



Abondance et impact des espèces concurrentes sur la régénération résineuse après coupe avec protection de la régénération dans un secteur de la forêt boréale du Québec

Mémoire

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Résumé

Nous avons mené une étude pour identifier les situations où les éricacées et des feuillus causent des problèmes de compétition aux conifères en forêt boréale.

Pour ce faire, nous avons lié les données d'un inventaire de régénération réalisé entre 2007 et 2011 à des données portant sur l'hypsométrie, la classification écologique, les sols et les peuplements forestiers avant la récolte. Nous avons analysé cet assemblage de données pour étudier les relations entre la végétation concurrente et les variables associées à la récolte et à l'environnement, puis nous avons estimé la probabilité d'observer une couverture d'espèces concurrentes donnée en fonction de ces variables. De plus, en 2015, nous avons rééchantillonné une partie des sites pour évaluer l'impact temporel de différents niveaux de compétition sur le coefficient de distribution (c.d.), la vigueur et la surface terrière de la régénération résineuse, là où elle était marginale tôt après la coupe.

L'analyse des données de l'inventaire de 2007 à 2011 montre, qu'après une coupe avec protection de la régénération et des sols, les éricacées et les feuillus ne sont pas associés aux mêmes types de milieux. Les éricacées se retrouvent surtout dans des milieux moins productifs associés à l'épinette noire et au pin gris. La distinction entre les milieux propices aux feuillus commerciaux intolérants à l'ombre et aux feuillus non commerciaux est moins nette puisqu'ils répondent souvent de façon semblable à une même variable. L'analyse des données de l'inventaire de 2015 montre une amélioration significative du c.d. lorsque les niveaux de compétition des feuillus commerciaux intolérants à l'ombre sont faibles (c.d. 0-40%) et lorsque les niveaux de compétition des éricacées sont modérés (c.d. 26-75%). Les différents types et intensités de compétition ne semblent pas affecter la vigueur ni influencer la surface terrière de la régénération résineuse de 9 à 14 ans après la coupe.

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Avant-propos

Ce mémoire débute par une introduction générale en français, suivie d'un chapitre central rédigé en anglais sous la forme d'un manuscrit d'article scientifique, puis d'une conclusion générale en français. Jean-Claude Ruel et Nelson Thiffault ont élaboré l'étude. J'ai conçu le protocole expérimental détaillé, planifié les travaux de terrain et réalisé l'inventaire de 2015. L'analyse des données et la rédaction ont été sous ma responsabilité, avec le support de Jean-Claude Ruel et Nelson Thiffault. Le projet a été financé par une subvention de recherche du Fonds québécois de la recherche sur la nature et les technologies (FRQNT) – Actions concertées accordée à une équipe dirigée par Jean Bégin.

Introduction générale

Les conifères constituent une part importante de l'économie forestière en forêt boréale. Or, après une coupe, des espèces feuillues et éricacées peuvent rapidement envahir les stations, ce qui risque d'empêcher ou de ralentir l'établissement de la régénération résineuse.

En fait, les feuillus peuvent à la fois faciliter ou inhiber la croissance et la survie des conifères. La facilitation peut prendre la forme d'une protection contre les insectes, les maladies, la photoinhibition, la photooxydation, les extrêmes de température et les extrêmes d'humidité (MacLean 1996, Gerlach et al. 1997, Man et Lieffers 1999a, 1999b, Man et Greenway 2011), d'une amélioration de la fertilité du sol (Fortin et al. 1983, Bradley et Fyles 1995, Wang et al. 1996, Laganière et al. 2010), ou un meilleur accès aux éléments nutritifs grâce à des mycorhizes (Simard et al. 1997, Philip et al. 2010). La compétition peut survenir par l'interception d'une partie de la lumière (ce qui semble être le mode de compétition principal des feuillus faisant l'objet de cette étude; Farmer et al. 1988, Simard 1990, Bell 1991, Jobidon 2000, Simard et Hannam 2000, Comeau et al. 2003, Filipescu et Comeau 2007), de l'eau (Lieffers et al. 1993, Jobidon 1995) et des éléments nutritifs (Lieffers et al. 1993, Simard et Sachs 2004) disponibles. Les feuillus, peuvent aussi causer des dommages physiques, par fouettement, aux semis de conifères (comme c'est le cas pour le peuplier faux tremble et bouleau à papier; Kagis 1952, Bell et al. 2011). Les problèmes de compétition semblent survenir lorsque les feuillus atteignent un seuil de densité qui varie selon les espèces en interaction (p. ex. Légaré et al. 2004, Hawkins et al. 2012, Hawkins et Dhar 2013).

Le bouleau à papier (*Betula papyrifera* Marsh.) et le peuplier faux-tremble (*Populus tremuloides* Michx.) sont deux des feuillus que l'on retrouve le plus souvent en forêt boréale québécoise (Saucier et al. 2009). Bien que ces espèces revêtent un intérêt commercial, leur valeur économique est généralement inférieure à celle des conifères en forêt boréale, ce qui contribue à ce qu'elles soient perçues comme des espèces concurrentes. De plus, elles peuvent attirer des herbivores qui pourraient endommager les semis de conifères (Parker 1984, DeLong 2000). Le peuplier faux-tremble a des besoins en nutriments plus élevés que l'épinette noire (*Picea mariana* (Mill.) B.S.P.) (Paré et al. 2002). Si on remplace une épinette noire par un peuplier faux-trembles, on peut donc s'attendre à une augmentation de la compétition pour les nutriments (Légaré et al. 2005). Cependant, en se décomposant, la litière de racines et de feuilles du

peuplier faux-tremble retourne une partie des éléments nutritifs absorbés dans le sol, les rendant ainsi disponibles pour les semis de conifères (Van Cleve et al. 1983, Paré et Van Cleve 1993, Wang et al. 1995, Légaré et al. 2005, Laganière et al. 2010). Le bouleau accumule lui aussi de grandes concentrations d'éléments nutritifs dans son feuillage (Wang et al. 1996). Le cyclage rapide des éléments contenus dans la litière de ces deux espèces pourrait s'avérer particulièrement utile sur des sites pauvres ou pour atténuer les effets négatifs de l'épinette noire sur le cyclage des éléments nutritifs (Man et Lieffers 1999a, Légaré et al. 2004). Simard et al. (1997) ainsi que Philip et al. (2010) ont également observé que des connexions mycorhiziennes permettent au bouleau à papier et au sapin de Douglas (*Pseudotsuga menziesii* (Mirb.) Franco) d'effectuer des transferts de carbone bidirectionnels. Le sapin de Douglas peut ainsi bénéficier d'un gain en carbone, lorsqu'il est en présence de bouleau à papier (Philip et al. 2010). De plus, Man et Lieffers (1999a, 1999b) ont observé que la présence d'un couvert résiduel de peupliers faux-trembles augmente l'humidité en sous-étage, diminue les problèmes de gels des semis et pourrait offrir une protection contre la photoinhibition, ce qui semble bénéficier à l'épinette blanche (*Picea glauca* (Moench) Voss). Dans un même ordre d'idées, les bouleaux créent de l'ombrage qui pourrait protéger les épinettes blanches contre la photoinhibition, la photooxydation ainsi que les extrêmes de température et d'humidité (Man et Greenway 2011). La présence de peupliers faux-trembles et de bouleaux à papier permettrait aussi d'atténuer la mortalité par le pourridié-agaric chez le sapin baumier, le mélèze laricin (*Larix laricina* (Du Roi) K. Koch) et l'épinette noire (Morrison et Mallett 1996, Gerlach et al. 1997). Dans des peuplements composés d'un mélange de bouleaux à papier et d'épinettes blanches, les problèmes de compétition commenceraient à se faire sentir lorsque les densités de bouleau dépassent 3000 à 4000 tiges par hectare (Hawkins et al. 2012, Hawkins et Dhar 2013). Dans des peuplements composés d'un mélange de peuplier faux-tremble et d'épinettes noires, Légaré et al. (2004) ont observé qu'à l'échelle du peuplement, les problèmes de compétition commencent à survenir quand le pourcentage en surface terrière du peuplier est supérieur à 41%.

L'aulne rugueux (*Alnus incana* subsp. *rugosa* (Du Roi) J. Clausen), l'érable à épis (*Acer spicatum* Lam.) et le cerisier de Pennsylvanie (*Prunus pensylvanica* L. f.) sont d'autres espèces feuillues fréquemment rencontrées en forêt boréale et ne possèdent actuellement aucune valeur commerciale. Elles semblent principalement inhiber la croissance des résineux en exerçant une compétition pour la lumière (Bell 1991, Jobidon 2000). En effet, l'aulne rugueux forme souvent un couvert très dense pouvant empêcher

l'établissement des conifères (Jobidon 1995). Par contre, cette espèce peut aussi fixer l'azote atmosphérique et en stocker une partie dans ses feuilles (Fortin et al. 1983, Hurd et al. 2001, Kaelke et Dawson 2003, Tobita et al. 2016). La litière de l'aulne rugueux se décompose rapidement et permet un cyclage rapide des éléments nutritifs (Daly 1966). À faible densité, cet arbuste pourrait donc faciliter la croissance des résineux en enrichissant le sol (Watt et Heinselman 1965, Johnston 1972, Jutras et al. 2006), ce qui pourrait être particulièrement avantageux sur des sites pauvres. L'érable à épis envahit rapidement les sites ayant bénéficié d'une ouverture de la canopée et forme des couverts denses pouvant supprimer les autres espèces pendant 30 à 60 ans (Vincent 1965, Archambault et al. 1998, De Grandpré et al. 2000). Cette espèce exerce également une compétition pour l'eau et sa litière inhibe la germination des résineux (Vincent 1965, Bell 1991, Jobidon 1995, Boulet et Beaudet 2013). L'érable à épis et le cerisier de Pennsylvanie constituent aussi des sources de nourriture et des couverts de protection pour des lièvres qui peuvent brouter de jeunes conifères situés à proximité (Parker 1984, Bell 1991). Le cerisier de Pennsylvanie peut également exercer une compétition pour l'eau et les éléments nutritifs (Bell 1991).

Les éricacées peuvent rapidement envahir un site à la suite d'une perturbation comme un feu ou une coupe (van Nostrand 1971, Viereck 1983, Mallik 1995, Hébert et al. 2010a). Le niveau d'inhibition et les mécanismes de compétition affectant la croissance des conifères peuvent varier en fonction de l'espèce éricacée et du type de site (Mallik 2003). Dans la zone boréale du Québec, la concurrence par les éricacées est principalement constituée du thé du Labrador (*Rhododendron groenlandicum* (Oeder) K.A. Kron et Judd), du kalmia à feuilles étroites (*Kalmia angustifolia* L.) et des bleuetiers (*Vaccinium* spp.) (Thiffault et Roy 2011). Ces espèces peuvent interférer avec la croissance des conifères en compétitionnant directement pour les nutriments (Thiffault et al. 2004b, Hébert et al. 2010b). Elles peuvent également s'associer à des mycorhizes éricoïdes qui les aideront à assimiler de l'azote (Malloch et Malloch 1981, Goulart et al. 1993, Mayor et al. 2012). Le feuillage du kalmia contient des composés phénoliques pouvant inhiber les mycorhizes bénéfiques aux conifères (Titus et al. 1995). Par contre, Yamasaki et al. (1998) ont observé que cette plante favorise la présence de *Phialocephala dimorphospora*, une pseudo-mycorhize qui nuit à la croissance de l'épinette noire (Richard et Fortin 1970). Le feuillage du kalmia contient aussi des composés pouvant inhiber la germination (Titus et al. 1995) et la croissance primaire des racines de l'épinette noire (Peterson 1965, Mallik 1987, Zhu et Mallik 1994). De plus, les tanins produits par cette plante réduisent la minéralisation de l'azote, possiblement

en inhibant l'activité enzymatique du sol ou en formant des complexes de protéines et de tanins (Bradley et al. 2000, Joannisse et al. 2007, 2009). C'est toutefois la compétition racinaire causée par le kalmia qui semble avoir le plus d'impact sur la croissance de l'épinette noire (Mallik et al. 2016). Le système racinaire extensif du kalmia lui permettrait d'accéder à un plus grand volume de sol, ce qui l'avantagerait face à l'épinette noire pour l'absorption de l'eau et des nutriments (Inderjit et Mallik 2002, Thiffault et al. 2004b, Mallik et al. 2016). Le feuillage du bleuet à feuilles étroites (*Vaccinium angustifolium* Aiton) aurait une capacité légèrement inférieure à celle du kalmia à inhiber la germination des semences d'épinettes noires (Titus et al. 1995). Les composés phénoliques présents dans le feuillage et la litière du thé du Labrador vont modifier la disponibilité des éléments nutritifs du sol (Inderjit et Mallik 1997). D'autre part, le kalmia et le thé du Labrador favorisent une accumulation de la couche de matière organique (Damman 1971, Inderjit et Mallik 1996), ce qui affecte négativement la croissance des semis résineux (Lavoie et al. 2007) en diminuant la qualité du lit de germination (Greene et al. 2007) et en abaissant la température du sol (Balisky et Burton 1997, Thiffault et al. 2004b).

Une gestion avisée de la végétation concurrente nécessite une compréhension des facteurs influençant son abondance ainsi que de l'impact de cette végétation sur les essences désirées. Or, peu d'études ont évalué les effets simultanés de différentes variables sur la présence des espèces concurrentes. Une caractérisation des variables biophysiques (c.-à-d. l'altitude, le drainage, les régions écologiques, perturbation d'origine du peuplement avant la coupe, composition du peuplement avant la coupe et les dépôts de surface) et des caractéristiques de récolte (c.-à-d. le procédé de récolte et la saison de la récolte) favorisant le développement de ces espèces permettrait de mieux prédire les sites où des travaux d'entretien seraient nécessaires et où une baisse de productivité devrait être attendue.

L'objectif principal de cette étude était donc d'identifier les problèmes de régénération liés à la compétition par les éricacées et les feuillus en fonction de la composition initiale du peuplement, des caractéristiques du site et des régions écologiques de la forêt boréale. Nos objectifs spécifiques étaient : i) d'identifier les caractéristiques de récolte et les variables biophysiques significativement corrélées à la présence de la végétation concurrente, ii) d'estimer la probabilité d'observer un groupe de végétation concurrente donné en fonction des caractéristiques de récolte et les variables biophysiques, et iii) d'évaluer l'impact de la végétation concurrente sur la régénération désirée lorsque celle-

ci est marginale. Nous avons donc émis l'hypothèse que la composition de la végétation concurrente pouvait être liée à des variables biophysiques et des caractéristiques de récolte. De plus, nous avons prédit que la nature et l'abondance de la végétation concurrente est principalement fonction des caractéristiques biophysiques. Finalement, nous avons avancé que l'intensité et la nature de la compétition devraient avoir une influence déterminante sur l'évolution de la régénération dans les zones récoltées comportant une régénération résineuse marginale. À des niveaux de compétition faibles, nous nous attendions à une augmentation de la régénération résineuse avec le temps, alors que sous des niveaux de compétition élevés, nous nous attendions à ce que le coefficient de distribution des tiges libres de croître, la surface terrière et la vigueur des jeunes résineux restent similaires ou diminuent avec le temps.

Chapitre 1. Abundance and impacts of competing species on conifer regeneration following careful logging in the eastern-Canadian boreal forest

Abstract

Conifers represent an important part of forest economy in northern countries. After harvesting, competing species can quickly invade cutovers and impair conifer regeneration establishment, with significant impacts on long-term site productivity. Our objective was to identify the biophysical and harvesting characteristics associated with ericaceous and hardwoods competing species that cause competition problems to conifers, so that reforestation or tending efforts could be better planned.

To do so, we linked data from the monitoring of 4,471 transects realized between 2007 and 2011 to data relating to elevation, ecological classification, soil attributes, and pre-harvest forest stands. We analyzed this assemblage of data to study the relationships between competing vegetation and harvesting and biophysical variables. We then estimated the probability of observing a given competing species cover based on these variables. In 2015, we re-sampled a portion of the sites to assess the temporal impact of different competing levels on the stocking, vigour and basal area of softwood regeneration, where conifer regeneration was marginal early after cutting.

Analysis of the data from the 2007-2011 inventory showed that, after a cut with protection of regeneration and soils, ericaceous shrubs and hardwoods were not associated with the same sets of sites features. Ericaceous shrubs were mainly found in low fertility sites associated with black spruce and jack pine. The distinction between suitable environments for commercial shade-intolerant hardwoods and non-commercial hardwoods was less clear, as they responded similarly to many variables. Analysis of data from the 2015 inventory showed a significant improvement in conifer stocking when commercial shade intolerant hardwood competing levels were low (stocking 0-40%) and when ericaceous shrubs competing levels were moderate (percent cover 26-75%). The different types and intensities of competition did not appear to affect the vigour or the basal area of softwood regeneration, 9 to 14 years after harvesting.

Introduction

Conifers represent an important part of forest economy in northern countries. However, after harvesting, some hardwoods and ericaceous shrubs can quickly invade cutovers and prevent or slow down conifer regeneration establishment.

In fact, hardwoods can both facilitate or impede conifers' growth and survival. Facilitation can happen by providing better protection against insects, disease, photoinhibition, photooxidation, temperature and moisture extremes (MacLean 1996, Gerlach et al. 1997, Man and Lieffers 1999a, 1999b, Man and Greenway 2011), by improving soil productivity (Fortin et al. 1983, Bradley and Fyles 1995, Wang et al. 1996, Laganière et al. 2010), or by nutrient gains through associations with mycorrhizae (Simard et al. 1997, Philip et al. 2010). Competition can occur through the interception of a part of the light (Jobidon 2000, Comeau et al. 2003, Filipescu and Comeau 2007), water (Lieffers et al. 1993, Jobidon 1995) and nutrients (Lieffers et al. 1993, Simard and Sachs 2004). Hardwoods can also cause physical damages to conifer seedlings by whipping (Kagis 1952, Man and Lieffers 1999a, Bell et al. 2011). Competing problems seem to occur when hardwoods reach a certain density threshold that varies depending on species (Légaré et al. 2004, Hawkins et al. 2012, Hawkins and Dhar 2013).

Ericaceous shrubs can quickly invade a site after a disturbance such as fires or harvesting operations (van Nostrand 1971, Viereck 1983, Mallik 1995, Hébert et al. 2010a). These plants may directly inhibit conifers' growth through competition for nutrients (Thiffault et al. 2004b, Hébert et al. 2010b). Additionally, ericaceous shrubs can impede conifer germination and primary root growth through allelopathy (Peterson 1965, Mallik 1987, Zhu and Mallik 1994, Titus et al. 1995, Mallik and Pellissier 2000). Tannins and other polyphenols present in the litter or roots of ericaceous plants cause allelopathy and can also lead to a nutrient imbalance in the soil (Jäderlund et al. 1996, Castells et al. 2005, LeBel et al. 2008). Some ericaceous species favour a thickening of the organic layer (Damman 1971, Inderjit and Mallik 1996, DeLuca et al. 2002), which negatively affects conifer growth (Lavoie et al. 2007) by decreasing the quality of the seed bed (Greene et al. 2007) and lowering soil temperature during summer (Balisky and Burton 1997, Thiffault et al. 2004b). Ericaceous shrubs are also associated with ericoid mycorrhiza that helps absorbing nitrogen in organic forms (Malloch and Malloch 1981, Goulart et al. 1993, Read et al. 2004, Mayor et al. 2012). Allelopathic substances can also inhibit the production of mycorrhizae that benefits conifers and, sometimes, favour the presence of

pseudo-mycorrhizae on coniferous roots (Robinson 1972, Yamasaki et al. 1998, Javaid 2007). The inhibition level and competition mechanisms affecting conifer growth may vary depending on ericaceous species, coniferous species and site types (Mallik 2003). For example, black spruce regeneration failure in presence of sheep laurel (*Kalmia angustifolia* L.) is mainly caused by root growth inhibition, nutrient deficiency, and competition (Mallik, 1987, 2003; Mallik and Newton, 1988), while Norway spruce regeneration problems in presence of bilberry (*Vaccinium myrtillus*) is mostly due to the germination inhibition (Pellissier, 1993, 1994; Mallik and Pellissier, 2000, Mallik 2003).

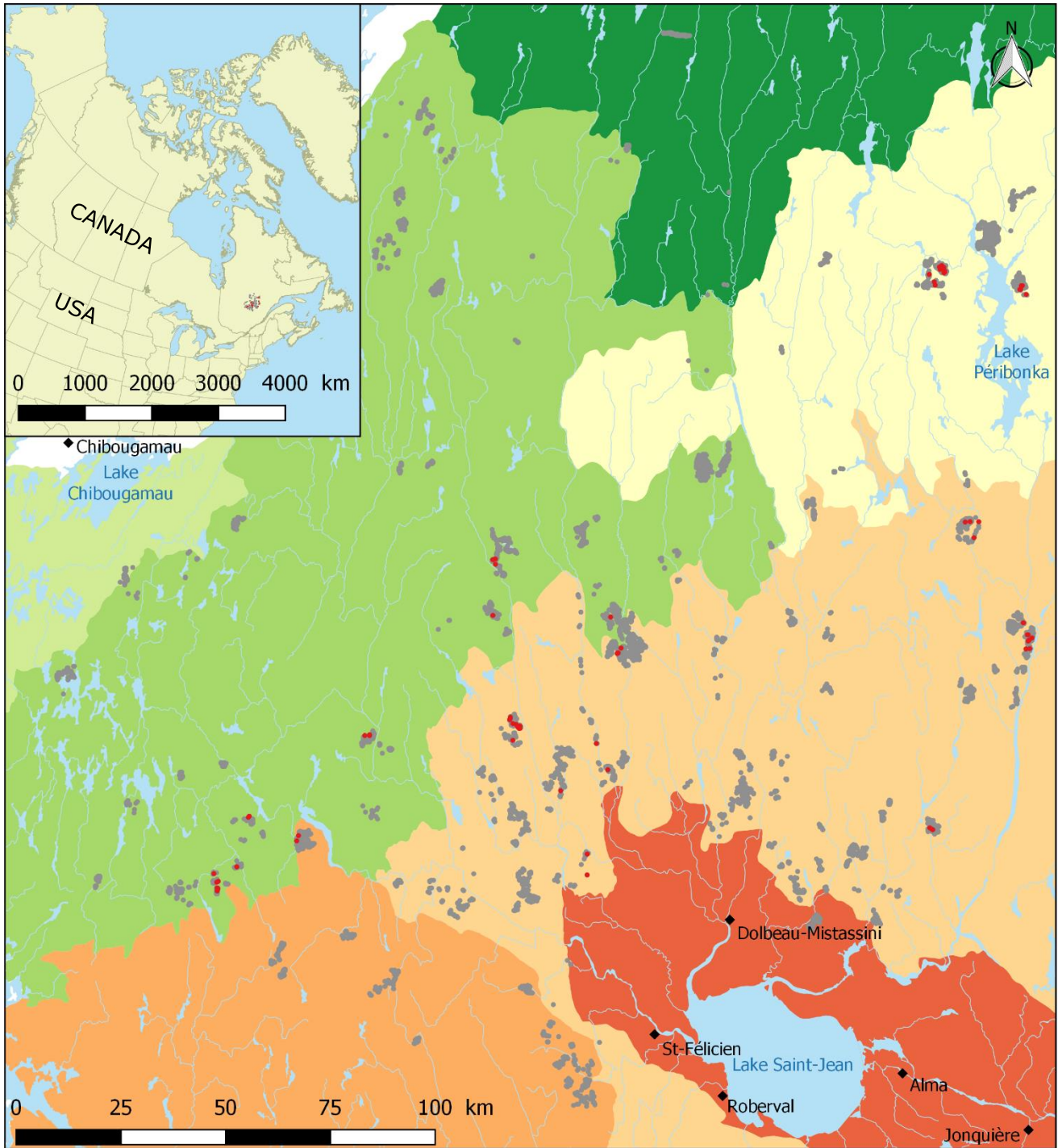
Management of competing vegetation requires an understanding of the factors influencing its abundance and its impacts on the most commercially desired species. A characterization of biophysical (e.g. pre-harvest stand dominant species group, type and year of the original disturbances, drainage, surficial materials, ecological region, elevation) and harvesting (e.g. harvesting method, harvesting season) characteristics favouring the development of these species would enable predicting sites where site preparation or tending operations would be required, based on biophysical characteristics and forest planning.

The main objective of our study was to identify regeneration problems related to competition by ericaceous shrubs and hardwoods in relation to initial stand composition, site characteristics and ecological units in the eastern Canadian boreal forest. Our specific objectives were to i) identify the harvesting characteristics and biophysical variables that are significantly correlated to competing vegetation dominance, ii) estimate the probability of observing a given competing species group according to harvesting and environmental characteristics, and iii) assess the impact of competing vegetation on conifer vigour and sapling basal area in cases of marginal regeneration. Therefore, we hypothesized that competing vegetation composition could be linked to harvesting and environmental characteristics. Also, we predicted that nature and abundance of competing vegetation is primarily a function of biophysical characteristics. Finally, we posited that competing vegetation intensity and nature should have a decisive influence on regeneration evolution on harvested areas featuring marginal softwood regeneration. Under low competition levels, we expected softwood regeneration to increase over time, whereas under high competition levels, we anticipated conifer saplings' free to grow stocking, basal area and vigour to remain similar or decrease over time.

Materials and Methods

Study area

The study area is located in northern Quebec, Canada, between 48°29'34.44"N and 50°47'44.16"N of latitude and 74°24'15.12"W and 71°8'20.4"W of longitude (Fig. 1). Inventory sites are found in the western balsam fir-white birch bioclimatic sub region (which includes ecological regions 5c and 5d), the eastern black spruce-moss bioclimatic sub region (which includes ecological region 6h) and western black spruce-moss bioclimatic sub region (which includes ecological regions 6c, 6d and 6g) and the northern part of the eastern balsam fir-yellow birch bioclimatic sub region (which includes ecological region 4e) (Saucier et al. 2009). The climate is characterized by a mean annual temperature ranging from -2.0 to 2.5 °C and mean annual precipitations ranging from 850 to 1450 mm (Saucier et al. 2009). Fires and insect outbreaks are the main disturbances driving forest dynamics in the study area (Saucier et al. 2009). Conifer stands dominate in the northern part of the study region (85%, area-based), followed by mixed wood stands (5–10%) and northern hardwood stands (2–3%) (Morneau and Landry 2007). The proportion of mixed and hardwood stands increases from north to south. The most common conifer species are black spruce (*Picea mariana* (Mill.) B.S.P.), balsam fir (*Abies balsamea* (L.) Mill.) and jack pine (*Pinus banksiana* Lamb.). The most common hardwoods are trembling aspen (*Populus tremuloides* Michx.) and paper birch (*Betula papyrifera* Marsh.) (Saucier et al. 2009). Even though they have commercial values, these hardwoods are often considered as competing species because they can impede the growth and survival of the more economically valuable conifers. Other common competing hardwoods are mountain maple (*Acer spicatum* Lam.), pin cherry (*Prunus pensylvanica* L. f.) and speckled alder (*Alnus incana* subsp. *rugosa* (Du Roi) J. Clausen) (Thiffault and Roy 2011, Cauboue 2013). Ericaceous competition is mainly caused by bog Labrador tea (*Rhododendron groenlandicum* (Oeder) K.A. Kron and Judd), sheep laurel and blueberries (*Vaccinium* spp.) (Thiffault and Roy 2011).



Legend

- | | | | | | |
|----------|----------------------------------|-------------------|------|------|------|
| Transect | | Ecological region | | | |
| ◆ City | • 2007-2011 inventory | ■ 4e | ■ 5d | ■ 6d | ■ 6h |
| ■ Water | • 2007-2011 and 2015 inventories | ■ 5c | ■ 6c | ■ 6g | |

Projection: NAD83(CSRS) / MTM Zone 8
 Figure 1. Location of the study area and sampling sites in Quebec (Canada). Gray dots represent transects from the 2007-2011's inventory and red dots represent transects that have been re-sampled in 2015. Ecological regions are those defined by Saucier et al. (2009).

Creation of a first database

We created a database (further referred to as "database 1") using four data sources: i) inventory data from the monitoring of regenerating stands in the study region following harvesting by cutting with protection of regeneration and soils (CPRS) between 2001 and 2006, ii) hypsometric data from governmental topographic maps (Québec 1999), iii) ecological classification data from the governmental ecological classification system (Québec 2016), and iv) pre-harvest forest stands and soil attributes from the governmental forest ecological survey dataset (Létourneau et al. 2009).

Data from the monitoring of post-harvest regenerating stands

We used data collected between 2007 and 2011, by AbitibiBowater Inc. (now Resolute Forest Products Inc.) in post-harvest regenerating stands. Monitoring was conducted within the first eight years (usually four or five years) following operational CPRS. Sampling was conducted in north-oriented transects of 10 micro-plots (sometimes less) separated 5 m from each other (centre to centre). Each micro-plot consisted in two superimposed circular plots with radii of either 1.13 m (plots $\approx 4 \text{ m}^2$) for conifer observations, or 1.69 m (plots $\approx 9 \text{ m}^2$) for hardwood observations (MRNF 2011; Fig. 2A). Data collected in each micro-plot consisted in 1) presence/absence of regenerating trees by species and height class (15–30 cm, 30–60 cm, 60–100 cm, >100 cm), and 2) percent cover for groups of competing species (ericaceous shrubs and non-commercial hardwoods) using 25% classes (0%, 1–25%, 26–50%, 51–75%, 76–100%). Non-commercial hardwoods and ericaceous shrubs were treated as groups during the monitoring to limit time and money expenses (i.e. percent covers were collected by groups and not by species). Using data from the micro-plots, we calculated stocking at the transect level by species (spruce sp., balsam fir, jack pine, trembling aspen, paper birch) and species groups (conifers, hardwoods).

For each transect, metadata from the inventory was cross-validated using external data sources (Bournival et al. 2014). Stand ages were adjusted according to known harvesting dates, and harvesting seasons were verified using Landsat images. Presence/absence of delimiting areas, skidding cones and orthogonal trails were used to validate the use of cut-to-length or full tree harvesting methods. Transect localization was also validated; when coordinates pointed to forest roads, gravel pits or outside a

CPRS cutblock, transects were removed from the database. Sites that had been affected by wildfires since 1969 were also eliminated from the database.

Hypsometric data from topographic maps

We used hypsometric data from Quebec's topographic database to determine transect elevation a.s.l. We converted the contour lines into a "smooth layer" using the "*Topo to raster*", "*Int*" and "*Raster to polygon*" tools of software ArcMAP 10.2 (ESRI, Redlands, CA, USA). We then used the "*Intersect*" tool of ArcMAP to verify where the transects intersected the layer and extracted the corresponding elevation value. Altitude ranged from 177 to 702 m a.s.l.

Ecological classification data from the governmental ecological classification system

The Ecological Land Classification system of Quebec describes ecosystem characteristics at various scales, based on ecological variables related to the vegetation, the physical environment, and climate (see Saucier et al. 2009 for details). Using this system, we associated each transects to the corresponding ecological region (Fig. 1), a hierarchical level of the ecological classification characterized by the composition and dynamics of the vegetation growing on mesic sites, and by the distribution of ecological types within the landscape.

Forest stands and soil attributes from forest ecological survey datasets

For each transect, we obtained information about the pre-harvest stand using ecological forest maps. We included information about drainage, surficial materials as well as the type and year of the original disturbance. Sites classified as alder groves, dry barrens or wet barrens were discarded, being considered as unproductive from a forest management perspective. As a result, 4,471 transects were retained, representing 43,972 microplots distributed in 1,277 cutblocks.

Creation of a second database

During summer 2015, we performed a stratified inventory in 72 of the transects from "database 1" to evaluate conifer regeneration and competing vegetation. This led to the creation of a new database (further referred to as "database 2") created from: 1)

vegetation and soil data collected during the 2015 inventory, and 2) initial data from the 72 corresponding transects in "database 1".

Stratified inventory

We selected 72 transects from database 1 that had an initial free-to-grow (FTG) conifer stocking varying between 40 and 60% and that were still accessible in 2015. FTG implied that no vegetation within a 1 m radius exceeded half the height of the target tree (Méthot et al. 2014). Five years after harvesting, a conifer stocking of 60% is about the minimum threshold for a stand to reach maximum yield at maturity (Pominville and Ruel 1995) and, in practice, a site is generally considered as non-regenerated when its commercial species stocking is less than 40% (Pominville and Doucet 1993, Agence régionale de mise en valeur des forêts privées de la Gaspésie-Les-îles 2013, Agence Forestière Lac St-Jean and Agence Forestière Saguenay 2014). Between these two thresholds, conifer establishment success is uncertain. It is therefore important to better understand the impact of competing vegetation on coniferous regeneration under those circumstances.

Sites were divided into three strata representing the initial level of competing vegetation (low, medium, high; see Table 1) and two strata representing the initial type of dominant competing vegetation (Table 1). Sites initially dominated by non-commercial hardwoods were not included in the stratification due to a lack of transects belonging to the "high" level of competition. Transects that had been submitted to mechanical site preparation and/or plantation were also avoided.

Table 1. Distribution of transects in the stratified inventory based on dominance by competing vegetation groups and levels of competition.

Level of competition	Type of dominant competing vegetation	
	Commercial shade-intolerant hardwoods	Ericaceous shrubs
Low	10	10
Medium	13	14
High	14	11

Ericaceous shrubs: low = percent cover between 1–25%, medium = percent cover between 26–75%, high = percent cover between 76–100%. Commercial shade-intolerant hardwoods: low = stocking between 0–40%, medium = stocking between 40–60%, high = stocking between 60–100%.

Based on the initial sampling, we established transects of 10 circular micro-plots separated by 5 m from each other, except for the fifth whose centre was distanced 7 m from the adjacent micro-plots (Fig. 2B). Micro-plot areas were similar to the ones used in the initial sampling (radius of 1.13 m and 1.69 m for conifer and hardwood

observations, respectively); vegetation cover estimation was conducted in a similar manner. In each micro-plots (Fig. 2B), we noted the presence/absence and FTG status of regeneration by species and height class (15–30 cm, 30–60 cm, 60–100 cm and more than 100 cm).

Saplings (defined as having a diameter at breast height, DBH > 1.0 cm and < 9,1 cm) were counted in a 5.64 m radius plot superimposed on the fifth micro-plot (Fig. 2B). In this micro-plot, three sample-trees representative of the modal height of the regeneration were selected; we noted the species, height, length of the live crown, length of the terminal shoot and length of the longest lateral branch of the last whorl. Tree height and length of the live crown were used to calculate a live crown ratio (Seidel 1980, Ruel and Doucet 1998, Ruel et al. 2000). Length of the terminal shoot and length of the longest lateral branch of the last whorl were used to calculate an apical dominance ratio (Kohyama 1980, Klinka et al. 1992, Parent and Messier 1995). Live crown ratio and apical dominance ratio are two indices used to estimate conifer vigour.

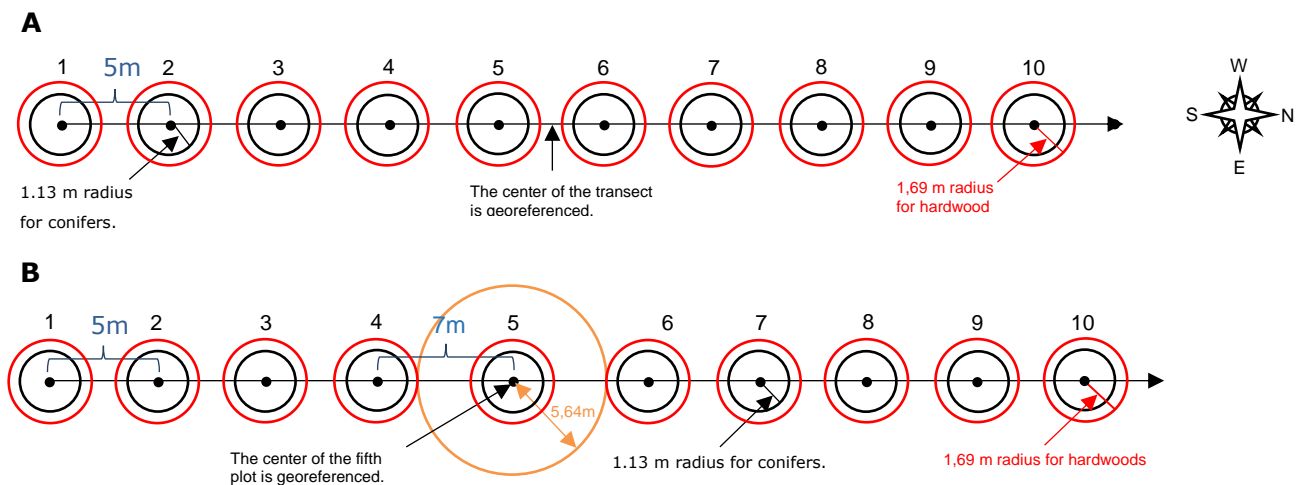


Figure 2. (A) Configuration of the micro-plots in a transect used in the 2007-2011 monitoring of post-harvest regenerating stands. (B) Configuration of the plot and the microplots in a transect for the 2015 stratified inventory.

Data analysis

Variables significantly linked to competing vegetation cover

To achieve objective i), we used data from database 1 to perform a redundancy analysis (RDA ; Borcard et al. 2011) using the *vegan* package (Oksanen et al. 2017) in R version 3.3.3 (R Core Team 2017). We split the data into two matrices. The first matrix (the Y

matrix) contained the dependent variables, namely, the percent cover of ericaceous shrubs, the percent cover of non-commercial hardwoods and the stocking of commercial shade-intolerant hardwoods. The second matrix (the X matrix) contained explanatory variables, namely, harvesting and forest characteristics such as pre-harvest stand dominant species group, type and year of the original disturbances, drainage, surficial materials, ecological region, elevation, harvesting method and harvesting season. Before the RDA, we kept explanatory variables containing more than 20 observations ($n > 20$), to detect reasonable size effects with reasonable power (Harrell 2015). We also applied a Hellinger transformation to the Y matrix to give low weights to variables with low counts and many zeros and thus maintain an ecologically meaningful distance among sites in the ordination (Legendre and Gallagher 2001). We also performed a forward selection using a double-stopping criterion (Blanchet et al. 2008) to select the best subset of explanatory variables and avoid strong multicollinearity. We verified multicollinearity by making sure variance inflation factors (VIF) were < 10 for the explanatory variables (Borcard et al. 2011).

Probability of observing a given competing species cover

To achieve objective ii), we performed a linear mixed effects analysis (LMM; Zuur et al. 2009) of the commercial shade-intolerant hardwood stocking with the *lme4* package (Bates et al. 2015) in R. Degrees of freedom and p-values for the LMM were obtained using the *lmerTest* package (Kuznetsova et al. 2016). We also performed two cumulative link mixed analyses (CLMM; Agresti 2002) of the cover of non-commercial hardwoods and ericaceous shrubs with the *ordinal* package (Christensen 2015). For LMM and CLMMs, cutblocks were used as a random effect factor and the X variables identified in the RDA were used as fixed effects. Commercial shade-intolerant hardwood stocking was used as a dependent variable for the LMM and percent cover of ericaceous shrubs or commercial shade-intolerant hardwoods were used as dependent variables for the CLMMs. We calculated a pseudo- R^2 for the LMM with the *MuMIn* package (Barton 2016).

Regeneration on sites with marginal FTG stocking

To achieve objective iii) we performed four mixed ANOVAs (also referred to as “nested ANOVA”; McDonald 2014) on data from “database 2” using the *nlme* package (Pinheiro et al. 2017) and the *anova* function of R. When a significant effect was detected ($p < 0.05$) for an interaction or a main effect, we proceeded to a pairwise comparison of the least square means with the *lsmeans* package (Lenth 2016) to determine if the

differences between means were significant ($p < 0.05$). For the first mixed ANOVA, we checked whether the competing cover type and level affected free-to-grow conifer stocking where conifer regeneration success was uncertain. To do so, we used the conifer stocking measured in both inventories as a dependent variable and the six strata of competing cover (Table 1), as well as the time of the inventory (1 for the first inventory, 2 for the second) as fixed effects. For the random effects, we used sites (to account for the repeated measures) and cutblocks (to account for the nested design). We tested for interaction between time and competing vegetation cover. For the second and third analyses, we asked if the competing level measured during the first inventory influenced the vigour of the conifer regeneration assessed at the second inventory. To do so, we relied on the two vigour indices (live crown ratio and apical index) and performed a mixed ANOVA using each of these as dependent variables and strata of competing covers as a fixed effect. We used cutblocks as a random effect to account for the nested design. Finally, we asked if the competing level measured in the first inventory influenced sapling basal area measured in the second inventory. To do so, we used sapling basal area as a dependent variable and the six strata of competing covers as a fixed effect. To account for the nested design, we used cutblocks as a random effect.

Results

Variables significantly linked to competing vegetation cover

Explanatory variables (Table 2) selected for the RDA accounted for 35.3% of the variation in the composition of competing vegetation; axes 1 and 2 respectively explained 32.98% and 2.02% of the variance (Fig. 3). Permutation tests indicate that the global model and canonical axes were significant at $p = 0.001$. Axis 1, which contains most of the information, contrasts conditions associated with ericaceous shrubs and those associated with other competing vegetation types. The ericaceous shrubs were positively correlated with imperfect drainage, altitude, hills of Lake Péribonka and pre-harvest stands dominated by black spruce (Fig. 3). Hardwoods were negatively correlated with all the above and positively correlated to the hills surrounding Lake Saint-Jean, tills 50-100 cm thick, pre-harvest stands dominated by paper birch and pre-harvest stands dominated by both balsam fir and paper birch. Non-commercial hardwoods were also positively correlated to partial harvesting.

Table 2. Description of the independent variables identified in the RDA and later used in the linear mixed model and the cumulative link mixed models.

Theme	Code	Description
Altitude	ALTITUDE	Altitude
Drainage	DR20	Good
	DR31	Moderate and lateral
	DR40	Imperfect
	DR50	poor
Ecological region	4e	Plain of Lake Saint-Jean and Saguenay
	5d	Hills surrounding Lake Saint-Jean
	6c	The plain of Lake Opemisca
	6g	Hillsides of Lake Manouane
	6h	Hills of Lake Péribonka
Harvesting method	AE	Full tree harvesting
	BT	Cut-to-length logging
	MA	Manual harvesting
Harvesting season	AUT	Harvested in fall
	ÉTÉ	Harvested in summer
	HIV	Harvested in winter
Pre-harvest stand's original disturbance	CHP	Partial windthrow
	CHT_M	Total windthrow
	CP	Partial harvesting
	CT_M	Clearcutting
	EL	Mild epidemic
Pre-harvest stand	BBBB	<i>Betula papyrifera</i> (>75% ^a)
	BBBBE	<i>Betula papyrifera</i> (>75% ^a) with <i>Picea mariana</i> (>50% ^b)
	BBBBS	<i>Betula papyrifera</i> (>75% ^a) with <i>Abies balsamea</i> (>50% ^b)
	BBPE	<i>Betula papyrifera</i> (50-75% ^a) with <i>Populus tremuloides</i> (25%-50% ^a)
	BJmR	<i>Betula alleghaniensis</i> (25%-50% of the basal area) with conifers
	EBB	<i>Picea mariana</i> (>50% ^b) with <i>Betula papyrifera</i> (>50% ^a)
	EE	<i>Picea mariana</i> (>75% ^b)
	EPG	<i>Picea mariana</i> (50-75% ^b) with <i>Pinus banksiana</i>
	ES	<i>Picea mariana</i> (50-75% ^b) with <i>Abies balsamea</i>
	PGE	<i>Pinus banksiana</i> (50-75% ^b) with <i>Picea mariana</i>
	PGPE	<i>Pinus banksiana</i> (>50% ^b) with <i>Populus tremuloides</i> (>50% ^a)
	PGPG	<i>Pinus banksiana</i> (>75% ^b)
	SBB	<i>Abies balsamea</i> (>50% ^b) with <i>Betula papyrifera</i> (>50% ^a)
	SE	<i>Abies balsamea</i> (50-75% ^b) with <i>Picea mariana</i>
Surficial materials	D_1AY	Till (50-100cm)
	D_1BP	Disintegration moraine
	D_2A	Juxtaglacial deposits
	D_2BE	Outwash
	D_7T	Thin organic deposits

^a of the hardwood basal area

^b of the conifer basal area

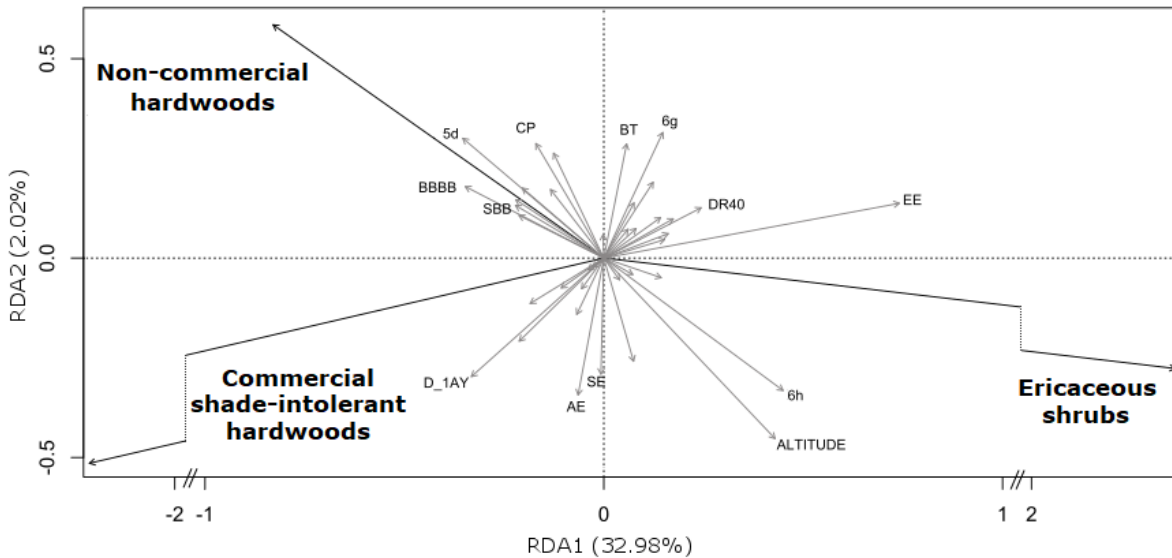


Figure 3. RDA ordination biplot showing the correlation between competing species groups (black arrows) and explanatory variables selected using a forward selection approach (grey arrows). Only variables with the highest contribution to axes RDA1 or RDA2 are labeled (i.e. coordinate on one axis was > 90th quantile or < 10th quantile of the distribution of variables coordinates on the same axis). Refer to Table 2 for variables description.

Probability of observing a given competing species cover

The LMM produced for the commercial shade-intolerant hardwoods had a marginal pseudo- R^2 of 0.34. Its coefficient estimates (Table 3) show that the chances of observing commercial shade-intolerant hardwoods significantly increased in presence of good drainage, full tree harvesting, tills 50-100 cm thick, and pre-harvest stands dominated by paper birch and accompanied by trembling aspen. These chances significantly decreased in presence of imperfect drainage, ecological regions 6g or 6h, winter harvesting, pre-harvest stands originating from total windthrow, clearcutting or mild epidemic, pre-harvest paper birch stands, pre-harvest stands containing black spruce or jack pine as a dominant or co-dominant species, disintegration moraine, juxtaglacial deposit, and outwash.

Table 3. Summary of the linear mixed models predicting commercial shade-intolerant hardwood stocking as a function of harvesting and biophysical variables.

Theme	Variable	Estimate	Standard Error	df	t value	Pr(> t)	
-	(Intercept)	0.54370	0.05373	1531	10.120	< 0.001	
Altitude	ALTITUDE	0.00009	0.00008	1900	1.153	0.249	
Drainage	DR20	0.07027	0.01119	4309	6.278	< 0.001	
	DR31	-0.01313	0.02284	4464	-0.575	0.565	
	DR40	-0.06080	0.01560	4452	-3.897	< 0.001	
	DR50	-0.10780	0.06686	4468	-1.613	0.107	
Ecological region	4e	0.06302	0.05910	1443	1.066	0.286	
	5d	0.02577	0.01754	1470	1.469	0.142	
	6c	-0.11330	0.07517	1213	-1.507	0.132	
	6g	-0.13250	0.06537	2211	-2.027	0.043	
	6h	-0.22990	0.02273	949	-10.116	< 0.001	
Harvesting method	AE	0.07429	0.02909	1068	2.554	0.011	
	BT	-0.03012	0.02895	1061	-1.040	0.299	
	MA	0.05013	0.05282	1333	0.949	0.343	
Harvesting season	AUT	-0.04905	0.02591	1494	-1.893	0.059	
	ÉTÉ	-0.01959	0.02511	1674	-0.780	0.435	
	HIV	-0.11760	0.02502	1437	-4.699	< 0.001	
Pre-harvest stand's original disturbance	CHP	-0.02564	0.02166	4470	-1.184	0.237	
	CHT_M	-0.19060	0.05479	4276	-3.480	< 0.001	
	CP	-0.01894	0.03065	3683	-0.618	0.537	
	CT_M	-0.16920	0.03891	4439	-4.348	< 0.001	
	EL	-0.04465	0.01382	4099	-3.232	0.001	
Pre-harvest stand	BBBB	-0.05861	0.02013	3702	-2.912	0.004	
	BBBBE	-0.09851	0.02590	4373	-3.804	< 0.001	
	BBBBS	-0.04788	0.03123	4303	-1.533	0.125	
	BBPE	0.07814	0.02977	3557	2.624	0.009	
	BJmR	-0.10780	0.05573	3560	-1.935	0.053	
	EBB	-0.11740	0.02796	4462	-4.199	< 0.001	
	EE	-0.28480	0.01368	4099	-20.815	< 0.001	
	EPG	-0.25630	0.02618	3929	-9.789	< 0.001	
	ES	-0.15870	0.01834	4444	-8.656	< 0.001	
	PGE	-0.24760	0.02642	4209	-9.372	< 0.001	
	PGPG	-0.14080	0.03621	3425	-3.889	< 0.001	
	SBB	-0.04816	0.02719	4206	-1.771	0.077	
	SE	-0.11720	0.02307	4470	-5.082	< 0.001	
	Surficial materials	D_1AY	0.06825	0.00954	4388	7.157	< 0.001
		D_1BP	-0.10830	0.04932	4407	-2.196	0.028
D_2A		-0.13000	0.02921	3908	-4.451	< 0.001	
D_2BE		-0.14630	0.03152	3843	-4.642	< 0.001	
D_7T		-0.06660	0.06767	4460	-0.984	0.325	

Refer to Table 2 for variable description. Bold indicate significance at $\alpha = 0.05$.

Proportional odds assumption was not met for the CLMMs of the ericaceous shrubs and non-commercial hardwoods; the explanatory variables did not have the same effect on the odds from one threshold to another. This assumption is however rarely met (Harrell 2015), especially in presence of many explanatory variables and a large sample size (O'Connell 2006), like in our case. However, these models can still be useful (Harrell 2015); estimates obtained from both models (Tables 4 and 5) provided a general idea of the changes in competing species' percent cover induced by the explanatory variables. Furthermore, for both CLMMs, altitude was put aside to avoid convergence problems.

The CLMM's coefficient estimates (Table 4) show that the chances of observing non-commercial hardwoods significantly increased in presence of good drainage, in ecological regions 4e or 5d, in pre-harvest stands originating from partial windthrow or partial harvesting, in pre-harvest paper birch stands and pre-harvest stands dominated by paper birch with balsam fir or trembling aspen as companion species. These chances significantly decreased in presence of imperfect or poor drainage, in ecological region 6h, in pre-harvest stands originating from total windthrow, in pre-harvest stands dominated by black spruce, in pre-harvest stands dominated by jack pine, in pre-harvest stands dominated by balsam fir and accompanied by black spruce, in disintegration moraine, juxtaglacial deposit and outwash.

The chances of observing ericaceous shrubs (Table 5) significantly increased in ecological region 6h, following winter harvesting, in pre-harvest stands originating from total windthrow, clearcutting, in pre-harvest stands dominated by paper birch and accompanied by black spruce, pre-harvest stands dominated by black spruce or jack pine, in juxtaglacial deposits and in outwash. Those chances significantly decreased in presence of the ecological regions 4e or 5d, full tree harvesting, cut-to-length logging, pre-harvest stands originating from partial windthrow or mild epidemic, pre-harvest paper birch stands, pre-harvest stands dominated by paper birch with balsam fir or trembling aspen as companion species, pre-harvest stands dominated by balsam fir with paper birch as companion species.

Table 4. Threshold coefficients and summary of the cumulative link mixed model predicting non-commercial hardwood percent cover as a function of harvesting and biophysical variables.

Threshold coefficients					
	Threshold	Estimate	Std. Error	z value	
	0 0.13	-5.0714	0.4069	-12.463	
	0.13 0.38	0.3689	0.3915	0.942	
	0.38 0.63	2.5542	0.3977	6.422	
	0.63 0.88	4.9381	0.4204	11.746	
Summary of the cumulative link mixed model					
Theme	Variable	Estimate	Std. Error	z value	Pr(> z)
Drainage	DR20	0.3812	0.1114	3.422	0.001
	DR31	0.0696	0.2300	0.303	0.762
	DR40	-0.4878	0.1657	-2.943	0.003
	DR50	-2.3104	0.6536	-3.535	< 0.001
Ecological region	4e	2.5180	0.5172	4.869	< 0.001
	5d	0.7600	0.1328	5.722	< 0.001
	6c	-0.6781	0.7818	-0.867	0.386
	6g	0.9201	0.6364	1.446	0.148
	6h	-1.9205	0.2282	-8.417	< 0.001
Harvesting method	AE	-0.0384	0.2872	-0.134	0.894
	BT	-0.5390	0.2868	-1.880	0.060
	MA	-0.2286	0.5125	-0.446	0.656
Harvesting season	AUT	-0.0861	0.2516	-0.342	0.732
	ÉTÉ	-0.0249	0.2438	-0.102	0.919
	HIV	-0.3902	0.2428	-1.607	0.108
Pre-harvest stand's original disturbance	CHP	0.5077	0.2218	2.290	0.022
	CHT_M	-1.8587	0.6112	-3.041	0.002
	CP	1.2115	0.2920	4.149	< 0.001
	CT_M	-0.5768	0.3873	-1.489	0.136
	EL	-0.0037	0.1378	-0.027	0.979
Pre-harvest stand	BBBB	0.9485	0.1881	5.043	< 0.001
	BBBBE	-0.3060	0.2482	-1.233	0.218
	BBBBBS	0.9878	0.2905	3.400	0.001
	BBPE	1.1753	0.2680	4.386	< 0.001
	BJmR	0.4597	0.5042	0.912	0.362
	EBB	-1.1451	0.2888	-3.965	< 0.001
	EE	-1.9998	0.1430	-13.986	< 0.001
	EPG	-1.1734	0.2714	-4.324	< 0.001
	ES	-1.4700	0.1912	-7.689	< 0.001
	PGE	-1.7468	0.2773	-6.300	< 0.001
	PGPG	-0.7324	0.3504	-2.090	0.037
	SBB	-0.1708	0.2596	-0.658	0.511
	SE	-1.4806	0.2460	-6.018	< 0.001
Surficial materials	D_1AY	0.0994	0.0963	1.032	0.302
	D_1BP	-1.3321	0.5583	-2.386	0.017
	D_2A	-0.6868	0.3020	-2.274	0.023
	D_2BE	-0.9578	0.3340	-2.867	0.004
	D_7T	0.8254	0.6412	1.287	0.198

Refer to Table 2 for variable description. Bold indicate significance at $\alpha = 0.05$.

Table 5. Threshold coefficients and summary of the cumulative link mixed model predicting ericaceous shrub percent cover as a function of harvesting and biophysical variables.

Threshold coefficients					
	Threshold	Estimate	Std. Error	z value	
	0 0.13	-2.5516	0.3616	-7.056	
	0.13 0.38	1.0497	0.3589	2.925	
	0.38 0.63	2.7395	0.3618	7.572	
	0.63 0.88	4.7524	0.3694	12.866	
Summary of the cumulative link mixed model					
Theme	Variable	Estimate	Std. Error	z value	Pr(> z)
Drainage	DR20	0.0668	0.1002	0.667	0.505
	DR31	-0.3836	0.2063	-1.860	0.063
	DR40	0.0989	0.1344	0.736	0.462
	DR50	-0.4695	0.5956	-0.788	0.431
Ecological region	4e	-1.1891	0.5260	-2.261	0.024
	5d	-0.5362	0.1198	-4.475	< 0.001
	6c	-0.5223	0.6569	-0.795	0.427
	6g	0.3594	0.5326	0.675	0.500
	6h	1.7799	0.1968	9.045	< 0.001
Harvesting method	AE	-0.8260	0.2625	-3.147	0.002
	BT	-0.8409	0.2618	-3.212	0.001
	MA	0.3715	0.4652	0.799	0.425
Harvesting season	AUT	0.4521	0.2311	1.956	0.050
	ÉTÉ	0.1765	0.2251	0.784	0.433
	HIV	0.9542	0.2237	4.265	< 0.001
Pre-harvest stand's original disturbance	CHP	-0.6950	0.1941	-3.581	< 0.001
	CHT_M	1.2666	0.4657	2.720	0.007
	CP	-0.3474	0.2776	-1.251	0.211
	CT_M	1.7252	0.3484	4.951	< 0.001
	EL	-0.3673	0.1250	-2.939	0.003
Pre-harvest stand	BBBB	-1.2135	0.1884	-6.442	< 0.001
	BBBBE	0.5869	0.2302	2.549	0.011
	BBBBBS	-1.2338	0.2977	-4.145	< 0.001
	BBPE	-0.7174	0.2776	-2.584	0.010
	BJmR	-0.7653	0.5338	-1.434	0.152
	EBB	0.5780	0.2499	2.312	0.021
	EE	1.7337	0.1236	14.031	< 0.001
	EPG	1.4064	0.2289	6.145	< 0.001
	ES	0.9399	0.1625	5.784	< 0.001
	PGE	1.4891	0.2289	6.506	< 0.001
	PGPG	1.0648	0.3196	3.332	0.001
	SBB	-1.0221	0.2571	-3.975	< 0.001
	SE	0.2655	0.2063	1.287	0.198
Surficial materials	D_1AY	-0.0539	0.0848	-0.636	0.525
	D_1BP	0.0940	0.4140	0.227	0.820
	D_2A	0.6050	0.2516	2.405	0.016
	D_2BE	0.6132	0.2703	2.268	0.023
	D_7T	1.0095	0.6018	1.677	0.093

Refer to Table 2 for variable description. Bold indicate significance at $\alpha = 0.05$.

Regeneration on sites with marginal FTG stocking

There was a significant interaction between time and competing cover strata ($F(5, 66) = 2.7, p = 0.028$). However, pairwise comparison of the least square means showed that the increase in stocking was only statistically significant for low competing levels of commercial shade-intolerant hardwoods ($t(66) = -5.992, p < 0.001$) and moderate competing levels of ericaceous shrubs ($t(66) = -5.653, p < 0.001$) (Fig. 4). We did not detect statistically significant differences over time for low competing levels of ericaceous shrubs ($t(66) = -3.205, p < 0.081$), high competing levels of ericaceous shrubs ($t(66) = -2.126, p < 0.607$), moderate competing levels of commercial shade-intolerant hardwoods ($t(66) = -3.300, p < 0.063$) and high competing levels of commercial shade-intolerant hardwoods ($t(66) = -2.709, p < 0.245$) (Fig. 4). Free-to-grow conifer stocking had a tendency to improve over time in every strata of competing cover (Fig. 4). On average, at the time of the second inventory, we observed free-to-grow conifer stocking exceeding 60% for every strata (Fig. 4), which is generally considered a sufficient regeneration level.

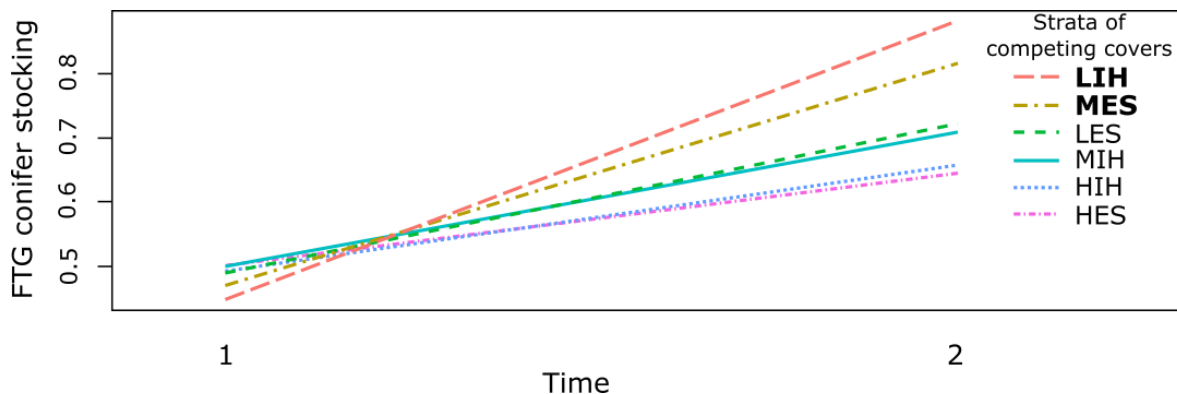


Figure 4. Free-to-grow conifer stocking per strata of competing cover and over two time periods. LIH: low competing level of commercial shade-intolerant hardwoods, MIH: moderate competing level of commercial shade-intolerant hardwoods, HIH: high competing level of commercial shade-intolerant hardwoods, LES: low competing level of ericaceous shrubs, MES: moderate competing level of ericaceous shrubs, HES: high competing level of ericaceous shrubs. Bold indicate significance at $\alpha = 0.05$.

There were no significant difference in live crown ratio ($F(5, 13) = 2.296, p = 0.106$) and apical index ($F(5, 13) = 1.030, p = 0.440$) according to competing cover strata. Most sampled trees were vigorous. For each competing cover strata, average live crown ratio was higher than 70% and average apical index was higher than 1.20. Least square

means did not detect any significant differences in sapling basal area between the different competing cover strata. Average sapling basal area ranged from 1.67 to 5.19 m²/ha for each competing cover strata.

Discussion

Ecological region and altitude

Our results indicate that hardwoods and ericaceous shrubs competition are not found in the same type of environments (Fig 3; Tables 3 to 5). Ecological regions located at the north of the study area had significantly lower odds of observing both the non-commercial and the commercial shade-intolerant hardwoods, whereas ecological regions located at the south of the study area had significantly higher odds of observing non-commercial hardwoods (Tables 3 and 4). The opposite occurred for ericaceous shrubs. Furthermore, ericaceous shrubs were positively correlated with altitude (Fig. 3). These latitudinal and altitudinal differences suggest that colder climates favour ericaceous shrubs presence over hardwoods.

Pre-harvest stand composition

We also found a close relationship between competing vegetation and stand type. Pre-harvest stands of jack pine or with black spruce in its dominant species increased the odds of observing ericaceous shrubs and reduced the chances to encounter hardwoods. This could partly be explained by climatic conditions. Colder climate favour conifers over hardwoods (Pastor and Mladenoff 1992, Sirois 1992, Pothier 2001) and we just mentioned that colder climates might favour ericaceous shrubs presence over hardwoods. Cold climate slows down decomposition rates and favours the accumulation of organic matter (Harden et al. 1997, Kurz et al. 2013), a substrate favourable to black spruce and ericaceous shrubs growth (Viereck and Johnston 1990, Jobidon 1995), while paper birch, trembling aspen, pin cherry and mountain maple are generally found on richer soils (Chapin et al. 1983, Bell 1991, Jobidon 1995). Furthermore, we observed that both hardwood categories had a better chance to grow on well-drained sites, an observation that concurs with previous studies (Marquis et al. 1969, Corns 1989, Bell 1991, Jobidon 1995). On the other hand, black spruce and some ericaceous shrubs are often found on poorly drained soils (Viereck and Johnston 1990, Jobidon 1995). Poor drainage favours accumulation of organic matter (Harden et al. 1997), which worsen conditions for hardwoods. Indeed, Lafleur et al. (2015) observed that organic layers accumulation hinders aspen seedling germination and growth as well as sucker development. Moreover, black spruce stands favour paludification by promoting *Sphagnum* spp. growth and the production of a litter that decomposes slowly (Flanagan

and Van Cleve 1983, Turetsky 2003, Légaré et al. 2004, Fenton et al. 2005). Sphagnum also favours the creation of acidic, wet and cold soils that decrease the decomposition rate of the organic matter, nutrients availability, microbial activity and plant growth (Turetsky 2003, Fenton et al. 2005, Lavoie et al. 2007). Ericaceous shrubs can also favour sphagnum growth through a scaffolding effect (Malmer et al. 2003, Fenton et al. 2005). Furthermore, sheep laurel and bog Labrador tea favour the accumulation of organic matter (Damman 1971, Inderjit and Mallik 1996). Sheep laurel produces tannins that inhibit nitrogen mineralization and bog Labrador tea produces phenolic compounds that modify soil nutrients availability (Inderjit and Mallik 1997, Bradley et al. 2000, Joanisse et al. 2007, 2009). Therefore, an increasing amount of nutrients get immobilized overtime in the organic layer where the understory is dominated by a shade-tolerant ericaceous shrub like sheep laurel (Mallik et al. 2012). Furthermore, jack pine can grow on very xeric sandy sites that are less favourable to hardwoods but on which ericaceous shrubs like sheep laurel can grow (Rudolph and Laidly 1990, Jobidon 1995).

Climate and soil fertility could also have been responsible for the lower chances of encountering ericaceous shrubs and the better odds of observing non-commercial hardwoods where pre-harvest stands were dominated by hardwoods without black spruce as a companion species. Also, paper birch and trembling aspen can facilitate non-commercial hardwood establishment. Although they can have detrimental effects on conifer growth by intercepting light, paper birch and trembling aspen canopies can attenuate weather extremes and increase humidity for understory vegetation (Man and Lieffers 1997, 1999b, Simard et al. 1997). Their litter decompose rapidly and increase nutrient availability (Wang et al. 1995, Peterson et al. 1997, Man and Lieffers 1999a). Moreover, paper birch is also known to facilitate carbon transfer to Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) through ectomycorrhizal connections (Simard et al. 1997, Simard and Vyse 2006). It is however unclear if it can also facilitate carbon transfer to conifer species present on our study sites. Furthermore, hardwoods let more light reach the understory than conifers (Messier 1996, Messier et al. 1998), which could help semi shade-tolerant species such as mountain maple to persist under their cover.

We only observed an increase in the probabilities to encounter commercial shade-intolerant hardwoods when pre-harvest stands were dominated by paper birch accompanied by trembling aspen (Table 3). Without aspen, the presence of paper birch as a dominant or a companion species in the pre-harvest stands did not increase the chances to observe commercial shade-intolerant hardwoods in the post-harvest

regeneration. Similarly to this observation, Harvey and Bergeron (1989) observed a reduction in paper birch density and an increase of trembling aspen density following clearcutting in northwestern Quebec. This could be due to reproductive characteristics of both species. Trembling aspen mainly propagates via root sprouting (Moss 1937, Maini 1968, David et al. 2001), which allows to quickly repopulate a site and overtop competition. Paper birch can also produce sprouts but rarely in a quantity that is sufficient to regenerate a stand (Marquis et al. 1969). It mostly regenerates through seeds that can disperse over relatively long distances (Safford et al. 1990), making it less tightly linked to the harvest site than trembling aspen. Also, trembling aspen grows faster than paper birch (Doyon et al. 2001), giving it better chances to overtop competition and form the dominant cover. Furthermore, in boreal forests, shade-tolerant species usually establish in the understory of mature shade-intolerant hardwood stands, slowly shifting site composition from broadleaves to conifers (Bélanger et al. 1993, Bergeron and Charron 1994, Bergeron 2000, Hébert 2003). If they have not reached merchantable size, those shade-tolerant trees are not harvested during CPRS. Trees left on cutovers intercept light, hence impeding potential site colonization by shade-intolerant species (Haeussler and Coates 1986, Doucet 1989).

Drainage and harvesting season

Our results show that well-drained sites increased the odds of observing both hardwood categories, while wet sites decreased those odds (Tables 3 and 4). Paper birch and trembling aspen are indeed known to grow best on well-drained sites (Marquis et al. 1969, Corns 1989). Mountain maple and pin cherry are generally present on relatively well-drained sites (Bell 1991, Jobidon 1995). Speckled alder, on the other hand, is commonly associated with poorly drained sites (Healy and Gill 1974, Jobidon 1995). Analyzing competing vegetation by functional groups might have affected our ability to predict the presence of hardwoods like speckled alder on imperfectly or poorly drained sites. We must also consider that wet sites are often harvested during winter to avoid damaging soils. The snow cover on the ground may help protecting preestablished shade-tolerant regeneration during harvesting (Groot 1995, Pothier 2000), making it harder for shade-intolerant hardwoods to repopulate those sites. This would also explain why the odds of encountering commercial shade-intolerant hardwoods diminished after winter harvesting (Table 3). Similarly, the increased odds of observing ericaceous shrubs after winter harvesting might be attributed to the fact that some ericaceous species can

grow on wet sites (e.g. bog Labrador tea and sheep laurel; Jobidon 1995, Hébert and Thiffault 2011).

Surficial materials

Deep tills are likely to feature good or moderate drainage (Grondin et al. 2005), which can explain why we observed that commercial shade-intolerant hardwoods were more likely to be found on tills 50-100 cm thick. This concurs with previous provincial scale assessments of paper birch and trembling aspen ecology that have shown that these species generally grow on glacial deposits (Jobidon 1995). On the other hand, disintegration moraines and juxtaglacial deposits are among the driest surficial deposits and are likely to limit seedling establishment (Mansuy et al. 2012), which can explain the decline of the odds to encounter hardwoods on those deposits. Outwash generally features low nutrient availability (Schreeg et al. 2005, Marquis and Pare 2009), which can explain why this deposit has a negative effect on the probabilities to encounter hardwoods. Similarly, previous observations showed that paper birch, trembling aspen, pin cherry, mountain maple and speckled alder are seldom found on fluvio-glacial deposits (Jobidon 1995) such as juxtaglacial deposits and outwash. The increase of the odds to encounter ericaceous shrubs on juxtaglacial deposits and outwash suggests that these deposits might favour ericaceous shrubs over hardwoods. Sheep laurel can indeed cause competition problems on dry sites (Mallik 1994, 1995) and bog Labrador tea and sheep laurel are prolific on nutrient-poor sites (Mallik 1995, Inderjit and Mallik 1999, Hébert and Thiffault 2011).

Pre-harvest stand original disturbance

Moreover, we observed better odds to encounter non-commercial hardwoods after the harvesting of stands that originated from partial windthrow or partial harvesting (Table 4). These disturbances create gaps in the canopy and let more light enter the lower strata of the stands which could benefit shade-intolerant or semi shade-tolerant species. In fact, small gaps seem to favour the proliferation of preestablished shade-tolerant species, while larger gaps seem favourable to the maintenance of shade-intolerant species (Kneeshaw and Bergeron 1998, Kneeshaw and Prévost 2007, Rich et al. 2007). Partial windthrows are more frequent in mixed stands (Mitchell 2013, Anyomi et al. 2017) so that the relation with partial windthrow could derive from the effect of stand type. It is also possible that non-commercial hardwoods were already established before windthrow. In this situation, small gaps could have allowed semi shade-tolerant species

like mountain maple to maintain itself in the stand until the clearcut (Vincent 1965, Sarvaala 1999, Bourgeois et al. 2004, Bose et al. 2014) and then invade the cutover (Archambault et al. 1998). Larger gaps could have allowed the conservation or the establishment of other species that grow better in full light like speckled alder or pin cherry (Man et al. 2008, Gendreau-Berthiaume et al. 2012, Mallik et al. 2014). Pin cherry start dying rapidly 30 years after its establishment, but produce a great amount of seeds that can survive in the ground for 50 years or even more (Marks 1974, Marquis 1975, Graber and Thompson 1978). So even if it has been suppressed from the stand, pin cherry could invade a cutover with the germination of seeds that previously fell directly from the tree or that have been brought by birds (Graber and Thompson 1978). Partial harvesting is often recommended to maintain structural and compositional diversity (Brais et al. 2013), and can therefore allow the maintenance or the introduction of hardwoods on the site. Following the same rationale as above, non-commercial hardwoods maintained or established under the canopy openings created by partial harvesting could have persisted until the clear cut and then invaded the cutover.

The decrease in probabilities to encounter commercial shade-intolerant hardwoods after the harvesting of stands that originated from clearcutting, total windthrow, or mild epidemic is surprising. The increase in light's availability should have benefited these trees (Marquis et al. 1964, Harvey and Bergeron 1989, Cortini et al. 2017). An explanation might be found in the composition of the pre-disturbed stands. Gauthier et al. (2010) showed that in eastern Canada, almost half of the stands affected by fire shifted directly from a black spruce stand to another black spruce stand. It is therefore possible that other major disturbances such as clearcutting (e. g. Harvey et al. 2002) or total windthrow could have had the same effect if advance regeneration was well developed. In the case of mild epidemic, it is possible that the size of the gaps created by the disturbance favoured preestablished species over shade-intolerant hardwoods (Kneeshaw and Bergeron 1998, Kneeshaw and Prévost 2007, Rich et al. 2007), as we explained for partial windthrow and partial harvesting. The fact that partial disturbances tend to lead to mixed stands (Harvey et al. 2002, Gauthier et al. 2010, Gendreau-Berthiaume et al. 2012) and that ericaceous shrubs seem linked to the previous presence of a conifer stand (Table 5) could explain the reduced probabilities of observing ericaceous shrubs after harvesting of stands that originated from partial windthrow, partial harvesting or mild epidemic.

Harvesting method

Full tree harvesting improved the odds to encounter commercial shade-intolerant hardwoods after a cut and had the opposite effect on ericaceous shrubs. With this method, trees are felled and transported to roadside without removing the branches or the top. Dragging the trees on the ground disturbs the soil (Waters et al. 2004), which increases soil surface temperatures and create mineral seedbeds (McInnis and Roberts 1995, Waters et al. 2004). Higher soil temperatures increase trembling aspen suckering (Maini and Horton 1966) and the mixing of organic and mineral soil layers favour paper birch germination (Marquis et al. 1964). Site preparation techniques are often used to impede ericaceous shrubs competition (Mallik 2003, Thiffault et al. 2004a). However, to be efficient, site preparation must remove the L and F horizons (Hébert and Thiffault 2011), which might be the case with full tree harvesting. Furthermore, sheep laurel rarely invades cutovers if not present before harvesting (Richardson 1979). Harvesting methods also seemed to be grouped by logging areas. So, it is possible that the impact observed for full tree harvesting is a combined effects of the area's ecosystem and the harvesting method.

We also observed that cut-to-length harvesting has a negative impact on the chances to encounter ericaceous shrubs after a cut. With this method, trees are felled, delimbed, bucked directly at the stump and then transported to the roadside. Soils are less disturbed than with full tree harvesting and slash is left on the ground (Waters et al. 2004). Slash might impede ericaceous shrub establishment by limiting light penetration to the understory or reducing available microsites (Stevens and Hornung 1990), which in turn would give better chances to pre-established regeneration to overcome competition. Cut-to-length has indeed been reported to leave more residual trees and to cause less damages to pre-established regeneration than full tree harvesting (MacDonell and Groot 1997, Waters et al. 2004). Logging residues can also reduce maximum soil temperature during summer and attenuate fluctuations of soil temperature, which can benefit to seedling growth (Trottier-Picard et al. 2014). As for full tree harvesting, it is probable that impact observed for cut-to-length logging is the result of combined effects of the area ecosystem and the harvesting method.

Free to grow conifer stocking evolution

We expected that low competing levels would lead to a significant improvement of the FTG conifer stocking, while high competing levels would stay similar or lead to a

significant decline of the FTG conifer stocking over time. However, FTG conifer stocking tended to improve for every competing levels of ericaceous shrubs or commercial shade-intolerant hardwoods. Only sites that featured low competing level of commercial shade-intolerant hardwoods and moderate competing levels of ericaceous shrubs during the first inventory showed a significant improvement of the FTG conifer stocking over time. Contrary to our expectations, we did not observe significant improvement of the FTG conifer stocking on sites that initially featured low ericaceous competing level. That seems to be due to the characteristics of the inventoried sites. Most sites featuring low competition by ericaceous shrubs were imperfectly or poorly drained, while most sites featuring moderate competition by ericaceous shrubs had good or moderate drainage. Therefore, conifers happened to have better growing conditions on sites where moderate ericaceous shrubs competition occurred. Indeed, even though black spruce and balsam fir can grow on imperfectly drained sites, they have better growth rates on moderately drained sites (Bolghari and Bertrand 1983, Bélanger et al. 1995). The tendency for FTG conifer stocking to improve no matter the competition type or intensity could be the result of the shade tolerance and nutrient requirement of the conifers. Almost every conifer encountered on the field were black spruces or balsam firs and those species are respectively shade-tolerant and very shade tolerant and can tolerate poor nutrient incomes (Sims et al. 1990). They can keep on growing under a competing cover until they finally overtop the hardwoods or the ericaceous shrubs.

Effects of competition on conifer vigour and basal area

Furthermore, we expected that low competing levels would lead to a more vigorous conifer regeneration and better basal area than high competing levels. However, our results show that the competing levels and the competing species do not have significant effects on conifer vigour or basal area over time. Trees with live crown ratio higher than 66% have high survival rates and trees with apical index higher than 1 are considered to be healthy (Ruel et al. 2000). For each competing cover strata, we observed average live crown ratio and average apical index above those values, which indicate that most trees were vigorous. The absence of significant effects on conifer vigour and basal area over time might be due to the shade tolerance and low nutrient requirements of the conifers present on the sites. A shade-intolerant species like jack pine might have shown significant differences in vigour depending on hardwood competition's intensity.

Conclusion

We identified situations where competition problems with ericaceous or deciduous trees are more likely to occur after a cut with protection of regeneration and soil (CPRS). Ericaceous shrubs and hardwoods were not associated with the same types of environments. Ericaceous shrubs were mainly found in less productive environments associated with black spruce and jack pine. After a CPRS, sites located in ecological region 6h, on juxtaglacial deposits or on outwash and where pre-harvest stands was dominated by jack pine or contained black spruce in its dominant species could therefore benefit from site preparation aimed at controlling ericaceous plants (Thiffault et al. 2005, Thiffault and Roy 2011) when regeneration is insufficient (i.e. when stocking is less than 40%; Pominville and Doucet 1993). Our results suggest that this would be especially recommendable after winter harvesting. Full tree and cut-to-length harvesting methods would also be well suited to these sites since the slash or the soil disturbances they produce seem to reduce the chances of observing ericaceous shrubs.

The distinction between suitable environments for commercial shade-intolerant hardwoods and non-commercial hardwoods was less clear since they responded similarly to some variables. It is also difficult to make general management recommendations regarding sites invaded by hardwoods, since the diverse species respond differently to silvicultural treatments. For example, site preparation stimulates the establishment of pin cherry and paper birch (Thurston et al. 1992, Mou et al. 1993, Prévost 1997), while deep scarification controls mountain maple and speckled alder (Jobidon 1995). Besides, shelterwood cutting controls pin cherry (Nyland et al., 2007).

However, based on our results and the fact that site preparation is known to favour the establishment of paper birch (Prévost 1997), we can suggest that, after CPRS, in stands dominated by paper birch and accompanied by trembling aspen, especially on sites featuring good drainage, located on till 50 to 100 m thick and not present in ecological regions 6g and 6h, site preparation could be avoided (or at least reduced in intensity), in situations where this practice is not necessary to ensure forestry workers' safety. Being able to skip site preparation or reduce its intensity could help lower silvicultural operation costs. On those type of sites, we also recommend avoiding relying to full tree harvesting as our results show that this system favours commercial shade-intolerant hardwoods. Cut to cut-to-length harvesting method or manual harvesting could serve as alternatives since they do not seem to have significant influence on hardwood presence.

Furthermore, our results also indicate that winter CPRS could be favoured in those type of sites, since it hinders commercial shade-intolerant hardwoods.

This study allowed us to observe that the different types and intensities of competition did not appear to affect the vigour or the basal area of softwood regeneration, 9 to 14 years after harvesting. In addition, FTG conifers' stocking tends to improve over time, regardless of ericaceous shrubs, paper birch or trembling aspen competition intensity, when FTG stocking is between 40 and 60%, during the first regeneration monitoring. Furthermore, Pominville and Doucet (1993) observed that productivity gains start to slow after attaining 40% conifer stocking and are negligible when conifer stocking exceed 60%. As, at the time of the second inventory, average free-to-grow conifer stocking exceeded 60% regardless of competing strata, our results suggest that a second regeneration monitoring could be avoided when FTG stocking is over 40% during the first monitoring. This measure could save time and money without sacrificing the stand productivity.

This study also validates observations presented in ecological classification works realized in Quebec (Blouin and Berger 2003, Morneau and Landry 2007, Blouin et al. 2008) and that are sometimes considered as "grey literature". It is a well know fact that ericaceous shrubs are more abundant on poor sites located in northern ecological regions such as the region 6h, while competition caused by hardwoods is more frequent after disturbance in southern ecological regions such as regions 4e or 5d. Our results allow to confirm those observations with modern statistical techniques.

The database that served as the starting point for this project represented both a strength and a weakness. On the one hand, it has given us access to a large amount of data describing competition problems in a section of the boreal forest of eastern Canada. On the other hand, the data were collected as part of the regular activities of a forest company, which resulted in few details regarding non-commercial species. Non-commercial hardwoods and ericaceous shrubs were grouped into two large groups without mention of species. It would have been interesting to have access to an inventory indicating each species of the competing vegetation encountered. This would have allowed us to gain precision by indicating the situations where each of the competing species was most likely to be encountered. It could also have allowed us to group hardwoods according to their ecological characteristics rather than grouping all hardwoods that have no economic value.

Conclusion générale

Cette étude a permis de définir les principales conditions associées à trois grands types de végétation concurrente. Des différences claires sont apparues entre les conditions propices à la prolifération des éricacées et celles propices aux feuillus intolérants ou non commerciaux.

Après une coupe avec protection de la régénération et des sols (CPRS), nous avons plus de chances de rencontrer des éricacées sur des dépôts juxtaglaciaires, des plaines d'épandage, des sites où les peuplements pré-récolte étaient des pinèdes grises ou étaient dominés par l'épinette noire, des sites où les peuplements pré-récolte provenaient de chablis totaux ou de coupes totales et des zones au climat frais comme la pessière à mousse ou des sites surélevés. Ces types de sites pourraient donc bénéficier de travaux de préparation de terrain visant à limiter la prolifération des éricacées (Thiffault et al. 2005, Thiffault et Roy 2011) lorsque la régénération est insuffisante (c.-à-d. quand le coefficient de distribution de la régénération est inférieur à 40%; Pominville et Doucet 1993). Cela serait particulièrement recommandable après une coupe d'hiver, puisque nos résultats montrent que les CPRS réalisées en hiver favorisent la présence d'éricacées. Les récoltes par arbres entiers et par bois tronçonnés seraient également bien adaptées à ces situations puisque les débris de coupe ou les perturbations du sol qu'elles engendrent semblent diminuer les chances d'observer des éricacées.

Sur la base de nos résultats et du fait que la préparation de terrain est connue pour favoriser l'établissement du bouleau à papier (Prévost 1997), nous pouvons suggérer qu'après une CPRS, là où les peuplements pré-récolte étaient dominés par le bouleau à papier et accompagnés de peupliers faux-trembles, en particulier sur des sites possédant un bon drainage, situés sur des tills de 50 à 100 cm d'épaisseur et à l'extérieur des régions écologiques 6g et 6h, la préparation de terrain pourrait être évitée (ou du moins réduite en intensité), dans les cas où cette pratique n'est pas nécessaire pour assurer la sécurité des ouvriers forestiers. Pouvoir ignorer la préparation de terrain ou réduire son intensité aurait pour avantage de réduire les coûts des opérations sylvicoles. Sur ces types de sites, nous recommandons également d'éviter de recourir à la récolte par arbres entiers, car nos résultats montrent que cette technique favorise les feuillus commerciaux intolérants à l'ombre. La récolte par bois tronçonnés ou l'abattage manuel pourraient constituer des solutions de rechange, car ces techniques ne semblent pas avoir

d'influence significative sur la présence de feuillus. D'autre part, nos résultats indiquent que les CPRS réalisées en hiver pourraient être privilégiées dans ces types de sites, car elles ont une influence négative sur les feuillus commerciaux intolérants à l'ombre.

Dans le cas des feuillus non commerciaux, après une CPRS, ils étaient plus fréquents sur des sols bien drainés, dans les climats plus chauds de la sapinière à bouleau blanc et de la sapinière à bouleau jaune, lorsque les peuplements pré-récolte étaient des bétulaies blanches, des bétulaies blanches à sapin ou des bétulaies blanches à peupliers faux-trembles et lorsque les peuplements pré-récolte provenaient de chablis partiels ou de coupes partielles. Il est difficile d'effectuer des recommandations d'aménagement générales pour ces sites, puisque les différentes espèces de feuillus non commerciaux réagissent différemment aux traitements sylvicoles. Une préparation de terrain stimule l'établissement du cerisier de Pennsylvanie (Thurston et al. 1992, Mou et al. 1993), alors qu'un scarifiage en profondeur maîtrise l'érable à épis et l'aulne rugueux (Jobidon 1995). Par contre, recourir à des coupes progressives permet de limiter la croissance du cerisier de Pennsylvanie (Nyland et al. 2007).

Cette étude nous a aussi permis de constater que les différentes intensités de compétition par les éricacées et les feuillus commerciaux intolérants à l'ombre ne semblent pas affecter la vigueur de la régénération résineuse 9 à 14 ans après la coupe. De fortes intensités de compétition ne semblent pas non plus nuire à la surface terrière de la régénération résineuse libre de croître sur une période variant de 9 à 14 ans après la coupe. De plus, les coefficients de distribution de conifères libres de croître ont tendance à s'améliorer avec le temps, peu importe l'intensité de la compétition exercée par les éricacées, le bouleau à papier ou le peuplier faux-tremble, lorsqu'un coefficient des distributions de conifère libres de croître se situe entre 40 et 60 % au cours d'un premier inventaire de régénération. Pominville et Doucet (1993) ont observé que les gains en productivité commencent à diminuer après que la régénération résineuse ait atteint un coefficient de distribution de 40% et sont minimales après que le coefficient de distribution des résineux ait dépassé 60%. Puisque dans notre étude, au moment du second inventaire, le coefficient de distribution libre de croître moyen dépassait 60% peu importe la strate de compétition, nos résultats suggèrent qu'un deuxième inventaire de régénération pourrait être évité lorsque le niveau de coefficient de distribution libre de croître des résineux dépasse 40% au cours du premier inventaire de régénération. Cette mesure pourrait permettre de sauver du temps et de l'argent sans sacrifier la productivité du peuplement.

Cette étude permet également de valider des observations présentées dans des travaux de classification écologique réalisés au Québec (Blouin et Berger 2003, Morneau et Landry 2007, Blouin et al. 2008) et qui sont parfois considérés comme de la « littérature grise ». Il est bien connu que les éricacées sont plus abondantes dans les sites pauvres situés dans des régions écologiques plus nordiques telles que la région 6h, tandis que la concurrence causée par les feuillus est plus fréquente après perturbations dans les régions écologiques situées plus au sud telles que les régions 4e ou 5d. Nos résultats permettent de confirmer ces observations avec des techniques statistiques modernes.

La base de données ayant servi de point de départ à ce projet constituait à la fois une force et une faiblesse. D'une part, elle nous a permis d'avoir accès à une énorme quantité de données permettant de dresser un portrait général des problèmes de compétition dans un secteur de la forêt boréale de l'est du Canada. D'autre part, les données ont été récoltées dans le cadre des activités régulières d'une compagnie forestière, ce qui a abouti en une perte d'informations concernant les espèces non commerciales. Les feuillus non commerciaux et les éricacées ont ainsi été regroupés dans deux grands groupes où on ne faisait aucune mention des espèces rencontrées. Il aurait été intéressant d'avoir accès à un inventaire indiquant chacune des espèces concurrentes rencontrées. Cela nous aurait permis de dresser un portrait plus précis en indiquant les situations où chacune des espèces concurrentes était le plus susceptible d'être rencontrée. Cela aurait aussi pu nous permettre de regrouper les feuillus en fonction de leurs caractéristiques écologiques plutôt que de regrouper tous les feuillus qui n'ont pas de valeur économique ensemble.

De plus, dans ce mémoire, nous avons étudié une à une les variables biophysiques et des caractéristiques de récolte pour évaluer comment elles influencent la présence et la nature de la végétation concurrente. Cette approche a pour avantage de ne pas supposer à l'avance de l'existence de classes prédéfinies, comme cela aurait été le cas si nous avions eu recourt à des types écologiques ou à des séries évolutives. Cela permet aussi de déterminer plus précisément quelles variables ont un effet sur la présence et la nature de la végétation concurrente. Toutefois, dans la nature, les différentes variables étudiées interagissent entre elles et avec la végétation. Dans la discussion de ce travail, nous avons d'ailleurs mentionné à plusieurs occasions qu'un effet observé puisse ne pas être en lien direct avec une seule variable, mais qu'il pourrait plutôt être causé par l'effet combiné de différentes variables. Une approche plus holistique faisant appel à des

variables intégratrices comme les types écologiques ou les séries évolutives auraient donc pu être une alternative valable à l'approche utilisée dans le présent document.

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