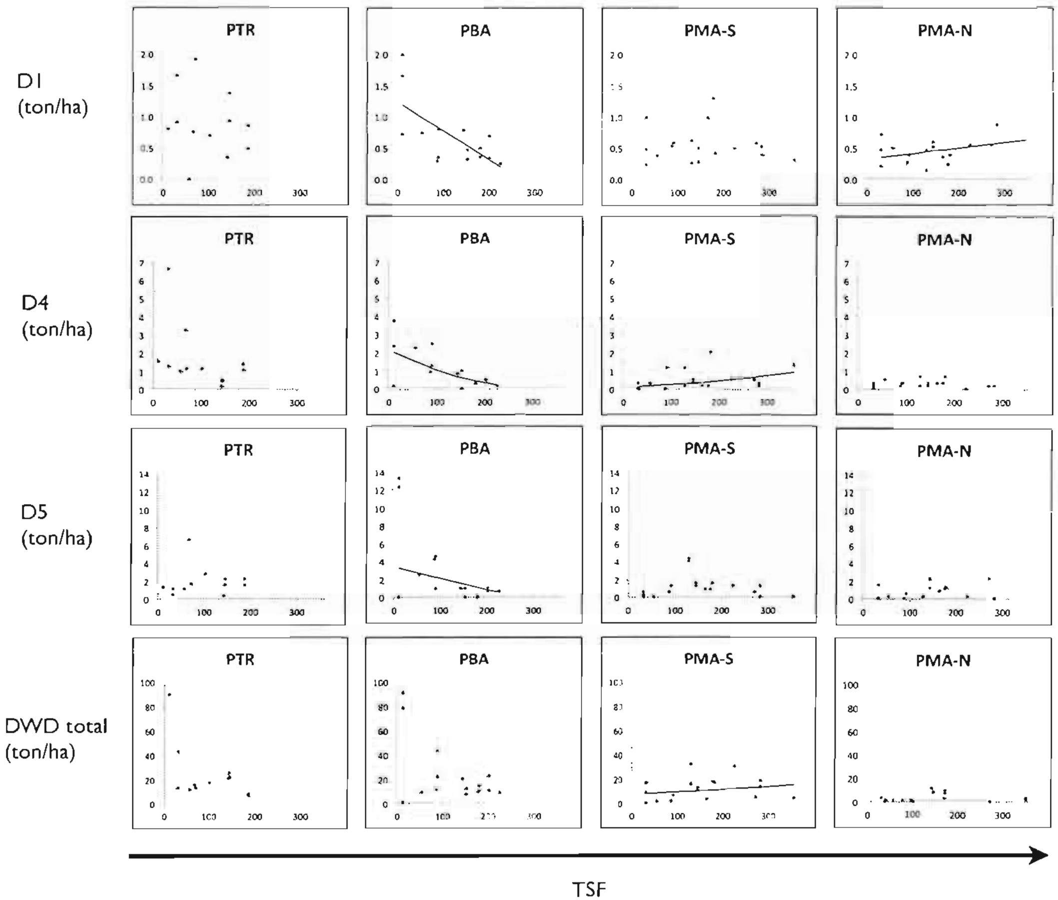
Forest Fire Map adapted from BERGERON, Y., GAUTHIER, S., FLANNIGAN, M., AND KAFKA, V. 2004. | Author: CEF, 2010

Figure 1.2 – Four different initial compositions observed in the Clay Belt region (adapted from Lecomte, 2005a).



Black spruce (*Picea mariana*); Jack pine (*Pinus banksiana*); Trembling aspen (*Populus tremuloides*).

Figure 1.3 – Fuel characteristics showing an age effect within individual ANCOVA analysis, either with an interaction or a single factor effect. Continued on next page.



Effect	F-test	p
Composition	2.31	0.0869
Âge	5.17	0.027
Interaction	4.27	0.009

Effect*	F-test	p
Composition	7.83	0.0046
Âge	4.87	0.0071
Interaction	5.98	0.0014

* Square root transformation

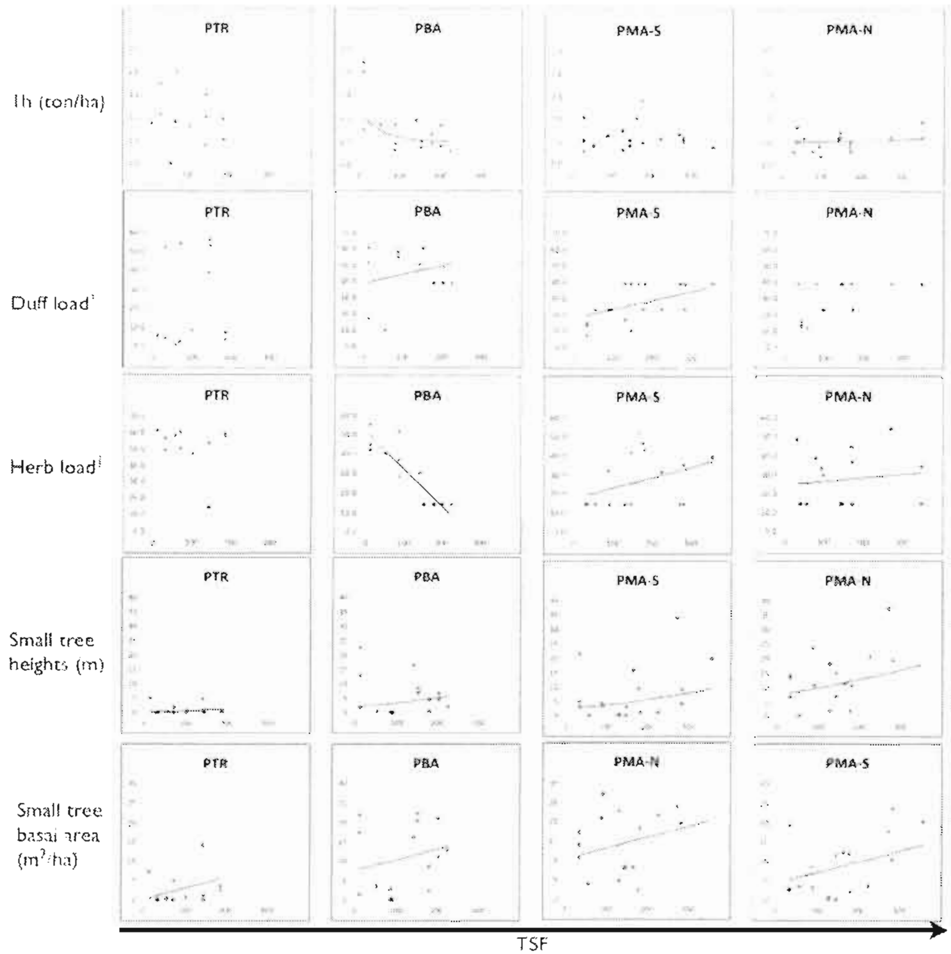
Effect*	F-test	p
Composition	1.36	0.1422
Âge	1.89	0.2495
Interaction	3.32	0.0268

* Box Cox transformation

Effect*	F-test	p
Composition	6.66	0.0007
Âge	5.49	0.0229
Interaction	3.41	0.024

* Square root transformation

Figure 1.3 - Continued



Effect	F-test	p
Composition	2.58	0.0631
Age	1.58	0.2144
Interaction	3.0	0.0384

* Test on the averaged ranks

Effect	F-test	p
Composition	6.24	0.001
Age	5.29	0.0252

* Test on the averaged ranks

Effect	F-test	p
Composition	5.59	0.037
Age	4.57	0.002
Interaction	6.67	0.0007

* Test on the averaged ranks

Effect	F-test	p
Composition	6.49	0.0036
Age	5.07	0.0136

Effect	F-test	p
Composition	6.23	0.0010
Age	4.11	0.0475

* Square root transformation

1- Results presented are based on ranks.

TABLES

Table 1.1 – Number of stands inventoried (n) per age class and initial composition.

Age class	Age span	Successional pathway				
		PTR	PBA	PMA-S	PMA-N	Total n/age class
1	0-50 years	3	3	3	3	12
2	50-100 years	3	4	3	4	14
3	100-150 years	4	1	4	3	12
4	150+ years	2	7	8	6	23
Total n/successional pathway		12	15	18	16	

Table 1.2 – Fuel component means by initial composition with respective ANCOVA results. For the results where a significant interaction involving TSF the min and max values are also reported.

		Fuel component		Values				p value
				PTR	PBA	PMA-S	PMA-N	
Loads (ton/ha)	1	D1 (ton/ha)	*min.*	*0.00*	*0.26*	*0.24*	*0.16*	Figure 1.3
			max.	*1.92*	*2.00*	*1.30*	*0.88*	
			mean	0.90	0.69	0.55	0.46	
	2	D2 (ton/ha)	mean	0.33 ^{AB}	0.33 ^{A}	0.17 ^{AB}	0.14 ^{B}	**0.0086**
	3	D3 (ton/ha)*	mean	2.45 ^{A}	1.21 ^{B}	0.64 ^{C}	0.46 ^{C}	<0.0001
	4	D4 (ton/ha)	*min.*	*0.17*	*0.00*	*0.00*	*0.00*	Figure 1.3
			max.	*6.67*	*3.79*	*2.08*	*0.69*	
			mean	1.66	1.15	0.53	0.29	
	5	D5 (ton/ha)	*min.*	*0.33*	*0.00*	*0.00*	*0.00*	Figure 1.3
			max.	*6.64*	*13.32*	*2.31*	*4.29*	
			mean	1.96	2.83	0.83	1.17	
	6	D6 (> 7cm) (ton/ha)**	mean	16.71 ^{A}	18.39 ^{A}	9.45 ^{A}	2.11 ^{B}	<0.0001
	7	DWD total load (0 to > 7cm) (ton/ha)	*min.*	*7.19*	*1.37*	*0.72*	*0.58*	Figure 1.3
			max.	*90.27*	*92.08*	*32.82*	*11.91*	
			mean	24.00	24.60	12.51	4.29	
	8	1h (ton/ha)	*min.*	*0.00*	*0.27*	*0.26*	*0.17*	Figure 1.3
			max.	*1.99*	*2.21*	*1.38*	*0.90*	
			mean	0.98	0.78	0.60	0.50	
	9	10h (ton/ha)	mean	2.13 ^{A}	1.18 ^{B}	0.61 ^{BC}	0.46 ^{C}	**<0.0001**
	10	100h (ton/ha)	mean	4.79 ^{A}	5.14 ^{A}	2.21 ^{AB}	1.48 ^{B}	**0.0416**
	11	Duff load (ton/ha)***	mean	1.37 ^{B}	2.86 ^{A}	1.37 ^{B}	1.40 ^{B}	0.001
	12	Herb load (ton/ha)	*min.*	*0.00*	*0.00*	*0.00*	*0.00*	Figure 1.3
			max.	*19.52*	*0.77*	*0.44*	*0.75*	
			mean	2.79	0.13	0.08	0.11	
	13	Shrub load (ton/ha)	mean	1.07	0.32	0.44	0.40	NS
Structural continuity	14	*Sphagnum* cover (m)*	mean	3.33 ^{B}	23.23 ^{AB}	46.77 ^{A}	45.37 ^{A}	0.0002
	15	*Pleurozium* cover (m)	mean	18.82 ^{B}	62.88 ^{A}	40.51 ^{AB}	46.78 ^{AB}	0.0194
	16	Dead leaves (deciduous) cover (m)	mean	76.75	13.33	0.00	0.62	NS
	17	Cladina sp. Cover (m)	mean	0.00	0.19	9.01	2.49	NS
	18	Vertical gap distance (m)	mean	5.99 ^{A}	2.05 ^{B}	1.36 ^{B}	0.73 ^{B}	<0.0001
	19	Horizontal gap distance (m)*	mean	23.08 ^{AB}	30.78 ^{A}	5.59 ^{B}	3.70 ^{B}	0.0016
	20	Small tree sum of heights (m)	mean	2.81 ^{B}	10.63 ^{AB}	8.37 ^{AB}	14.22 ^{A}	0.0036
	21	Small tree basal area (m^2/ha)*	mean	1.03 ^{B}	5.56 ^{AB}	7.34 ^{AB}	12.99 ^{A}	0.001

* Significance achieved by transforming values to square root (values untransformed are shown)
** Significance achieved by transforming values with the Box Cox transformation (values untransformed are shown)
*** Model performed on the averagesd ranks (values untransformed are shown)
Bold - Normality of the residuals not reached
NS - Non-significant

APPENDIX 1

Stand characteristics, FBP fuel type and basal area (m^2/ha) by species for each plot.

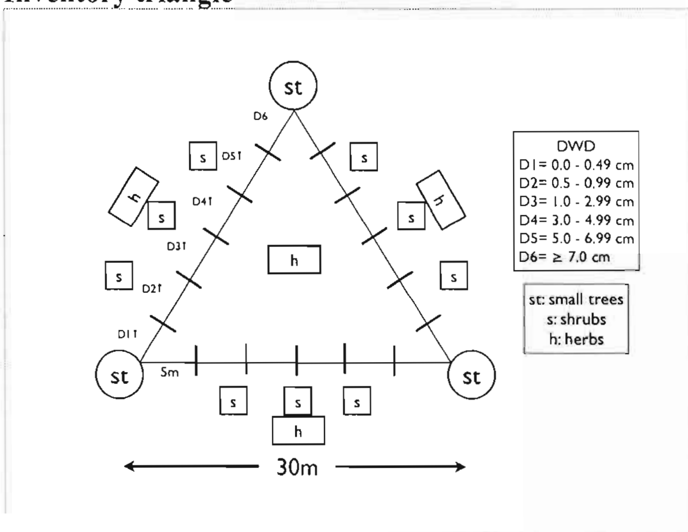
					Basal area (m^2/ha)					
Site name[1]	TSF	Age Class	Initial composition	FBP type[2]	P. mariana	P. banksiana	P. tremuloides	A. balsamifera	B. papyrifera	Total
PTRC1	11	1	PTR	M2 - 90%	0.00	0.00	0.00	0.00	0.00	0.00
Ptr64a	32	1	PTR	M2 - 100%			Missing data			
Ptr64b	32	1	PTR	M2 - 100%						
Lofuel	57	2	PTR	M2 - 95%	1.45	4.57	60.33	0.57	0.00	66.91
Andy 3	68	2	PTR	M1 - 95%	2.75	0.00	19.28	1.55	0.00	24.31
Mask II	71	2	PTR	M2 - 60%	24.76	2.49	12.51	0.36	5.69	45.01
Wmist	102	3	PTR	M2 - 60%	19.33	0.00	26.06	0.16	0.00	47.22
Mir 1	142	3	PTR	C2	12.04	0.00	4.92	0.00	0.00	16.06
Andy 1	145	3	PTR	M2 - 50%	19.94	0.00	10.51	0.00	0.00	30.76
Andy 1*	145	3	PTR	M2 - 60%	19.94	0.00	10.51	0.00	0.00	30.76
Jou2B (a)	187	4	PTR	M2 - 35%	23.06	0.00	36.51	20.35	5.83	75.32
Jou2B (b)	187	4	PTR	M2 - 30%	23.06	0.00	36.51	20.35	5.83	75.32
2RS3	11	1	PBA	C4	0.00	0.00	0.00	0.00	0.00	0.00
RS4 New	11	1	PBA	C4	0.00	0.00	0.00	0.00	0.00	0.00
RS4 B New	11	1	PBA	C4	0.00	0.00	0.00	0.00	0.00	0.00
54	54	2	PBA	C3	1.14	32.35	0.00	0.00	0.00	33.49
38	87	2	PBA	50% C2, 50% C3	27.89	16.38	0.00	0.00	0.00	43.58
23	89	2	PBA	C3	16.49	27.03	0.00	0.00	0.00	53.37
23*	89	2	PBA	C3	16.49	27.03	0.00	0.00	0.00	53.37
69	142	3	PBA	C2	25.29	0.00	0.00	0.00	0.00	25.29
66	152	3	PBA	80% C2, 20% C3	23.14	11.41	0.00	0.00	0.00	34.55
66*	152	3	PBA	C3	23.14	11.41	0.00	0.00	0.00	34.55
83	180	3	PBA	C2	6.64	3.04	0.00	0.00	0.00	9.69
83*	180	3	PBA	80% C2, 20% C3	6.64	3.04	0.00	0.00	0.00	9.69
65	207	4	PBA	80% C2, 20% C3	0.00	0.00	0.00	0.00	0.00	0.00
65*	207	4	PBA	C2	0.00	0.00	0.00	0.00	0.00	0.00
64	225	4	PBA	C2	20.60	0.00	0.00	0.00	0.00	20.60
60B	32	1	PMA-S	M2 - 5%	0.00	0.00	0.00	0.00	0.00	0.00
59C	32	1	PMA-S	M2 - 15%	0.00	0.00	0.00	0.00	0.00	0.00
34E	32	1	PMA-S	M2 - 20%	0.00	0.00	0.00	0.00	0.00	0.00
4	55	2	PMA-S	C2	44.02	0.00	0.00	0.00	0.00	44.02
2	87	2	PMA-S	C2	32.22	0.00	0.00	0.00	0.00	33.56
57New	91	2	PMA-S	60% C2, 40% C3	36.50	0.00	0.00	0.00	0.00	36.50
18*	129	3	PMA-S	80% C2, 20% C3	34.52	0.00	0.00	0.00	0.00	35.96
18	129	3	PMA-S	60% C2, 40% C3	34.52	0.00	0.00	0.00	0.00	35.96
Andy 1C	145	3	PMA-S	50% C2, 50% C3	18.00	0.00	2.00	0.00	0.00	20.00
Andy 1D	145	3	PMA-S	50% C2, 50% C3	25.50	0.00	0.50	0.00	0.00	26.00
C-150	165	4	PMA-S	70% C2, 30% C3	31.48	0.00	0.00	0.00	0.00	31.48
8	177	4	PMA-S	C2	20.79	0.00	0.00	0.00	0.00	20.79
50	225	4	PMA-S	90% C2, 10% C3	13.86	0.00	0.00	5.45	0.00	19.31
L22	272	4	PMA-S	C2	21.96	0.00	0.00	0.00	0.00	22.89
6	283	4	PMA-S	C2	18.53	0.00	0.00	0.00	0.00	18.53
16	283	4	PMA-S	C2	14.77	0.00	0.00	0.00	0.00	14.77
20	356	4	PMA-S	C2	12.92	0.00	0.00	0.00	0.00	12.92
62D	32	1	PMA-N	C2	0.00	0.00	0.00	0.00	0.00	0.00
11	41	1	PMA-N	C2	3.44	0.00	0.00	0.00	0.00	3.44
11*	41	1	PMA-N	C2	3.44	0.00	0.00	0.00	0.00	3.44
53	57	2	PMA-N	80% C2, 20% C3	15.06	0.00	0.00	0.00	0.00	15.06
78	78	2	PMA-N	C2	7.13	0.00	0.00	0.00	0.00	7.13
3	96	2	PMA-N	C2	8.31	0.00	0.00	0.00	0.00	8.31
60	100	2	PMA-N	C2	11.55	0.00	0.00	0.00	0.00	11.55
68	142	3	PMA-N	C2	17.64	0.00	0.00	0.00	0.00	17.64
63	146	3	PMA-N	80% C2, 20% C3	12.30	0.00	0.00	0.00	0.00	12.30
63*	146	3	PMA-N	70% C2, 30% C3	12.30	0.00	0.00	0.00	0.00	12.30
Chafi #5	170	4	PMA-N	C2	29.00	0.00	0.00	0.00	0.00	29.00
5	172	4	PMA-N	C2	18.55	0.00	0.00	0.00	0.00	18.55
5*	172	4	PMA-N	C2	18.55	0.00	0.00	0.00	0.00	18.55
POP	181	4	PMA-S	40% C2, 60% C3	23.59	0.00	0.00	0.00	0.00	23.59
L9724	272	4	PMA-N	C2	20.14	0.00	0.00	0.00	0.00	20.14
H1A	350	4	PMA-N	C2	2.70	0.00	0.00	0.00	0.00	2.70
H1B	350	4	PMA-N	C2	2.70	0.00	0.00	0.00	0.00	2.70

1- Replicated plots are marked with an asterisk

2- Percentages attributed on site based on canopy height, DWD load, litter compactness and tree density

APPENDIX 2

Inventory triangle



APPENDIX 3

Allometric formulas used to extrapolate shrub weight by Hély *et al.*[1] (unpublished results) and Pelletier-Bergeron *et al.*[2] (unpublished results).

Species	Formulas wt = weight (g) D = basal diameter (cm)	R^2
Lonicera canadensis[1]	ln (total wt) = -2.33 + 2.64 ln (D)	0.82
Ribes sp.[1]	ln (total wt) = -2,17 + 2.32 ln (D)	0.79
Rosa acicularis[1]	ln (total wt) = -2.08 + 2,40 ln (D)	0.82
Viburnum edule[1]	ln (total wt) = -2.55 + 2.62 ln (D)	0.84
Rhododendron groenlandicum[2]	ln (total wt) = -2.69 + 2.68 ln (D)	0.94
Kalmia angustifolia[2]	ln (total wt) = -2.15 + 2.47 ln (D)	0.92
Vaccinium angustifolium[2]	ln (total wt) = -2.15 + 2.41 ln (D)	0.76
Chamaedaphne calyculata[2]	ln (total wt) = -3.03 + 3.03 ln (D)	0.95

CHAPITRE II

SIMULATION OF FIRE BEHAVIOR IN THE CLAY BELT BOREAL FOREST USING TWO PREDICTION MODELS: EFFECTS OF INITIAL STAND COMPOSITION AND TIME SINCE FIRE

Par Mathieu Paquette, Sylvie Gauthier, Christelle Hély et Yves Bergeron
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Contribution des auteurs:

Mathieu Paquette: Recherche, méthodes et protocole d'analyse, inventaire, base de données, rédaction.
Sylvie Gauthier: Assistance continue, corrections, statistiques
Christelle Hély: Spécialiste en modélisation
Yves Bergeron: Corrections, conseiller

RÉSUMÉ

Le feu est l'une des perturbations les plus importantes affectant la succession forestière dans la forêt boréale du Canada. Parmi plusieurs facteurs comme la météo et la topographie, le combustible a un effet majeur sur le comportement des feux de forêt. Toutefois, très peu d'études ont visé à voir comment le temps depuis feu (TDF) affecte le comportement du feu à travers les modifications des caractéristiques du combustible. L'objectif principal de cet article est donc l'étude des effets du TDF ainsi que la composition initiale sur 4 variables du comportement du feu: la vitesse de propagation, l'intensité du front de flamme, l'aire brûlée ainsi que le type de feu (surface, intermittent ou de cime). Un objectif additionnel inclue la comparaison de 2 modèles de prédiction des feux de forêt (*FBP* et *BehavePlus*). Au total, 61 peuplements âgés entre 11 et 356 ans ont été inventoriés et regroupés en fonction de leur âge et de leur composition initiale. En tout, 122 simulations ont été réalisées dans *BehavePlus* et 20 dans *FBP*, en incorporant deux scénarios météorologiques (normal et extrême). L'ANOVA, la régression ainsi que l'analyse par khi^2 ont ensuite été utilisées pour tester l'effet du TDF et de la composition initiale sur les 4 variables du comportement du feu. En général, l'effet de la composition initiale semble être plus fort que celui du TDF. Par exemple, la composition initiale de l'épinette noire semble avoir un comportement du feu de plus grande intensité dans les simulations avec *BehavePlus* ou *FBP*. Aussi, dans les deux modèles, les différences de combustibles notées précédemment entre les peuplements feuillus et résineux se sont traduits en comportements du feu très différents. Nous suggérons donc que l'effet du TDF sur le comportement des feux est indirect, alors qu'il modifie la composition des peuplements avec l'âge, alors que ceux-ci ont un effet direct sur le comportement des feux.

Mots clés: *comportement du feu, paludification, chronoséquence, pessière, MCPCI, BehavePlus*

ABSTRACT

Fire is one of the most important disturbance affecting forest successions in the boreal forest of Canada. Among other factors like weather and topography, fuel plays a major role in controlling fire behavior. However, very few studies have been made that aim to understand how time since fire (TSF) and initial composition interact with fire behavior through the modification in fuel characteristics. The main objective of this paper is then to study the effects of TSF and initial compositions on 4 fire behavior variables: the rate of spread (ROS), the head fire intensity (HFI), the fire type (surface, intermittent or crown fire) and the area burned. Other objectives included the comparison of 2 fire behavior models (*FBP* and *BehavePlus*). In total, we inventoried fuel characteristics in 61 different stands aged between 11 and 356 years and grouped them in function of their age and initial composition. While incorporating 2 weather scenarios (normal and extreme fire weather), 122 simulations were performed in *BehavePlus* and 20 in *FBP*. ANOVAs, regressions and khi^2 tests were then used to test the effects of TSF and initial composition on the 4 fire behavior variables. In general, the effect of initial composition seems to be stronger than TSF. For all variables and for both fire behavior prediction models, black spruce stands from a non-severe fire would have a stronger fire behavior than other chronosequences. Also, in both models, the differences in fuel characteristics noted in the precedent chapter were translated in the largest difference in fire behavior. The conclusions are that the effect of TSF on fire behavior is indirect as it modifies forest composition through succession, and that this modification has a direct impact on fire behavior.

Keywords: *fire behavior, paludification, chronosequence, black spruce, FBP, BehavaPlus*

INTRODUCTION

The boreal forest is an ecosystem that spans all across Canada and is affected by large-scale natural disturbances, such as insect outbreaks and fires. In fact, the majority of forest fires are large, of high intensity (released energy) and high canopy severity (high level of tree mortality). For example, fires burning up 100 000 ha are common in the boreal forest of Canada (Johnson 1992). Furthermore, in the period between 1980 and 1989, large scale fires (> 200 ha) represented 3% of all fires only, but 97% of the burned area in Canada (Stocks *et al.* 2003). The three main components influencing fire behavior are weather, topography and fuel, and they constantly interact (Agee 1997). However, the respective roles of each of these components change according to the region, the ecosystem type, and its historical events (Fryer and Johnson 1988, Harrington *et al.* 1991, Johnson 1992).

For example, some studies (Bessie and Johnson 1995, Hély *et al.* 2001) have shown that the weather factor was more important than fuel for affecting fire ignition and behavior in the western and eastern parts of the Canadian boreal forest. On the other hand, in some ecosystems, different studies have described an increased risk of fire ignition and propagation after long-term accumulations in forest fuels (Dodge 1972, Wright and Bailey 1982, Aber and Melillo 1991, Schimmel and Granström 1997). To explain these differences in interpretation, Flannigan and Harrington (1988) suggested that the weather may become the most important factor when fire frequency is low and/or when fires occur under extreme weather conditions. Another study (Hély *et al.* 2001) also proposed that the vegetation composition might be the driving factor when fire frequency is high within a forest mosaic where the stand composition is quite variable. The vegetation composition would then play an important role in defining the fire regime.

For this study, the interest lies in the Black spruce (*Picea mariana*) - feathermoss forest of Northwestern Quebec. This region is an interesting place to test this hypothesis since, under similar conditions we find multiple initial compositions in overstory tree composition that can co-occur within a landscape (Harper *et al.* 2002). Also, in the particular case of the northwestern Quebec Black spruce - feathermoss forest, the prolonged absence of fire leads to a convergence of stand structure, whatever the initial composition (Gauthier *et al.* 2000). In this forest, we observe a convergent structural development of forests composed of either trembling aspen (*Populus tremuloides*), jack pine (*Pinus banksiana*) or dense, closed black spruce stands initially, towards unproductive, low density, pure black spruce stands after 150 - 200 years (Lecomte, 2005a). This phenomenon is mainly triggered by paludification (accumulation of peat having for main consequence the rise of the water table and a resulting loss in productivity), which is a common problem in the area (Fenton *et al.* 2005, Simard *et al.* 2007).

Also, although the structural dynamics of the region are well understood, the long-term effects of these changes in fuel structure and loading with time since fire (TSF) on the fire behavior are less defined. In fact, no studies have looked at the effects of TSF and initial compositions on fire behavior and occurrence. The main objective of this study is then to describe the effects of the transformation in fuel structure and loading with TSF in four different initial compositions (trembling aspen, jack pine and two black spruce chronosequences separated based on the soil severity of the last fire event). To achieve this objective, empirical fuel data for 61 plots and 2 theoretical weather scenarios (normal and extreme fire weather) will be used with two fire behavior prediction models: the *Canadian Fire Behavior Prediction Model* (CFBPM) (Forestry Canada Fire Danger Group, 1992) and *BehavePlus* (Andrews 2007).

METHODOLOGY

Study area

The study area (Figures 2.1 & 2.2, 49°00' – 50°00' N, 78°30' – 80°00' W) is located in the eastern North American coniferous boreal forest and is within the black spruce - feathermoss bioclimatic domain (Robitaille and Saucier, 1998), just north of La Sarre in Abitibi. This area is located in the northeastern Ontario and northwestern Québec Clay Belt, a physiographic unit composed mostly of clay deposits left by pro-glacial Lake Ojibway (Veillette 1994). This area covers 125 025 km^2 and spans on both sides of the Quebec-Ontario frontiers. The topography of the region is mostly flat with a mean elevation of 250 m above sea level. Average annual temperature (1971-2000) recorded at the closest weather station to the north (Matagami, 49°46' N, 77°49' W) and to the south (La Sarre, 48°46' N, 79°13' W) are respectively -0.7°C and 0.7°C with an average of 906 and 890 mm of precipitation annually (Environment Canada). The area is dominated by black spruce, which tends to form monospecific, structurally diverse stands (Harper *et al.* 2002; 2003; 2005) with a forest floor dominated either by *Sphagnum spp.* or *Pleurozium schreberi* (Boudreault *et al.* 2002). Occasional deciduous (trembling aspen and white birch - *Betula papyrifera* Marsh.) and pine dominated stands are dispersed across the landscape. Caused by the cold climate and the impermeable deposits, important organic material accumulation of 60 cm on half the territory is observed. Wetland types like bogs and fens are also common in the region. Although agricultural settlement south of the study area began in the middle of the 1930s, intensive logging of this area only began in the late 1970s (Lecomte *et al.* 2006a). Fire is therefore the main disturbance that terminates and initiates secondary succession. Fire cycle length (time necessary to burn an area similar to the study area) has increased from 101 years before 1850 to 398 years since 1920; mean stand age is 148 years (Bergeron *et al.* 2004).

Plot selection & fuel inventory

Out of the 61 plots inventoried (Figures 2.1 & 2.2), 43 were plots already visited by Nicolas Lecomte during the summers of 1999 to 2002 (Lecomte, 2005a). Revisiting these sites had the advantage that many variables like: TSF, initial composition, the organic layer depth, the basal area and the density by species were already known. Obviously, we adjusted TSF values to the actual date. In all, N. Lecomte inventoried 43 sites originating from several spatially distinct fires. On each site, one or more 10x10m (100m^2) quadrat(s) were installed, in which a thorough dendroecological analysis was performed where they recorded the DBH and height of all live and dead stems > 2m. Also, dead trees buried under the organic matter were exhumed for analysis of species based on bark and branch morphology. Stand age was assessed in young stands (<100 yrs) with the stand initiation map (Bergeron *et al.* 2004) and by counting the number of rings on tree cross-sections. In older stands, cross sections of the dominant trees were finely sanded and crossdated. In stands where no fire scars were visible, or when trees were older than 200 years, samples of carbonized plant remains found in the uppermost charcoal layer were dated by AMS (accelerator mass spectrometry) carbon dating. To complete the sampling, a total of 18 plots were added from plots used by other authors, or, in some larger stands, we just replicated plots, as we assumed that the variability within a fire is very important (Leduc *et al.* 2007 proceedings) so that we could consider two plots close to each other as two different stands. We are aware that selecting new plots next to others might be considered as pseudo-replication. We assume that the results might lose some significance from this situation but we preferred a higher number of plots. All pseudo-replicated plots are marked in Appendix 1 of chapter 1. However, when selecting new sites, we applied the same criteria used by Lecomte *et al.* (2005a); the plots needed to be located less than 2km away from a road, on a very slight incline, on fine material (clay), and the last disturbance had to be fire. Sites where anthropogenic, insect or wind disturbance signs were found were rejected.

In each stand, we estimated the downed woody debris (DWD) load with a variant of the line-intersect method (Van Wagner 1968) proposed by McRae *et al.* (1979) and applied by Hély *et al.* (2000). More precisely, we inventoried all woody pieces along an equilateral triangle of 30m sides. We first used the McRae *et al.* (1979) diameter classes. Afterwards, we used linear interpolation to split the class diameter loads presented above, to the three American classes:1-h, 10-h and 100-h time lag dead woody loads following the Hély *et al.* (2000) methodology.

Shrubs, herbs and litter fuels (Brown *et al.* 1982) were measured in evenly spaced quadrats all along the triangular transect. The species, basal diameter, percentage of dead branches and height of all shrubs was measured in 9x1m^2 plots at the 7m, 14m and 21m on each side of the triangle. Shrub loads were then calculated from allometric formulas determined by the previous works of Hély *et al.* (2000) from samples collected in the Duparquet area and the actual work of Pelletier-Bergeron *et al.* (*in prep.*) from samples collected in the study area. In the same way, herb loads per site were measured by establishing 4 x 0.5m^2 quadrats at the 15m marks of each triangle side and one in the middle of the triangle. The highest herb load was visually estimated among the 4 replicates, clipped, collected, dried and weighted (± 0.1g). On site, we visually estimated what percentage of the highest load quadrat could represent each of the three other quadrats to give us a mean herb load on 2m^2 which could later be transformed to ton/ha. We were then able to fill all the inputs of *BehavePlus*: 1h, 10h, 100h, live herbaceous and live woody fuel loads but for *FBP* simulations, we also needed to describe each plot with one of the 16 available fuel models. We felt that these classes did not describe the stand with enough precision, hence, we decided to describe plots with proportions of two fuel types (*e.g.* 20% C2 and 80% C3). The fuel type proportions were evaluated in the field based on the structure of the different fuel layers. A description of the fuel types per plot can be examined in table 2.1 and a summary of fuel types per age class and initial composition in table 2.2. The guidelines to attribute fuel types were as follows

(Forestry Canada fire danger group, 1992):

- **C2**: The organic layer is deep and compacted. There is a low to moderate quantity of coarse woody debris (CWD, ≥ 7 cm in diameter) on the soil and a continuous ericaceous cover is present. The stand is mostly composed of black spruce of moderate relative density. Tree crowns almost reach ground level.

- **C3**: The organic layer is moderately deep and compact. Sparse CWD cover the soil. In the understory, few conifer trees can be seen. The stand is composed mostly of mature pine of adequate relative density.

- **C4**: This fuel type is characterized by pure, dense jack pine or lodgepole pine (*Pinus contorta* Dougl. ex Loud.) stands (10,000–30,000 stems/ha) in which natural thinning mortality results in a large quantity of standing dead stems and DWD fuel load. Vertical and horizontal fuel continuity is characteristic of this fuel type. Surface fuel loadings are greater than in fuel type C3, and organic layers are shallower and less compact. Ground cover is mainly needle litter suspended within a low shrub layer (*e.g. Vaccinium* spp.).

- **M1/M2**: This fuel type (and its "green/summer" counterpart, M2) is characterized by stand mixtures consisting of the following coniferous and deciduous tree species in varying proportions: black spruce, white spruce (*Picea glauca* (Moench) Voss), balsam fir (*Abies balsamea* (L.) Mill.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), trembling aspen, and white birch. On any specific site, individual species can be present or absent from the mixture. M1, the first phase of seasonal variation in flammability, occurs during the spring and fall. The rate of spread is weighted according to the proportion (expressed as a percentage) of softwood and hardwood components.

Fire weather

To understand the role of humidity and moisture of the different categories of fuel on fire behavior, we have chosen to model two weather scenarios: one of normal fire risk, and another of extreme fire weather. In order to be sure to define realistic weather scenarios for the region, we used weather data associated with the Large Fire Data Base (LFDB, Stocks *et al.* 2003) for the 1959-1999 period. In this database all the fires with a total final size of more than 2 km^2 that occurred between 1959 and 1999 were compiled. By using data taken only from large fires, we were sure that we were using weather conditions for fire predictions under which fire could be sustained. Available data included: the date, weather (temperature, relative humidity, wind speed, rainfall), area burned, and the fire weather indices (FWI computed from the FFMC, BUI, DMC and DC) for the 21st days of each fire. These FWIs system components are considered as fuel moisture codes and fire behavior indexes. For example, the fine fuel moisture code (FFMC) rates the moisture content of litter and other cured fine fuels. It is an indicator of the relative ease of ignition, fire spread and flammability of fine fuel. The duff moisture code (DMC) represents the moisture content of loosely compacted, decomposing organic matter weighing about 5 kg m^{-2} when dry. It relates to the probability of lightning ignition and fuel consumption. Finally, the DC (drought code) represents a deep layer of compact organic matter weighing about 25 kg m^2 when dry. It relates to the consumption of heavier fuels and the effort required to extinguish a fire. The buildup index (BUI) is a combination of DMC and DC and is a numerical rating of the total amount of fuel available for combustion. FWI is a combination of ISI (the initial spread index) and the BUI representing intensity of the spreading fire as energy rate per unit length of fire front. It is often used as a single integration of fire weather. As a referent, a fire declared under a FWI of 5 would be considered of low intensity, with 15 of moderate intensity and above 25 of extreme intensity.

With this database, the first step was to extract the weather data for the Abitibi plains ecoregion, which spans across the border of Quebec and Ontario (region #96 in Figure 2.1). Then, we calculated the total area burned during the first 21 days for each fire and ordered them in an ascending way. Afterwards, we found which burned area value represented the 50th and 95th percentile, and extracted data of 5 fires with burned area values higher then the selected value and 5 fires with burned area values lower than the selected fire, for a total of 11 fires for each scenario (50th and 95th percentile). The next step was then to select the day with the highest value of FWI for each fire of each series of 11 fires, and compute the mean values for temperature, wind, FFMC, DMC, DC and BUI (Table 2.3). These values were then used directly (wind speed, FFMC and BUI) in *FBP* or used to extrapolate moisture contents of 1h, 10h and 100h fuel categories in *BehavePlus*.

In order to find the corresponding moisture values to reflect the humidity characteristics of the region for the 1h and 10h time lag fuel diameter categories, we used the formulas described in Bradshaw *et al.* (1983). The authors describe formulas to calculate the moisture content of each fuel category based on a constant, multiplied by the equilibrium moisture content of dead wood. The EMC has been calculated with the formula described in Simpson (1998). Their formulas incorporate values of relative humidity and temperature, which we found for the 50th and the 95th percentile size of the fires within the LFDB. For the 100h time lag dead fuel categories, the formulas described in Bradshaw *et al.* (1983) required values that were impossible to find or extrapolate. As the 100h time lag fuel category does not participate much in the initial spread of a fire, we performed a sensitivity analysis to verify the range of moisture variations required to see a change in fire behavior predictions. Like Burgan and Rothermel (1984), we found that the 100h fuel category does not participate much in the propagation of a fire, they rather burn by smoldering combustion after the passage of a fire. Hence, we used random values of 9% and 11% to the 100h moisture content for the extreme and normal fire weather respectively. A description of the two moisture scenarios values and equilibrium moisture contents, can be found in Table 2.3.

Fire behavior prediction system background

For this study, the interest lied mostly on fire behavior intensity at the stand scale. We do not want to predict tree mortality nor soil severity (organic matter depth of burn). In each of the two prediction systems used (*FBP* and *BehavePlus*), we only wanted to compute the fire front rate of spread (ROS - m/min), the head fire intensity (HFI - kW/m), the area burned (AREA, ha burned in 2h) and the fire type (surface, intermittent or crowning fire). Both systems output is computed by generating the maximum fire behavior values obtained for each variable. Then, for AREA, the relation for both systems is the maximum rate of spread x time, which was set at two hours for both models.

The Canadian Fire Behavior Prediction Model (CFBPM system)

Detailed information about the Canadian Forest Fire Danger Rating System and its subsystems can be found in Canadian Forestry service (1987), Forestry Canada Fire Danger Group (1992), and Hirsch (1996). Here we will present a brief summary of the functions and capabilities of this system. The *CFBPM* system is composed of two sub-systems, the FWI (Van Wagner 1987) and the *FBP*. The FWI relates to the potential initial wildland fire behavior, while the *FBP* system relates to the actual ongoing fire behavior when the equilibrium state has been reached. The *FBP* system has 16 general fuel types, which represent many, but not all, of the major fuel types found in Canada (Hirsch 1996). For this study we mostly used the 4 types described earlier (C2, C3, C4 and M1/M2). For the weather inputs, the *FBP* system uses the FFMC and the BUI index from the FWI system (Van Wagner 1987, Amiro, 2004). These indexes are considered as fuel moisture in the uppermost litter layer and fire behavior index related to available fuel to burn, as they are calculated from 12:00 local standard time observations of temperature, relative humidity, wind speed, and precipitation for the previous 24 hours.

BehavePlus 5.0

The BEHAVE fire behavior prediction and its fuel sub-system, was among the early computer systems developed for wildland fire management (Burgan and Rothermel 1984). Since then, it has been updated and expanded, and is now called the *BehavePlus* fire modeling system to reflect its expanded scope (Andrews 2007). *BehavePlus* version 1.0 was released in 2002, versions, 2.0 and 3.0 added modeling capabilities and features in 2003 and 2005, version 4.0 was released in 2007 (Andrews 2007), and version 5.0, which adds only minor improvements on version 4.0, was released in June 2009. Unlike *FBP*, *BehavePlus* features more fuel modeling capabilities enabling the user to choose from 53 standard fire behavior fuel models including the original 13 described by Anderson (1982), plus the forty defined by Scott and Burgan (2005). Added to this, the user has the possibility to modify the existing fuel models, making the fuel modeling capabilities limitless. *BehavePlus* provides also means of modeling fire behavior parameters such as the *FBP* (ROS, HFI, crowning and spotting distance) and fire effects (such as scorch height and tree mortality. As mentioned earlier, only ROS, HFI, AREA and fire type were used in this study.

Simulation characteristics

FBP simulations

FBP does not allow much freedom when it comes to fuel models. The user has to choose amongst 16 fuel models, but only four reflected the stand structure and fuel quantity of the studied plots: C2 (*Picea mariana* dominated site), C3 (mature *Pinus banksiana* dominated site), C4 (immature pine stand) and M1/M2 (spring/summer; mixed stand with relative coniferous stem fraction provided by the user).

To better handle fuel type variation in stands, we attributed different percentage combinations to each plot (Tables 2.1 and 2.2), based on the characteristics given for each fuel type by Stocks *et al.* (1987). For example, a certain plot could have been characterized as being 80% C2 and 20% C3. The fire behavior outputs of this particular plot would then be the relative weighted mean of the two fire behavior outputs. In total, 20 runs were performed in *FBP*, based on the different percentage combinations (9) and the different conifer compositions for M2 (11). Due to the low representation of M2 in other initial compositions, simulations were done both for summer and spring in the case of PTR. This way, we acknowledge the unequal potential fire behavior in deciduous stands with and without leaves. GPS locations were set to the center of the study area, with no effect of wind direction, slope, aspect and elevation. Finally, we set the duration of the fire to 2 hours (using line ignition) to ensure that we have large enough area burned values (ha) and to compare with *BehavePlus*.

BehavePlus simulations

For the *BehavePlus* simulations, we built a custom fuel model for each plot, as all the data needed was available. Therefore, we made 61 fuel models X 2 moisture scenarios, for a total of 122 runs. The worksheet used in *BehavePlus* is shown in Appendix 1. Many values were held constant for all the *BehavePlus* runs. For example, live herbaceous and live woody surface area to volume ratio (SA/V cm^{-1}) were held constant with respective values of 115 and 80 cm^{-1}, dead and live fuel heat contents were held constant at 18700 kJ/kg and a moisture of extinction of 25% was used for all simulations (Schimmel and Granström 1997). We used the numbers of Schimmel and Granström (1997) because 1) their climate is similar to ours and 2) their study area is relatively similar to the boreal forest of the region, where, in their case, different assemblages of pleurocarpous mosses, *Picea spp.*, *Betula spp.* and *Pinus sylvestris* are present. Only the soils are different, with till type soils instead of clay. For canopy bulk density (kg/m^3), we used a constant of 0.112 kg/m^3, which is the value of bulk density that Scott & Reinhardt (2005) have found for the Lodgepole pine, a tree species similar to the Jack pine and Black spruce. We used this value as a constant because, after some experimentation with the numbers, we noticed that the canopy bulk density variable did not have a great influence on the outputs in fire behavior given by *BehavePlus*. Finally, the slope was held at 0, the elapsed time at 2 hours and the wind adjustment factor (WFA) at 0.3, to reflect the partial sheltering from wind inside the forests we estimated from the ratio of canopy height to total tree height.

Many other variables changed from plot to plot (Table 2.1). First, the 1h SA/V (cm^{-1}) for litter fuels changed depending on the relative presence of mosses, versus other types of less dense litter materials. Schimmel & Granström (1997) used values of 115 cm^{-1} for pleurocarpous mosses and fruticose lichens, and values of 45 cm^{-1} for other types of soil coverings like needles, bark fragments and dwarf-shrub litter. In this case we only had two types of soil coverings, bryophytes (*Sphagnum spp.* and *Pleurozium sp.*) and dead leaf litter. Therefore we balanced the 1h SA/V value in each site using their values, depending on the % cover of mosses. For fuel loadings (ton/ha) of 1h, 10h, 100h, live herbaceous and live woody components, we used the data we have measured in the field with the techniques described above. For fuel bed depth (m), we used the mean height of shrubs that we also measured on site. Likewise, canopy base height (m) value was linked to the mean low branch heights for each sub-plot that we have assessed visually. Finally, for the foliar moisture input, we used the values of 80% and 90% published by Chrosciewicz (1986) for, respectively, Black spruce and Jack pine for the month of July. For trembling aspen, we used the graph presented in an advanced course on fire behavior presented by the SOPFEU (2006, section 2B) to find the value of 105% of foliar moisture during the month of July. With the foliar moisture contents of every dominant tree species, we could balance the mean moisture content, based on the surface area ratio of each species, to the closest 5% (Table 2.1).

Statistical analyses

For analysis purposes, we decided to classify inventoried plots within four age classes: 1: 0-50 years, 2: 50-100 years, 3: 100-150 years and 4: >150 years. We also distributed plots among 4 initial compositions for *BehavePlus* (PTR, PBA, PMA-S, PMA-N) and 5 initial compositions for *FBP*. The additional chronosequence in *FBP* is the trembling aspen without leaves (PTR spring) that we created by changing the fuel type in all the plots where we used M2 for M1 (leafless boreal mixedwood). The purpose of verifying the fire behavior of deciduous stands in the spring is because we wanted a realistic comparison with other chronosequences. Most of the fires in these stands are spring fires, as no leaves with a high moisture content limit the propagation of the fire. With these initial compositions and age classes, we were mainly interested in understanding the effects of TSF (age classes) initial compositions, and their interaction (TSF*initial compositions) on four fire behavior outputs: ROS, HFI and area burned from both fire behavior models (*FBP* and *BehavePlus*) and both weather scenarios (normal and extreme fire weather). To test these effects, we used the ANOVA technique, for a total of 12 ANOVAs. When it was impossible to obtain a normal distribution of the residuals, we re-performed an ANOVA, but on transformed data in ranks. For what pertains to the effects of age classes and initial compositions on "fire type" (surface, intermittent or crown fire), we used the khi^2 analyses. To be sure that the age class attribution did not shadow any variable effect that could have existed, we also performed regression analyses. In all, 12 regressions were performed. We tested regressions three levels (R^1, R^2, R^3) of equations with a stepwise regression. When building and choosing the models the aim was to include as few factors as possible and get the best significance level possible. Finally, for *FBP*, having a normal distribution of the residuals was arduous, and most of the time, impossible. Therefore, we ranked the values from 1 to 100 and made an ANOVA on these values.

RESULTS

Comparisons of the two fire behavior prediction systems

In resume, for *BehavePlus*, the values for the ROS ranged from 0 to 8.7 m/min. with averages of 2.1 and 2.6 respectively for the normal and extreme fire weather (Table 2.4). For HFI, the values ranged from 0 to 239 kW/m with averages of 35.9 and 44.0 kW/m for the 50^{th} and 95^{th} percentile (Table 2.4). Finally, the area burned values varied from 0 to 65.2 ha for average values of 6.7 and 8.9 ha for both fire weathers (Table 2.4). On the other side, values for *FBP* were much higher, and thus, more realistic for the region. For the Canadian model, the ROS ranged from 0.1 to 20.1 m/min. with respective average values of 1.9 and 15.0 m/min. for the normal and extreme fire weathers (Table 2.5). The values of HFI ranged from 25 to 19 800 kW/m, with averages of 1370.8 and 13 984.6 kW/m for the normal and extreme fire weathers (Table 2.5). *FBP* also predicted much larger burned areas with values ranging between 0 and 296.7 ha. The fire weather average values for this parameter were equal to 3.9 and 204.4 ha burned (Table 2.5). Moreover, all fire parameters were more intense in the spring simulations compared to the ones in the summer. With respect to fire types, *BehavePlus* simulations resulted in surface fires 67% of the time, while only 33% resulted in intermittent fires (Table 2.6). No crown fires were produced. In *FBP*, 25% were surface fires, 39% were intermittent fires and the remaining 36% were crown fires (Table 2.7).

Of course, what should be observed is purely hypothetical in this case, since we have not performed experimental burns to compare the outputs of both fire behavior prediction systems with real observed values. However, this situation where *BehavePlus* greatly underestimates fire behavior was also noted by Hély *et al.* (2001). The authors had found that *Behave's* predictions were so low, that they would only correspond to smoldering fires in deep organic layers, when in reality, harsher fire behavior had been achieved in their test burns. Also, most of the time, *Behave* did not even achieve a minimum threshold beyond which a fire could propagate. These differences could come from the fact that for *BehavePlus*, we used custom fuel complexes, whereas for *FBP*, we used preset fuel types, and all the problems associated with it as mentioned earlier.

Effects of initial compositions and TSF on fire behavior in *BehavePlus*

In general, the difference in fire speed, intensity, area and type was negligible between normal and extreme fire weather scenarios in *BehavePlus* (Table 2.4). The values for the extreme fire weather scenario are always higher than the normal fire weather scenario, but never reach twice the normal value. For example, the highest average value for ROS 50 is 5.1 m/min., whereas for ROS 95 it is 6.0 m/min. (Table 2.4). Regarding ANOVAs, interactions (initial compositions*TSF) were found for both fire weather scenarios in ROS (Table 2.4, p=0.0317 and p=0.0306) and AREA (Table 2.4, p=0.0449 and p=0.0396), whereas no significant factors were observed for HFI. For these variables, an in depth analysis of average values reveals that this effect is mostly controlled by the initial composition rather than by the TSF. Noticeable intra-pathway patterns include the difference between PTR values and the values of the three other coniferous chronosequences in which PTR has always the lowest values (Table 2.4). The PTR chronosequence was also most different from PMA-N, as we always found the highest average values of ROS and AREA. PBA and PMA-S were intermediates between the two.

This was also confirmed by the X^2 analysis for fire type (Table 2.6), where more surface fires and less intermittent fires were produced in PTR than what was expected for both fire weather scenarios. For both HFI (normal and extreme fire weather scenarios) no significant effects were found. However, it is interesting to note that this variable seems to follow a different pattern than the ROS and AREA. In

HFI, the chronosequence with the highest values is PTR and the weakest is PMA-N. Again, PBA and PMA-S are intermediates.

With respect to TSF effects, we found no general and synchronized pattern with TSF for all initial compositions in *BehavePlus*. This situation was expected since different initial compositions may have different timings of structural changes (density, productivity, composition). Nevertheless, some intra pathway trends were observed. The most obvious are the average values of PTR and PMA-N for all variables, which seem to decrease with TSF. However, the regression analyses only confirm this trend for ROS 50 (p=0.0347) and 95 (p=0.0362) in PMA-N (Figure 2.3), as they gradually decrease up to 200 years, and re-increase afterwards. Also, it appears that this modification in ROS with TSF for PTR and PMA-N is not large enough to produce different fire types in *BehavePlus*, as the khi^2 analyses show no difference in expected and observed fire types for each age classes, except for PMA-N in the first age class (0-50 years after fire) where more intermittent fires are observed vs. expected (Table 2.6). For PBA, the regression analyses show that the ROS 50 (p=0.0293) and 95 (p=0.0195) increase up to a plateau near 150 years after fire, and decrease very slowly afterwards (Figure 2.3). This is also visible in the khi^2 analyses where from 100 to 150 years old, more intermittent fires are observed than what was expected (Table 2.6).

Effects of initial compositions and TSF on fire behavior in *FBP*

In opposite to what was found in *BehavePlus*, the difference between the results of the normal and extreme fire weather scenarios were very important within *FBP* (Table 2.5). In fact, the values of the extreme fire weather scenario were always at least seven times higher than the normal fire weather scenario. For example, the highest average ROS 50 calculated was 2.8 m/min. whereas in ROS 95 it reached 20.1 m/min (Table 2.5). Also, unlike *BehavePlus*, the effects of initial compositions, TSF and their interaction were all significant for all fire behavior parameters and in both fire weather scenarios. However, like in *BehavePlus*, when looking at the interaction effect, we observed that it is mostly affected by the initial composition rather than by the TSF. Interestingly, the inter-initial composition patterns are similar to what was found in *BehavePlus*. First, both PTR chronosequences (spring and summer) always have the weakest values for all fire behavior parameters, whereas PMA-N has the highest (Table 2.5). PBA and PMA-S are also intermediates between the two (Table 2.5). This was also obvious in the khi^2 analysis for fire type, where more surface fires were counted than expected in both PTR chronosequences (Table 2.7). Also, more high intensity fires (intermittent and crown) were counted in PMA-N compared to what was expected (Table 2.7). Interestingly, we found a very small difference between the two PTR chronosequences, spring simulations resulting in higher propagation speeds and intensity, but not important enough to make a difference on the fire type produced (Table 2.7).

Regarding intra-pathway TSF effects in *FBP*, two main tendencies are observed. First, in opposite to *BehavePlus*, all fire behavior parameters (not only HFI) seem to increase with TSF in both PTR chronosequences (Table 2.5). This is also confirmed by the regression analyses (Figure 2.4). Second, all coniferous chronosequences (PBA, PMA-S and PMA-N) have more or less constant propagation speeds, intensity and area burned with TSF (Table 2.5). One exception might be PBA between 50 and 100 years, where fire behavior parameters seem lower than other age classes (Table 2.5). This difference in ROS and HFI even seems large enough to produce less intense fire types in this age class (Table 2.7).

DISCUSSION

Effects of initial compositions and TSF on fire behavior

In the first chapter of this thesis, we have found that initial compositions were significantly different from each other in many of the fuel characteristics measured. In general, the computed fire behaviors of the two models we used translate these differences. Earlier in this work, we found that PTR was the initial composition with the highest value with respect to DWD load, followed by PBA which was an intermediate and the two initial compositions of black spruce (PMA-S and PMA-N) were the lowest. From this data, we expected the HFI and fire types to follow this general trend; and to a lesser degree the ROS which is more linked to the continuity between fuel layers and the fire weather than to the fuel load within the fire behavior simulation models. This was the case with *BehavePlus* in the average per initial compositions of both HFI 50 and 95. However, for *FBP*, PBA was intermediate but PTR (summer and spring) had the lowest HFI and the initial compositions of black spruce had the highest. We attribute this difference to the fact that *BehavePlus* deals with custom fuel loads, whereas *FBP* is limited to preset fuel types. We think this might have been an important problem in this research, as the variability in fuel complexes was hard to represent in *FBP*. Thus, we feel that a big part of the natural variations we encountered on site were not well represented in the *FBP* system.

For example, in *FBP*, the variations between the three coniferous types mostly came from the different proportions of each fuel type (C2, C3 and C4 mostly) attributed on site. We had to use judgment to attribute these types, based on the factors listed in the methods. As these measures are qualitative, the user has to gain experience of the fire behavior response of each fuel type first, and then, based on this knowledge, attribute a fuel type to a particular stand. This situation could be problematic for the casual user (like us) who wants to attribute a fuel type based on the structural attributes used to differentiate fuel models (*i.e.* litter compactness, DWD load, composition, canopy characteristics and structure of ladder fuels). We doubt that fire can move with more ease, and with more vigor in forests with less trees that are further from each other compared to a dense productive black spruce stand. In opened stands, fire would remain at the surface moving slowly through living shrubs while in dense productive plots, crowning could be achieved more easily and be sustained. We are not proposing that our inexperience might have biased the results; rather, we argue that this difficulty of incorporating black spruce stands structural differences only reinforces the fact that the *FBP* prediction system needs to add new fuel model types for unproductive, paludified black spruce stands, where the crown height would be lower, but with a much lower tree density. In fact, Pelletier *et al.* (2009) have encountered the same problem in their work of attributing an *FBP* fuel type to all major forest compositions across the Quebec province. The authors have come across black spruce sites (and other resinous stands) that were impossible to classify because they did not meet the structural nor the compositional characteristics of the preset fuel types of *FBP*. Rather, they attributed for these sites a C-2a type (C2-other). Moreover, when summing the area covered by undistinguished C2, about 77% of the land was attributed a C-2a for the commercial forest of Quebec.

Nonetheless, the ROS in both prediction systems were similar to the predetermined fuel data based on load, with a low ROS for PTR and higher similar ROS for the three coniferous initial compositions (PBA, PMA-S and PMA-N). These similarities indicate that the structural description of the plots in both systems (fuel type % in *FBP*; canopy base height and fuel bed depth for *BehavePlus*) were similar enough to produce similar relative ROS results. In fact, in both prediction systems, we found that PTR would never produce a HFI strong enough to produce a crown fire, since the canopy base height is higher than in the other chronosequences and leaves tend to burn with more difficulty than needles. Interestingly, for PTR we have found that fire behavior parameters tend to increase with TSF in *FBP*. This result makes sense, since the coniferous proportion of the stands increase with TSF, and this value has a large impact on the *FBP* calculations. However, in the first chapter, we showed that DWD tends to decrease with TSF and that there was no significant change in canopy base height with TSF in PTR. In *BehavePlus*, this fact is reproduced accurately as fire behavior parameters values decrease with TSF. This illustrates the important variations in results that one can get by using the two different fire behavior models. *FBP* neglects the finer fire behavior variations due to fuel load and structure of ladder fuels, whereas *BehavePlus* appears to give too much importance to fuel load and structure variations and overlooks tree composition.

Finally, for both prediction systems, fire behavior is always the weakest during the second age class in the PBA initial composition. For *BehavePlus*, this result comes from the fact that two of the plots of this age class have 0 for ROS and HFI because there was no shrubs and thus, a fuel bed depth of 0. These ROS values lower the average value. In *FBP*, most of the variations in fire behavior came from the fuel type proportions, and, from 50-100 years old in PBA, 100% of the plots were described by pure C3 to describe the higher canopy base and the sparse shrub layer, which explains the weak fire behavior. To explain this, we propose that post-fire fuels are totally degraded in jack pine stands of this age class, and the understory canopy is not well developed, limiting fire to the surface.

CONCLUSION

The objectives of this paper were to test the effects of initial composition and TSF on fire behavior based on empirical fuel data by using two fire behavior prediction systems: *BehavePlus* and *FBP*. We also wanted to test how different fuel characteristics get translated in the two fire behavior models. The results were that initial composition and TSF have different effects on fire behavior depending on the prediction system used, but some interesting similarities were observed. However, in both fire behavior models used, initial composition effects were more important. In *FBP* we have found the most plausible fire behavior, but we found few TSF effects.

This should only confirm that like in the previous chapter, we can conclude that TSF only has an indirect effect on fire behavior by changing the composition of the stands.

FBP then seems to be the best fire behavior model for use in the boreal forest of Canada as its predictions were realistic with the fire weather scenarios we used unlike *BehavePlus*, in which corresponding fires were mostly of very low intensity. By adding a new set of fuel types to *FBP* (incorporating a paludified black spruce type), all the problems associated with the difficulty of accurately describing stands with the preset fuel types could be limited and therefore produce more accurate fire behavior readings. We suggest that a special model type should be developed in *FBP*, representing opened, low-productivity black spruce sites resultant of paludification like proposed by Pelletier *et al.* (2009).

Finally, another limitation we encountered is that both fire behavior prediction systems lack modules to evaluate how much duff will burn by smoldering for different moisture scenarios, and, this measure is really the one that is important to understand how the accumulation of peat (hence paludification) might affect surface fire behavior. If fire is less frequent with climatic changes, leaving duff to accumulate for a longer period, maybe beyond a certain point all this organic material will become unburnable, even with high intensity fires. Therefore, we need to develop tools to understand smoldering combustion vs. moisture and the drying times associated for different litter materials. The model Canfire (Canadian fire), which is the new modification of the old model Borfire (Boreal fire - De Groot *et al. 2003*) is a new model in preparation that allows the user to calculate the depth of burn in different peat materials. This new tool will be useful in the understanding of the actual and future effects of paludification on fire behavior.

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FIGURES

Figure 2.1 – Ecoregion 96 (Abitibi plains) from which moisture scenario data was extracted in the Large Fire Database (Stocks *et al.* 2003)

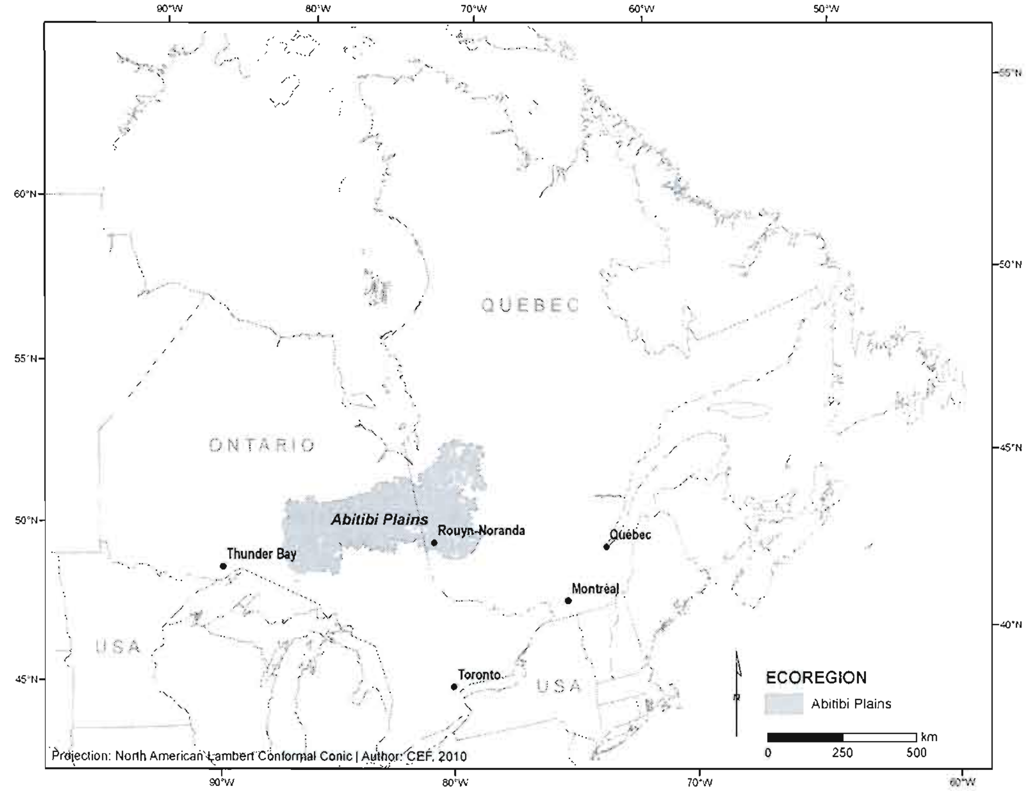
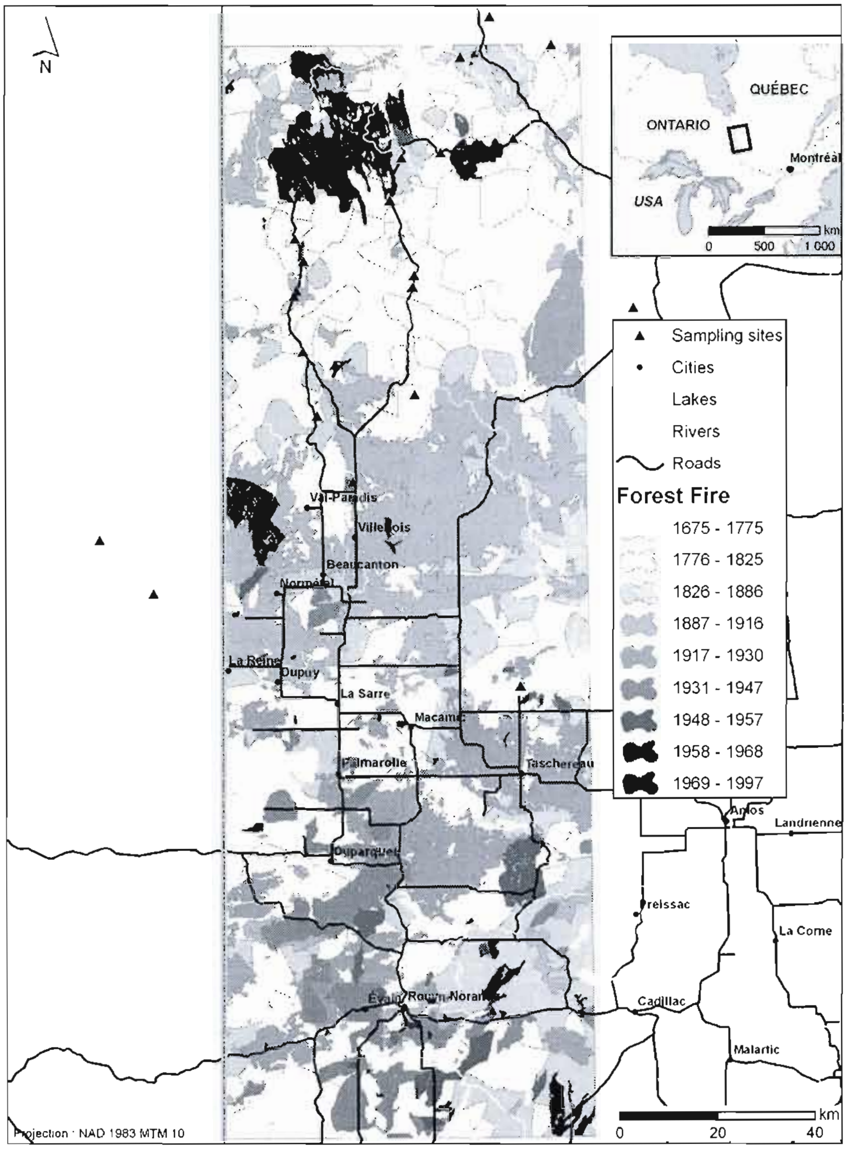


Figure 2.2 – Study area and sites (*due to scale, some sites overlap)



Forest Fire Map adapted from BERGERON, Y., GAUTHIER, S., FLANNIGAN, M., AND KAFKA, V. 2004. | Author: CEF, 2010

Figure 2.3 – Regression analyses for significant *BehavePlus* fire behavior outputs. PBA: ROS 50 *p=0.0293*; ROS 95 *p=0.0195*, PMA-N: ROS 50 *p=0.0347*; ROS 95 *p=0.0362*.

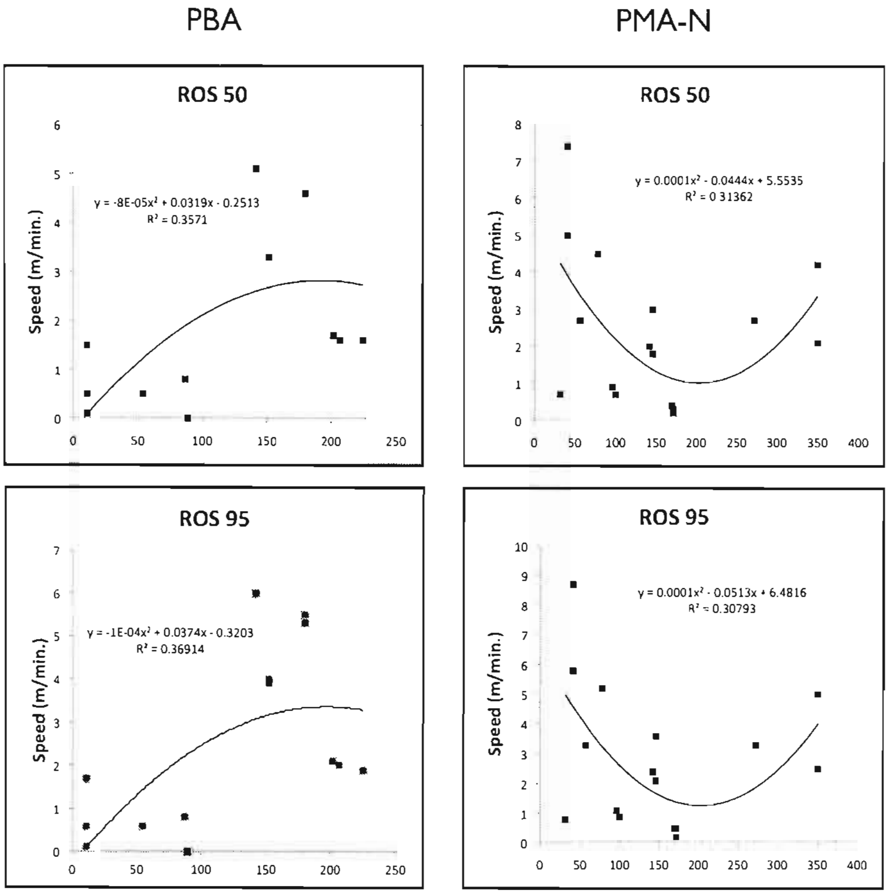
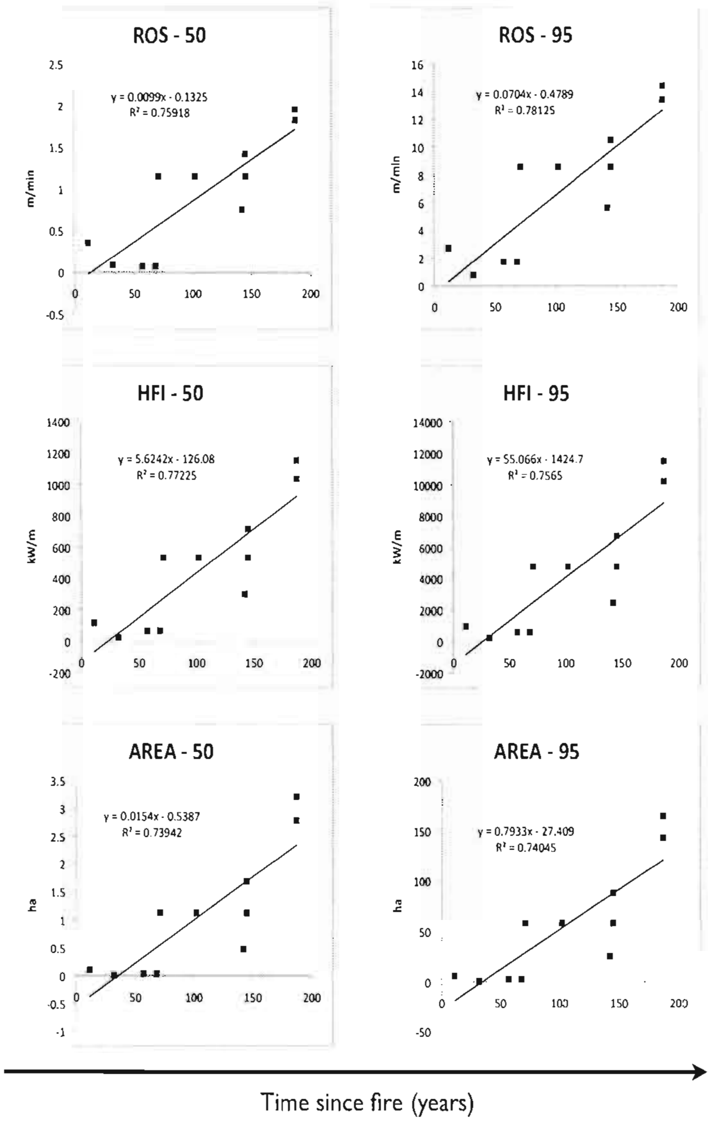


Figure 2.4 – Regression analyses for all *FBP* fire behavior outputs for the PTR initial composition.



TABLES

Table 2.1 - Input data by plot necessary for *BehavePlus* and *FBP*.

# Site	Age	Succession	Fuel load (ton/ha) 1h	10h	100h	Live woody	Live herbaceous	1h SA/V	Fuel bed depth (m)	Canopy base height (m)	Foliar moisture (%)	FBP fuel type	% conifer (M2)
PetC1	11	PTR	0,89	1,39	3,77	0,25	19,52	60,95	0,88	0,95	105	M2	10,0
Ptr64a	32	PTR	1,07	1,59	2,27	1,13	0,37	45,00	1,58	7,50	105	M2	0,0
Ptr64b	32	PTR	1,72	4,70	9,50	0,62	1,04	45,00	0,70	8,25	105	M2	0,0
Lofuel	57	PTR	0,00	0,85	2,85	2,24	1,77	45,00	1,25	10,00	105	M2	5,0
Andy 3	68	PTR	0,91	3,79	12,96	5,80	4,72	45,00	0,60	4,33	105	M2	5,0
Mask II	71	PTR	1,99	2,76	4,18	0,39	0,39	57,60	1,25	10,00	105	M2	40,0
Wmist	102	PTR	0,82	2,01	5,39	0,03	0,29	49,50	0,13	8,00	105	M2	40,0
Mir 1	142	PTR	0,40	1,99	1,16	0,02	0,00	115,00	0,80	0,70	90	M2	25,0
Andy 1A	145	PTR	1,50	1,09	2,91	0,24	0,00	102,31	0,53	5,75	90	M2	50,0
Andy 1B	145	PTR	1,00	2,50	4,24	0,10	0,49	96,15	0,53	6,00	90	M2	40,0
Jou2B (a)	187	PTR	0,96	1,39	4,36	2,04	3,77	45,00	2,00	12,75	80	M2	65,0
Jou2B (b)	187	PTR	0,53	1,46	3,85	0,02	1,08	45,00	0,15	8,00	80	M2	70,0
RS4 B New	11	PBA	1,98	2,34	20,38	0,42	0,77	45,00	0,08	0,25	90	C4	
RS4 New	11	PBA	2,21	2,63	20,44	1,01	0,24	45,00	0,30	0,14	90	C4	
2RS3	11	PBA	0,74	0,36	0,26	0,53	0,20	115,00	0,20	0,08	90	C4	
54	54	PBA	0,84	1,39	6,05	0,00	0,15	115,00	0,18	4,00	90	C3	
38	87	PBA	0,31	0,63	6,82	0,01	0,40	115,00	0,33	3,50	80	50% C2, 50% C3	
23B	89	PBA	0,84	0,89	4,03	0,09	0,11	115,00	0,00	5,00	90	C3	
23	89	PBA	0,43	1,65	7,84	0,16	0,02	115,00	0,00	6,00	90	C3	
69	142	PBA	0,95	2,11	2,66	0,41	0,04	115,00	1,35	0,00	90	100% C2	
66B	152	PBA	0,37	0,10	0,00	0,23	0,00	115,00	0,30	8,75	80	C3	
66A	152	PBA	0,49	0,43	2,44	0,06	0,00	115,00	0,83	4,00	80	80% C2, 20% C3	
83B	180	PBA	0,43	0,78	0,52	0,33	0,00	115,00	1,00	2,75	90	80% C2, 20% C3	
83	180	PBA	0,64	1,85	0,79	1,20	0,00	115,00	1,27	0,33	80	100% C2	
65B	202	PBA	0,82	1,40	2,14	0,10	0,00	115,00	0,35	0,25	80	100% C2	
65	207	PBA	0,38	0,65	1,55	0,09	0,00	115,00	0,43	2,50	80	80% C2, 20% C3	
64	225	PBA	0,27	0,44	1,16	0,20	0,00	113,06	0,53	0,25	80	100% C2	
60B	32	PMA-S	0,26	0,12	0,45	0,45	0,00	115,00	0,20	0,00	80	M2	95,0
34E	32	PMA-S	1,02	0,63	0,52	0,27	0,00	73,00	0,58	0,13	80	M2	80,0
59C	32	PMA-S	0,52	0,57	1,00	0,71	0,00	98,67	0,24	0,00	80	M2	85,0
4	55	PMA-S	0,40	0,29	0,42	0,28	0,00	108,64	0,78	0,00	80	100% C2	
2	87	PMA-S	0,58	0,57	1,00	1,61	0,06	115,00	0,38	0,00	80	100% C2	
57New	91	PMA-S	0,62	0,51	3,06	0,01	0,00	115,00	0,48	5,50	80	60% C2, 40% C3	
18A	129	PMA-S	0,72	0,33	6,41	0,15	0,00	115,00	0,33	2,00	80	60% C2, 40% C3	
18B	129	PMA-S	0,29	0,56	5,95	0,14	0,00	115,00	0,43	2,75	80	80% C2, 20% C3	
Andy 1C	145	PMA-S	0,40	0,61	2,60	0,16	0,17	113,25	0,41	6,75	80	50% C2, 50% C3	
Andy 1D	145	PMA-S	0,51	0,43	2,36	0,09	0,00	115,00	0,63	4,75	80	50% C2, 50% C3	
C-150	165	PMA-S	1,00	0,12	1,50	0,18	0,44	115,00	0,55	3,25	80	70% C2, 30% C3	
8	177	PMA-S	1,38	0,83	1,65	0,81	0,27	115,00	0,70	1,88	80	100% C2	
POP	181	PMA-S	0,46	0,75	4,44	0,08	0,20	115,00	1,18	6,25	80	40% C2, 60% C3	
50	225	PMA-S	0,53	0,85	2,46	0,16	0,05	115,00	0,48	0,15	80	90% C2, 10% C3	
L22	272	PMA-S	0,62	0,35	1,46	0,15	0,00	115,00	0,50	1,00	80	100% C2	
16	283	PMA-S	0,50	2,04	2,43	0,87	0,09	115,00	0,45	0,00	80	100% C2	
6	283	PMA-S	0,56	1,20	0,67	1,24	0,00	115,00	1,28	0,00	80	100% C2	
20	356	PMA-S	0,36	0,28	1,43	0,48	0,12	111,50	0,55	0,13	80	100% C2	
62D	32	PMA-N	0,26	0,68	2,68	0,05	0,33	115,00	0,35	0,13	80	100% C2	
11A	41	PMA-N	0,50	0,08	0,00	0,45	0,00	105,56	0,80	0,00	80	100% C2	
11B	41	PMA-N	0,80	0,52	0,26	0,64	0,00	106,83	0,70	0,13	80	100% C2	
53	57	PMA-N	0,56	0,58	1,09	0,00	0,00	115,00	0,40	1,75	80	80% C2, 20% C3	
78	78	PMA-N	0,29	0,25	0,23	0,33	0,11	115,00	0,88	0,00	80	100% C2	
3	96	PMA-N	0,39	0,53	1,36	0,17	0,07	112,70	0,26	0,50	80	100% C2	
60	100	PMA-N	0,17	0,09	0,62	0,27	0,03	115,00	0,33	0,00	80	100% C2	
68	142	PMA-N	0,55	1,84	1,62	0,17	0,00	115,00	0,53	0,08	80	100% C2	
63	146	PMA-N	0,58	0,47	2,17	0,10	0,00	108,00	0,70	2,75	80	80% C2, 20% C3	
63B	146	PMA-N	0,68	0,68	3,34	0,10	0,00	112,28	0,45	5,00	80	70% C2, 30% C3	
Chafi #5	170	PMA-N	0,37	0,17	1,69	0,86	0,22	115,00	0,43	1,75	80	100% C2	
5	172	PMA-N	0,28	0,54	2,21	1,80	0,00	115,00	0,40	1,50	80	100% C2	
5B	172	PMA-N	0,46	0,38	2,48	1,08	0,09	115,00	0,30	4,25	80	100% C2	
L9724	272	PMA-N	0,57	0,09	0,45	0,11	0,75	115,00	0,48	0,00	80	100% C2	
H1A	350	PMA-N	0,57	0,14	3,23	0,09	0,00	115,00	0,60	1,00	80	100% C2	
H1B	350	PMA-N	0,90	0,26	0,23	0,11	0,09	115,00	0,33	0,75	80	100% C2	

Table 2.2 – *FBP* fuel type attributions per age class and initial compositions.

Age class	Successional pathways			
	PTR	PBA	PMA-S	PMA-N
0-50 years	100% M2 n=3	100% C4 n=3	100% M2 n=3	100% C2 n=3
50-100 years	100% M2 n=3	100% C3 n=4	87% C2 13% C3 n=3	95% C2 5% C3 n=4
100-150 years	100% M2 n=4	63% C3 37% C2 n=1	63% C2 37% C3 n=4	83% C2 17% C3 n=3
150+ years	100% M2 n=2	77% C2 23% C3 n=7	88% C2 12% C3 n=8	100% C2 n=6

Table 2.3 - Weather values for the two weather scenarios (Values computed from the day of highest FWI for each 11 fires).

	Percentile	
	50th	**95th**
AREA (ha)	1078.33	3803.37
Temp. (°C)	25.98	25.04
HR (%)	40.08	30.47
Wind (km/h)	12.67	13.53
FFMC	83.36	93.19
BUI	56.60	64.64
FWI	22.75	33.89
EMC (%)	7.60	6.10
1h (% humidity)	7.83	6.28
10h (% humidity)	9.73	7.81
100h (%humidity)	11.00	9.00

Table 2.4 – Comparison of rate of spread (ROS), head fire intensity (HFI) and area burned values for the two fire weather scenarios as computed with *BehavePlus*.

		Successional pathways					
	Age Class	**PTR**	**PBA**	**PMA-S**	**PMA-N**	**Average**	*p*
	0-50 years	2.0^{ABCD}	0.7^{CD}	1.9^{ABCD}	4.4^{A}	2.24	Succession: $p=0.5400$
ROS 50*	**50-100 years**	2.0^{ABCD}	0.3^{D}	2.3^{ABCD}	2.2^{ABCD}	1.72	TSF: $p=0.5153$
(m/min.)	**100-150 years**	2.1^{ABCD}	**5.1** ^{A}	1.5^{BCD}	2.3^{ABCD}	2.73	Interaction: $p=0.0317$
	150+ years	0.8^{BCD}	3.0^{AB}	2.8^{ABC}	1.7^{BCD}	2.05	
	Average	1.7	2.3	2.1	2.6		
	0-50 years	2.3^{ABCD}	0.8^{CD}	2.3^{ABCD}	5.1^{A}	2.62	Succession: $p=0.5003$
ROS 95*	**50-100 years**	2.3^{ABCD}	0.2^{D}	2.8^{ABCD}	2.6^{ABCD}	1.98	TSF: $p=0.4950$
(m/min.)	**100-150 years**	2.5^{ABCD}	**6.0** ^{A}	1.8^{BCD}	2.7^{ABCD}	3.24	Interaction: $p=0.0306$
	150+ years	0.9^{BCD}	3.5^{AB}	3.3^{ABC}	2.0^{BCD}	2.43	
	Average	2.0	2.6	2.5	3.1		
	0-50 years	87.7	30.0	34.0	51.0	50.67	Succession: $p=0.1838$
HFI 50	**50-100 years**	86.7	6.8	18.3	14.3	31.50	TSF: $p=0.3697$
(kW/m)	**100-150 years**	39.8	**98.0**	19.5	25.0	45.56	Interaction: $p=0.1311$
	150+ years	14.5	32.7	50.0	19.3	29.14	
	Average	57.1	41.9	30.5	27.4		
	0-50 years	103.7	35.7	41.7	61.7	60.67	Succession: $p=0.2121$
HFI 95	**50-100 years**	104.0	7.8	22.7	18.0	38.10	TSF: $p=0.3895$
(kW/m)	**100-150 years**	49.5	**122.0**	24.0	31.3	56.71	Interaction: $p=0.1266$
	150+ years	17.5	39.7	62.1	25.7	36.25	
	Average	68.7	51.3	37.6	34.2		
	0-50 years	6.1^{ABCD}	0.7^{CD}	5.6^{ABCD}	24.2^{AB}	9.14	Succession: $p=0.6820$
AREA 50*	**50-100 years**	5.5^{ABCD}	0.2^{D}	11.2^{ABCD}	6.5^{ABCD}	5.84	TSF: $p=0.4377$
(ha)	**100-150 years**	5.5^{ABCD}	**23.5** ^{A}	2.3^{ABCD}	4.9^{ABC}	9.05	Interaction: $p=0.0449$
	150+ years	0.8^{BCD}	9.4^{AB}	8.2^{AB}	4.4^{ABCD}	5.68	
	Average	4.5	8.5	6.8	10.0		
	0-50 years	7.6^{ABCD}	0.9^{CD}	7.4^{ABCD}	31.8^{AB}	11.93	Succession: $p=0.5956$
AREA 95*	**50-100 years**	7.1^{ABCD}	0.2^{D}	7.5^{ABCD}	8.7^{ABC}	5.88	TSF: $p=0.3848$
(ha)	**100-150 years**	7.7^{ABC}	**31.6** ^{A}	3.2^{ABCD}	6.8^{ABC}	12.30	Interaction: $p=0.0396$
	150+ years	1.0^{BCD}	12.5^{A}	11.0^{AB}	6.2^{ABCD}	7.66	
	Average	5.8	11.3	7.3	13.4		

* ANOVA results achieved by transforming data with the Box Cox transformation.

Data in bold - Note that the average value of PBA between 100-150 years contains only one replicate (n=1).

Table 2.5 – Comparison of rate of spread (ROS), head fire intensity (HFI) and area burned values for the two fire weather scenarios as computed with *FBP*.

		Successional pathways						
	Age Class	PTR Spring	PTR Summer	PBA	PMA-S	PMA-N	Average	p*
ROS 50 (m/min)	0-50 years	0.5 ^{E}	0.2 ^{E}	2.8 ^{A}	2.4 ^{ABCD}	2.6 ^{ABCD}	1.98	
	50-100 years	0.9 ^{DE}	0.4 ^{E}	0.5 ^{E}	2.3 ^{ABC}	2.5 ^{AB}	1.44	Succession: $p<0.0001$ Age class: $p=0.0001$
	100-150 years	1.4 ^{CDE}	1.1 ^{DE}	2.6 ^{ABCD}	1.5 ^{CDE}	2.2 ^{ABCD}	1.85	Interaction: $p<0.0001$
	150+ years	2.1 ^{ABCDE}	1.9 ^{BCDE}	2.0 ^{BCD}	2.3 ^{AB}	2.6 ^{AB}	2.21	
	Average	1.2	0.9	2.0	2.1	2.5		
ROS 95 (m/min)	0-50 years	4.3 ^{F}	1.4 ^{F}	20.1 ^{A}	17.6 ^{BCDE}	19.3 ^{ABCD}	14.61	
	50-100 years	6.5 ^{EF}	4.0 ^{F}	11.0 ^{DEF}	16.1 ^{ABCD}	19.3 ^{AB}	12.62	Succession: $p<0.0001$ Age class: $p=0.0003$
	100-150 years	10.2 ^{DEF}	8.3 ^{EF}	19.3 ^{ABCD}	12.0 ^{CDEF}	17.2 ^{ABCD}	14.18	Interaction: $p<0.0001$
	150+ years	14.9 ^{BCDEF}	13.9 ^{BCDEF}	17.1 ^{BC}	17.8 ^{AB}	19.3 ^{AB}	17.02	
	Average	9.0	6.9	16.9	15.9	18.8		
HFI 50 (kW/m)	0-50 years	166.7 ^{FG}	56.0 ^{G}	1362.0 ^{ABCDEF}	1594.0 ^{ABCDE}	2034.0 ^{ABCD}	1261.50	
	50-100 years	340.7 ^{EFG}	224.0 ^{FG}	353.1 ^{FG}	1637.6 ^{ABC}	2005.2 ^{A}	1054.98	Succession: $p<0.0001$ Age class: $p=0.0003$
	100-150 years	647.0 ^{CDEFG}	521.5 ^{DEFG}	2034.0 ^{ABCD}	1105.1 ^{BCDEFG}	1666.3 ^{ABCDE}	1331.72	Interaction: $p=0.0016$
	150+ years	1217.0 ^{ABCDEFG}	1096.0 ^{ABCDEFG}	1594.9 ^{AB}	1795.2 ^{AB}	2034.0 ^{A}	1630.03	
	Average	592.8	474.4	1336.0	1533.0	1934.9		
HFI 95 (kW/m)	0-50 years	1432.7 ^{E}	483.0 ^{E}	18817.0 ^{ABCD}	16387.3 ^{ABCD}	19800.0 ^{ABC}	13871.83	
	50-100 years	3008.7 ^{E}	1980.3 ^{E}	9101.4 ^{CDE}	16063.0 ^{ABC}	19574.6 ^{AB}	11679.83	Succession: $p<0.0001$ Age class: $p=0.0012$
	100-150 years	7053.8 ^{DE}	4678.5 ^{E}	19800.0 ^{ABC}	10239.9 ^{CDE}	16457.9 ^{ABCD}	12794.10	Interaction: $p=0.0030$
	150+ years	11667.0 ^{BCDE}	10861.5 ^{BCDE}	15328.4 ^{ABC}	17636.8 ^{AB}	19800.0 ^{A}	15906.68	
	Average	5790.5	4500.8	15761.7	15081.8	18908.2		
AREA 50 (ha)	0-50 years	0.3 ^{F}	0.0 ^{F}	6.4 ^{A}	4.9 ^{ABC}	5.6 ^{ABCDE}	4.23	
	50-100 years	0.8 ^{EF}	0.4 ^{F}	0.7 ^{F}	4.6 ^{ABCD}	5.6 ^{AB}	2.82	Succession: $p<0.0001$ Age class: $p=0.0005$
	100-150 years	1.7 ^{DEF}	1.1 ^{EF}	5.6 ^{ABCDE}	3.1 ^{CDEF}	4.8 ^{ABCDE}	3.66	Interaction: $p<0.0001$
	150+ years	3.8 ^{BCDEF}	3.0 ^{BCDEF}	4.4 ^{BCD}	5.1 ^{ABC}	5.6 ^{AB}	4.52	
	Average	1.7	1.1	4.3	4.4	5.4		
AREA 95 (ha)	0-50 years	15.72 ^{GH}	2.22 ^{H}	322.24 ^{A}	248.89 ^{BCDEF}	296.73 ^{ABCDE}	217.52	
	50-100 years	41.29 ^{GH}	20.92 ^{GH}	91.15 ^{EFGH}	240.33 ^{ABCD}	293.21 ^{AB}	161.40	Succession: $p<0.0001$ Age class: $p=0.0002$
	100-150 years	87.68 ^{FGH}	57.22 ^{GH}	296.73 ^{ABCDE}	146.81 ^{CEFG}	232.14 ^{BCDEF}	183.22	Interaction: $p<0.0001$
	150+ years	185.67 ^{BCDEFG}	154.06 ^{CDEFGH}	210.81 ^{BCDE}	270.80 ^{ABD}	296.73 ^{AB}	233.10	
	Average	82.6	58.6	230.2	226.7	279.7		

* - p value for ANOVA

Table 2.6 – Comparison of fire type per initial compositions or age class by initial compositions as computed with *BehavePlus*.

A) Normal fire weather

Successionnal pathways effect

(p=0,0644)

		Successional pathways			
Fire type	Value	PTR	PBA	PMA-S	PMA-N
Surface	*Observed*	**12 +**	10	10	10
	Expected	**8.26**	10.33	12.39	11.02
	X^2	**1.69**	0.01	0.46	0.09
Intermittent	*Observed*	**0 -**	5	8	6
	Expected	**3.73**	4.67	5.61	4.98
	X^2	**3.73**	0.02	1.02	0.21

Age class effect for PTR

(p=N/A)

		Age classes			
Fire type	Value	0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	3	3	4	2
	Expected	3	3	4	2
	X2	0	0	0	0

Age class effect for PBA

*(p=0,089)**

		Age classes			
Fire type	Value	0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	1	4	0	5
	Expected	2	2.66	0.66	4.67
	X2	0.5	0.67	0.67	0.02
Intermittent	*Observed*	2	**0 -**	**1 +**	2
	Expected	1	**1.33**	**0.33**	2.33
	X2	1	**1.33**	**1.33**	0.05

Age class effect for PMA-S

*(p=0,065)**

Fire type	Value	*Age classes* 0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	**0 -**	2	**4 +**	4
	Expected	**1.67**	1.67	**2.22**	4.44
	X2	**1.67**	0.67	**1.42**	0.04
Intermittent	*Observed*	**3 +**	1	**0 -**	4
	Expected	**1.33**	1.33	**1.78**	3.56
	X2	**2.08**	0.08	**1.78**	0.06

Age class effect for PMA-N

*(p=0,132)**

Fire type	Value	*Age classes* 0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	**0 -**	3	2	5
	Expected	**1.87**	2.5	1.86	3.75
	X2	**1.86**	0.1	0.0083	0.42
Intermittent	*Observed*	**3 +**	1	1	1
	Expected	**1.13**	1.5	1.13	2.25
	X2	**3.13**	0.17	0.014	0.69

B) Extreme fire weather

Successionnal pathways effect

(p=0,0312)

Fire type	Value	*Successional pathways* PTR	PBA	PMA-S	PMA-N
Surface	*Observed*	**12 +**	10	9	9
	Expected	**7.86**	9.84	11.8	10.49
	X^2	**2.17**	0.0027	0.66	0.21
Intermittent	*Observed*	**0 -**	5	**9 +**	7
	Expected	**4.13**	5.16	**6.2**	5.51
	X^2	**4.13**	0.0052	**1.27**	0.4

Age class effect for PTR

(p=N/A)

Fire type	Value	Age classes 0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	3	3	4	2
	Expected	3	3	4	2
	X2	0	0	0	0

Age class effect for PBA

*(p=0,089)**

Fire type	Value	Age classes 0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	1	4	0	5
	Expected	2	2.67	0.67	4.67
	X2	0.5	0.67	0.67	0.02
Intermittent	*Observed*	2	**0 -**	**1 +**	2
	Expected	1	**1.33**	**0.33**	2.33
	X2	1	**1.33**	**1.33**	0.05

Age class effect for PMA-S

*(p=0,056)**

Fire type	Value	Age classes 0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	**0 -**	1	**4 +**	4
	Expected	**1.5**	1.5	**2**	4
	X2	**1.5**	0.17	**2**	0
Intermittent	*Observed*	**3 +**	2	**0 -**	4
	Expected	**1.5**	1.5	**2**	4
	X2	**1.5**	0.17	**2**	0

Age class effect for PMA-N

*(p=0,145)**

Fire type	Value	Age classes 0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	**0 -**	2	2	5
	Expected	**1.69**	2.25	1.69	3.38
	X2	**1.69**	0.03	0.06	0.78
Intermittent	*Observed*	**3 +**	2	1	1
	Expected	**1.31**	1.75	1.31	2.63
	X2	**2.17**	0.04	0.07	1

Numbers in **bold** are categories where observed and expected values are significatively different from each other. Freeman-Tukey deviate = 1,2

*Indicates we used the "Exact Contingency Method" as many cells were inferior to an observed value <5

Table 2.7 – Comparison of fire type per initial compositions or age class by initial compositions as computed with *FBP*.

A) Normal fire weather

Successionnal pathways effect

(p=<0,0001) - Freeman-Tukey deviate = 1,2

		Successional pathways				
Fire type	Value	PTR spring	PTR summer	PBA	PMA-S	PMA-N
Surface	*Observed*	**12**	**12**	8	**4**	**0**
	Expected	**5.92**	**5.92**	7.4	**8.88**	**7.89**
	X^2	**6.25**	**6.25**	0.05	**2.68**	**7.89**
Intermittent	*Observed*	**0**	**0**	7	**14**	**16**
	Expected	**6.08**	**6.08**	7.6	**9.12**	**8.1**
	X^2	**6.08**	**6.08**	0.05	**2.6**	**7.67**

Age class effect PTR spring

(p=N/A)

		Age classes			
Fire type	Value	0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	3	3	4	2
	Expected	3	3	4	2
	X2	0	0	0	0

Age class effect PTR Summer

(p=N/A)

		Age classes			
Fire type	Value	0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	3	3	4	2
	Expected	3	3	4	2
	X2	0	0	0	0

Age class effect for PBA

(p=0,002) - Freeman-Tukey=1,2*

		Age classes			
Fire type	Value	0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	**3 +**	**4 +**	0	**1 -**
	Expected	**1.6**	**2.13**	0.53	**3.73**
	X2	**1.23**	**1.63**	0.53	**2**
Intermittent	*Observed*	**0 -**	**0 -**	1	**6 -**
	Expected	**1.4**	**1.87**	0.47	**3.27**
	X2	**1.4**	**1.87**	0.61	**2.29**

Age class effect for PMA-S

(p=0,010) - Freeman-Tukey=1,2*					
		Age classes			
Fire type	Value	0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	**3 +**	0	0	1
	Expected	**0.67**	0.67	0.89	1.78
	X2	**8.17**	0.67	0.89	0.34
Intermittent	*Observed*	**0 -**	3	4	7
	Expected	**2.33**	2.33	3.11	6.22
	X2	**2.33**	0.19	0.25	0.09

Age class effect for PMA-N

(p=N/A)					
		Age classes			
Fire type	Value	0-50 years	50-100 years	100-150 years	150+ years
Intermittent	*Observed*	1	6	3	6
	Expected	1	6	3	6
	X2	0	0	0	0

B) Extreme fire weather

Successionnal pathways effect

(p=<0,0001)- Freeman-Tukey = 1,39						
		Successional pathways				
Fire type	Value	PTR spring	PTR summer	PBA	PMA-S	PMA-N
Surface	*Observed*	**5 +**	**6 +**	**0 -**	**0 -**	**0 -**
	Expected	**1.81**	**1.81**	**2.26**	**2.71**	**2.41**
	X^2	**5.63**	**9.71**	**2.26**	**2.71**	**2.41**
Intermittent	*Observed*	**5 +**	**5 +**	5	**1 -**	**0 -**
	Expected	**2.63**	**2.63**	3.28	**3.94**	**3.5**
	X^2	**2.13**	**2.13**	0.89	**2.19**	**3.5**
Crown	*Observed*	**2 -**	**1 -**	10	**17 +**	**16 +**
	Expected	**7.56**	**7.56**	9.45	**11.34**	**10.08**
	X^2	**4.09**	**5.69**	0.03	**2.82**	**3.47**

Age class effect PTR spring

(p=0,001) - Freeman-Tukey = 1,39*

Fire type	Value	*Age classes* 0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	**3 +**	2	**0 -**	0
	Expected	**1.25**	1.25	**1.67**	0.83
	X2	**2.45**	0.45	**1.67**	0.84
Intermittent	*Observed*	0	1	**4 +**	0
	Expected	1.25	1.25	**1.67**	0.84
	X2	1.25	0.05	**3.27**	0.83
Crown	*Observed*	0	0	0	2
	Expected	0.5	0.5	0.67	0.33
	X2	0.5	0.5	0.67	8.33

Age class effect PTR summer

(p=0,152) - Freeman-Tukey 1,39*

Fire type	Value	*Age classes* 0-50 years	50-100 years	100-150 years	150+ years
Surface	*Observed*	**3 +**	2	1	0
	Expected	**1.5**	1.5	2	1
	X2	**1.5**	0.17	0.5	1
Intermittent	*Observed*	0	1	3	1
	Expected	1.25	1.25	1.67	0.84
	X2	1.25	0.05	1.1	0.03
Crown	*Observed*	0	0	0	**1 +**
	Expected	0.25	0.25	0.33	**0.17**
	X2	0.25	0.25	0.33	**4.17**

Age class effect for PBA

(p=0,009) - Freeman-Tukey = 1,2*

Fire type	Value	*Age classes* 0-50 years	50-100 years	100-150 years	150+ years
Intermittent	*Observed*	0	**4 +**	0	1
	Expected	1	**1.33**	0.33	2.33
	X2	1	**5.33**	0.33	0.76
Crown	*Observed*	3	**0 +**	1	6
	Expected	2	**2.67**	0.67	4.67
	X2	0.5	**2.67**	0.17	0.38

Age class effect for PMA-S

(p=1,0) - Freeman-Tukey = 1,2*

Fire type	Value	*Age classes* 0-50 years	50-100 years	100-150 years	150+ years
Intermittent	*Observed*	0	0	0	1
	Expected	0.17	0.17	0.22	0.44
	X2	0.17	0.17	0.22	0.69
Crown	*Observed*	3	3	4	7
	Expected	2.83	2.83	3.78	7.56
	X2	0.0098	0.0098	0.01	0.04

Age class effect for PMA-N

(p=N/A)

Fire type	Value	*Age classes* 0-50 years	50-100 years	100-150 years	150+ years
Crown	*Observed*	1	6	3	6
	Expected	1	6	3	6
	X2	0	0	0	0

Numbers in **bold** are categories where observed and expected values are significatively different from each other.
*Indicates that we used the "Exact Contingency Table" method because many observed values were <5.

APPENDIX 1

Worksheet used in *BehavePlus*

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Inputs: SURFACE, CROWN, SIZE

Description

Fuel/Vegetation, Surface/Understory		
Fuel Model Type		
1-h Fuel Load	tonne/ha	
10-h Fuel Load	tonne/ha	
100-h Fuel Load	tonne/ha	
Live Herbaceous Fuel Load	tonne/ha	
Live Woody Fuel Load	tonne/ha	
1-h SA/V	cm2/cm3	
Live Herbaceous SA/V	cm2/cm3	
Live Woody SA/V	cm2/cm3	
Fuel Bed Depth	m	
Dead Fuel Moisture of Extinction	%	
Dead Fuel Heat Content	kJ/kg	
Live Fuel Heat Content	kJ/kg	
Fuel/Vegetation, Overstory		
Canopy Base Height	m	
Canopy Bulk Density	kg/m3	
Fuel Moisture		
1-h Moisture	%	
10-h Moisture	%	
100-h Moisture	%	
Live Herbaceous Moisture	%	
Live Woody Moisture	%	
Foliar Moisture	%	
Weather		
20-ft Wind Speed (upslope)	km/h	
Wind Adjustment Factor		
Terrain		
Slope Steepness	%	
Fire		
Elapsed Time	h	

Run Option Notes

(continued on next page)

APPENDIX 2

BehavePlus output data by plot

			50th percentile moisture scenario				95th percentile moisture scenario			
Plot #	Age	Succession	ROS (m/min)	HFI (kW/m)	AREA (ha)	FD	ROS (m/min)	HFI (kW/m)	AREA (ha)	FD
PetC1	11	PTR	0.2	3.0	0.1	Surface	0.3	4.0	0.1	Surface
Ptr64a	32	PTR	4.3	147.0	16.5	Surface	4.9	172.0	20.5	Surface
Ptr64b	32	PTR	1.4	113.0	1.7	Surface	1.6	135.0	2.1	Surface
Lofuel	57	PTR	1.7	37.0	2.5	Surface	1.9	43.0	3.1	Surface
Andy 3	68	PTR	0.5	25.0	0.2	Surface	0.5	30.0	0.3	Surface
Mask II	71	PTR	3.9	198.0	13.8	Surface	4.5	239.0	17.8	Surface
Wmist	102	PTR	0.2	8.0	0.1	Surface	0.3	10.0	0.1	Surface
Mlr 1	142	PTR	3.5	27.0	11.1	Surface	4.3	35.0	15.9	Surface
Andy 1A	145	PTR	3.2	83.0	9.0	Surface	3.8	104.0	12.5	Surface
Andy 1B	145	PTR	1.4	41.0	1.8	Surface	1.6	49.0	2.3	Surface
Jou2B (a)	187	PTR	1.3	20.0	1.5	Surface	1.5	25.0	1.9	Surface
Jou2B (b)	187	PTR	0.3	9.0	0.1	Surface	0.3	10.0	0.1	Surface
2RS3	11	PBA	1.5	28.0	2.0	Intermittent	1.7	33.0	2.5	Intermittent
RS4 B New	11	PBA	0.1	1.0	0.0	Surface	0.1	1.0	0.0	Surface
RS4 New	11	PBA	0.5	61.0	0.2	Intermittent	0.6	73.0	0.3	Intermittent
54	54	PBA	0.5	9.0	0.3	Surface	0.6	12.0	0.4	Surface
38	87	PBA	0.8	18.0	0.5	Surface	0.8	19.0	0.5	Surface
23	89	PBA	0.0	0.0	0.0	Surface	0.0	0.0	0.0	Surface
23B	89	PBA	0.0	0.0	0.0	Surface	0.0	0.0	0.0	Surface
69	142	PBA	5.1	98.0	23.5	Intermittent	6.0	122.0	31.6	Intermittent
66A	152	PBA	3.3	25.0	10.0	Surface	4.0	31.0	14.1	Surface
66B	152	PBA	3.3	20.0	9.8	Surface	3.9	25.0	13.2	Surface
83	180	PBA	4.6	101.0	19.1	Intermittent	5.3	119.0	24.1	Intermittent
83B	180	PBA	4.6	38.0	19.3	Surface	5.5	47.0	25.8	Surface
65B	202	PBA	1.7	24.0	2.7	Intermittent	2.1	30.0	3.8	Intermittent
65	207	PBA	1.6	11.0	2.4	Surface	2.0	14.0	3.3	Surface
64	225	PBA	1.6	10.0	2.4	Surface	1.9	12.0	3.2	Surface
34E	32	PMA-S	4.1	78.0	15.4	Intermittent	4.9	96.0	20.4	Intermittent
59C	32	PMA-S	0.9	17.0	0.7	Intermittent	1.0	20.0	0.9	Intermittent
60B	32	PMA-S	0.8	7.0	0.6	Intermittent	1.0	9.0	0.9	Intermittent
4	55	PMA-S	4.5	31.0	18.3	Intermittent	5.3	38.0	24.4	Intermittent
2	87	PMA-S	0.4	4.0	0.2	Surface	0.5	5.0	0.2	Intermittent
57New	91	PMA-S	2.1	20.0	4.1	Surface	2.6	25.0	6.0	Surface
18A	129	PMA-S	1.1	21.0	1.1	Surface	1.3	26.0	1.5	Surface
18B	129	PMA-S	1.2	24.0	1.3	Surface	1.4	29.0	1.7	Surface
Andy 1C	145	PMA-S	1.0	12.0	0.9	Surface	1.2	14.0	1.2	Surface
Andy 1D	145	PMA-S	2.6	21.0	5.9	Surface	3.1	27.0	8.2	Surface
C-150	165	PMA-S	3.4	64.0	10.4	Surface	4.0	79.0	14.0	Surface
8	177	PMA-S	4.1	124.0	14.9	Surface	4.8	152.0	19.7	Surface
POP	181	PMA-S	2.7	34.0	6.6	Surface	3.2	43.0	8.8	Surface
50	225	PMA-S	1.6	18.0	2.3	Intermittent	1.9	23.0	3.1	Intermittent
L22	272	PMA-S	2.9	28.0	7.5	Surface	3.5	35.0	10.4	Surface
6	283	PMA-S	4.7	87.0	19.9	Intermittent	5.6	110.0	26.9	Intermittent
16	283	PMA-S	1.1	27.0	1.1	Intermittent	1.3	32.0	1.4	Intermittent
20	356	PMA-S	1.7	18.0	2.5	Intermittent	1.9	23.0	3.3	Intermittent
62D	32	PMA-N	0.7	8.0	0.4	Intermittent	0.8	9.0	0.6	Intermittent
11A	41	PMA-N	7.4	64.0	49.7	Intermittent	8.7	77.0	65.2	Intermittent
11B	41	PMA-N	5.0	81.0	22.4	Intermittent	5.8	99.0	29.6	Intermittent
53	57	PMA-N	2.7	17.0	6.4	Surface	3.3	23.0	9.4	Surface
78	78	PMA-N	4.5	28.0	18.1	Intermittent	5.2	34.0	23.6	Intermittent
3	96	PMA-N	0.9	8.0	0.7	Surface	1.1	10.0	1.0	Surface
60	100	PMA-N	0.7	4.0	0.6	Surface	0.9	5.0	0.8	Intermittent
68	142	PMA-N	2.0	25.0	3.6	Intermittent	2.4	31.0	4.9	Intermittent
63	146	PMA-N	3.0	28.0	8.3	Surface	3.6	35.0	11.5	Surface
63B	146	PMA-N	1.8	22.0	2.8	Surface	2.1	28.0	3.9	Surface
Chafi #5	170	PMA-N	0.4	2.0	0.1	Surface	0.5	3.0	0.2	Surface
5	172	PMA-N	0.2	1.0	0.0	Surface	0.2	2.0	0.1	Surface
5B	172	PMA-N	0.3	2.0	0.1	Surface	0.5	6.0	0.2	Surface
L9724	272	PMA-N	2.7	35.0	6.5	Intermittent	3.3	47.0	9.4	Intermittent
H1A	350	PMA-N	2.1	21.0	3.8	Surface	2.5	27.0	5.3	Surface
H1B	350	PMA-N	4.2	55.0	15.9	Surface	5.0	69.0	22.0	Surface

APPENDIX 3

FBP output data by plot

Plot #	Succession	Age	50th percentile moisture scenario: ROS (m/min.)	Spring ROS (m/min.)	HFI (kW/m)	Spring HFI (kW/m)	AREA (ha)	Spring AREA (ha)	FD	Spring FD	95th percentile moisture scenario: ROS (m/min.)	Spring ROS (m/min.)	HFI (kW/m)	Spring HFI (kW/m)	AREA (ha)	Spring AREA (ha)	FD	Spring FD
23	PBA	89	0.2		113.0		0.0		Surface		9.6		7573.0		61.8		Intermittent	
38	PBA	87	1.4		1073.5		2.8		Surface		14.6		13686.5		179.3		Intermittent	
54	PBA	54	0.2		113.0		0.0		Surface		9.8		7573.0		61.8		Intermittent	
64	PBA	225	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
65	PBA	202	2.1		1649.8		4.5		Intermittent		17.4		13442.0		174.6		Crown	
69	PBA	142	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
83	PBA	180	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
23B	PBA	89	0.2		113.0		0.0		Surface		9.8		7573.0		61.8		Intermittent	
2R53	PBA	11	2.8		1362.0		6.4		Surface		20.1		18817.0		322.2		Crown	
65B	PBA	202	2.6		2034.0		5.6		Intermittent		19.3		19800.0		295.7		Crown	
66A	PBA	152	2.1		1649.8		4.5		Intermittent		17.4		13442.0		174.6		Crown	
66B	PBA	152	0.2		113.0		0.0		Surface		9.8		7573.0		61.8		Intermittent	
83B	PBA	180	2.1		1649.8		4.5		Intermittent		17.4		13442.0		174.6		Crown	
RS4 B New	PBA	11	2.8		1362.0		6.4		Surface		20.1		18817.0		322.2		Crown	
RS4 New	PBA	11	2.8		1362.0		6.4		Surface		20.1		18817.0		322.2		Crown	
3	PMA-N	96	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
5	PMA-N	172	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
53	PMA-N	57	2.4		1918.7		5.3		Intermittent		19.3		18898.5		282.6		Crown	
60	PMA-N	100	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
63	PMA-N	146	2.1		1649.8		4.5		Intermittent		17.4		13442.0		174.6		Crown	
68	PMA-N	142	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
78	PMA-N	78	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
11A	PMA-N	41	2.6		2034.0		5.6		Intermittent		19.3		19800.0		295.7		Crown	
11B	PMA-N	41	2.6		2034.0		5.6		Intermittent		19.3		19800.0		295.7		Crown	
5B	PMA-N	172	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
62D	PMA-N	32	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
63B	PMA-N	146	1.8		1315.1		4.3		Intermittent		14.8		16132.0		225.1		Crown	
Chah #5	PMA-N	170	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
H1A	PMA-N	350	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
H1B	PMA-N	350	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
L9724	PMA-N	272	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
2	PMA-S	87	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
4	PMA-S	55	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
6	PMA-S	283	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
8	PMA-S	177	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
16	PMA-S	283	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
20	PMA-S	356	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
50	PMA-S	225	2.3		1830.6		5.1		Intermittent		17.4		17820.0		267.1		Crown	
18A	PMA-S	129	1.6		1098.4		3.0		Intermittent		10.4		10692.0		160.2		Crown	
18B	PMA-S	129	1.9		1464.5		4.1		Intermittent		13.9		8553.6		128.2		Crown	
34E	PMA-S	32	2.2	2.4	1408.0	1521.0	4.1	5.0	Surface	Surface	16.3	17.9	14315.0	14855.0	212.6	240.7	Crown	Crown
57New	PMA-S	91	1.6		844.8		2.5		Intermittent		9.6		8589.0		127.5		Crown	
59C	PMA-S	32	2.4	2.5	1543.0	1652.0	4.7	5.6	Surface	Surface	17.3	17.8	15818.0	16235.0	238.7	264.8	Crown	Crown
60B	PMA-S	32	2.6	2.8	1831.0	1930.0	5.8	6.7	Surface	Surface	19.3	19.5	19029.0	19167.0	295.5	316.4	Crown	Crown
Andy 1C	PMA-S	145	1.2		784.0		2.3		Intermittent		9.0		8027.5		119.6		Crown	
Andy 1D	PMA-S	145	1.4		1073.5		2.8		Intermittent		14.6		13686.5		179.3		Crown	
C-150	PMA-S	165	1.9		1457.7		4.0		Intermittent		16.5		15292.5		226.2		Crown	
L22	PMA-S	272	2.6		2034.0		5.6		Intermittent		19.3		19800.0		296.7		Crown	
POP	PMA-S	181	1.6		903.5		3.5		Surface		11.7		8982.0		189.4		Intermittent	
Andy 1A	PTR	145	1.4	1.7	718.0	844.0	1.7	2.43	Surface	Surface	10.5	12.0	6731.0	12802.0	87.6	120.33	Intermittent	Intermittent
Andy 1B	PTR	145	1.2	1.4	534.0	660.0	1.1	1.77	Surface	Surface	8.6	10.4	4775.0	5928.0	58.1	89.39	Intermittent	Intermittent
Andy 3	PTR	68	0.1	0.6	69.0	181.0	0.0	0.28	Surface	Surface	1.7	4.6	583.0	1549.0	2.3	17.24	Surface	Surface
Jou2B (a)	PTR	187	1.8	2.0	1037.0	1159.0	2.8	3.61	Surface	Surface	13.4	14.5	10212.0	11064.0	143.3	175.35	Intermittent	Crown
Jou2B (b)	PTR	187	2.0	2.2	1155.0	1275.0	3.2	4.05	Surface	Surface	14.4	15.3	11511.0	12270.0	164.9	195.98	Crown	Crown
Lofuel	PTR	57	0.1	0.6	69.0	181.0	0.0	0.28	Surface	Surface	1.7	4.6	583.0	1549.0	2.3	17.24	Surface	Surface
Mask II	PTR	71	1.2	1.4	534.0	660.0	1.1	1.77	Surface	Surface	8.6	10.4	4775.0	5928.0	58.1	89.39	Intermittent	Intermittent
Mir 1	PTR	142	0.8	1.1	300.0	424.0	0.5	0.98	Surface	Surface	5.6	7.9	2431.0	3557.0	25.1	51.59	Surface	Intermittent
PetC1	PTR	11	0.4	0.7	118.0	234.0	0.1	0.42	Surface	Surface	2.7	5.4	975.0	1934.0	5.8	24.11	Surface	Intermittent
Ptr64a	PTR	32	0.1	0.5	25.0	133.0	0.0	0.18	Surface	Surface	0.8	3.8	237.0	1182.0	0.4	11.53	Surface	Surface
Ptr64b	PTR	32	0.1	0.5	25.0	133.0	0.0	0.18	Surface	Surface	0.8	3.8	237.0	1182.0	0.4	11.53	Surface	Surface
Wrnist	PTR	102	1.2	1.4	534.0	660.0	1.1	1.77	Surface	Surface	8.6	10.4	4775.0	5928.0	58.1	89.39	Intermittent	Intermittent

CONCLUSION GÉNÉRALE

En incorporant une description détaillée de la charge et de la structure des différentes strates de combustible dans 61 sites âgés de 11 à 356 ans et dans 4 compositions initiales différentes, ce mémoire participe à établir une meilleure compréhension de la dynamique structurale des forêts de la pessière à mousse du nord-ouest du Québec. De plus, l'étude des comportements potentiels théoriques des feux de forêts associés avec ces inventaires améliore notre connaissance des facteurs influençant la variabilité du comportement des incendies forestiers dans cette région. Auparavant, très peu d'études avaient envisagé l'étude du combustible et de toutes ses strates comme étant un élément descripteur important de la dynamique forestière. Dans notre région, la productivité est basse et la décomposition est lente, ce qui suggèrerait une lente accumulation de matière morte (Schimmel et Granström 1997) et donc une augmentation de l'intensité des feux de forêts avec le TDF. Toutefois, dans notre aire d'étude, la paludification est un phénomène qui affecte grandement la dynamique naturelle des peuplements, en réduisant la qualité des sols et donc, la productivité générale, et très peu d'études ont vérifié si une accumulation de matière morte est observée dans cette région particulière.

La première contribution importante de ce mémoire réside donc dans la meilleure compréhension qu'il apporte au niveau des effets du TDF et de la composition initiale des peuplements sur les caractéristiques des combustibles, notamment, la matière morte. En effet, nous sommes maintenant capables d'affirmer qu'il n'y a pas d'accumulation importante et significative de combustibles forestiers au fil du temps. Par rapport à d'autres régions, cette différence peut s'expliquer par le fait que la productivité des peuplements diminue avec le TDF et que les débris ligneux morts au sol sont absorbés par la tourbe ce qui peut obscurcir la courbe d'accumulation car ce combustible n'est plus disponible pour un feu potentiel. Pour appuyer cette affirmation, il n'y a qu'à regarder les charges de débris ligneux morts au sol qui diminuent avec le TDF. Aussi les charges moyennes qui sont significativement plus basses dans la composition initiale de l'épinette noire issue d'un feu non sévère (PMA-N), où la tourbe recouvre une plus grande surface que dans les autres compositions initiales, et où elle s'installe plus rapidement après un feu. Selon nos résultats, les vieilles forêts sont donc des endroits où les feux de forêts ont autant de chances d'être intenses qu'une jeune forêt. Toutefois, nous n'avons pas trouvé d'effet négatif et significatif de la paludification sur l'arrangement des différentes couches de combustible. En fait, après l'analyse des données, la composition initiale de l'épinette noire issue d'un feu non sévère (PMA-N) aurait même plus de facilité à propager un feu de cime que les autres compositions initiales. Nous proposons néanmoins que le TDF a un effet indirect sur plusieurs des caractéristiques des combustibles. En effet, certaines études (*e.g.* Lecomte *et al.* 2005a) ont montré que les forêts de la ceinture d'argile affichent une convergence successionelle au niveau de la structure des peuplements en fonction du TDF. Alors que la composition initiale a un effet significatif dans notre étude, nous pensons donc que le changement de composition dû au TDF a un effet sur les combustibles, et non le temps lui-même.

La deuxième contribution de ce mémoire pour la communauté scientifique concerne les comportements du feu résultants de données empiriques. Notre objectif était d'évaluer l'effet de la composition initiale et du TDF sur le comportement des feux, tout en vérifiant si une différence significative au niveau des combustibles pouvait se traduire en comportement des feux différents. Nous tentions aussi de comparer l'utilisation de deux modèles de comportement du feu, le modèle canadien *FBP* et américain *BehavePlus*. En général, les résultats diffèrent selon le modèle de prévision du comportement du feu utilisé, mais certaines tendances sont communes aux deux modèles. Par exemple, dans les deux modèles, l'effet de la composition initiale s'est traduit en un comportement du feu moins intense dans les forêts de feuillus, alors qu'en forêt résineuse, l'intensité était maximale dans la chronoséquence de PMA-N et intermédiaire pour PMA-S et PBA. Les peuplements d'épinette noire issus d'un feu non sévère et feuillus présentent donc une différence structurale assez grande pour produire des comportements différents dans les deux modèles. Néanmoins, nous pensons aussi que les différences significatives observées au niveau des caractéristiques des combustibles sont rarement traduites dans le calcul d'un comportement du feu. Cette traduction était surtout visible avec *BehavePlus* qui possède la qualité de considérer les variations subtiles des combustibles, comparativement avec *FBP* qui lui, force l'utilisateur à attribuer des modèles de combustibles généraux ne représentant pas forcément le comportement du feu associé à ce type. Malgré cela, comme Hély *et al.* (2001), nos résultats avec *BehavePlus* sont beaucoup moins intenses que ceux produits avec *FBP*. *BehavePlus* n'a produit aucun résultat de feu excédant en intensité un feu intermittent, alors que les données du combustible et les données météo proviennent d'une région où les feux de cime très intenses sont fréquents. Même si nous n'avons pas fait de feux dirigés pouvant nous servir de comparatif, il est clair que les résultats de la *MCPCI* étaient beaucoup plus réalistes.

Toutefois, bien qu'étant le mieux adapté à la forêt boréale, nous jugeons que le système de la *MCPCI* pourrait bénéficier de quelques améliorations. Tout comme Pelletier *et al.* (2009), la plus importante selon nous serait l'addition d'un nouveau type de combustible similaire au C2 (pessière boréale) mais qui incorporerait les effets de la paludification. Pendant l'inventaire, lorsqu'il fallait attribuer un type de combustible de la *MCPCI* au peuplement inventorié, il était souvent ardu de trouver un bon descripteur pour les peuplement très paludifiés. Ayant classé des peuplements d'épinette noire denses comme étant des C2, nous jugions la densité ainsi que la hauteur des arbres des peuplements paludifiés non représentatives de ce même modèle de combustible. Malgré cela, nous avons attribué le type C2 à ces peuplements. Nous pensons donc qu'une partie de la variabilité et de l'effet du TDF sur l'intensité des feux potentiels a été perdue à cause de ce fait. Lecomte *et al.* (2005b) ont montré que la densité des petits arbres augmente avec l'âge et que la surface terrière diminue avec le TDF pour toutes les compositions initiales. Nous doutons donc que nos résultats indiquant un comportement du feu similaire tout le long de la succession soit réalistes. Les peuplements subissent de très grands changements structuraux avec le TDF dus à la paludification. Notre incapacité de bien traduire cette information dans la *MCPCI* cache probablement cette tendance sur le comportement du feu calculé.

Les résultats inclus dans ce mémoire participent donc à un effort concerté pour mieux comprendre les dynamiques naturelles et ainsi mettre en place un aménagement écosystémique dans cette région en présentant la variabilité qui devrait être préservée et/ou simulée en expliquant ses effets sur la perturbation principale qu'est le feu. Toutefois, ils révèlent aussi le besoin d'améliorer nos outils de prédiction du comportement des feux de forêt en ajoutant un nouveau type de combustible représentant des peuplements d'épinette noire paludifiés dans la *MCPCI*.

En conclusion, maintenant que l'effet de la paludification a été éclairci au niveau de plusieurs caractéristiques des combustibles, il serait intéressant de comprendre la capacité qu'a le feu de brûler la tourbe accumulée au sol en fonction de l'intensité d'un feu potentiel de surface et de différentes conditions d'humidité. Le développement d'un modèle spécial d'évaluation de la combustion lente pourrait alors nous renseigner sur la capacité naturelle d'un feu à brûler toute la matière organique accumulée au sol, et ainsi réinitialiser la succession naturelle. Dans un contexte où les changements climatiques pourraient modifier les conditions d'humidité des complexes de combustible et du sol, ces renseignements pourraient nous indiquer les mesures à prendre pour préserver la variabilité naturelle de productivité au niveau des peuplements de pessière à mousse du nord-ouest du Québec.

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