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IMPACT DES ÉCLAIRCIES COMMERCIALES SUR LA CROISSANCE ET LA QUALITÉ DU BOIS DE L'ÉPINETTE NOIRE (*PICEA MARIANA* (MILL.) BSP) EN FORÊT BORÉALE.

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RÉSUMÉ

Depuis dix ans, les limites d'exploitation des forêts d'intérêt commercial ont été atteintes dans certaines régions pour des raisons de protection du territoire. Les compagnies forestières de la région 02 (Saguenay-Lac-Saint-Jean) effectuent actuellement des traitements d'éclaircie commerciale dans les peuplements naturels d'épinette noire pour augmenter le volume du bois produit en forêt. Si l'évaluation du gain en volume demeure une priorité, le fait que l'augmentation de la croissance radiale induite par les traitements puisse entraîner une diminution des propriétés mécaniques du bois est à prendre en considération. En effet, s'il s'avérait que les traitements d'éclaircie effectués sur des milliers d'hectares ne rencontraient pas les standards de l'industrie en matière de résistance mécanique ou perdaient de la valeur qualitativement, l'impact sur la valeur marchande du bois serait économiquement néfaste pour la région. Nous supposons que la croissance radiale par site augmente après le traitement, mais que tous les arbres ne réagiront pas positivement à l'éclaircie. L'accélération de la croissance radiale après le traitement se traduisant par une augmentation du bois initial devant le bois final, nous devrions observer une baisse de densité du matériau. Les trois principaux objectifs de la thèse étaient donc : 1) Évaluer la variabilité de l'accroissement radial à l'échelle de la station selon les techniques standards utilisées en dendroécologie et quantifier l'accroissement en volume des tiges. 2) Déterminer la qualité du bois formé avant et après éclaircie à l'aide du module d'élasticité (MOE) et de la densité de cerne. 3) Établir un portrait économique du traitement.

Les résultats suggèrent que l'éclaircie commerciale entraine une augmentation de la croissance radiale des individus. Cette augmentation dépend cependant des caractéristiques des arbres résiduels et de leurs compétiteurs. Bien que l'accroissement radial observé suite au traitement soit plus important à la base de l'arbre, cela n'entraine pas de variation significative de la forme ou du défilement de la tige. Aucune variation significative du MOE et de la densité n'a été notée après le traitement. Finalement sous certaines conditions de marché, l'éclaircie commerciale peut augmenter la valeur finale du peuplement par rapport à un peuplement non traité. Le "timing" de l'opération pourrait donc influencer la rentabilité des éclaircies commerciales.

Mots Clés : Éclaircie commerciale, Épinette noire, qualité du bois, croissance radiale, module d'élasticité, défilement, densité de cerne, rendement, forêt boréale, défilement.

ABSTRACT

For the last ten years the forests allocated to commercial interests have declined due land conservation, to respect the territorial claims of the First Nations and because the limits of exploitation were attained in certain regions. It is thus necessary to find strategies to increase the volume of wood produced in the remaining forests. The silvicultural practices, such as the thinning, have been effective for several decades in mixed and leafy forests in southern Quebec, but more recently have been used in a less informed way in the northern forests. The forestry companies of the region 02 (Saguenay Lac St-Jean) currently use treatments of commercial thinning in black natural spruce stands. The evaluation of the volume yield in volume remains a priority; on the other hand, the increase in radial growth caused by the thinning treatments can be associated with a decrease in mechanical wood properties. This has to be considered both during the first transformation and when evaluating the wood quality. Coniferous trees respond to increased light by producing some weaker density wood. If it turns out that thinning performed on thousands of hectares of land does not attain the industry standards in terms of mechanical resistance or depreciated quality, the impact on the market value of the wood coming from region 02 would be economically fatal. The main objectives of the thesis were to: 1) Establish radial and volume growth increment at the individual and at the stand scale using dendroecological methods. 2) Determine wood quality variations (modulus of elasticity – MOE – and ring density) before and after thinning. 3) Estimate economical returns in thinned and control stands based on recovery products available after CT and final harvest. The results suggest that commercial thinning leads to an increase of radial growth at the individual level. Response depends upon tree diameter and competition, with the biggest trees exhibiting the lowest response to the treatment. Growth increment in thinned trees appears to occur at the expense of natural radial growth in the upper part of the stem. However, no significant variation in taper or stem shape has been noticed. Moreover, no significant variation in average ring density due to CT was observed after treatment, which may be explained by between-stand variability. The thinning treatment showed no significant effect on flexural MOE over a ten-year period. Eventually, compared with financial incomes for control stands, it appeared that "timing" may influence CT returns. Indeed, doing CT in natural black spruce stands 10 years before final harvest may be profitable when the lumber market was high during CT and low or lower during final harvest.

Key words: Commercial thinning, wood quality, black spruce, boreal forest, yield, radial growth, Modulus of Elasticity, ring density, taper.

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CHAPITRE 1

INTRODUCTION GENERALE

1.1. IMPORTANCE DE L'ÉPINETTE NOIRE POUR LA FORÊT BORÉALE CANADIENNE

Les forêts boréales couvrent 14.5 pour cent du territoire terrestre (Melillo *et al.*, 1993), formant du nord au sud, une ceinture continue de 1000 km de largeur. Elles s'étendent en Amérique du Nord, en Europe et en Asie (Encyclopédie Canadienne, 2009). Élément de la biodiversité mondiale, l'épinette noire (*Picea mariana* (Mill.) BSP), domine largement la forêt boréale de l'est du continent Nord-Américain (Gagnon et Morin, 2001). Présente uniquement en Amérique du Nord (Gagnon, 1988; Viereck *et al.*, 1990), elle est de par son abondance et ses propriétés, une essence très importante économiquement. La qualité des ses fibres en fait une espèce très appréciée autant dans la fabrication du papier que dans celle du bois d'œuvre (Gagnon et Morin, 2001; Zhang et Koubaa, 2008).

Pourtant, ces dernières années, les attentes sociétales envers l'aménagement sylvicole en forêt boréale ont évolué. Les forestiers doivent désormais relever autant de défis que la protection de la diversité et de la qualité environnementale, l'intégration du style de vie des premières nations, le maintien des activités récréotouristiques et la production de matériel renouvelable (Côté et Bouthillier, 1999). Ainsi, la réduction de la disponibilité en bois de sciage recommandée en 2004 par la Commission Coulombe (Coulombe *et al.*, 2004), associée à l'augmentation de la compétition mondiale au sein de l'industrie forestière, implique la mise en place de nouvelles stratégies sylvicoles pour augmenter le volume de bois produit sur un territoire limité, tout en permettant l'atteinte des objectifs sociétaux à grande échelle. Contrairement aux traitements sylvicoles associés à la régénération des peuplements tels que la coupe à blanc ou les coupes progressives, l'éclaircie commerciale est généralement considérée comme un moyen d'éduquer les peuplements au même titre que l'élagage ou le débroussaillage (Doucet *et al.*, 2009). Cependant, les coupes partielles, dont font partie les éclaircies, apparaissent selon certains auteurs comme un choix judicieux pour atteindre les contraintes de développement et de mondialisation du marché tout en conservant une bonne qualité de production (Zhang *et al.*, 2006; Thorpe et Thomas, 2007; Thorpe *et al.*, 2007).

1.2. UNE TECHNIQUE SYLVICOLE ÉPROUVÉE POUR RÉPONDRE AUX BESOINS D'AUJOURD'HUI : L'ÉCLAIRCIE COMMERCIALE ?

L'éclaircie commerciale est en vigueur depuis plusieurs décennies dans les forêts mélangées et feuillues du sud du Québec, aux États-Unis et en Europe (Worthington et Staebler, 1961 ; Bella et De Franceschi, 1974). Plus récemment, et de façon moins documentée, les compagnies forestières ont réalisé des traitements d'éclaircie commerciale dans les peuplements naturels d'épinettes noires en forêt boréale. L'intervention consiste en une coupe partielle effectuée dans un peuplement qui n'est pas arrivé à maturité afin de stimuler la croissance des tiges résiduelles tout en récoltant une certaine quantité de bois (Doucet *et al.* 2009). Théoriquement, il existe différentes manières de réaliser une éclaircie (Doucet *et al.* 2009), soit :

— l'éclaircie par le bas : on enlève les tiges dans l'étage dominé afin de favoriser celles de l'étage dominant;

— l'éclaircie par le haut : on élimine les dominants les moins prometteurs afin de stimuler la croissance des autres tiges de ce même étage;

— l'éclaircie jardinatoire : on enlève les tiges dominantes pour favoriser celles des étages codominants et intermédiaires;

— l'éclaircie libre : on intervient dans plusieurs étages à la fois;

— l'éclaircie systématique : on laisse un espacement constant entre les tiges résiduelles.

La pratique d'éclaircie commerciale est préconisée dans les peuplements moyennement âgés pour augmenter la disponibilité en bois de sciage, réduire la période de révolution des peuplements (Curtis et Marshall, 2002) et leurs coûts d'aménagement (Cameron, 2002). Cependant, les objectifs varient suivant le type de peuplement (plantation ou naturel) dans lequel elle est réalisée (Gouvernement du Québec, 2003). En effet, par le choix d'un scénario d'éclaircies, le sylviculteur peut façonner en grande partie l'évolution du peuplement et atteindre les objectifs de production prédéterminés (Thiffault *et al.*, 2003). Les effets de l'éclaircie commerciale ont ainsi été étudiés sur différents peuplements de pin gris (*Pinus banksiana* Lamb., Bella et De Franceschi, 1974 ; Schneider *et al.*, 2008), de pin sylvestre (*Pinus sylvestris* L., Mäkinen et Isomäki, 2004b ; Mäkinen *et al.*, 2005) ou d'épinette de Norvège (*Picea abies* (L.) Karst., Jaakola *et al.*, 2005). Les auteurs s'accordent généralement sur le fait que l'éclaircie régularise l'accroissement et la croissance d'une forêt (Prégent, 1998 ; Petrás, 2002). Plus particulièrement, les éclaircies par le bas peuvent favoriser la sélection des meilleurs phénotypes et accélérer le temps de récolte en haussant l'âge auquel l'accroissement annuel moyen culmine (O'Neil, 1998 ; Cameron, 2002). L'effet réel sur le gain en volume reste cependant controversé. Alors que Stinson (1999) observe un accroissement du volume total de la récolte dans les peuplements de sapin Douglas (*Pseudotsuga* *menziessii* (Mirb.) Franco) 50 ans après le traitement, Mäkinen et Isomäki (2004a), qui travaillent sur des peuplements d'épinette de Norvège, 27 ans après le traitement, constatent que l'accroissement total du volume et le volume marchand produit par hectare sont plus importants chez les peuplements témoins. Lussier (2007), qui étudie des pessières noires 40 ans après le traitement, pourrait «réconcilier» ces auteurs puisqu'il suggère qu'alors qu'une éclaircie commerciale modérée ne se justifie pas pour augmenter le volume marchand à courte échéance; à longue échéance une éclaircie de forte intensité pourrait apporter un gain en volume en raison de l'augmentation de la vigueur du peuplement.

1.3. OUVERTURE DU PEUPLEMENT ET RÔLE DES RACINES

Pourtant, l'ouverture du peuplement peut entraîner des conséquences néfastes sur la stabilité des arbres. Ainsi, l'éclaircie commerciale peut entraîner des dommages conséquents à la charge de la neige sur les branches ou encore rendre les peuplements plus susceptibles aux chablis (Cameron, 2002). D'après Cremer *et al.* (1982) ou Savill (1983), les dommages causés par la neige et la chute des arbres lors des tempêtes pourraient ainsi augmenter du fait de la plus faible stabilité des arbres lors de l'ouverture des milieux et entraîner une perte économique significative dans les peuplements éclaircis. Parce que la stabilité des individus dépend du développement adéquat du système racinaire (Fayle, 1975), certains auteurs ont étudié le développement des racines et son rôle sur la stabilité du peuplement après ouverture de la canopée (Stokes *et al.*, 1995 ; Nicoll et Dunn, 2000 ; Ruel *et al.*, 2003 ; Bergeron *et al.*, 2009). Nicoll et Dunn (2000) ont démontré une croissance adaptée à la pression du vent favorisant la distribution de la croissance des racines proches de la base des tiges d'épinette de Sitka

(*Picea sitchensis* (Bong.) Carr.). D'autres études ont porté sur la compétition pour l'eau et les nutriments (Mitchell *et al.*, 1993). Pourtant, alors que le système racinaire semble être un très bon indicateur sur la croissance de l'arbre et la qualité du bois (Böhm, 1979 ; Bernier *et al.*, 1995), peu d'études concernant le développement des racines en réaction à l'éclaircie ont jusqu'alors été réalisées (Mitchell, 2000 ; Valinger *et al.*, 2000).

1.4. DU GAIN DE CROISSANCE À LA QUALITÉ DU BOIS : VERS LA VALEUR AJOUTÉE

La qualité est une notion subjective qui doit être précisée dans chaque contexte. Josza et Middleton (1997) définissent la qualité du bois en fonction des caractéristiques qui le valorisent dans le cadre d'une utilisation donnée. Les caractéristiques déterminant la qualité d'un bois peuvent être inhérentes à l'espèce ou dépendre des conditions de croissance.

Plusieurs auteurs ont démontré qu'une augmentation de croissance chez les conifères induisait généralement un rehaussement de la largeur du bois initial par rapport à celle du bois final et l'allongement du temps de transition entre le bois juvénile et le bois mature (Barbour *et al.*, 1994; Zhang *et al.*, 1996; Koga et Zhang, 2002). Les résineux répondraient donc à l'éclaircie en produisant du bois de densité plus faible (Carter *et al.*, 1986; Barbour *et al.*, 1992; Debell *et al.*, 2004; Kang *et al.*, 2004). Bien que l'évaluation du gain en volume demeure une priorité, le fait que l'accroissement radial induit par les traitements puisse entraîner une diminution des propriétés mécaniques du bois (Zhang *et al.*, 1998) est un élément important à prendre en considération. De plus, Viens (2001), Pape (1999) ou encore Barbour *et al.* (1992) ont démontré que les premières années suivant le traitement, la forme de la tige, notamment son défilement, pouvait être modifiée. Cameron (2002) a observé que les arbres résiduels produisaient plus de bois de réaction, ce qui diminue la qualité de la fibre.

Enfin, le poids spécifique, considéré par certains auteurs comme le meilleur indice pratique de la qualité du bois (Shepard et Shottafer, 1990; Szymanski et Tauer, 1991) semble diminuer après le traitement. Or, les propriétés des produits forestiers dépendent fortement des caractéristiques du matériau bois. En particulier, la densité du bois joue un rôle important sur le rendement, la qualité et la valeur des matériaux composites et solides produits (Shi *et al.*, 2007). Reliée aux autres propriétés du matériau, résistance mécanique, retrait, rendement en pâte à papier et propriété de cette pâte (Josza et Middleton, 1997); elle est couramment utilisée comme indicateur de la qualité du bois et les variations annuelles de la densité de cerne déterminent souvent, l'utilisation du bois à des fins spécifiques (Echols, 1972; Koubaa *et al.*, 2002).

Un autre indicateur de qualité du bois est son module d'élasticité (MOE). L'épinette noire est ainsi l'une des principales essences utilisées pour la classification mécanique du bois ("Machine Stress Rated", MSR) qui dépend essentiellement du module d'élasticité (Tong *et al.*, 2009).

Quelques études ont porté sur la relation entre le taux de croissance et la qualité du bois chez différentes essences commerciales mais les résultats sont contradictoires (Pneuvmaticos *et al.*, 1979; Kellogg et Warren, 1984; Castéra *et al.*, 1996; Koga et Zhang, 2002; Zhang *et al.*, 2002). Chez le pin gris, comme chez le sapin baumier (*Abies balsamea* L.) Barbour *et al.* (1994) et Kang *et al.* (2004), ont observé une réduction de la densité du bois après une éclaircie commerciale. Bendtsen (1978), a trouvé que les effets de l'accélération de croissance sur les propriétés du bois étaient négligeables par rapport à la différence entre le bois mature et le bois juvénile. Zobel et Van Buijetenen (1989) quant à eux, ont conclu que la relation négative entre le taux de croissance et la densité du bois était commune pour certaines espèces d'*Abies*, mais que cette généralisation présentait de nombreuses exceptions. Pourtant, la plupart de ces études ont été réalisées pour évaluer l'impact de la densité initiale de peuplement sur la valeur des produits transformés (Koga et Zhang, 2002; Zhang *et al.*, 2002; Alteyrac *et al.*, 2005) et peu d'entre elles discutent des variations des propriétés mécaniques du bois après une éclaircie commerciale dans les peuplements naturels d'épinettes noires.

Finalement, les propriétés mécaniques du bois varient aussi en fonction de la position dans l'arbre des échantillons testés (Larson, *et al.*, 2004; Alteyrac *et al.*, 2005). Le besoin est grand de développer une stratégie d'optimisation d'utilisation des billots en fonction de leur emplacement dans la tige pour maximiser la valeur de la ressource (Shi *et al.*, 2007). Plusieurs auteurs mentionnent en effet un retard de la recherche sur l'effet des traitements sylvicoles sur la valeur des produits de deuxième transformation. Celle-ci trainant derrière la recherche sur la croissance et le rendement et créant une déconnexion au niveau de la chaine de valeur ajoutée, l'industrie forestière ne possédant pas les informations de base liant la croissance des arbres à la valeur des produits (Briggs et Fight, 1992; Kang *et al.*, 2004).

1.5. LE TERRITOIRE ÉTUDIÉ

L'étude a été réalisée dans la région 02 du Saguenay-Lac-Saint-Jean. Au total 10 sites éclaircis entre 1995 et 1997 ont été échantillonnés. Tous ces sites à l'exception d'un seul (MM96) ont pu être associés à un site témoin présentant des caractéristiques d'âges, d'essences et de structures similaires. Bien qu'inclus dans les chapitres 2 et 4, le site

MM96 a été exclu des chapitres 3, 5 et 6 pour simplifier les analyses statistiques. Pour les sites localisés dans les Monts Valins (MV) et dans Hebertville (HB), un témoin a été sélectionné et associé à plusieurs sites éclaircis. Au total donc 17 sites ont été échantillonnés, 17 étudiés aux chapitres 2 et 4 et 16 pour les chapitres suivants. Tous les peuplements étudiés sont des peuplements naturels purs d'épinette noire, non éduqués.

1.6. HYPOTHÈSES ET OBJECTIFS

L'éclaircie commerciale étant à l'origine d'une ouverture de la canopée et d'un gain d'espace pour les arbres résiduels, l'hypothèse de recherche sous-jacente à ce projet est la suivante : L'éclaircie commerciale induira un gain de croissance des tiges résiduelles associé au développement particulier de celles-ci. Chez les résineux, une augmentation de croissance peut se traduire par une diminution de la proportion du bois final par rapport à celle du bois initial (Koga et Zhang, 2002). La qualité du bois, en termes de résistance mécanique et de densité, des arbres résiduels peut donc diminuer. Le principal objectif de cette thèse est donc de déterminer l'impact des éclaircies commerciales sur la croissance d'épinettes noires et les conséquences sur la qualité du bois produit après traitement d'éclaircie. À ce titre, l'intensité de l'éclaircie ne sera pas un facteur étudié dans la réponse au traitement. L'hypothèse posée pour appuyer ce choix est qu'après avoir intégré le circuit de deuxième transformation, aucune distinction n'est faite entre les types ou les intensités d'éclaircies réalisées dans le peuplement. L'effet du traitement à l'échelle du peuplement et de l'individu sera étudié. Un objectif plus spécifique est de déterminer quels sont les facteurs qui influencent l'intensité de la réaction des arbres au traitement. Si nos hypothèses sont confirmées, la valeur du peuplement résiduel pourrait augmenter après l'éclaircie par rapport à un peuplement non traité (lors de l'éclaircie commerciale, les tiges de moins bonne qualité sont prélevées, de plus la qualité des tiges résiduelles augmente après l'éclaircie). Le dernier objectif de la thèse est d'évaluer la rentabilité d'une éclaircie commerciale et les facteurs affectant cette rentabilité par rapport à une unique coupe finale.

Suite à cette introduction, les chapitres 2, 3, 4, 5 et 6 présentent les résultats de la thèse en répondant chacun à des objectifs spécifiques. Ces chapitres sont présentés en anglais sous forme d'articles. Les chapitres 2 et 3 traitent de l'impact sur la croissance des arbres et de l'ensemble du peuplement.

Le chapitre 2 considère de plus la réaction des racines au traitement et les paramètres influençant la croissance de chaque individu. Certaines études ont démontré une variation de l'accroissement radial inter- et intra-site suite au traitement (Zarnovican *et al.*, 2001 ; Skovsgaard, 2009). Nous posons l'hypothèse que, au sein d'un peuplement, les caractéristiques des tiges (diamètre, compétiteurs, hauteur) vont jouer un rôle dans l'accroissement relatif des arbres résiduels. L'objectif est alors de déterminer quels sont ces caractéristiques et de modéliser leur effet sur la variation de croissance observée après le traitement.

Le troisième chapitre se place dans un contexte d'aménagement sylvicole. Il présente les variations observées en termes de surface terrière et de volume de peuplement. Dans cette étude une première analyse de la structure du peuplement résiduel est réalisée. L'hypothèse testée est que l'accroissement radial observé peut se traduire par un gain en surface terrière et en volume. L'objectif est de quantifier ce gain de croissance.

Les chapitres 4 et 5 concernent la qualité du bois.

Au chapitre 4 l'évolution de la forme de la tige et son défilement sont étudiés. L'hypothèse testée dans ce chapitre est que l'accroissement radial est localisé sur la tige entrainant une variation de la forme de la tige. L'influence de certaines caractéristiques des tiges sur ces paramètres est étudiée.

Le chapitre 5 concerne les propriétés physiques et mécaniques des tiges traitées. Le module d'élasticité et la densité sont les deux paramètres étudiés. L'hypothèse sous-jacente est que l'augmentation du taux de croissance observée après le traitement, se traduisant par des cernes plus larges, va entrainer une diminution de la densité du bois (Zhang *et al.*, 1996). Cette diminution peut se refléter au niveau du module d'élasticité. L'analyse porte sur la variation avant et après le traitement et sur la variation entre tiges traitées et témoins.

Finalement, le chapitre 6 concerne les retombées économiques du traitement. L'éclaircie commerciale est souvent critiquée car les coûts de récolte associés au traitement dépassent les revenus liés au gain de croissance des arbres. Pour que l'éclaircie commerciale soit une opération profitable, il faut que le gain de valeur du peuplement résiduel soit supérieur au coût net de l'éclaircie. Par contre l'éclaircie permet d'améliorer la valeur finale du peuplement. Or la valeur sur pied des arbres varie en fonction de leur dhp et des fluctuations de prix. Nous avons posé l'hypothèse qu'en période de faible prix, seuls les arbres les plus gros avaient une valeur positive, les arbres les plus petits ayant une valeur négative. Dans ce cas, la présence de petits arbres réduit la valeur de la récolte totale. Si ces mêmes arbres sont prélevés par une éclaircie commerciale, la valeur de la récolte totale peut être accrue. Pour que ce soit financièrement intéressant, il faut que la récolte des petits bois par éclaircie se fasse pendant une période de prix élevés (pour réduire les coûts de l'éclaircie) et que la récolte finale se fasse en période de prix faible. Il faut donc évaluer si cette combinaison de conditions se réalise et selon quelle probabilité.

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CHAPITRE 2

RADIAL GROWTH RESPONSE OF BLACK SPRUCE ROOTS AND STEMS TO COMMERCIAL THINNING IN THE BOREAL FOREST

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CHAPITRE 2

RADIAL GROWTH RESPONSE OF BLACK SPRUCE ROOTS AND STEMS TO COMMERCIAL THINNING IN THE BOREAL FOREST

2.1. ABSTRACT

Black spruce is one of the most important boreal tree species in Canada. In the current ecosystem-based management context, commercial thinning (CT) could be a sound choice for attaining sustainable forest management while still achieving maximum returns on competitive timber markets. Through stand density regulation, CT aims to increase tree growth and enhance stand productivity, but the pattern and level of treatment responses are still unknown. This study examined the radial growth response of roots and stems to commercial thinning in 10 thinned stands and their controls. A split-plot unbalanced model was developed to describe growth variations over time. The study shows that CT leads to an increase in the radial growth of stems and roots for at least 10 years following the treatment. The 10-year post-treatment radial growth increment of stems is from 20 to 100 per cent higher than the pre-treatment 10-year mean growth. Response depends upon tree diameter and competition, with the biggest trees exhibiting the lowest response to the treatment. Nevertheless, these variables only explain a fraction of the response ($R^2 = 0.0511$), suggesting that much of the observed variation may be due to variability between the stands and between trees within a stand. Moreover, stem growth response is correlated with, but lags behind root growth response. This study suggests that CT results may be enhanced by the selection of retained trees based on initial diameter at breast height.

2.2. INTRODUCTION

The Boreal forest biome covers much of the landmass of the northern hemisphere and stores most of the global carbon stock (Melillo *et al.*, 1993; Dixon, *et al.*, 1994). Society's expectations of forest management in the boreal forest have evolved in recent years. Foresters now face challenges such as protecting biodiversity and environmental quality, integrating First-Nation traditional lifestyles, maintaining recreational activities and procuring renewable material. This called for strategies to optimize timber growth without removing the entire canopy (Côté and Bouthillier, 1999). Silvicultural practices such as thinning could be a sound choice for attaining sustainable development within global market constraints while still achieving maximum value (Zhang *et al.*, 2006).

Black spruce (*Picea mariana* (Mill.) BSP) is one of the most important boreal tree species in Canada (Parent and Fortin, 2008; Zhang and Koubaa, 2008). Its abundance and properties make it a valuable resource for the timber industry. The impacts of silvicultural treatments such as commercial or pre-commercial thinning (CT) have already been studied for different eastern species, including jack pine (*Pinus banksiana* Lamb., Bella and De Franceschi, 1974; Schneider *et al.* 2008), Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L., Mäkinen and Isomäki, 2004a, b), but the effects of CT still have to be studied in natural black spruce stands.

Theoretically, CT aims to regularise the size and growth of a forest to maintain its productivity throughout its life cycle (Prégent, 1998; Petrás, 2002). The main advantages of thinning are to increase saw timber availability, decrease rotation age and management costs, while enhancing stand value and quality (Cameron, 2002). However, results differ depending on authors and studied species. Bella and De Francheschi (1974) on jack pine and Curtis and Marshall (2002) or Stinson (1999) on Douglas fir (*Pseudotsuga menziessii*) noticed an increase in relative stem volume after treatment. Instead, Mäkinen and Isomäki (2004a, b) observed no significant differences between stem volume increments in Norway spruce and Scots pine stands at different thinning intensities, including no thinning. Thinning influences not only tree growth, but also stem shape, tapering (Barbour *et al.*, 1992; Viens, 2001; Koga *et al.*, 2002) and wood properties (Petrás, 2002; Raulier *et al.*, 2003; Zhang *et al.*, 2006). Tasissa's team (Tasissa *et al.*, 1997; Tasissa and Burkhart, 1998), working reforested on a loblolly pine (*Pinus taeda* L.) cutover, observed a significant impact on stem characteristics after a second thinning. However, Viens (2001) studying jack pine, as well as Bouillet and Lefevre (1996) working on khasi pine (*Pinus kesiya* Royle ex Gordon), concluded that thinning did not induce worsening of shape along stems. The disparity observed between stands (Zarnovican *et al.*, 2001) and within stands (Skovsgaard, 2009) may therefore be worth considering.

The risk of uprooting by strong winds is particularly high during clearing of the surroundings (Cremer *et al.*, 1982) and may be responsible for significant economic losses in thinned stands. Because the stability of individual trees depends upon the adequate development of root systems (Fayle, 1975), some authors studied root development and its role on stand stability after opening up the canopy (Stokes *et al.*, 1995; Nicoll and Dunn, 2000; Ruel *et al.*, 2003; Bergeron *et al.*, 2009). Nicoll and Dunn (2000) demonstrated adaptive growth to wind loading favouring the allocation of growth to roots near the base of Sitka spruce trees (*Picea sitchensis* (Bong.) Carr.). Other studies focused on root adaptation to competition for water and nutrients (Mitchell *et al.*, 1993). But while the root system is supposed to be a very good indicator of tree growth and wood quality (Böhm, 1979; Bernier *et al.*, 1995), its role in radial growth increment after commercial thinning has been less studied and little information is available on root growth response to thinning in black spruce stands.

In this study we investigate the 10-year pattern of stem and root increment in response to various thinning intensities in operationally thinned stands. Our first hypothesis was that trees showing an increase in radial diameter growth after treatment will also show increased root growth preceding the stem growth response as an adaptation to environmental changes after thinning. A second hypothesis contends that thinning response will vary depending on tree characteristics and their competitors.

2.3. METHODS

2.3.1. Study Area

This study was based on 10 commercially thinned stands and their control stands in the boreal forest of Quebec, Canada. Latitudes ranged from 47.9 °N to 49 °N, longitudes from 70.5 °W to 72.7 °W and altitudes from 210 to 671 m (Table 2.1). The region is characterized by cold winter temperatures and short vegetation periods. Over the past 30 years, the average minimum temperature for this region was -18.4 °C during the coldest month, and the average maximum was 17.9 °C during the warmest month. Average annual precipitations vary from 920 cm to 1187 cm in the studied stands (Environment Canada, 2000). Essentially pure, unmanaged natural black spruce stands were selected. The mean age of the stands at the time of treatment varied from 47.8 years to 99.1 years. Other than CT, no silvicultural treatment has been applied. Basal area density, evaluated by number and basal diameter of all trees within a 20 x 20 m quadrat, was between 800 and 3900 trees per hectare (Table 2.1). The herbaceous and moss layers are mainly composed of *Pleurozium schreberi* (Brid.) Mitt., *polytrichum sp.*, *Ptilium crista-castrensis* (Hedw.) De Not., *Ledum groenlandicum* Oeder, *Vaccinium angustifolium* Ait. and *Kalmia angustifolia* L.. As thinning is still a recent silvicultural treatment applied to boreal forests, no standard methods have yet been developed and no information is available about thinning types and techniques. Stand selection was thus based on two main criteria: (i) thinning was done 10-12 years before sampling in unmanaged natural stands; (ii) all stands had to have similar site characteristics and stand densities before thinning. Whenever possible, a nearby unthinned natural black spruce stand with similar characteristics was selected as a control. In two instances, the same control stand was used for comparison with more than one nearby thinned stand where all stands had the same environmental characteristics (Table 2.1).

Due to the large number of selected stands, the following nomenclature was adopted: the initial letters refer to stand location, followed by numbers representing the thinning year or the letter C for control stands. Stands were also numbered from 1 to 16 to simplify figure headings (Table 2.1).

2.3.2. Data

In order to specify the number of samples required, an *a priori* power analysis was conducted at each site to allow for estimating the variance of the population. It was determined that at least 35 trees per stand were required to cover stand variation and increase the statistical power of the analysis. Consequently, quadrats comprising at least 35 black spruces (Dbh > 9 cm) were selected. At one site, LJC, only 25 trees were selected because of environmental constraints (Table 2.1). The stand characteristics of each quadrat, such as vegetation composition, topography and depth to mineral soil or woody debris, were determined. Each tree in the quadrat was measured for height, diameter at breast height (d.b.h.), at stump (diameter at stump height), and stem height at the lowest living branch (Table 2.1). Tree positions within the quadrat were recorded using a measuring tape and plotted onto a map. Stump circumferences and their positions within the quadrat were also determined.

An increment core was taken from each tree at 25 cm above the ground along the north-south axis and two other cores along one randomly chosen main horizontal root, at about 25 cm (R25) and 70 cm (R70) from the stump. Root increment cores were taken vertically from the upper side of the roots.

2.3.3. Dendrochronology

A dendrochronogical analysis was done on the stem and root increment samples of each tree. Preparation, measurements and sample analyses were conducted following standard dendroecology techniques (Stokes and Smiley, 1968; Krause and Morin, 1995). The cores were sanded using up to 400-grit paper, ring width was measured to 0.01 mm using a manual Henson micrometer, and semi-automatic Windendro^{TM} width measuring machine (Guay *et al.*, 1992). Tree-ring series were then cross-dated on a light table and verified statistically (COFECHA, Holmes, 1983). Ring series for each root were calculated and cross-dated with the corresponding stem curve and between different root cores. Root cross-dating was also verified using COFECHA, but visual dating was more often used than statistical dating, due to the short series length of the root samples. As a consequence of the core state, ~ 5 per cent of the cores per site were rejected for interdatation. Final index chronologies were developed for individual trees based on raw data, using ARSTAN (Cook and Holmes, 1986).

2.3.4. Radial Growth

Radial growth in the thinned and control stands was evaluated based on average 10-year index values before treatment. Mean growth increments since the year of thinning were then calculated with the average of all years after treatment equation (1). An annual growth increment was also calculated for each year after treatment equation (2).

$$\gamma = \frac{\sum_{t=TY}^{t=i} \alpha_t \Big/ (i - TY)}{\sum_{t=TY-10}^{t=TY} \alpha_t \Big/ 10} \times 100 \qquad (1)$$

$$\gamma_t = \frac{\alpha_t}{\sum_{t=TY-10}^{t=TY} \alpha_t \Big/ 10} \times 100 \qquad (2)$$

where γ is the radial growth increment (per cent), *TY* is the thinning year, *i* is the sampling year (i = 2006 or 2007) and t = time (year); α is the growth index (dimensionless).

Five radial growth increment classes were determined: class 1 ($\gamma \leq 80$ (per cent)), class 2 ($80 < \gamma \leq 120$), class 3 ($120 < \gamma \leq 150$), class 4 ($150 < \gamma \leq 200$), and class 5 ($\gamma > 200$). This classification was chosen arbitrarily since no classification standard was available in the literature and is used for stem and root growth increment in both thinned and control stands.

To determine the relative growth between stem and roots, the ratio of root growth to stem growth was calculated according to the following equations (3 and 4):

$$\gamma_{R25/S} = \gamma_{R25} / \gamma_S \, , \qquad (3)$$

$$\gamma_{R70/S} = \gamma_{R70} / \gamma_S \, . \qquad (4)$$

2.3.5. *Competition Index*

Based on the work of Mailly *et al.* (2003), the competition index (CI) for each tree within a given quadrat was calculated using Hegyi's diameter-distance CI in equation (5):

$$\mathrm{CI} = \sum_{j=1}^{n}\left(\frac{D_j}{D_i} \times \frac{1}{DIST_{ij}}\right), \qquad (5)$$

where D_i is the d.b.h. of subject tree i; D_j is d.b.h. of the competitor tree j; $DIST_{ij}$ is the distance between subject tree i and competitor j. Studied trees belongs to R, the search radius (= 3.5 x mean crown radius of canopy trees, 4 m in our study).

Two different Hegyi's CI types were calculated: (1) the stump competition index ($\mathrm{CI_S}$) and (2) competition index at thinning year ($\mathrm{CI_{TY}}$) of the remaining trees (alive trees). $\mathrm{CI_S}$ characterizes the influence of tree harvesting on the growth of remaining trees, whereas $\mathrm{CI_{TY}}$ illustrates the competition among remaining trees after thinning. $\mathrm{CI_{TY}}$ was calculated using data collected during field work and then corrected after dendrochronology analysis to fit with the thinning year.

2.3.6. *Statistical Analyses*

Data were compiled using an analysis of variance (ANOVA) multifactor model with a Restricted Maximum Likelihood procedure (mixed model). A 10-block, unbalanced, split-plot design was used for radial growth increment and root growth increment with time as the main plot level, and with treatment (thinning/control) at the subplot level. ANOVAs were performed using JMP software (SAS Institute Inc., Cary, NC). Post-hoc one factor ANOVAs on data were used to extract the evolution of stem and root growth along the time-release treatment.

To determine the influence of independent variables on radial growth increment, simple regression tests were conducted between radial growth increment (γ) and $\mathrm{CI_S}$,

CI_{TY}, d.b.h., tree height, and crown length. A multiple regression model was used to determine which variable has the most influence on γ after thinning. In all cases, the confidence level was 95 per cent.

2.4. RESULTS

As shown in Table 2.1, the treated stands had a mean age of 62 years at thinning. For control stands, the mean age was 55 years. Based on the initial basal area, thinning intensity in the different stands varied from 17 to 62 per cent (Table 2.1) and can be classified as light to heavy thinning.

2.4.1. Stem Growth Response

Pre- and post-thinning comparison of the radial growth index of chronology values based on all stands together showed a significant increase in stem radial growth due to treatment ($p = 0.0199$ for interaction treatment × time, Figure 2.1A, Table 2.2B). The radial growth index is similar in the control and thinned stands before treatment, but after the thinning, the radial growth index values increase immediately in the thinned stands (Figure 2.1A).

By comparing the thinned stands with the control stands, most of the treated stands show significantly higher radial growth index values ($p = 0.0081$, Table 2.2A). The radial index values between the thinned and control stands vary from 20.4 to 170.5 per cent. However, two stands (HEB95, LB95) show post-thinning radial growth increments which are lower than their corresponding control stands (Figure 2.2A).

Response at the tree scale is heterogeneous within each stand (Figure 2.3A). For the thinned stands, the percentage of trees with positive growth response (classes 3, 4 and 5 together) varies from 67.6 to 97.4 per cent, with a mean of 81.6 per cent. On the contrary, these three classes represent less than 50 per cent of trees in the control stands. Two types of thinned stands can be defined (Figure 2.3) based on tree response. In six of these stands (1, 2, 8, 4, 6 and 11), ~ 60 per cent of the trees belonging to classes 3-5 showed growth responses, in the remaining three stands, ~ 90 per cent of trees had growth responses above 120 per cent. Stand LBC seems to be an exception for the control stands, with 41 per cent of trees showing class 5 growth increments after 1995.

Variability in tree growth response, apart from their own characteristics, could be explained by the influence of the number and characteristics of tree competitors on thinning efficiency. When all independent variables are computed separately, only CI_S and d.b.h. have a significant effect on post-treatment stem growth increment. A negative correlation between d.b.h. and γ was found, and a positive one between CI_S and γ (Table 2.3). Significant correlation was found between tree heights and crown lengths, but none between CI_{TY} and γ. Yet, fitting CI_S, d.b.h. and CI_{TY} using the stepwise forward procedure and the Akaike Information Criterion (AIC) as a selection criterion (Akaike, 1974; Mac Nally, 2000) resulted in a significant model ($p = 0.0042$, Table 2.4) explaining ~ 5 per cent of the γ variance after thinning. d.b.h. was the most significant predictor (std $\beta = -0.2223$), indicating that trees with larger diameters have lower relative radial growth (Table 2.4).

2.4.2. Root Response

CT also has a positive effect on root growth (Figure 2.1B), with a significant increase over time due to treatment ($p < 0.0001$ for interaction treatment×time for both R25 and R70, Table 2.2B).

Comparing the thinned and control stands shows that thinning has a positive effect on root growth (Table 2.2A, $p = 0.0005$ and $p = 0.0059$ for Roots R25 and R70 respectively). Roots R25 show a 51.1 per cent mean increase in radial growth index values after treatment, varying from 4.4 to 183 per cent, depending on site (Figure 2.2B). The same trend can be observed for roots R70 (Figure 2.2B), with growth increments ranging from -11.3 to 59.3 per cent, and a mean of 37.7% for the thinned stands. In the control stands, radial growth index values for R25 and R70 after the thinning year vary from -4.5 to 26.1 per cent and from -16.3 to 33.4 per cent, respectively.

2.4.3. Comparison between Stem and Root Radial Growth

A significant relationship between stem and root growth after treatment was found, where increased root growth is associated with increased stem growth (Likelihood ratio and Pearson test both < 0.0001 for roots R25 and R70, data not shown). A Student's *t*-test shows that tree root growth classes are significantly linked with stem response (Figure 2.4, $p < 0.0001$).

Stem and root responses occur at different times after thinning. The effect of treatment appears first and stronger in the roots (Figure 2.1C). Four years after thinning a stabilization of root growth index is observed, whereas stem growth index values continue to increase (Figure 2.1C). A 1-year delay after treatment can be observed before stem growth starts to increase compared with roots (Figure 2.1A and B). Indeed, after 1 year, γ_1 is ~ 135.6 per cent for roots, which is an increase of 27 per cent compared with γ_{TY}. For stems, γ_1 is equal to 113.79 per cent, a decrease of 0.3 per cent compared with γ_{TY}. A similar 27 per cent growth increase is observed for roots 2 years after thinning (γ_2 =163 per cent), whereas stem growth increases by 18 per cent (Figure 2.1C).

Nevertheless, statistical analysis does not show any significant difference in root and stem growth between the control and thinned stands.

2.5. DISCUSSION

2.5.1. Growth Response

It is well known that increased light penetration to the forest floor of thinned stands can increase the temperature of the surface soil layers and thus accelerate nitrogen mineralization (Thibodeau *et al.*, 2000). This effect can contribute to increased short-term tree growth and could become an important benefit, particularly in cold climates such as those in the boreal forest zone (Pothier, 2002). The increase in stem radial growth, in our 10 stands, varied from 20 to 99 per cent, 10 years after thinning. This range of growth increment after thinning is similar to the one observed for other tree species in North America. Radial growth after thinning increases by 30 to 70 per cent in jack pine (*Pinus banksiana* Lamb.) 15 years after treatment (Bella and De Franceschi, 1974), and by 41 per cent in balsam fir (*Abies balsamea* (L.) Mill.) 3 years after thinning (Pape 1999). Aussenac and Granier (1988) observed that radial growth increases by 100 per cent 5 years after treatment in a 19-year-old Douglas fir (*Pseudotsuga menziesii* var. *menziesii* Engelm.) plantation. When thinning is coupled with a fertility treatment this increase can reach 115 per cent in Scots pine stands (*Pinus sylvestris* L.) 25 years after thinning (Mäkinen and Isomäki, 2004b).

Interestingly, despite a generally positive response to thinning, the radial growth increments in two stands (LB95 and HEB95) are lower than those of the corresponding control stands (Figure 2.2). Considering the equation (2) used, the negative difference observed between thinned and control stands may be due to the slower growth of control trees before treatment. This low growth for both thinned and control stands before thinning may have been due to the spruce budworm outbreak, which occurred in the region in the late 1970s (Morin *et al.*, 2000). Several studies have examined the interaction between spruce budworm outbreaks and CT (Bergeron *et al.*, 1995; Bauce, 1996; Pothier, 1998) or pre-CT (Thibault *et al.*, 1995; Tremblay, 2006). However, none of them deal with thinning conducted on a stand defoliated by spruce budworm a few years earlier. The percentage of dead trees resulting from a spruce budworm outbreak could have an impact on stand density and on tree response to treatment. According to Pothier (1998), mortality rate after an outbreak could be comparable to self-thinning. Moreover, if only vigorous trees were kept alive in a stand after treatment, the thinning effect could be attenuated. Figure 2.2 shows that LB95 roots strongly reacted to thinning, as opposed to LBC roots, which may imply that root growth was not reflected by stem growth. The age of LB95 trees at thinning may also be an explanation for this low stem growth reaction following thinning (Table 2.1).

2.5.2. Variables Influencing Response to Thinning

Large variations in growth response to treatment were noted between stands. Given the experimental design, it is assumed that this variation is representative of thinning in natural boreal forest black spruce stands. Moreover, variations within stands have also been noticed, which contribute to the success of the treatment (the percentage of trees reacting positively to the treatment within a stand). Among five variables studied, only three (d.b.h., CI_S and CI_{TY}) are significantly correlated with stem growth increment (Table 2.3 and Table 2.4). These results confirm the findings of Larson (1969, in Pape 1999), that intermediate and suppressed trees should respond better to thinning, in terms of relative growth, than dominant trees which already have large crowns. Similarly, Hamilton (1969) on Sitka spruce and Medhurst *et al.* (2001) on *Eucalyptus nitens* also reported that dominant trees with large crowns showed minimal response to thinning, which merely helps them to maintain their rapid growth rate. Observations by Pape (1999) on Norway spruce could explain this phenomenon, as he noted that light thinning from below did not have any direct effect on radial growth increment. Indeed, only heavy thinning that removed a total of 40 per cent of the basal area considerably enhanced diameter growth. A large number of competitor characteristics also influence tree growth (diameter, distance, height, crowding, shading, species, etc.) (Canham *et al.*, 2004). These are not all considered in this study and may also explain the poor influence of competitors on growth response (Table 2.4).

The influence of tree characteristics on thinning response should play a part in the selection of thinning type. Specifically, the production of lumber with high nominal dimensions largely depends on the d.b.h. of harvested trees (Duchesne and Swift, 2009). Since small-diameter trees seem to respond better to thinning, not only harvesting damaged trees and trees with undesirable attributes for paper, but also bigger trees, may enhance the financial return of the first harvest while maintaining the positive effects of thinning on tree growth rate.

2.5.3. Roots and Stem Growth

Comparison between root and stem growth increments in the first years following thinning suggests that root growth increases more and sooner than stem growth. For thinned stands, stem growth increase becomes significant 4 years after treatment, whereas root growth increase starts to be significant as early as 3 years after thinning (Figure 2.1A and B). Similar results have been found by Urban *et al.* (1994), for white spruce (*Picea glauca* (Moench) Voss) after the removal of neighbouring trees, and Ruel *et al.* (2003) in balsam fir following pre-CT. Kneeshaw *et al.* (2002), reported that this latency period observed after partial cutting would result in stem growth decrease just after thinning, to the benefit of root growth in lodgepole pine (*Pinus contorta* Dougl. ex Loud.) and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedlings. Different mechanisms can explain this delay in stem growth response to thinning.

Root growth increment can be beneficial in terms of tree stability (Urban *et al.*, 1994; Ruel *et al.*, 2003), as thinning increases wind penetration into the stand, which in turn induces tree swaying. Nicoll and Dunn (2000) demonstrated that, in these conditions, adaptive growth favoured the allocation of roots near the base of Sitka spruce trees.

On the other hand, canopy release will influence photosynthetic and respiration rates. With wider spacing, the higher wind penetration into the stand and greater light intensity increase the transpiration rate (Whitehead *et al.*, 1983; Pothier and Margolis, 1990; Pothier and Margolis, 1991) either by increasing boundary layer conductance, or increasing the amount of sunlit leaf area. Root systems contribute largely to flow resistance (Running, 1980; Sperry *et al.*, 1998). To counterbalance this higher transpiration rate, the uptake of water and its transport from roots to leaves must increase, which is supported by the increase in radial root growth all along the main root (R25 and particularly R70, Figure 2.1B). Roots close to the stem ensure the stability of the tree, whereas the more distant roots secure the transport of water and nutrients and store assimilates (Krause and Eckstein, 1993). The smaller number of trees left after thinning increases the availability of soil moisture through a reduction in transpiration on a per-hectare basis, due to decreased root competition and rainfall interception (Fayle, 1983; Brix and Mitchell, 1986). Moreover, immediately after opening up of the canopy, growth conditions become less light limited, which could lead to an increase in the carbon balance (Kneeshaw *et al.*, 2002). Indeed, radial increments along the root system are an indicator of resource allocation (Krause and Morin, 1995). Nevertheless, taking cores in just one position at the base of the stem may not only reflect changes in allocation of radial growth increment along the stem but also increases in ring thickness resulting from more wood production than naturally occurs at the base of the stem (Larson, 1960; Jozsa and Middleton, 1997).

2.6. CONCLUSIONS

This study put the usually positive effects of CT on tree growth into perspective. The numerous thinned and control stands used in the research yielded a more realistic perception of the impact of CT on boreal forest species. CT leads to increased radial growth of roots and stems for at least 10 years after treatment, but response varies within stands and from stand to stand. Based on our results, trees with the smallest diameters respond better (in terms of relative growth) to thinning. This could explain some negative results observed after thinning from below. It would therefore be interesting to study stand response after thinning from above and compare this with thinning from below, which is more commonly used in commercial conifer stands (Pape, 1999). Furthermore, the impacts on wood quality of radial growth increase after CT need to be studied more closely to enhance our knowledge.

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Table 2.1: Stands characteristics

Block	Name (#)[1]	Location	Number of trees analysed	Treatment[2]	Thinning year	Density cut by thinning (trees/ha)	Residual density after thinning (trees/ha)	Stand age at thinning time (year)	Annual precipitation (mm)	Temperature	DBH (cm)	Height (m)	Crown length (m)
1	HEB96-1 (1)	N48,315 W71,679	35	CT	96	133	667	58.7 ±9	992.9	-12.1/17.9 °C	20.6±4.1	14.3±2.9	9.7±2.8
	HEBC (3)	N48,145 W71,589	43	∅	∅	∅	2250	51.3 ±9	992.9	-12.1/17.9 °C	16.1±5.2	13.6±2.5	8.4±2.7
2	HEB96-2 (2)	N48,279 W71,683	41	CT	96	600	1250	53.2 ±8	992.9	-12.1/17.9 °C	17.3±4	13.9±2.6	6.8±2
	HEBC (3)	N48,145 W71,589	43	∅	∅	∅	2250	51.3 ±9	992.9	-12.1/17.9 °C	16.1±5.2	13.6±2.5	8.4±2.7
3	MM96 (4)	N48,054 W71,063	37	CT	96	550	2550	99.1 ±12	893.5	-17.3/17.2 °C	13.2±2.4	13.3±1.7	4.7±2.4
4	MV96 (5)	N48,76 W70,551	43	CT	96	1550	1225	59.5 ±8	1187.3	-16.1/17.5 °C	16.2±2.4	12.3±1.4	7.7±1.8
	MVC (7)	N48,764 W70,55	47	∅	∅	∅	2750	52.8 ±12	1187.3	-16.1/17.5 °C	15±3.8	11.9±1.6	7.6±2.3
5	MV95 (6)	N48,794 W70,544	46	CT	95	1425	1200	60.9 ±11	1187.3	-16.1/17.5 °C	16±3.1	12.2±2.5	6.3±1.3
	MVC (7)	N48,764 W70,50	47	∅	∅	∅	2750	52.8 ±12	1187.3	-16.1/17.5 °C	15±3.8	11.9±1.6	7.6±2.3
6	HEB95 (8)	N47,887 W71,464	46	CT	95	825	1125	48.4 ±10	992.9	-12.1/17.9 °C	16.3±3.7	11.6±1.8	7±2.7
	HEBC (3)	N48,145 W71,589	43	∅	∅	∅	2250	51.3 ±9	992.9	-12.1/17.9 °C	16.1±5.2	13.6±2.5	8.4±2.7
7	LB95 (9)	N48,033 W72,33	41	CT	95	675	1175	81.9 ±27	1012.7	-16.8/17.3 °C	17.5±3.2	15.3±2.4	8.3±2.6
	LBC (10)	N48,032 W72,334	38	∅	∅	∅	950	67.1 ±23	1012.7	-16.8/17.3 °C	15.2±4.4	12.9±3.5	8.2±3.8
8	LC96 (11)	N48,143 W71,879	40	CT	96	1250	1050	56.3 ±6	1036.7	-11.7/19.3 °C	17.8±1.8	15.5±3.2	8.4±3.3
	LCC (12)	N48,143 W71,878	32	∅	∅	∅	1000	54.9 ±13	1036.7	-11.7/19.3 °C	21±4.8	16.6±2.7	8.7±4.6
9	LJ96 (13)	N48,983 W72,738	39	CT	96	1250	1650	46.8 ±6	919.8	-18.4/17.6 °C	13.8±2.5	12.8±1.5	5.6±1.8
	LJC (14)	N48,983 W72,741	25	∅	∅	∅	3906	53.1 ±7	919.8	-18.4/17.6 °C	12.7±2.5	13.4±1.3	4.2±1.4
10	SL97 (15)	N48,874 W71,747	33	CT	97	925	575	57.1 ±7	1061.4	-11.7/18.2 °C	19.7±4.7	16.6±2.4	8.4±2.6
	SLC (16)	N48,874 W71,475	31	∅	∅	∅	1289	50.2 ±7	1061.4	-11.7/18.2 °C	15.8±5.6	14.4±2.9	7.4±2.4
Mean for thinned stands			44		96	918	1247	62	1028	-14.4/17.9	16.8	13.8	7.3
Mean for control stands			36				2024	55	1035	-14.5/18	16	13.8	7.4

1, Stands nomenclature: First letters refer to stand location, followed by thinning year or C to indicate control stands. Stands have also been numbered from 1 to 16.

2: CT = Commercial Thinning, ∅ = controls

Table 2.2: Effects from the analysis of variance (ANOVA) for A) log(γ), where γ is the mean growth increment since thinning year for stems, roots 25 (R25) and roots 70 (R70), treatments (thinning and controls) are compared; and B) log(γ_t), where γ_t is the annual growth increment, temporal analysis is presented. Data are transformed in logarithmic value when necessary.

Factor	Source	DF	DFDen	F Ratio	Prob > F
A) Variable = log(γ)					
Stem	Block	9	7.13	0.8592	0.5932
	Treatment	1	7.13	13.1782	0.0081
R25	Block	9	8.901	1.5400	0.2662
	Treatment	1	8.643	28.4747	0.0005
R70	Block	9	8.134	2.2104	0.1371
	Treatment	1	7.854	13.9465	0.0059
B) Variable = log(γ_t) for stem and root growth indexes for roots R25 and R70					
Stem	Block	9	177.2	7.3425	<.0001
	Time	19	167	8.6314	<.0001
	Treatment	1	168.8	6.4298	0.0121
	Treatment*time	19	177.9	1.8580	0.0199
R25	Block	9	157.8	3.5876	0.0004
	Time	19	152.6	5.9286	<.0001
	Treatment	1	147.6	52.9094	<.0001
	Treatment*time	19	154.4	6.5649	<.0001
R70	Block	9	158.4	4.0336	0.0001
	Time	19	150.8	4.2382	<.0001
	Treatment	1	163.1	72.1401	<.0001
	Treatment*time	19	168.8	7.3339	<.0001

Table 2.3 : Regression coefficients for independent variables: diameter at breast high (dbh), Competition Index at Thinning Year (CI_{TY}), Stump Competition Index (CI_S), tree height (height) and crown length. Data are transformed in logarithmic value when necessary.

Term	Estimate	Std Error	t Ratio	Prob >|t|
Intercept	5.3012411	0.110967	47.77	<.0001
dbh	0.017583	0.006395	-2.75	0.0063
Intercept	5.0000121	0.032415	154.25	<.0001
Log(CI_{TY})	0.002898	0.03184	0.09	0.9275
Intercept	4.9875598	0.030493	163.57	<.0001
Log(CIs)	0.0662934	0.033655	1.97	0.0499
Intercept	5.1148595	0.132239	38.68	<.0001
height	-0.008365	0.009474	-0.88	0.3778
Intercept	5.0739145	0.119619	42.42	<.0001
Crown length	-0.036406	0.060453	-0.60	0.5474

Table 2.4: A) Stepwise regression for the model of log(γ), radial growth increment, B) Whole model of the multivariate regression resulting from the stepwise analysis and C) Independent variables. Data are transformed into logarithmic values when necessary.

A) Stepwise regression

Step	R^2	Sequential SS	P	ΔAIC	Variable added
1	0.0161	0.0161	0.0411	2.212	Log(CI_S)
2	0.0403	0.403	0.0114	4.493	dbh
3	0.0511	0.0511	0.0901	0.923	Log(CI_{TY})

B) Whole Model

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	2.931633	0.977211	4.5114
Error	258	55.884636	0.216607	**Prob > F**
C. Total	261	58.816269		0.0042

C) Independent variables

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Intercept	5.5850384	0.197022	28.35	<.0001		
dbh	-0.03294	0.01079	-3.05	0.0025	-0.2223	1.4397139
LogCI_{TY}	-0.075988	0.044009	-1.73	0.0854	-0.11796	1.2673534
LogCIs	0.0298397	0.036304	0.82	0.4119	0.053577	1.1537206

Note: Results from stepwise regression using the forward procedure with AIC as indicator, ΔAIC (ΔAIC = AIC before enter- AIC after enter) has to be positive to enter.

CI_{TY} = Competition Index at thinning year

CI_S = Stump competition index

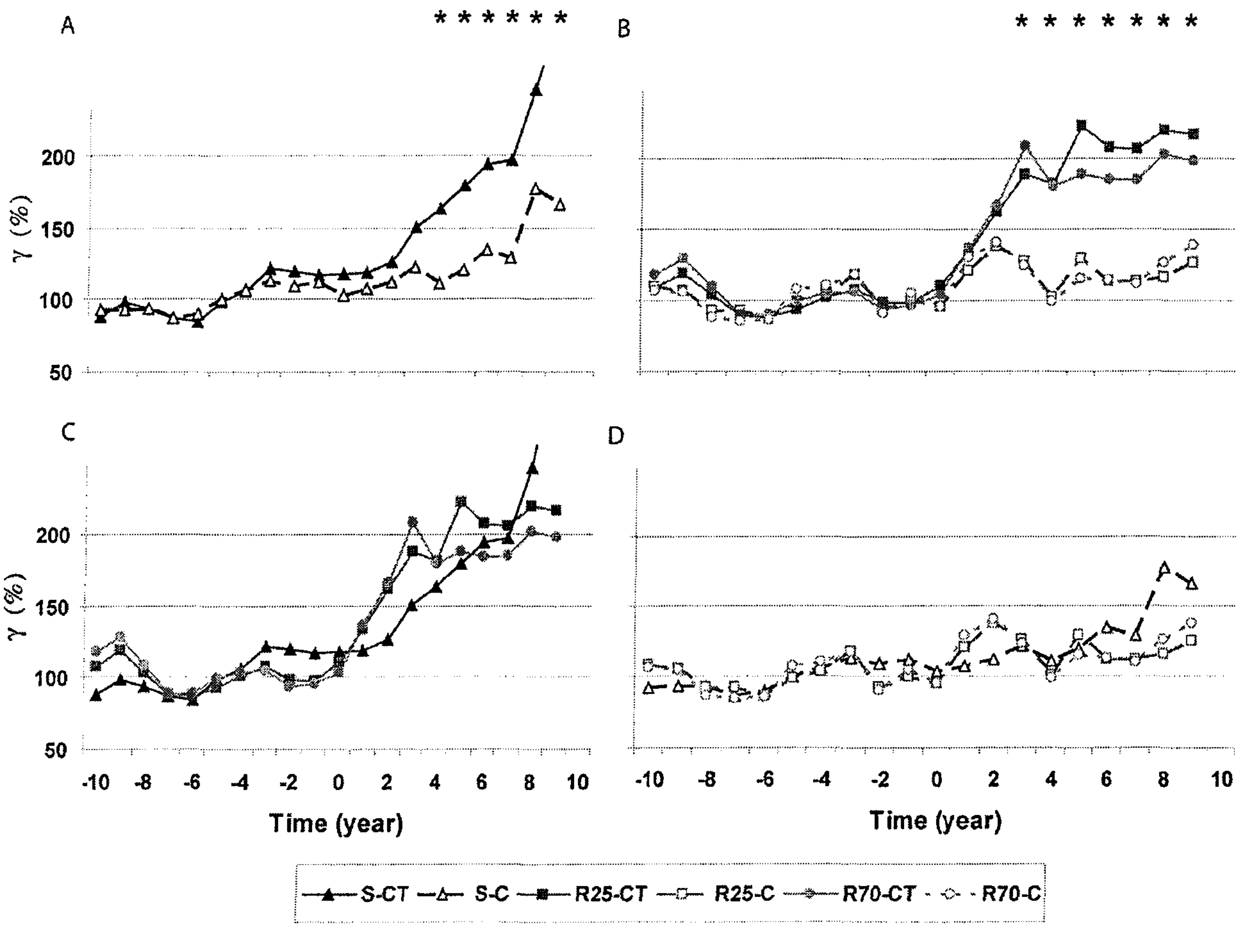

Figure 2.1: A) Radial growth increments (γ) over time of stems (S), built with all thinned stands (CT – in black plain line) and compared with controls (C – black dashed line). B) Radial growth increments of roots R25 (blue line) and R70 (grey line) over time built with all thinned stands (plain line) and compared with controls (dashed line). C) Root and stem growth increment pattern over time for thinned stands. D) Root and stem growth increment pattern over time for control stands. Time 0 = year of thinning, negative numbers correspond to years before treatment and positive ones to years after thinning. Asterisks mean significant treatment*time interactions. C = Control stands and CT = Commercial thinning.

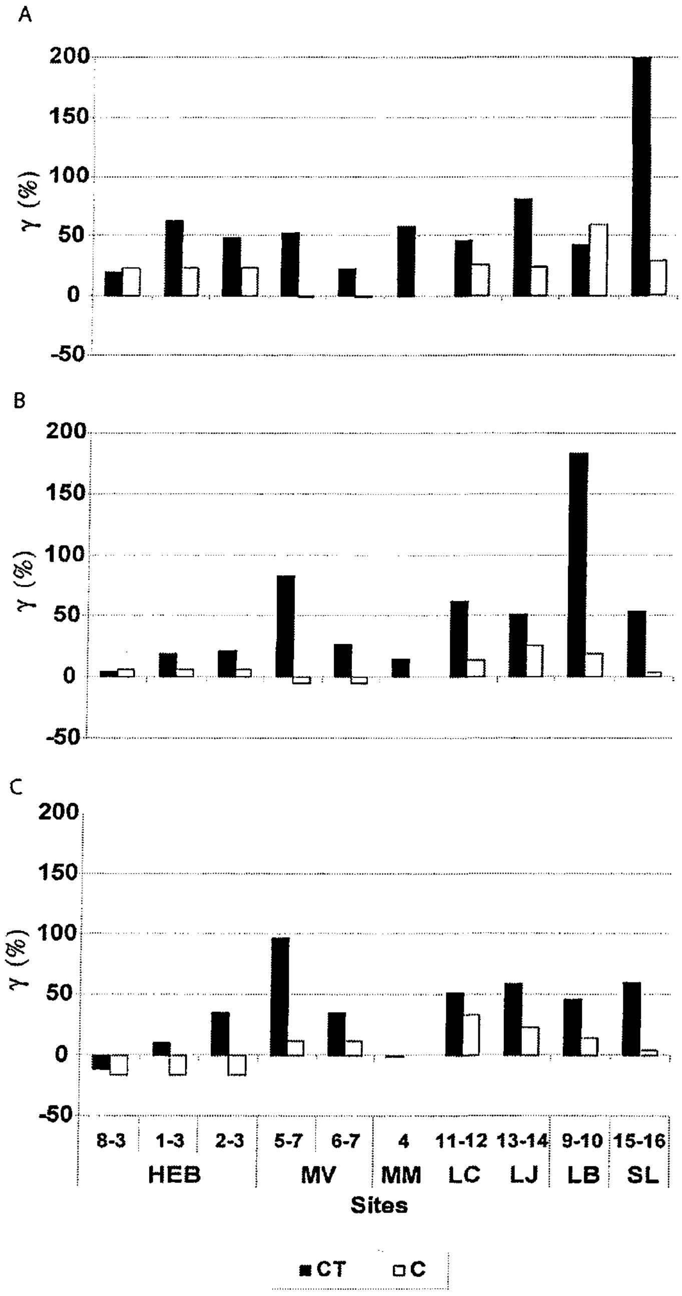

Figure 2.2: A) Stem growth increment (γ) by thinning (CT) stands (black); comparison with control (C) stands (white). B) Roots R25 growth increment by thinning stands; comparison with control stands. C) Roots R70 growth increment by thinning stands; comparison with control stands. For each graph, stand (first number) is grouped with its control (second number) by location.

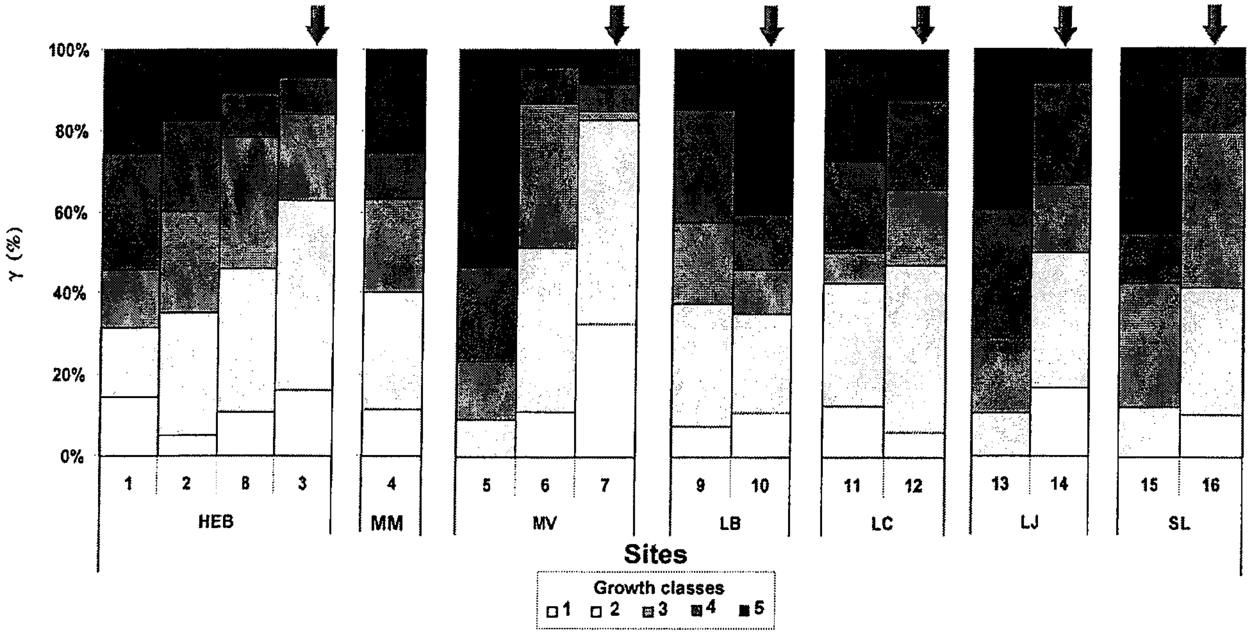

Figure 2.3: Percentage of trees within stands as a function of their growth increment (γ) after thinning year for thinned stands (left part on each graph) and control stands (last part of each graph, arrows). Different colours correspond to the five growth response classes described in the methods.

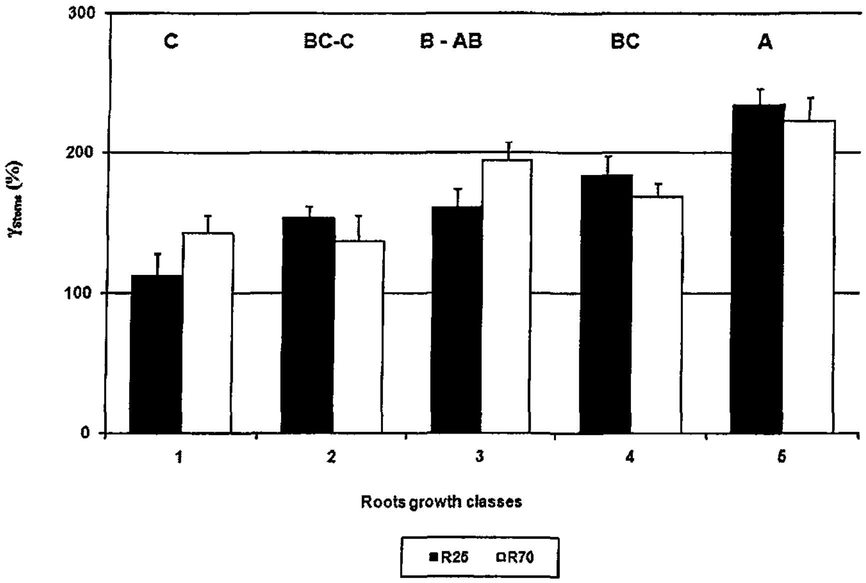

Figure 2.4: Relation between stem growth increment (γ) after thinning and root growth classes after thinning for all thinned stands (levels not connected by same letter are significantly different).

CHAPITRE 3

YIELD OF BLACK SPRUCE STANDS FOLLOWING COMMERCIAL THINNING: A WAY TOWARDS FULFILLING NEW MANAGEMENT EXPECTATIONS

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Keywords: *partial cutting; boreal forest; Picea mariana, dbh distribution, wood products, basal area.*

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CHAPITRE 3

YIELD OF BLACK SPRUCE STANDS FOLLOWING COMMERCIAL THINNING: A WAY TOWARDS FULFILLING NEW MANAGEMENT EXPECTATIONS

3.1. ABSTRACT

The effects of commercial thinning on individual and stand volume increment were investigated in nine commercially thinned and control black spruce stands in northern Quebec's commercial boreal forest. Dendrochronological data were used to determine individual volume variations 10 years after treatment. Thinning significantly increased individual volume increment compared to the 10-year period before treatment (p = 0.0442). An average decadal volume increment of 25 per cent for thinned stands and 9 per cent for controls was observed. CT density, number and characteristics of competitors influenced individual response. Analysing tree volume from germination to felling it appeared that total wood volume produced by thinned stands 10 years after treatment was not significantly different from controls. Variability between stands may explain this result. These results are interesting from an ecosystem-management context that may intensify the use CT realization in unmanaged natural black spruce stands.

Keywords: partial cutting; boreal forest; *Picea mariana*, dbh distribution, wood products, basal area.

3.2. INTRODUCTION

Black spruce (*Picea mariana* (Mill.) B.) is the most important commercial and reforested species in Eastern Canada (Parent and Fortin, 2008; Zhang and Koubaa, 2009). The traditional harvesting method used in black spruce stands is clear-cutting but society's expectations of forest management in the boreal forest have evolved. In Quebec, the reduced land base for fiber production (Coulombe *et al.,* 2004) coupled with increasing global competition in the forest industry has led to the development of new strategies to increase the volume of wood produced in the remaining forests. Partial cutting such as commercial thinning (CT) could be a sound choice to attain sustainable development within global market constraints while still achieving maximum value (Zhang *et al.*, 2006). Toward this goal CT effects on tree growth, mortality and stand yield have been studied for different softwood species, including jack pine (*Pinus banksiana* Lamb.) (Bella and De Franceschi, 1974; Schneider *et al.*, 2008), Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.) (Mäkinen and Isomäki, 2004a, b) and black spruce (Shepard and Shottafer, 1990). Indeed, CT is usually performed in plantations (Gouvernement du Québec, 2003). According to previous studies, diameter at breast height (Dbh), growth rate, tree status (dominant or oppressed) and competition strongly influence response to the treatment (Koga *et al.*, 2002; Pape 1999; Sharma and Zhang, 2004). But, although a radial increase is usually observed at the stem scale (Barbour *et al.,* 1992; Johnstone, 1997; Stinson, 1999), some studies have pointed out that thinning had no effect on the cumulative yield of merchantable volume at stand level (Mäkinen and Isomäki, 2004a, b; Viens, 2001).

However, CT can also be done in natural, unmanaged stands, in unproductive plantations or old managed the stands (Gouvernement du Québec, 2003; OMNR, 1997). In the current ecosystem-based management context, CT of natural unmanaged stands may be particularly attractive since it responds to recent ecological expectations, for forest cover retention and species conservation and to ensure an intermediate harvest during critical supply period. Consequently, CT may to be perceived as a means to accommodate human use while maintaining ecological integrity (Grumbine, 1994; Thorpe and Thomas, 2007). Despite the potential benefits of using CT as an ecosystem management tool in the boreal, most research on the subject has focused on wildlife response (Artman, 2002; Coxson *et al.,* 2003). To the author's knowledge, only a few studies have been conducted on CT in naturally regenerated unmanaged black spruce stands (Hillman and Takyi, 1998; Vincent *et al.*, 2009; Weetman *et al.*, 1980) and few projects have evaluated how residual trees respond (Vincent *et al.,* 2009) to the treatment. Authors have reported large variation in individual-tree radial growth responses, even in the same stand that may contrast with volume increment observed at the stand scale. These differences may be related to processes occurring at small-scales, *e.g.* the neighborhood effects influencing the amount of release in residual trees (Thorpe and Thomas, 2007; Vincent *et al.,* 2009).

In this study, we assumed that CT led to an individual volume increment but that there may be a gap between individual volume increments and volume increment observed at the stand level. The objective of this study was to quantify, based on different thinned stands and controls, individual volume increment after CT and the volume increment at the stand level. An additional objective was to discuss the implications in an ecosystem-based management context in natural unmanaged black spruce stands.

3.3. MATERIAL AND METHODS

3.3.1. Study area

This study was based on 9 CT stands and their controls in the boreal forest of Quebec, Canada. Stands had to be accessible by truck and located close to trails in order to carry field material and samples on foot. As thinning is still a recent silvicultural treatment applied to natural black spruce stands, no standard methods have yet been developed and no information was available about thinning types and techniques. Latitude ranged from 47.9°N to 49°N, longitude from 70.5°W to 72.7°W and altitude from 210 to 671m. The region is characterized by cold winters and short growing season. Over the last 30 years, the average minimum temperature was -18.3 °C during the coldest month and the average maximum was 17.9 °C during the warmest month. Average annual precipitation varied from 920 cm to 1187 cm in the studied stands (Environment Canada, 2008). Essentially pure unmanaged natural black spruce stands were selected. The mean age of the stands at treatment varied between 47.8 and 81.9 years (Table 3.1). No silvicultural treatment other than CT was applied. Basal area density, evaluated by all trees within a 20 x 20 m quadrat, was between 800 and 3900 trees per hectare before treatment. The herbaceous and moss strata were mainly composed of: *Pleurozium schreberi* (Brid.) Mitt., *polytrichum* sp., *Ptilium crista-castrensis* (Hedw.) De Not., *Ledum groenlandicum* Oeder, *Vaccinium angustifolium* Ait. and *Kalmia angustifolia* L.. Stand selection was based on two main criteria: (i) thinning year, thinning treatments were done 10-12 years before sampling; (ii) thinning of unmanaged natural black spruce stands (Table 3.1). Whenever possible, a nearby unthinned natural black spruce stand with similar characteristics was selected as a control. Control stands selection was mainly based on stand age and location close to thinned stands. In two instances where all stands had the same environmental characteristics, the same control stand was used for comparison with more than one nearby thinned stand.

3.3.2. Sampling and volume calculation

In each stand a 20x20 quadrat comprising at least 35 black spruces (Diameter at breast height > 9 cm) was selected. Total tree height (H), diameter at breast height (Dbh), and at stump (Dsh) were measured for each tree in the quadrat. Site quality was estimated using height of dominant trees and production tables (Pothier and Savard, 1998) (Table 3.1), tree Dbh distribution was also evaluated (Figure 3.1).

Merchantable basal area (G) was calculated using thinned tree data collected during field work (1). G was calculated with Dsh. It was then corrected with the ratio Dbh/Dsh for comparison with the theory.

$$G = \frac{\pi \times factor}{40000} \times \sum_{i=1}^{n} Dbh_i^{\,2} \qquad (1)$$

G is the basal area (m^2/ha) and factor is the conversion factor for correcting obtained values to the ha scale (Perron *et al.*, 2009). Stems volume was calculated with volume table for black spruce trees, function of stems Dbh and H (Perron, 1985). The average volume per stem (AVS) and the volume by hectare (V) were calculated at thinning year (AVS_{TY}, V_{TY}, m^3, including thinned stems) and at the final harvest year (AVS_f, V_f, m^3) for both thinned and control stands and presented on a per hectare basis (Table 3.2). For the purpose of the analysis, stands were considered ready for the final felling at the year of sampling. Because the studied stands are even-aged, and CT isn't supposed to modify tree H (Hillman and Takyi, 1998; Viens, 2001), harvested trees H was assessed with residual stems of similar stump diameter within and close to the quadrat.

Six black spruce trees in each thinned stand and three in control stands were randomly selected and felled. Thus, a total of 72 trees were harvested for stem analysis (one tree was excluded because of manipulations errors in the laboratory). Because interpretation of stand response may be limiting by the small number of trees, neighborhood conditions of sample trees were recorded (Table 3.3). A previous study based on the same studied stands presented all collected data by stand such as tree position, tree dimensions, competition and radial growth increment at stump height (Vincent *et al.*, 2009). Neighborhood trees were considered to be competitors when in the search radius (3.5 × mean crown radius of canopy trees, 4 m in our study).

Stems were cut every meter, starting at ground level and moving up to the crown to collect samples for dendrochronological analysis. Each sample disk was dried and sanded. Tree-ring widths were measured from four perpendicular radii using Mac Henson and WinDendro software (Guay *et al.*, 1992) and cross-dated (Krause *et al.*, 2003; Stokes and Smiley, 1968). Dating of rings was checked with the Cofecha program (Holmes, 1983).

The computer program WinStem™ was run to conduct stem analysis. It produced the volume as a function of age, using the Carmean (1972) method. WinStem™ calculates the volume for each tree section as a cylinder (2).

$$V = \frac{1}{3}\pi h(a^2 + ab + b^2) \qquad (2)$$

Where V = volume of a 1 m segment

h = length of the segment

a = radius at the top of the segment

b = radius at the bottom of the segment

The segments were then added to obtain the volume yield of the tree, resulting in an estimate of volume yield at each age (V_{cum}). Differences in volume yield for adjacent years resulted in annual volume increment (V_{inc}). Cumulative radius, diameter, basal area and height over time were also calculated annually for each tree.

To compare volume growth between trees, decadal volume increment after CT (V_{10}) was calculated with WinStem^{TM} data before and after thinning (3).

$$V_{10} = \frac{\sum_{t=1}^{t=10} V_{inc,t}}{\sum_{t=-9}^{t=0} V_{inc,t}} \times 100 \qquad (3)$$

3.3.3. Statistical analysis

Data were compiled using an ANOVA multifactor model with an REML procedure (mixed model). A seven-block unbalanced split-plot design was used for volume growth increment, with treatment (thinning/control) as the main level. Sites were nested within blocks and trees were nested within sites. Both blocks and sites were random effect factors.

Regression analyses were performed to examine relationships between individual tree growth and tree size, competitors' size and number and stand characteristics.

Statistical analysis ANOVAs were performed using JMP software (SAS Institute Inc. Cary, NC) with a confidence level of 95 per cent.

3.4. RESULTS

At year of thinning, thinned stands had a mean age of 58 years while that of controls was 55 years (Table 3.1). Based on the initial basal area, merchantable thinning intensity in different stands varied from 9.7 to 52.5 per cent, which can be classified as light to heavy thinning.

Moreover, the Dbh ratio of residual and thinned stems at thinning year (Dbh_{RES} at TY/Dbh_{THI} at TY) can be used to highlight different CT types. When Dbh_{RES} at TY/Dbh_{THI} at TY is inferior to one, CT from above was realized (biggest trees thinned), on the other hand when Dbh_{RES} at TY/Dbh_{THI} at TY is superior to one, the CT was from below (Table 3.1). Only LJ96 is considered as a CT from above.

Thinned, residual and control stem distribution for all stands put together is presented in figure 3.1. A student's *t*-test conducted for each Dbh class when appropriate revealed a significant difference between thinned, residual and control stems proportions for Dbh classes 10, 20, 22 and 28 cm (Figure 3.1).

3.4.1. Individual tree volume growth

Selected tree environments are presented in Table 3.3. Selected tree Dbh's for stem analysis from thinned stands varied from 9.1 cm to 28.5 with a mean of 16.9 cm, whereas the Dbh of trees selected from control stands varied from 9.5 cm to 23.5 with a mean of 16.1 cm. The mean of selected tree Dbh's from both thinned and control stands was 16.7 cm (Table 3.3).

On average, selected trees from thinned stands presented about 2.2 competitors with a Dbh varying between 11.2 cm and 33.2 cm and a mean Dbh of 17.2 cm. Selected trees from control stands presented an average of about 3.4 competitors with a Dbh varying from 8.8 cm to 25.7 cm and a mean Dbh of 15 cm (Table 3.3).

Selected trees from thinned stands presented about 1.3 competitor stumps around them. Nevertheless, the number of competitor stumps around a selected tree, varied from 0 to 6. Mean Dsh of competitor stumps was 14.2 cm, varying from 8.3 cm to 35 cm.

All thinned stands presented a higher decadal volume increment (V_{10}) calculated from selected trees than control stands (Figure 3.2). By stand, V_{10} was about 125 per cent for thinned stands, varying between 115 and 139 per cent, whereas it was about 109 per cent for control stands, with a range of 88 to 130 per cent (Figure 3.2). Statistically, V_{10} for thinned stands was significantly higher than controls ($p = 0.0442$, Table 3.4A).

Linear regression was performed to detect the effect of initial stand density on V_{10} observed for both thinned and control stands. Despite variations between stands before treatment, stand density before thinning did not significantly influence V_{10}.

However, regarding selected tree characteristics, a significant negative relationship was found between V_{10} and number of competitors ($p = 0.0383$; $R^2 = 0.055$), whereas a positive one was found between V_{10} and stump number ($p = 0.0300$; $R^2 = 0.067$; Table 3.5A). CT intensity (G thinned, %) also positively influenced V_{10} ($p = 0.0062$; $R^2 = 0.105$).

Regarding individual wood volume produced since germination to felling, CT did not significantly influence individual wood produced (V_{cum}, $p = 0.3574$ data not shown) and despite a slight trend between selected tree Dbh and V_{cum} ($p = 0.0589$) no significant relation was found between V_{cum} and selected trees and environmental characteristics (Table 3.5B). On the other hand, G thinned (%) positively influence V_{cum} ($p = 0.0186$; $R^2 = 0.078$).

3.4.2. Stand increment

Stand volume at thinning year and 10 years after treatment is presented on a hectare basis in Table 3.2. 10 years after treatment, the volume of CT stands represented about 70 per cent of the volume of control stands. Including the volume thinned, average volume of CT stands was equal to the average volume of controls stands (Table 3.2). On the other hand, regarding only residual stems after thinning, average volume increment by thinned stand was slightly higher than the average volume increment from control stand (respectively 110 per cent and 106 per cent). As a result, no significant influence of treatment on stands volume increment was observed (Table 3.4B).

Considering only residual stem increment, two of the nine stands presented a volume increment after thinning lower than control stands HEB96-1 and LB95. In contrast, three stands presented a stand volume increment after CT, higher than their associated controls: LC96, LJ96 and MV96 (respectively equal to 10.5, 13 and 9.5% of controls stands volume increment, Table 3.2). Merchantable volume increment by stand (volume thinned + residual volume) is presented in figure 3.4. As observed for residual growth increment by stand, merchantable volume increment by stand varied between blocks. Merchantable volume increment varied from 2.9% to 9.4% with a mean of 6.4% for CT stands whereas it varied from 3.3% to 14.5% with a mean of 6.3% for controls stands. Four blocks, LC, LJ, MV and SL presented a merchantable volume increment higher 10 years after treatment for thinned stands than controls.

3.5. DISCUSSION

3.5.1 Individual tree volume growth

In the thinned stands, individual tree volume growth increment is significantly higher 10 years after CT than the 10 years before (Table 3.4A). Similar volume increment per stem after CT was observed for jack pine and Douglas fir (Bella and De Franceschi, 1974; Curtis and Marshall, 2002; Stinson, 1999). Individual volume increment was significantly affected by the number of competitors (thinned and live) around selected trees (Table 3.5). Different authors demonstrated before that number and size of competitors and selected and thinned trees characteristics may influence individual volume increment (Pape, 1999; Vincent *et al.,* 2009). Moreover, thinning intensity (G thinned, %) explained also a part of individual volume growth variability (Table 3.5). We assume that these parameters affect differently individual volume growth. Indeed, whereas competitors and residual tree characteristics may have an effect at the individual scale, G thinned would probably more affect general intensity of individual volume growth and will be reflected at the stand level. Eventually, initial stand density does not significantly affect individual volume increment.

Eventually, individual wood volume produced 10 years after treatment wasn't affected by CT. Many authors demonstrated in the past that thinning effects depend on tree diameter before treatment (e. g. Burkhart and Bredenkamp, 1989; Newton *et al.,* 2005; Vincent *et al.,* 2009). Indeed, whereas smaller trees may exhibit better relative growth rates, large trees remain large in absolute terms (Morris *et al.,* 1994). Moreover, some studies have reported a large variation in individual-tree growth responses, even among members of the same species in the same stand (Skovsgaard, 2009). These differences underline the importance of using individual-based models to predict stand-level growth responses to CT.

3.5.2. Stand increment

No significant variation in stand volume increment after thinning was observed in this study. However, regarding merchantable volume increment, five stands presented a higher increase 10 years after treatment than their associated controls (Figure 3.4). Among the two others blocks, HEB96-1 and LB95 presented a stand volume increment based for residual stems, after CT, lower than their associated controls (Table 3.2). According to field data, both stands were subject to very low thinning intensity (respectively, 9.7 and 13.1 per cent of basal area at thinning year) which may explain the absence of a thinning response. Indeed Weetman *et al.* (1980), demonstrated that for black spruce, light thinning (25%) seemed to have little impact on the growth of single trees from a 65-year old stand, while a 50% thinning caused an increase of 30% in basal area growth rate, 15 years after thinning. Eventually, the results from the block LB may be questionable because LBC presented a G_{TY} almost half low that of LB95 (Table 3.1). It could thus be argued that these two stands were not comparable. However, a previous study working with same field material demonstrated that both LB95 and LBC were affected by spruce budworm (*Choristoneura fumiferana* (Clemens)) outbreaks, which occurred in the region in the late 1970s (Morin *et al.*, 2000; Vincent *et al.*, 2009). Comparing radial growth along time it seems that spruce budworm outbreaks affected LBC longer (about two years) than LB95. Moreover the resumption of radial growth for LBC after the outbreak appeared faster and higher than LB95 (Vincent *et al.*, 2009). The low stand density of LBC at the year of thinning may be a consequence of outbreaks whereas the high stand volume increment observed may correspond to the resumption of growth after it. Apart from Stinson (1999), who found an increase in bole size and total harvested volume in thinned Douglas fir stands, authors generally noticed no increase or even a decrease in the volume produced by thinned stands compared to controls (Mäkinen *et al.,* 2005; Skovsgaard, 2009).

Important variability between stands was observed in this study. Despite the fact that this variability in CT practices in the studied region, it complicated the analysis of thinning response at the stand level. It is obvious that stand characteristics also interfere with CT response. Thus, it may be argued that initial stand density, which varied between studied stand, may interfere in stand response to CT. A study based on the influence of CT on stand increment following initial stand density may be interesting to conduct. Nevertheless, working with naturally regenerated unmanaged stands implies that initial stand density isn't a controlled parameter.

3.5.3. Yield allocation and implication for ecosystem-based management

The main advantage expected from commercial thinning is to increase the diameter of residual trees by decreasing competition for light (Sheedy, 1997; Stiell, 1980; Thiffault *et al.,* 2003) which seems to be the case in natural black spruce stands despite stand variability. A great advantage of increasing individual tree size, over and above improving harvesting efficiency, is the opportunity to produce different products, thereby increasing market flexibility (Morris *et al.,* 1994). Thus, in the case of jack pine for example, commercial thinning may prove economically beneficial by allowing a shift from the pulpwood market to providing a mixture of saw log and round wood material (Morris *et al.*, 1994). Another advantage with the increase of individual tree size is the decrease of wane, a processing defect often responsible for the downgrading of lumber (Zhang *et al.,* 2006).

On the contrary, merchantable stand volume increment after CT seems to be limited. Indeed, within seven blocks, five presented a merchantable volume about 3.3% higher than controls (Table 3.3). Between these stands, one of the best responses at the stand scale was noticed for LJ96. According to stand characteristics CT conducted in this stand was a CT from above (Table 3.1). Moreover at the individual scale it seems that volume increment is inversely influenced by tree Dbh (Pape, 1999). Since CT was not originally designed to emulate natural disturbance, because spruce budworm outbreaks impact has also been showed in evidence in this study it may be interesting to analyze CT effect in the eyes of this boreal perturbation. According to previous studies, it seems that spruce budworm outbreaks essentially affect the biggest and oldest trees in black spruce stands (Lussier *et al.,* 2002). Regarding similarities between spruce budworm outbreaks and CT effect on stand dynamics, and because of the results observed in the present study, CT, may be deemed to be a sound choice in terms of ecosystem management. Indeed, it has been noticed that silvicultural treatments such as clear-cutting tended to create homogenous patterns compared to natural variability observed following natural disturbances (Bergeron *et al.*, 2002), partial cutting such as CT appears like an alternative to usual treatment because it's a mean to retain old forest associated features on managed landscapes.

3.6. CONCLUSION

This paper describes the 10-year thinning results in natural black spruce stands yield and volume. To the authors' knowledge, very few studies have dealt with commercially thinned natural black spruce stands. Black spruce reacted to CT with an increase in volume produced per stem but no significant impact on total volume produced per stand. According to our results, the number of competitors around a tree negatively influenced individual tree volume growth. On the other hand, initial stand density did not influence individual response to treatment. Disparities between studied stands make difficult a global analysis but allow defining future orientations for this subject. Two types of studies may therefore be undertaken: studies based on stand yield according to stand and treatment characteristics (such as initial stand density) and studies about residual stand characteristics in terms of ecosystem-based management. According to these results however, CT may be relevant in an ecosystem-management context as well as providing intermediate timber supply. Indeed, using commercial thinning in natural stands may contribute to forest cover retention while still increasing residual stems volume increment.

3.7. ACKNOWLEDGMENTS

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3.8. REFERENCES

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Table 3.1: Stands characteristics

Sites	Location	Annual precipitation (mm)	Temperature (average min/average max, °C)	TY	Stand Age at TY	Dbh at TY (cm)	G at TY (RES+THI m²/ha)	Merchantable Thinning intensity (%)	Dbh_{RES} at TY / Dbh_{THI} at TY	Site Index at 50 years
HEB95	N47.887 W71.464	992.9	-12.1/17.9	1995	48.4 ±10	13.0	29.2	19.6	1.4	12-15
HEB96-1	N48.315 W71.679	992.9	-12.1/17.9	1996	58.7 ±9	15.4	23.8	9.7	1.0	15-18
HEB96-2	N48.279 W71.683	992.9	-12.1/17.9	1996	53.2 ±8	16.6	41	31.8	1.0	15-18
HEBC	N48.145 W71.589	992.9	-12.1/17.9		51.3 ±9	15.8	48.3			15-18
LB95	N48.033 W72.33	1012.7	-16.8/17.3	1995	81.9 ±27	14.7	33.1	13.1	1.4	15-18
LBC	N48.032 W72.334	1012.7	-16.8/17.3		67.1 ±23	14.6	17.2			15-18
LC96	N48.143 W71.879	1036.7	-11.7/19.3	1996	56.3 ±6	15.1	44.8	39.6	1.3	18-21
LCC	N48.143 W71.878	1036.7	-11.7/19.3		54.9 ±13	20.7	35.2			18-21
LJ96	N48.983 W72.738	919.8	-18.4/17.6	1996	46.8 ±6	13.6	42.3	52.5	0.8	15-18
LJC	N48.983 W72.741	919.8	-18.4/17.6		53.1 ±7	12.3	48.9			12-15
MV95	N48.794 W70.544	1187.3	-16.1/17.5	1995	60.9 ±11	14.1	40	39.7	1.3	12-15
MV96	N48.76 W70.551	1187.3	-16.1/17.5	1996	59.5 ±8	12.9	33	30.8	1.3	12-15
MVC	N48.764 W70.55	1187.3	-16.1/17.5		52.8 ±12	14.6	49.8			15-18
SL97	N48.874 W71.747	1061.4	-11.7/18.2	1997	57.1 ±7	17.1	40	37.4	1.3	18-21
SLC	N48.874 W71.475	1061.4	-11.7/18.2		50.2 ±7	15.5	34			18-21
Mean for CT stand					58	14.7	38.5	30.5	1.2	
Mean for C stands					55	15.6	38.9			

TY = Thinning Year, Dbh = Diameter at breast high, G = basal area, RES = residual stem, THI = thinned stem.

Grey line = control, ± = standard deviation

Table 3.2: Stands volume (V) and average volume per stem (AVS) at thinning year (TY) and 10 years after treatment (f).

Stands	G_{TY} (m^2/ha)	G Thinned (%)	V_{TY} (m^3/ha)	Vf (m^3/ha)	AVS_{TY} (m^3)	AVS_f (m^3)	Stand volume increment (%) (only RES stems)
HEB95	29	20	84	70	0.073	0.10	107.8
HEB96-1	24	10	219	204	0.195	0.22	103.2
HEB96-2	41	32	248	182	0.14	0.15	109.3
HEBC	48		285	306	0.127	0.14	107.3
LB95	33	13	205	188	0.134	0.16	107.1
LBC	17		96	110	0.101	0.12	114.5
LC96	45	4	272	180	0.125	0.19	114.1
LCC	35		229	237	0.255	0.26	103.5
LJ96	42	53	240	125	0.084	0.08	118.0
LJC	49		284	298	0.073	0.08	105.1
MV95	40	40	191	125	0.079	0.11	109.4
MV96	33	31	157	120	0.068	0.10	114.0
MVC	50		269	280	0.098	0.10	104.4
SL97	40	37	264	184	0.162	0.22	108.9
SLC	34		218	225	0.14	0.15	103.3
Mean for CT stands	36.4	30,5	209	153	0.12	0.15	110.2
Mean for C stands	38.9		230	243	0.13	0.14	106.3

CT = Commercial Thinning, C = controls, G = basal area.

Grey line = control

Table 3.3: Selected trees characteristics and environment

Sites	Number of selected trees	Mean of selected trees Dbh	Mean of selected trees H	Average number of alive competitors	Mean of alive competitors Dbh	Average Number of stumps competitors	Mean of stumps competitors Dbh
HEB95	6	17.1±3.4	12.5±1.4	1.5±1.5	13.4±1.8	1.3±1	11.6±3.7
HEB96-1	6	17.2±3.1	14.4±2.1	2.2±1	19.7±2.7	0.7±1.2	18.8±2.5
HEB96-2	6	19.4±3.2	16.3±2.3	2.7±0.8	15.2±2.1	0.8±0.4	18.3±6.2
HEBC	3	18.9±4.5	16±2.3	3.3±1.2	14.4±3.2	0	0
LB95	6	16.7±2.9	16.1±2.6	3±2.5	17.5±1.1	1.7±1.2	18±4.6
LBC	3	16.9±6.1	14.1±3.6	2.7±0.6	16.5±0.8	0	0
LC96	6	22.5±5.6	18.2±1.9	1.8±0.8	19.2±2.2	2.5±2.2	11.2±0.7
LCC	3	17.9±3.4	16.6±0.6	2.3±1.2	23.4±2	0	0
LJ96	6	12.3±2	13.2±0.9	2.2±0.8	13.2±0.8	1.7±1.2	12.8±2.9
LJC	3	12.2±2.4	14±1.6	6±1.7	11.1±0.6	0	0
MV95	6	15.1±3.6	13±1.7	2.5±1.6	15.8±1	0.7±0.8	12.7±1.2
MV96	5	14.4±1.6	12.7±0.7	2±1.6	15±1.1	1.6±1.8	9.8±0.2
MVC	3	16.2±1.6	12.7±0.7	2.3±2.1	12.1±1.3	0	0
SL97	6	17±3.2	16±1.5	1.8±1	25.2±7.3	0.8±1.3	15±1.7
SLC	3	14.4±3.5	13.9±2.7	3.7±2.1	11.5±2.4	0	0
Mean for CT stands	6	16.9±1.2	14.7±0.5	2.2±0.6	17.2±2	1.3±0.5	14.2±1.9
Mean for C stands	3	16.1±3.6	14.5±1.9	3.4±1.5	14.8±1.7	0	0

Dbh = Diameter at breast high, H = high

Grey line = Control stands, ± = standard deviation

Table 3.4: Effects from A) the analysis of variance (ANOVA) for V_{10}, and B) the analysis of variance (ANOVA) for volume increment by stand.

Source	**DF**	**DfDen**	**F Ratio**	**Prob > F**
A) ANOVA V_{10}				
Blocks	5	8.801	0.6019	0.7009
Treatment	1	12.96	4.9633	0.0442*
B) ANOVA Volume increment by stand				
Blocks	5	4.628	0.3432	0.8662
Treatment	1	4.734	2.3930	0.1858

Table 3.5: R^2, p and correlation coefficients (a) between A) V_{10} (decennial volume increment, %) and selected trees characteristics and competitors (alive and stumps) characteristics; and B) individual tree volume growth (V_{cum}) and selected trees characteristics and competitors (alive and stumps) characteristics.

$n = 71$	A) V_{10}			B) V_{cum}		
	R^2	a	p	R^2	a	p
Selected tree Dbh	0.001	-0.276	0.786	0.051	1.155	0.0589
Number of competitors	0.062	-5.41	0.0383*	1,639e-5	0.053	0.9735
Mean of competitors Dbh	0.055	-1.48	0.0669	0.009	-0.455	0.4526
Number of stumps	0.067	6.74	0.03*	0.026	2.253	0.1835
Mean of stumps Dsh	0.002	-0.32	0.796	0.061	-0.985	0.1599
G thinned (%)	0.1	0.63	0.0062*	0.078	0.33	0.0186*
Density after thinning	0.05	-0.83	0.0709	$1.92e^{-}5$	-0.010	0.9712

***Significant at $p < 0.05$**

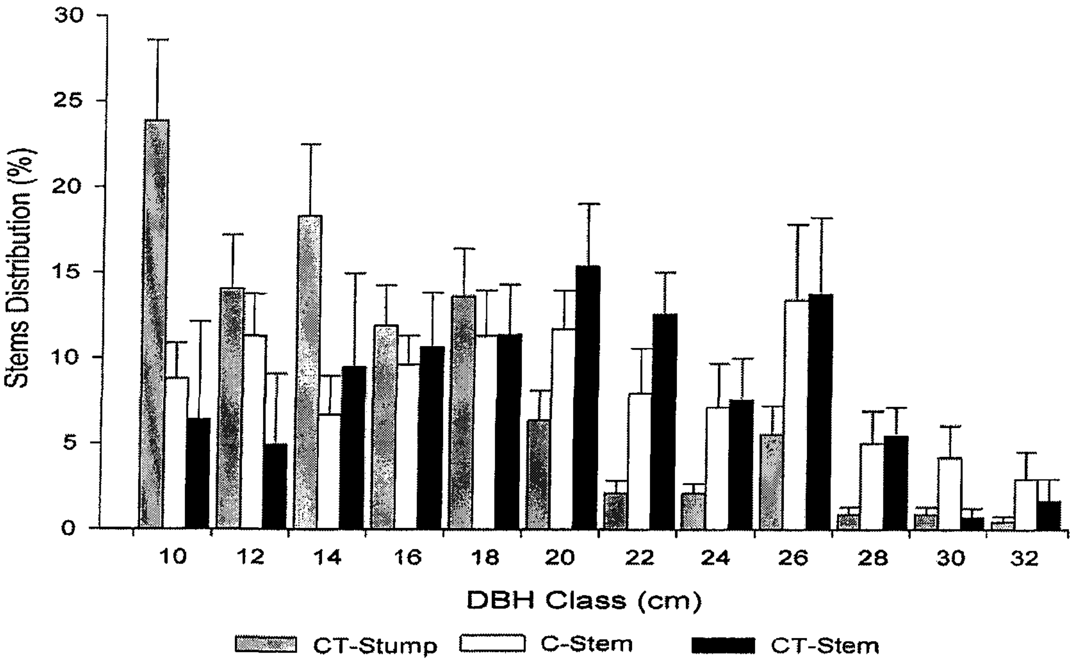

Figure 3.1: Stem distribution (%) following Dbh class (cm). Stems from control (white) and thinned (black) stands are represented as well as stumps from thinned (grey) stands.

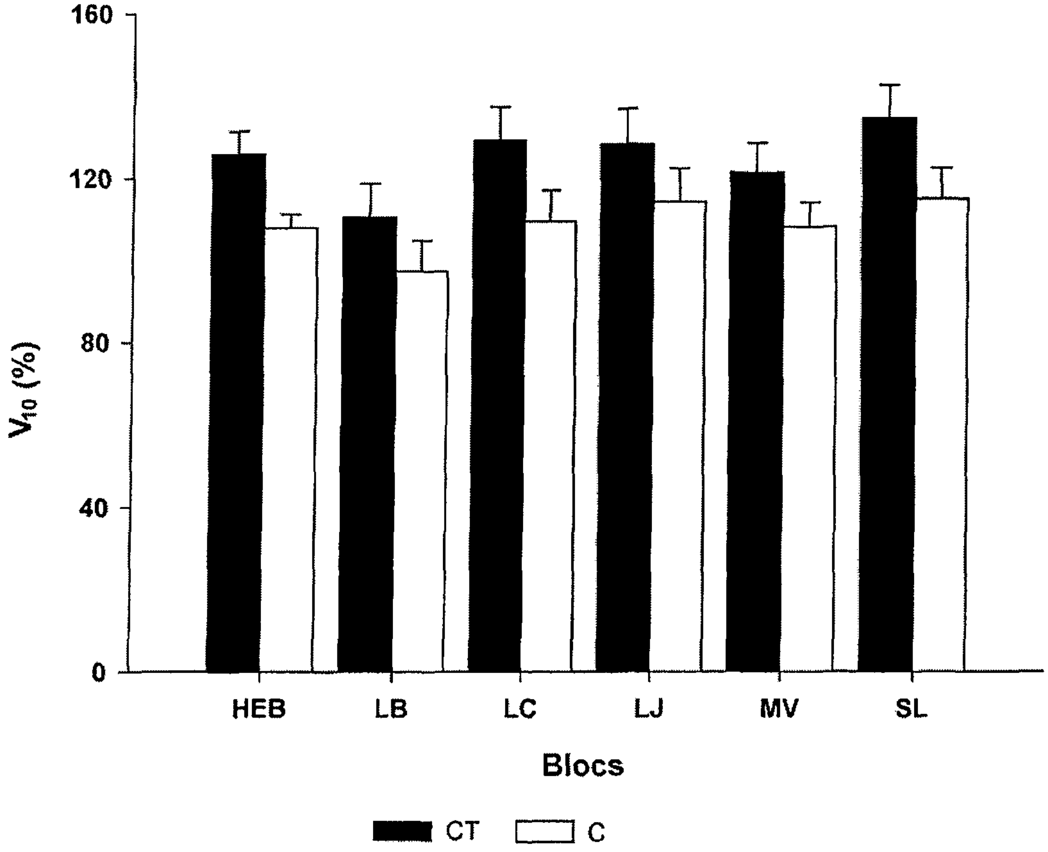

Figure 3.2: Decennial volume increment, V_{10} (%), by block. Comparison between thinned (black) and control (white) stands.

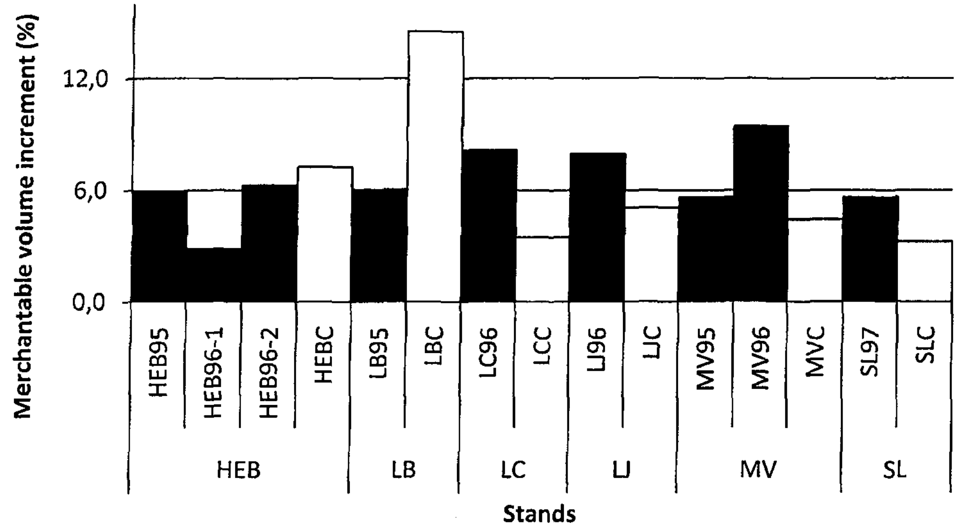

Figure 3.3: Stand volume increment (%), by block. Comparison between thinned (black) and control (white) stands.

CHAPITRE 4

HOW DOES COMMERCIAL THINNING INFLUENCE PROFILE SHAPE IN PICEA MARIANA: A CASE-STUDY IN QUÉBEC'S BOREAL FOREST.

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CHAPITRE 4

HOW DOES COMMERCIAL THINNING INFLUENCE PROFILE SHAPE IN PICEA MARIANA: A CASE-STUDY IN QUÉBEC'S BOREAL FOREST.

4.1. ABSTRACT

Based on 10 thinned stands and their controls, this paper appraised the impacts of commercial thinning on stem shape of black spruce (*Picea mariana* (Mill.) B.). A statistical mixed model was developed to describe growth variations up the stem depending on treatment and shape variations 10 years after treatment. Three parameters were examined in this paper, growth location along the stem, taper and stem shape after thinning and compared with the control. The study showed that commercial thinning led to a radial growth increment in the lower part of the stem. On the contrary, control trees had higher radial growth at the top. Growth increment in thinned trees appears to occur at the expense of natural radial growth in the upper part of the stem. However, no significant variation in taper or stem shape was noticed. More precisely, stem shape seems to be mainly affected by living crown height and tree height whereas taper seems to be affected by competition and diameter at breast height. These results support the theory of an increase in timber volume after thinning.

4.2. INTRODUCTION

The boreal forest covers much of the landmass of the northern hemisphere and stores most of the global carbon stock (Melillo *et al.*, 1993; Dixon *et al.*, 1994). In Eastern Canada, black spruce (*Picea mariana* (Mill.) B.) is one of the most widespread commercial and reforested species (Parent and Fortin, 2008; Zhang and Koubaa, 2009). The traditional harvesting method in black spruce stands is clear-cutting but society's expectations from forest management in the boreal forest have evolved to more diversified goals. Foresters face such challenges such as protecting biodiversity and environmental quality, maintaining recreational activities and procuring renewable material (Côté and Bouthillier, 1999). In Quebec, the reduced land base for fiber production (Coulombe *et al.*, 2004), coupled with increasing global competition in the forest industry, has led to the development of new strategies to optimize timber growth without removing the entire canopy (Côté and Bouthillier, 1999). Partial cutting such as thinning may be a sound choice to attain sustainable development within global market constraints while achieving maximum value (Zhang *et al.*, 2006; Thorpe and Thomas, 2007; Thorpe *et al.*, 2007). The impacts of silvicultural treatents such as commercial (CT) or pre-commercial (PCT) thinning have already been studied for different species, including jack pine (*Pinus banksiana* Lamb.) (Bella and De Franceshi, 1974; Schneider *et al.*, 2008), Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) (Mäkinen and Isomäki, 2004a, b). Studies point out that thinning influences not only tree growth, but also stem shape (Barbour *et al.*, 1992; Viens, 2001; Koga *et al.*, 2002), and wood properties (Petrás, 2002; Raulier *et al.*, 2003; Zhang *et al.*, 2006). According to Tasissa and Burkhart (1998), thinning modifies stem shape on the lower bole on Loblolly pine (*Pinus taeda* L.). On Scots pine, stand density after thinning has a significant effect on stem shape (Ulvcrona *et al.*, 2007).

For the timber industry, stem shape is an important quality attribute under several aspects. It can be used to predict wood volume (Garber and Maguire 2003, Newnham 1988, Kozak, 1988) and lumber yield (Barbour *et al.*, 1994; Zhang *et al.*, 2006). Indeed, two stems having the same volume with different tapers will produce two different lumber volumes. Forester require thus more accurate volume information and many attempts have been made to improve stem shape equations over the last century and thereby reduce the need for destructive sampling (Forslund, 1991; Bouillet and Lefevre, 1996; Lejeune, 2004; Sharma and Zhang, 2004).

Stem shape equations for black spruce have been recently developped by Sharma and Zhang (2004) but still few attempts have been made to determine which factors affected stem shape after thinning.

This study was undertaken to test the hypothesis that thinning treatments induce a change in radial growth along the stem. This variation may lead to a change of taper and stem shape. In this context stem shape refers to the geometric shape of the stem. Stem shape is assumed to be a neiloid in the lower bole area, a paraboloid in the middle and a cone in the living crown (Newnham, 1988). Taper will refers to the rate of decrease in diameter with increasing height up the stem (Newnham, 1992). The main objective of the study is therefore to evaluate the impact of commercial thinning on stem shape and stem taper in natural black spruce stands. A second objective is to examine factors influencing thinning impact on stem taper.

4.3. MATERIAL AND METHODS

4.3.1. Study area

This study was based on 10 commercially thinned and control stands in the boreal forest of Quebec, Canada. Stands had to be accessible by truck and located close to the trails in order to carry field material and samples on foot. As thinning is still a recent silvicultural treatment applied to natural black spruce stands, no standard methods have yet been developed and no information was available about thinning types and techniques. The main information we have is the data collected and analyzed during field work. Stands were selected according to two main criteria: the thinning treatment was performed 10–12 years before sampling, and thinning was performed in naturally regenerated unmanaged natural black spruce stands (Table 4.1). Whenever possible, a nearby unthinned natural black spruce stand with similar characteristics was selected as a control (Table 4.1). Control stands were selected mainly for stand age and location close to a thinned stand. In two instances where all stands had the same environmental characteristics, the same control stand was used for comparison with more than one nearby thinned stand. Latitudes ranged from 47.9°N to 49°N, longitudes from 70.5°W to 72.7°W and altitude from 210 to 671m (Table 4.1, Figure 4.1). The region is characterized by cold winter temperatures and a short growing season. Over the past 30 years, the average minimum temperature in the region was -18.4 °C during the coldest month and the average maximum temperature 17.9 °C during the warmest month. Average annual precipitation varies from 920 cm to 1187 cm in the studied stands (Environment Canada, 2008). The mean age of stands at treatment varied from 47.8 years to 99.1 years. Basal area density, evaluated by total number of trees within a 20 x 20 m quadrat, was between 800 and 3900 trees ha^{-1} (Table 4.1). The herbaceous and moss layers were mainly composed of: *Pleurozium schreberi* (Brid.) Mitt., *polytrichum* sp., *Ptilium crista-castrensis* (Hedw.) De Not., *Ledum groenlandicum* Oeder, *Vaccinium angustifolium* Ait. and *Kalmia angustifolia* L..

4.3.2. Sampling

A 20x20 quadrat comprising at least 35 black spruce trees (diameter at breast height > 9 cm) was selected in each stand. Total tree height (H), diameter at breast height (Dbh), diameter at stump height (Dsh) and stem height at the lowest living branch were measured for each tree in the quadrat. At one site, LJC, only 25 trees were selected because of environmental constraints (Table 4.1). Tree positions within the quadrat were recorded using a measuring tape and plotted onto a map. Stump circumferences and their positions within the quadrat were also determined.

Six black spruce trees in each thinned stand and three in control stands were randomly selected and felled, for a total of 72 trees harvested for stem analysis (one tree was excluded due handling errors in the laboratory). Stems were cut at every meter, starting at ground level and moving up the crown. Each sample disk was dried and sanded. Tree ring widths were measured from four perpendicular radii using Mac Henson and WinDendro software (Guay *et al.*, 1992) and cross-dated (Krause *et al.*, 2003). Dating of rings was checked with the Cofecha program (Holmes, 1983).

Stem analysis was conducted by running the computer program WinStem^{TM}, which allows the data produced by the WinDendro file to be visualized.

WinStem^{TM} produced the mean radius, diameter and area for all stem disks as well as tree height and volume as a function of age by using Carmean's method (1972). Radius for each year and top and bottom of each section were obtained by summing the ring widths up to that year. The height was then estimated at each age, using the annual ring width measurements. In this way, the radii and lengths were reconstructed for each tree at each age. Cumulative radius, diameter, basal area and height over time were also calculated annually for each tree (Krause *et al.*, 2009).

4.3.3. *Radial growth and relative height*

To compare trees of different height and size, relative height and growth values were used following Assman's methodology (Assman, 1970 in Viens, 2001). The relative height (y) of all selected trees was calculated as the ratio between h and H, where h is the height where the measurements have been taken and H the total height (equation 2),

$$y = \frac{h}{H} \,. \qquad (2)$$

Relative growth (α_{rel}) was expressed based on y, for the 10 years before (equation 3) and the 10 years after treatment (equation 4).

$$\alpha_{rel-before} = \frac{\sum_{t=-9}^{t=0} \alpha_y}{\sum_{t=-9}^{0} \alpha_{1.3/H}}, \qquad (3)$$

$$\alpha_{rel-after} = \frac{\sum_{t=1}^{t=10} \alpha_y}{\sum_{t=-9}^{t=0} \alpha_{1.3/H}}, \qquad (4)$$

where t is the time (year, $t = 0$ at thinning year) and α the radial growth (mm) at the relative height y; H is the total height. α_{rel} was measured for every disc taken along the stem.

For statistical analyses the ratio γ between $\alpha_{rel\text{-}after}$ and $\alpha_{rel\text{-}before}$ was calculated.

4.3.4. *Stem shape and taper calculation*

A common approach to study stem shape is to assume a tree is made of three segments with form being constant within a segment and different between them. Each segment is described by a continuous function with an exponent. The limit between segments is commonly called the inflexion point. Different studies have suggested that the inflexion point ranges from 20 to 25% of total height from the ground (Demaershalk and Kozak, 1977; Perez *et al.*, 1990) and that its relative height is relatively constant within a species regardless of tree size (Kozak, 1988). Thus, to calculate stem shape characteristics, stem diameters were taken at two relative positions along the bole following Morris and Forslund (1992): one located at 0.2 and the other at 0.7 of the total height. These positions were fixed for the tree height at the time of harvest.

Taper was calculated by determining the change in stem diameter divided by the length of the stem between the two diameter measurements (Morris and Forslund, 1992), (5).

$$T = \frac{D_{y=0.2} - D_{y=0.7}}{L}, \qquad (5)$$

stem shape was calculated using the equation suggested by Forslund (1991) (6)

$$A_{SEC} = \frac{\ln\left((1-0.2)/(1-0.7)\right)}{\ln\left(D_{y=0.2}/D_{y=0.7}\right)}, \qquad (6)$$

where T is the taper and A_{SEC}, stem shape. D_y is diameter at relative height y and L the length between the two relative heights. Profile shape is defined as the geometrical shape of the stem profile between the two diameter measurements and is quantified by the exponent A in the power function. Stem shape values equaling 2 represent paraboloids, whereas values of 1 represent cones (Morris and Forslund, 1992).

Taper and stem shape (A_{SEC}) have been calculated for every ten years prior to treatment and every ten years following it.

4.3.5. Other parameters influencing taper and stem form

The last part of this work identified the various factors affecting taper and profile shape. Simple regression tests were conducted between taper and stem shape (A_{SEC}) and selected variables, such as Competition Index (CI), diameter at breast height (Dbh), tree height (H), crown length (Ch), tree age, thinning density (Td) and stand density after thinning (d).

According to Mailly *et al.* (2003), the competition index (CI) for each tree within a quadrat was calculated using Hegyi's diameter-distance CI in equation (7):

$$\mathrm{CI} = \sum_{j=1}^{n}\left(\frac{D_j}{D_i} \times \frac{1}{DIST_{ij}}\right), \qquad (7)$$

where D_i is the Dbh of subject tree i; D_j is Dbh of the competitor tree j; $DIST_{ij}$ is the distance between subject tree i and competitor j.

Two different Hegyi's CI types were calculated: (1) the stump competition index ($\mathrm{CI_S}$) and (2) competition index at thinning year ($\mathrm{CI_{TY}}$) of the remaining trees. $\mathrm{CI_S}$ characterizes the influence of tree harvesting on the growth of remaining trees, whereas $\mathrm{CI_{TY}}$ illustrates the competition among remaining trees after thinning. $\mathrm{CI_{TY}}$ was calculated using data collected during field work and then corrected after dendrochronological analysis to fit the thinning year.

4.3.6. Statistical analysis

Data were compiled by multifactor analysis of variance (ANOVA) using restricted maximum likelihood (mixed model). A 7-block unbalanced design was used for radial growth increment, with relative height at the main plot level and treatment (thinning/control) as subplots. Trees were nested inside blocks and blocks were a random effect factor. The same type of model has been used to study taper and stem shape variation with time at main plot level and treatment at subplot. Post-hoc one factor ANOVAs on data were used to extract the evolution of radial growth increment along the time-release treatment. This methodology allowed variability between blocks inherent to such an important design to be taken into account. Nevertheless, it induces a statistical Type I error that may be corrected with the Bonferroni procedure. Thus significance level to control Type I error rates is adjusted and each comparison is tested at α/c where α is the nominated significance level and c is the number of comparisons in the family (Quinn and Keough, 2002).

A multiple regression model was performed to determine which variable has the most influence on taper and stem shape after thinning. ANOVA analyses were performed using JMP software (SAS Institute Inc. Cary, NC) with a 95% confidence level.

4.4. RESULTS

4.4.1. Radial growth response along stem, taper and stem shape

Decadall relative radial growth (α_{rel}) was compared between controls and thinned stands following trees relative height (Figure 4.2). According to figure 4.2A, it appears that α_{rel} increased slightly after thinning. This increase is not observed for control stands (Figure 4.2B). α_{rel} before treatment is similar for thinned and control stands (Figure 4.2C), but an increase occurred after treatment in the lower part of the stem for thinned stands (Figure 4.2D). Control stands presented a growth increment at the top of the stem after the thinning year (Figure 4.2D).

Thinning leads to a significantly different variation of relative growth increment (γ) along the stem ($p < 0.0001$ for interaction treatment*hr, Table 4.2, Figure 4.3). Beyond 0.6 relative height there is no significant difference of γ due to treatment (Figure 4.3).

Figure 4.4 shows relative diameter variations up the stem during four 5-year periods. Very little difference between thinned and control stands is observed. Growth increase occurs mainly during the second 5-year period after treatment, first at the top of the stem. Despite these qualitative observations, there is no significant variation over time of stem shape (A_{SEC}) and taper due to the treatment (Table 4.3). However, thinned trees showed a higher A_{SEC} than controls. On the contrary, taper is significantly higher for controls than thinned trees (Table 4.3).

4.4.2. Parameters influencing taper and stem shape

When all independent variables were computed separately, only height (H), crown length (Ch) and Dbh showed a significant correlation with A_{SEC}. Yet, fitting H and Ch using the stepwise forward procedure resulted in a significant model ($p = 0.004$, Table 4.4A) explaining approximately 14% of the A_{SEC} variance. Trees with a short living crown showed higher A_{SEC} (paraboloidal shape). From the regressions results, CI_{TY}, CI_S and Dbh are correlated with taper variation. When combined in a multiple linear regression using stepwise forward procedure, CI_{TY}, Dbh, H and Td explained about 25% ($p = 0.0002$, Table 4.4B) of taper variance. H, CI_{TY} and Dbh contributed to the taper variation in the model (Table 4.4B).

4.5. DISCUSSION

It is recognized for different species that commercial thinning leads to an increase in the radial growth of residual stems (Bella and De Franceschi, 1974; Aussenac and Granier, 1988; Pape, 1999; Mäkinen and Isomäki, 2004b, c; Vincent *et al.*, 2009), but this study showed that radial growth increment occurred primarily in the lower part of stem. Since stem-form theories were first proposed (Larson, 1963), it has been admitted that every silvicultural practice resulting in an alteration in growth is reflected by a change in stem shape. Different authors suggested that the pattern of wood deposition along the stem was affected by a variation in crown size, which in turn was affected by tree characteristics, and stand conditions, particularly stand density (Larson, 1963; Tasissa and Burkhart, 1998; Sharma and Zhang, 2004). However, in this study, this growth variation did not lead to a significant change of taper or stem shape 10 years after thinning. Similar results were found by Viens (2001) for jack pine and by Bouillet and Lefevre (1996) who concluded that intensive and early thinning on khasi pine (*Pinus kesiya* Royle ex Gordon) did not induce form variation along the stem. Tong and Zhang (2005), studying pre-commercial thinning effects on jack pine stands, observed that pre-commercial thinning had little effect on diameter growth at the top of tree. For shade-tolerant species such as black spruce, opening the canopy may not necessarily induce an effect on branch development, and by the way on taper or stem shape.

On the other hand, analyzing growth differences along the stem (Figure 4.2) may be done in two different ways: growth variation before and after treatment, and growth variation between control and residual trees after thinning. Observation of Figure 4.2, showed that the difference of growth for residual trees after thinning, is mainly located at the base of the stem and at the top of the stem. Thus, the part of the bole studied for taper and stem shape variations is not affected by growth variation, which may explain that no-significant difference of taper and stem shape variation is observed through time. Comparison of growth location between control and residual trees after thinning underlined that radial growth of residual trees was higher than control trees only below 0.7 total height. This does not imply a change in taper and stem shape. Indeed, radial increment due to treatment appears to be equally distributed in this part of the stem.

Within-stand variability may also explain the lack of significant change of taper and stem shape between control and residual trees after thinning. Indeed, certain individual trees responded to thinning by an increase in taper but this was not observed for the whole stand. This may be explained by the different tree classes within a stand. In general, dominant trees have the highest taper and very cylindrical suppressed trees frequently increase in basal area growth following release (Larson, 1963).

Different results were obtained by Tasissa's team (Tasissa *et al.*, 1997; Tasissa and Burkhart, 1998), working on loblolly pine reforested cutovers, after second thinning. These authors observed a significant impact of treatment on stem characteristics. Nevertheless, they suggested that variations observed 12 years after treatment could decrease with time. In this study, stand age may explain the response observed in taper and stem shape variations. Indeed, it is recognized that the bole becomes more cylindrical with tree age, thus with advancing stand age tree form becomes more stable and changes in taper that may have occurred after thinning appears lower. This is why studies on pre-commercial thinning impact on stem taper and profile found significant results a few years after treatment (Morris *et al.*, 1994), contrarily to commercial thinning studies. The experimental design studied here is the first established in natural black spruce stands. It should be noted that thinning was done particularly late during the trees' growth cycle. But the timing of the intervention strongly determines the thinning success. A late first thinning may compromise thinning response (Dean and Baldwin, 1993; Petrás, 2002; Thiffault *et al.*, 2003). To be well applied, the results obtained will thus have to take this parameter into account.

The results also demonstrated that individual characteristics influenced stem taper and shape. Taper was thus accentuated on trees with higher Dbh and lower CI_{TY} whereas the tallest trees with small living crown presented a cylindrical shape. This result confirms that dominant trees may have higher taper than suppressed ones.

Within a yield prediction context, it is essential to define how to take these effects into account. Many authors tested different parameters in different models. Burkhart and Walton (1985) examined the effect of incorporating crown ratio into a segmented-polynomial taper equation for loblolly pine, while Muhairwe *et al.* (1994) studied the effects of adding crown class, crown ratio, site class, Dbh and age to Kozak's variable-exponent taper equation for Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), western red cedar (*Thuja plicata* Donn), aspen (*Populus tremuloides* Michx.) and lodgepole pine. Both studies found that adding these stand variables to the taper equations did not significantly improve prediction accuracy. The efforts made to improve diameter prediction by incorporating stand level factors into Tasissa and Burkhart's (1998) study also obtained limited success. Furthermore, individual tree characteristics may also influence within stand thinning results (Vincent *et al.*, 2009). It thus seems more judicious to use these characteristics as selection criteria for choosing thinned trees rather than using them as model predictors. Larson (1963) remarked that even if stem taper generally increases with increasing thinning intensity, the disparities are more apparent than real and can be traced to differences in experimental methods and interpretation of results. This comment is particularly relevant in experimental cases or silvicultural trials such as those investigated in this study.

Because the thinning treatment did not accentuate taper or conical stem shape, we may suppose that economic loss during sawmilling will be avoided. On the contrary, the merchantable part of the stem increased significantly at the expense of its upper part.

Nevertheless, the lower and upper stem sections can be used for by-products (biomass, pulp, millwork, etc; Burkhart and Bredenkamp, 1989; Bouillet and Lefevre, 1996). A great advantage in increasing individual tree size, over and above improving harvesting efficiency, is the opportunity to produce different products, thereby increasing market flexibility (Morris *et al.*, 1994). Commercial thinning may allow a shift from a pulpwood market to providing a mixture of saw log and round wood material, and prove to be economically beneficial (Morris *et al.*, 1994). Another advantage from the increase of individual tree size is the decrease of wane, a processing defect often responsible for downgrading lumber (Zhang *et al.*, 2006).

4.6. CONCLUSION

The study hypothesis is partially supported since, while commercial thinning significantly increased radial growth in the lower part of stem, profile shape and taper were not significantly affected by the thinning treatment.

Nevertheless, taper and stem shape variations haven been analyzed only on the main commercial section of the stem, i.e. that used for saw logs. Further studies are necessary to throw light on the economic returns from commercial thinning in natural black spruce stands. Moreover, these results reflect the reaction of slow-growing trees under boreal climate conditions and growth rate may influence thinning effect.

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Table 4.1: Stands characteristics

Block	Name (#)[1]	Location	Number of trees analysed	Treatment[2]	Thinning year	Density cut by thinning (trees/ha)	Residual density after thinning (trees/ha)	Stand age at thinning time (year)	Annual precipitation (mm)	Temperature	DBH (cm)	Height (m)	Crown length (m)
1	HEB96-1 (1)	N48,315 W71,679	35	CT	96	133	667	58.7 ±9	992.9	-12.1/17.9 °C	20.6±4.1	14.3±2.9	9.7±2.8
	HEBC (3)	N48,145 W71,589	43	∅	∅	∅	2250	51.3 ±9	992.9	-12.1/17.9 °C	16.1±5.2	13.6±2.5	8.4±2.7
2	HEB96-2 (2)	N48,279 W71,683	41	CT	96	600	1250	53.2 ±8	992.9	-12.1/17.9 °C	17.3±4	13.9±2.6	6.8±2
	HEBC (3)	N48,145 W71,589	43	∅	∅	∅	2250	51.3 ±9	992.9	-12.1/17.9 °C	16.1±5.2	13.6±2.5	8.4±2.7
3	MM96 (4)	N48,054 W71,063	37	CT	96	550	2550	99.1 ±12	893.5	-17.3/17.2 °C	13.2±2.4	13.3±1.7	4.7±2.4
4	MV96 (5)	N48,76 W70,551	43	CT	96	1550	1225	59.5 ±8	1187.3	-16.1/17.5 °C	16.2±2.4	12.3±1.4	7.7±1.8
	MVC (7)	N48,764 W70,55	47	∅	∅	∅	2750	52.8 ±12	1187.3	-16.1/17.5 °C	15±3.8	11.9±1.6	7.6±2.3
5	MV95 (6)	N48,794 W70,544	46	CT	95	1425	1200	60.9 ±11	1187.3	-16.1/17.5 °C	16±3.1	12.2±2.5	6.3±1.3
	MVC (7)	N48,764 W70,50	47	∅	∅	∅	2750	52.8 ±12	1187.3	-16.1/17.5 °C	15±3.8	11.9±1.6	7.6±2.3
6	HEB95 (8)	N47,887 W71,464	46	CT	95	825	1125	48.4 ±10	992.9	-12.1/17.9 °C	16.3±3.7	11.6±1.8	7±2.7
	HEBC (3)	N48,145 W71,589	43	∅	∅	∅	2250	51.3 ±9	992.9	-12.1/17.9 °C	16.1±5.2	13.6±2.5	8.4±2.7
7	LB95 (9)	N48,033 W72,33	41	CT	95	675	1175	81.9 ±27	1012.7	-16.8/17.3 °C	17.5±3.2	15.3±2.4	8.3±2.6
	LBC (10)	N48,032 W72,334	38	∅	∅	∅	950	67.1 ±23	1012.7	-16.8/17.3 °C	15.2±4.4	12.9±3.5	8.2±3.8
8	LC96 (11)	N48,143 W71,879	40	CT	96	1250	1050	56.3 ±6	1036.7	-11.7/19.3 °C	17.8±1.8	15.5±3.2	8.4±3.3
	LCC (12)	N48,143 W71,878	32	∅	∅	∅	1000	54.9 ±13	1036.7	-11.7/19.3 °C	21±4.8	16.6±2.7	8.7±4.6
9	LJ96 (13)	N48,983 W72,738	39	CT	96	1250	1650	46.8 ±6	919.8	-18.4/17.6 °C	13.8±2.5	12.8±1.5	5.6±1.8
	LJC (14)	N48,983 W72,741	25	∅	∅	∅	3906	53.1 ±7	919.8	-18.4/17.6 °C	12.7±2.5	13.4±1.3	4.2±1.4
10	SL97 (15)	N48,874 W71,747	33	CT	97	925	575	57.1 ±7	1061.4	-11.7/18.2 °C	19.7±4.7	16.6±2.4	8.4±2.6
	SLC (16)	N48,874 W71,475	31	∅	∅	∅	1289	50.2 ±7	1061.4	-11.7/18.2 °C	15.8±5.6	14.4±2.9	7.4±2.4
Mean for thinned stands			44		96	918	1247	62	1028	-14.4/17.9	16.8	13.8	7.3
Mean for control stands			36				2024	55	1035	-14.5/18	16	13.8	7.4

CT = Commercial Thinning,

∅ = Control,

± = standard deviation

Table 4.2: Effects from the analysis of variance (ANOVA) for log(γ), where γ is the radial growth increment (γ = mean growth before/mean growth after). Hr is relative height. Blocks and sites are random factors, sites are nested within blocks and trees are nested within sites.

Variant: log(γ)

Source	DF	DFDen	F Ratio	Prob > F
block	6	6.832	0.5438	0.7621
hr	9	61.56	10.7981	<.0001*
treatment	1	11.97	4.4170	0.0574
treatment*hr	9	61.12	7.7530	<.0001*

* Significant results. Significance control level adjusted following Bonferroni procedure. Each comparison is tested at α/c where α is the set significance level ($\alpha = 0.05$) and c is the number of comparisons in the family ($c = 10$).

Table 4.3: Effects from the analysis of variance (ANOVA) for A) log(A_{SEC}) and B) log(Taper). Blocks and sites are random factors, sites are nested within blocks and trees (#) are nested within sites.

A) **Variant : log(A_{sec})**

Source	DF	DFDen	F Ratio	Prob > F
block	6	12.4	1.1087	0.4105
time	19	5.13	67.7614	<.0001
treatment	1	12.28	4.3360	0.0589
treatment*time	19	1	0.7112	0.7497

B) **Variant : log(Taper)**

Source	DF	DFDen	F Ratio	Prob > F
block	6	8.237	3.2528	0.0612
time	19	1444	12.6810	<.0001
treatment	1	8.043	5.6945	0.0440
treatment*time	19	1444	0.1529	1.000

Table 4.4: Stepwise regression, whole model of multivariate regression resulting from the stepwise analysis, and independent variables for A) A_{SEC} and B) Taper. Ch = Crown height, H = total height, Dbh = diameter at breast height and Td = Thinning density.

A) **Stepwise regression: A_{SEC}**

Step	R^2	Seq SS	P	ΔAIC	Variable added
1	0.0561	0.492758	0.0394	2.386	Ch
2	0.1403	0.740136	0.0092	5.103	h

Whole model

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	1.2212655	0.610633	5.9405
Error	74	7.6065362	0.102791	Prob > F
C. Total	76	8.8278017		0.0040

Independent variable

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Intercept	1.9412436	0.223196	8.70	<.0001	0	.
H	-0.035862	0.013598	-2.64	0.0102	-0.2852	1.0043644
Ch	0.0331529	0.013881	2.39	0.0195	0.258291	1.0043644

B) **Stepwise regression : Taper**

Step	R^2	Seq SS	P	ΔAIC	Variable added
1	0.1216	2.939e-5	0.0020	7.855	CI_{TY}
2	0.1930	1.726e-5	0.0131	4.445	Dbh
3	0.2284	8.542e-6	0.0735	1.404	h
4	0.2536	6.095e-6	0.1258	0.526	Td

Whole model

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	0.00006542	0.000016	6.5163
Error	72	0.00018071	2.51e-6	Prob > F
C. Total	76	0.00024613		0.0002

Independent variable

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Intercept	0.0081866	0.001172	6.98	<.0001	0	.
CI_{TY}	-0.000133	0.000105	-1.27	0.2095	-0.1493	1.3634998
Dbh	0.0002561	7.473e-5	3.43	0.0010	0.605296	3.0586947
H	-0.000244	0.000108	-2.26	0.0271	-0.36753	2.6018528
Td	-5.787e-7	3.537e-7	-1.64	0.1061	-0.17199	1.0833061

Note: Results from stepwise regression using the forward procedure with AIC as indicator, (ΔAIC = AIC before enter- AIC after enter) has to be positive to enter.

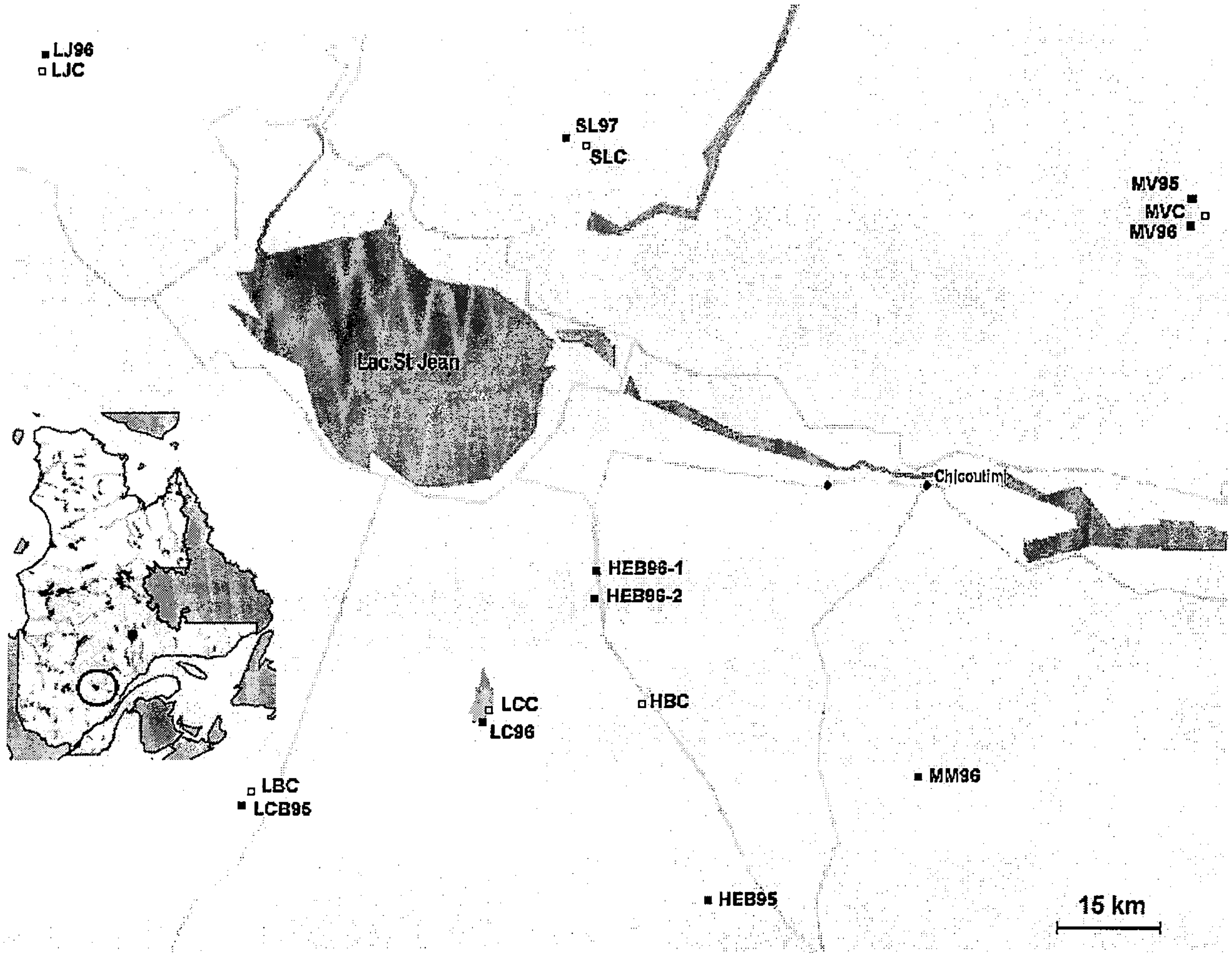

Figure 4.1: Map showing the locations of study stands around the St-Jean Lake, Quebec, Canada. Black squares = thinned stands, white squares = control stands.

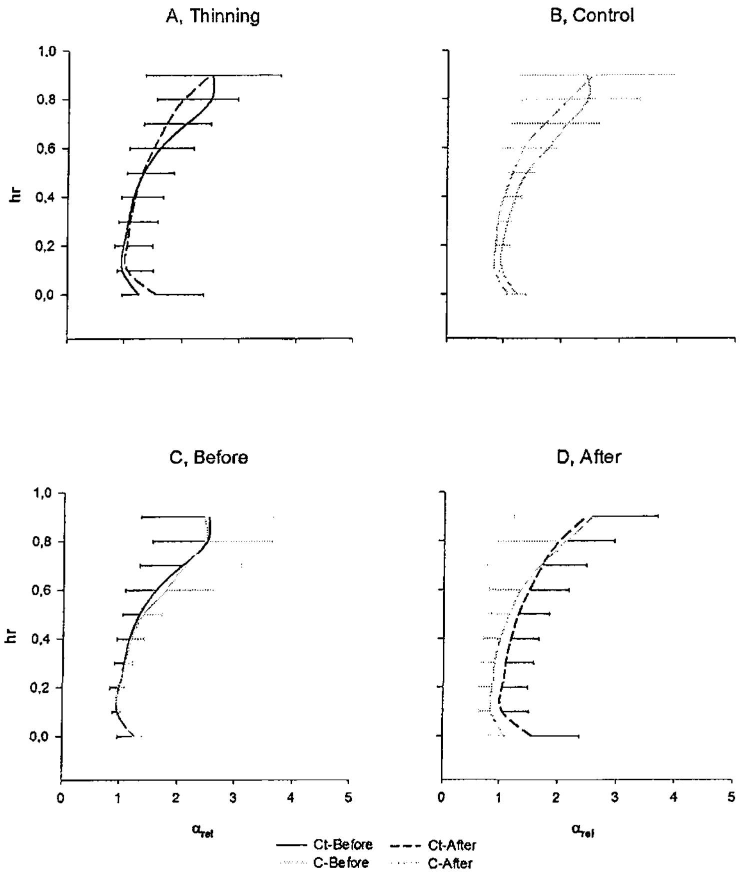

Figure 4.2: Mean of relative radial growth (α) ten years before (solid line) and ten years after (dash line) the treatment along the bole for thinned (black) and control (grey) stands. Data have been transformed into relative values so are thus without units. A) α for thinned stands before and after treatment; B) α for control stands before and after treatment; C) α before treatment, comparison between thinned and control stands; D) α after treatment comparison between thinned and control stands.

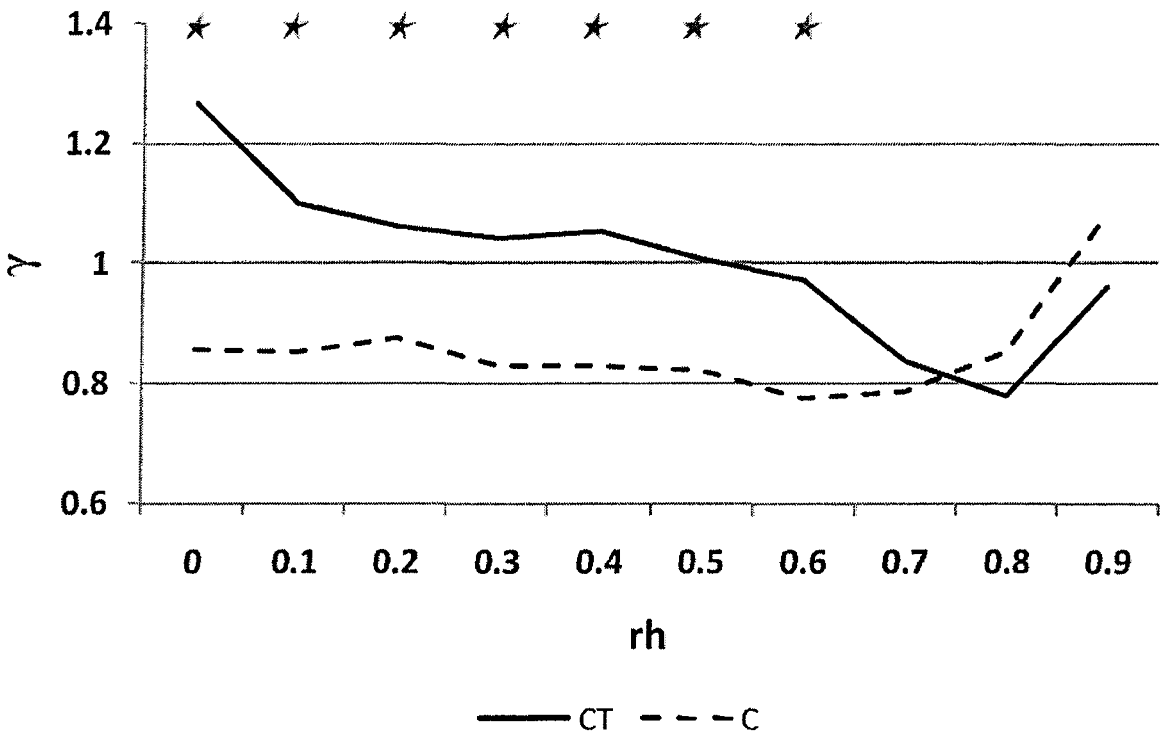

Figure 4.3: Radial growth increment (γ) 10 years after thinning along relative height (rh) for thinned (dash line) and control (solid line) trees. Stars mean significant treatment*hr interactions. C = Control and CT = Commercial thinning.

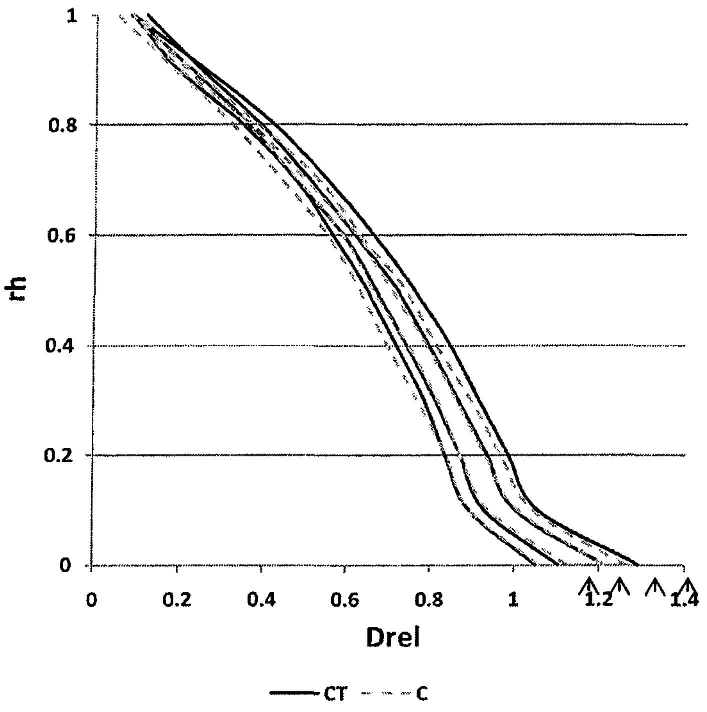

Figure 4.4: Relative diameter (D_{rel}) along relative height (rh) for 4 five-year periods around thinning year. Arrows indicate the start of each five-year period: 10 years before thinning year, 5 years before thinning year, 5 years after thinning year and 10 years after thinning year. C = Control (dashed grey line) and CT = Commercial Thinning (black line)

CHAPITRE 5

VARIATION IN BLACK SPRUCE (*PICEA MARIANA* (MILL.) BSP) WOOD QUALITY AFTER THINNING

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CHAPITRE 5

VARIATION IN BLACK SPRUCE (*PICEA MARIANA* (MILL.) BSP) WOOD QUALITY AFTER THINNING

5.1. ABSTRACT

Growth rate, ring density and flexural modulus of elasticity (MOE) of trees may change after commercial thinning (CT). Seventy-one trees from nine thinned stands and controls were selected and harvested in Quebec, Canada. Static bending tests and X-ray densitometry were conducted along the first four meters of the stem. Despite a significant increase in ring width due to treatment ($p = 0.0001$), annual variations in ring density were subtle. No significant variation in average ring density due to CT was observed ($p = 0.1977$) after treatment, which may be explained by between-stand variability. Treatment showed no significant effect on flexural MOE over a ten-year period. Moreover, variability in average ring density along the stem with tree height was greater than that induced by the treatment. A significant decrease in ring density was observed up the stem (from 490kg.m^{-3} to 463kg.m^{-3} up to the fourth meter, $p = 0.0002$). Because it induced increased growth without negative effects on mechanical wood properties, thinning is advisable for slowly growing naturally regenerated black spruce stands in the northern boreal region.

5.2. INTRODUCTION

The boreal forest biome covers much of the landmass of the northern hemisphere and contains most of the global carbon stock (Melillo *et al.*, 1993; Dixon *et al.*, 1994). Black spruce (*Picea mariana* (Mill.) BSP.) is one of the most widespread boreal tree species in Canada (Parent and Fortin, 2008; Zhang and Koubaa, 2009). Its excellent wood and fibre quality makes it highly valued for pulpwood and lumber production (Zhang and Koubaa, 2009). However, black spruce stems are relatively small in diameter, especially in northern areas, resulting in very low lumber volume recovery per stem volume (Pnevmaticos *et al.*, 1979). Increased light penetration to the forest floor after commercial thinning can raise the temperature of surface soil layers, thereby accelerating nitrogen mineralization (Thibodeau *et al.*, 2000) and increasing the light available to individual trees. This can contribute to increased short-term tree growth, and would be particularly beneficial in a cold climate, as in boreal regions (Pothier, 2002). Partial cutting through thinning could therefore be a sound choice for sustainable development within global market constraints while achieving maximum value (Zhang *et al.*, 2006).

Many studies have reported that commercial thinning (CT) regularized forest size and growth, increased saw timber availability, decreased rotation age and management costs, and enhanced stand value and quality (Prégent, 1998; Cameron, 2002; Petrás, 2002). However, forest product properties also depend strongly on wood characteristics such as ring density, basic density, modulus of elasticity (MOE) and microfibril angle (Downes *et al.*, 2002; Zhang *et al.*, 2005). More specifically, wood density has a major impact on the yield, quality and value of wood-based composites and solid wood products (Shi *et al.*, 2007). Both microfibril angle and intra-ring wood density variation determine a wood's suitability for specific end uses (Echols, 1972; Koubaa *et al.*, 2002). Numerous studies have investigated the relationship between growth rate and wood quality in many commercial species, with somewhat inconsistent results (Kellogg and Warren, 1984; Castéra *et al.*, 1996; Zhang *et al.*, 2002). Moreover, whereas many studies have evaluated the impact of initial spacing on the wood value recovery chain (Koga and Zhang, 2002; Zhang *et al.*, 2002; Alteyrac *et al.*, 2005), to our knowledge, none have addressed variations in wood mechanical properties after commercial thinning in natural black spruce stands. Nevertheless, black spruce is one of the main species used in machine stress-rated (MSR) lumber production, and MOE is one of the most important lumber bending properties used to determine end uses and MSR grade yield.

Because mechanical wood properties vary with position in the tree (Larson *et al.*, 2004; Alteyrac *et al.*, 2005), there is an increasing need to develop optimal log allocation strategies in order to allocate logs to best uses, maximize the value of the resource and ensure end-product quality (Shi *et al.*, 2007). According to some authors, however, research on the effect of silvicultural practices on the value recovery chain has lagged behind research on growth and yield. The result is a disconnection across the value-added chain, as the forest industry still lacks some basic information linking tree growth to product value (Briggs and Fight, 1992; Kang *et al.*, 2004).

This study tested the hypothesis that thinning treatments are followed by changes in flexural MOE and density of black spruce wood. The objectives were to evaluate the impact of commercial thinning on the lumber quality of nine thinned stands compared to controls and to determine whether this impact varies longitudinally along the first four meters of the stem.

5.3. MATERIALS AND METHODS

5.3.1 *Study Area*

Wood from nine thinned stands and control stands in the boreal forest of Quebec, Canada were investigated. Stands had to be accessible by truck and located close to trails so that field material and samples could be transported by foot. Stands were selected according to two main criteria: thinning treatment was performed 10–12 years before sampling, and thinning was performed in naturally regenerated unmanaged natural black spruce stands (Table 5.1). Whenever possible, a nearby unthinned natural black spruce stand with similar characteristics was selected as a control (Table 5.1). Control stands were selected mainly for stand age and location close to a thinned stand. In two instances where all stands had the same environmental characteristics, the same control stand was used for comparison with more than one nearby thinned stand. To identify the stands, initial letters refer to the stand location followed by a number representing the thinning year or the letter C for control (Table5.1).

Latitude ranged from 47.9°N to 49°N, longitude from 70.5°W to 72.7°W and altitude from 210 to 671m (Table 5.1). The boreal forest is characterized by cold winter temperatures and short vegetation periods. Over the last 30 years, the average minimum temperature for this region was -18.4 °C and average maximum temperature was 19.3 °C. Average annual precipitation varied from 920 mm to 1187 mm in the studied stands (Environment Canada, 2008). Average age of the studied stands at time of treatment varied from 47 to 82 years. Other than CT, no silvicultural treatment had been applied. Basal area at thinning year ranged between 17 and 50 m²/ha (Table 5.1). The herbaceous and moss layers were composed mainly of *Pleurozium schreberi* (Brid.) Mitt., *Polytrichum sp.*, *Ptilium crista-castrensis* (Hedw.) De Not., *Ledum groenlandicum* Oeder, *Vaccinium angustifolium* Ait. and *Kalmia angustifolia* L.

5.3.2 Sampling

A 20x20 quadrat comprising at least 35 black spruce trees (diameter at breast height > 9 cm) was selected in each stand. Total tree height (H), diameter at breast height (Dbh), diameter at stump height (Dsh, ≈ 10 cm) and stem height at the lowest living branch were measured for each tree in the quadrat. Site quality was estimated using dominant tree height and production tables (Pothier and Savard, 1998) (Table 5.1). Six black spruce trees in each thinned stand, and three in control stands, were randomly selected and felled. A total of 72 trees were thus harvested for stem analysis (one tree was excluded due to handling errors in the laboratory). Stems were cut at every meter, starting at ground level and moving up to the fourth meter, to collect 50-cm-long bolts for mechanical analysis and disks for density analysis.

Disks for density analysis were cut to yield 1.57 mm thick (longitudinal) x 5 mm (tangential) samples in a north–south direction along the pith using a specially designed pneumatic twin-blade saw (FPInnovations, Forintek Division). Sawn strips were extracted with a cyclo-hexane/ethanol (2:1) solution for 24 h and then with hot water for another 24 h to remove extractives. After extraction, strips were air-dried under restraint to prevent warping.

From the sampled bolts, 10 mm (radial) x 10 mm (tangential) x 150 mm (longitudinal) specimens from bark to pith were processed along both northern and southern radial directions. Specimen dimensions were defined so that the outermost samples contained mainly tree rings formed after CT and inner samples had tree rings formed before CT. Defect-free specimens were then dried under restraint from green to 12% moisture content in a conditioning room (20 °C, 65% HR) and selected for bending tests (see Alteyrac et al., (2006) for a detailed description). These samples were used to test MOE before and after CT.

5.3.3 Sample analyses

Strips were scanned by X-ray densitometry in air-dry conditions. To accommodate a logistic change, densitometry tests were conducted at FPInnovations, Forintek Division., Quebec City, and at UQAT, Rouyn-Noranda, Canada. The same conditions (sample size, preparation and relative humidity) were imposed. However, because X-ray densitometry is a relative measure, density values may vary with the measuring instrument. Reference samples were tested with both densitometers to evaluate the method and verify the coherence of results. Moreover, controls and associated thinned sites were measured with the same instrument. X-ray densitometry provided the radial patterns of several properties, including ring width (RW), early-wood width (EWW), late-wood width (LWW), ring density (RD), maximum ring density (MaxRD), minimum ring density (MinRD), early-wood density (EWD) and late-wood density (LWD). Mean annual RD was calculated for ten years before and after treatment.

Bending tests were performed at UQAC, Chicoutimi, Canada according to ASTM D-143 standard test methods for small clear specimens (ASTM, 2007). Specimens were placed with growth rings horizontal and with a span of 110 mm. The modulus of elasticity (MOE, stiffness) was evaluated using an MTS-Alliance RT/100 material testing system.

5.3.4 Statistical analyses

Data were compiled by multifactor analysis of variance (ANOVA) using restricted maximum likelihood (mixed model). A 6-block unbalanced split-plot design was used for ring characteristics and MOE variations with time at main plot level and with treatment (thinning/control) at subplot level. Stands were nested inside blocks and block was a randomized factor. To evaluate height influence on RD and MOE variation, time was chosen at the plot level height (0, 1, 2 and 3 meters) was chosen at the subplot level and treatment (thinning/control) as sub-subplot level. Simple regression tests were conducted to determine the relationship between independent wood quality variables. All statistical tests were performed using JMP software (SAS Institute Inc., Cary, NC) with a 95% confidence level.

5.4. RESULTS

At the year of thinning, thinned stands had a mean age of 58 years and controls 55 years (Table 5.1). Based on the initial basal area, merchantable thinning intensity varied from 9.7 to 52.5% across stands, classified as light to heavy thinning. Moreover, based on the Dbh ratio of residual and thinned stems at thinning year (Dbh_{RES} at TY/Dbh_{THI} at TY), different CT types can be identified. When this ratio is less than 1, that is, dominant trees are removed to accelerate residual tree growth, CT from above was performed. When the ratio is greater than 1, that is, smallest trees are released to stimulate the biggest trees, CT from below was performed (Table 5.1).

5.4.1. Growth variation

During a 20-year period including the thinning year, RW varied from 0.03 mm to 2.6 mm with a mean of 0.58 mm for wood from control stands and from 0.03 mm to 2.6 mm with a mean of 0.6 mm for wood from thinned stands (Figure 5.1A).

RW varied from 0.57 mm before treatment to 0.62 mm after treatment for thinned stands and from 0.6 mm before thinning to 0.57 mm after thinning for control stands (Figure 5.1A). A 12% increase in RW was observed for thinned stands, whereas a 2% decrease in RW was observed for control stands (Table 5.2). Statistical analysis revealed a significant influence of treatment on RW variation over time ($p < 0.0001$ for interaction time*treatment, Table 5.3a).

Early-wood width (EWW) for thinned stands varied from 0.39 mm before treatment to 0.43 mm after treatment (Figure 5.1B), or a 5 % increase in EW proportion (Table 5.2). For control stands, EWW varied from 0.41 mm before thinning year to 0.38 mm after, or a 4 % decrease in EW proportion (Figure 5.1B, Table 5.2). EWW followed the same pattern as RW over time (Figure 5.1B), and a significant influence of interaction time*treatment on EWW was noted ($p < 0.0001$ for interaction time*treatment, Table 5.3b). In contrast, late-wood width (LWW) varied from an average of 0.21 mm before treatment to 0.22 mm after treatment for thinned stands, or a slight 1% increase in LW proportion (Table 5.2). LWW in control stands varied from 0.21 mm before thinning year to 0.23 mm after thinning year, or a 15% increase in LW proportion. Despite the very small difference between thinned and control stands (Figure 5.1C), treatment significantly influenced LWW (Table 5.3c).

5.4.2. Ring density variation

Before treatment, RD of thinned stands was about 504 kg/m³, decreasing thereafter by about 2% to approximately 493 kg/m³. RD for control stands varied from 472 to 471 kg/m³ (Figure 5.2A, Table 5.2). Before treatment, RD for thinned stands was higher than the annual RD for control stands, and decreased after thinning year (time = 0,

Figure 5.2A). The third year after treatment, RD for thinned stands was lower than RD for controls, and continued decreasing thereafter. However, no significant difference was found over time due to treatment ($p = 0.1977$ for interaction time*treatment, Table 5.3d). Despite a decrease in average RD after treatment for thinned stands (Figure 5.2B), no significant variation due to treatment was noted ($p = 0.3116$ for interaction time* treatment, Table 5.3e).

5.4.3. MOE variation with thinning

MOE for wood from thinned stands varied from 9.16 GPa to 12.14 GPa with a mean of 10.53 GPa, and MOE for wood from control stands varied from 10.53 to 11.16 GPa with a mean of 9.63 GPa (Figure 5.3). Figure 5.3 shows increased MOE for both thinned and control stands after treatment. No significant variation due to treatment over time ($p = 0.0627$ for interaction time*treatment, Table 5.3f) was seen.

5.4.4. Stem height influence on MOE and average RD

Figure 5.4 shows a decrease in average RD with increasing height along the stem for both thinned and control stands ($p = 0.0002$ for Height, Table 5.4). Average RD varied from 490 kg/m^3 at the bottom of the log to 463 kg/m^3 in the upper part of the log (Figure 5.4A, B). However, treatment did not influence average RD up the stem ($p =$ 0.9262 for the interaction Treatment*Height*Time; Table 5.4A). On the contrary, a slight increase in MOE with increasing tree height for both thinned and control stands is seen in Figure 5.4C, D. MOE varied from 9.81 GPa at the bottom of the log to 10.33 GPa in the upper part of the log, and Table 5.4 shows significant differences in MOE between thinned and control stands.

5.5. DISCUSSION

5.5.1. Variation in wood characteristics due to thinning

CT significantly increased RW, EWW and LWW (Table 5.3). Moreover, EW proportion increased at the expense of LW proportion (Table 5.2) after CT in thinned stands. Because silvicultural treatments such as thinning are mainly used to increase growth rate, many studies have addressed the impact of silvicultural treatments on tree growth (Yang *et al.*, 1988; Yang and Hazenberg, 1994; Tong and Zhang, 2005) and the influence of growth rate on wood anatomical features. A recent study demonstrated that CT led to increased radial growth at the stem base in naturally regenerated black spruce stands (Vincent *et al.*, 2009a). Koga *et al.* (2002) showed that in balsam fir stands, the annual radial growth response to precommercial thinning (PCT) was limited to EWW, whereas LWW showed little response. According to these authors, lightly thinned and control plots had comparable EWW and latewood percentage. In our case, CT influenced both EWW and LWW, with a more pronounced increase in EWW.

Given the decrease in LW proportion after CT, a decrease in RD would be expected. However, despite a slight decrease in RD after the thinning year (Figure 5.2), this variation was not statistically significant (Table 5.3d). No clear relationship between wood density and growth rate was found. Zhang *et al.* (1996) and Zobel and Van Buijtenen (1989) observed that although a negative relationship generally exists between wood density and growth rate in conifer species, there were many exceptions, and a non-significant or even a weak positive relationship between wood density and growth rate can be found in some families. Koubaa *et al.* (2000) reported a significant negative relationship between wood density and growth rate in juvenile black spruce only. In mature wood, this relationship was no longer significant. In jack pine (*Pinus banksiana*

Lamb.) and balsam fir (*Abies balsamea* L.), Barbour *et al.* (1994) and Kang *et al.* (2004) observed a reduction in wood density after thinning and with increasing initial spacing. Bendtsen (1978) found negligible effects of accelerated growth on wood properties compared with differences in the properties of mature and juvenile wood. The same result was obtained recently in black spruce stands by Tong *et al.* (2009), who found no significant variation in average ring density between control and two precommercial thinning (PCT) intensities. Therefore, treatment intensity may have varying influence on growth ring features. Indeed, in terms of wood anatomy, ring growth increment may be insufficient to lead to decreased RD. This implies that increased growth rate is not necessarily linked to decreased wood mechanical properties. Moreover, external factors may also explain the variable results on mechanical properties. For example, St-Germain and Krause (2008) demonstrated that wood growth features such as RW, EWW and LWW decreased with latitude. The age of the studied trees and the length of the studied period also contributed to explain recorded RD. Koubaa *et al.* (2000) demonstrated a decreasing correlation between RW and RD with increasing age.

Table 5.1 presents between- and within-block differences in terms of treatment influence. Specifically, block LB is questionable because LBC presented a G_{TY} nearly half that of LB95 (Table 5.1). It is therefore arguable that these two stands were not comparable. However, a previous study on the same material demonstrated that both LBC and LB95 were affected by outbreaks of spruce budworm (*Choristoneura fumiferana* (Clemens)) in the late 1970s (Morin *et al.*, 2000; Vincent *et al.*, 2009b). Comparing radial growth over time, these outbreaks appear to have affected LBC longer (by about two years) than LB95 (data not shown). Moreover, radial growth for LBC after the outbreaks resumed faster and was greater than for LB95 (Vincent *et al.*, 2009b). These variations in tree growth may influence changes in RD and affect the results. In fact, most studies in this area show a predominance of between-stand, inter-tree and intra-tree variability in silvicultural impacts on mechanical wood properties. Dutilleul *et al.* (1998) noted that the correlation between RW, RD and mean tracheid length may be affected by heavy thinning, which would partly explain the contradictory results reported in the literature.

No significant variation in MOE due to treatment was observed in this study (Table 5.3f). MOE differed between thinned and control stands, and increased after thinning year in both thinned and control stands. However, average RD tended to decrease after thinning, with a slight increase in MOE after thinning. Although variations in MOE due to different initial spacings were observed, the influence of CT on MOE was more ambiguous. Zhang *et al.* (2002) studied lumber strength variation following three different initial spacings of black spruce plantations. Compared to natural stand lumber currently processed in eastern Canada, the stiffness of plantation-grown black spruce lumber was 28.9% lower on average. As a result, a high percentage of the plantation-grown lumber did not meet the bending design values (Zhang *et al.*, 2002). In contrast, CT in plantations increased radial growth and did not lead to decreased MOE. From a wood supply standpoint, bigger logs from thinned stands would not be expected to have the lower mechanical properties associated with plantation logs of similar dimensions.

5.5.2. Variation in wood characteristics with tree height

RD and MOE varied significantly with tree height, but no significant effect of thinning with tree height was observed. It was noted previously that logs cut from different positions in the tree had different wood and fibre characteristics (Larson *et al.*, 2004; Tong *et al.*, 2009). Moreover, studies have revealed variations in growth rate with log position in the stem after silvicultural treatment (Koga *et al.*, 2002; Vincent *et al.*, 2009b). In balsam fir, Koga *et al.* (2002) observed that annual radial growth rate responded positively to PCT, especially in the lower part of the stem. However, sampling height appeared to have a higher impact on density variation than growth rate on RD (Alteyrac *et al.*, 2005). Koga *et al.* (2002) reported that few correlations between RW and wood density components varied significantly with stem position from the stump to the stem top at the inter-tree level. Koga and Zhang (2004) observed a negative correlation between RD and RW in balsam fir, which was significant in the butt log but decreased to insignificance at and above a height of 3 m. The present study is in agreement with these authors (Table 5.4), but more work on the entire stem height is needed to confirm these findings. The rapid decrease in cambial age with tree height may explain changes in ring density up the stem.

Regarding MOE variation with log position, Tong *et al.* (2009) found no significant correlation between lumber MOE and log position in precommercially thinned black spruce plantations when all log positions were considered. However, when butt logs (0–2.5 m) were excluded, MOE decreased steadily with increasing log height. In the present paper, butt logs were included in the analysis, which may explain the unexpected observations: the differing MOE within butt logs may be attributed to the presence of various stages of both unsound and compression wood (Larson *et al.*, 2004; Tong *et al.*, 2009). In fact, Tong *et al.* (2009) recorded a higher percentage of unsound wood in lumber pieces from butts than from other logs. To our knowledge, no study has addressed the role of the root system close to the stump and its influence on wood properties at stem base. Nevertheless, it is evident that root fibre and stem orientation differ, and that the transition between root and stem is not clearly defined. Microfibril angle variation with stem height may also influence MOE (Barnett and Bonham, 2004).

5.6. CONCLUSION

The main conclusion of this study is that RW significantly increased after CT but no significant variation in RD due to this treatment was observed. Moreover, despite a slight increase observed for thinned stands, MOE did not vary significantly after treatment. These results support the argument for commercial thinning in natural black spruce stands in the boreal forest without concerns about wood quality after treatment. Moreover, the high density associated with lumber stiffness properties of black spruce makes it a good candidate for lumber end uses. However, the large variation in MOE should be taken into account.

Finally, this study showed that mechanical wood properties vary up the stem, and that this variation is greater than the variation due to thinning. These results are of interest, given the increasing need to develop optimal log allocation strategies. As the forest industry shifts towards value-added end uses, it has become important to allocate logs to the best uses to maximize the value of the resource and ensure end-product quality.

Further studies are needed to enhance our knowledge in this area, notably the influence of different wood mechanical properties on MSR lumber yield, which is usually used for saw log classification.

5.7. ACKNOWLEDGEMENTS

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Table 5.1: Stand characteristics.

Block	Site	Location	Annual precipitation (mm)	Temperature (average min/average max, °C)	TY	Stand age at TY	Dbh at TY (cm)	G at TY (RES+THI m²/ha)	Merchantable thinning intensity (%)	Dbh_{RES} at TY / Dbh_{THI} at TY	Site index at 50 years
1	HEB95	N47.887 W71.464	992.9	-12.1/17.9	1995	48.4 ±10	13.0	29.2	19.6	1.4	12–15
	HEB96-1	N48.315 W71.679	992.9	-12.1/17.9	1996	58.7 ±9	15.4	23.8	9.7	1.0	15–18
	HEB96-2	N48.279 W71.683	992.9	-12.1/17.9	1996	53.2 ±8	16.6	41	31.8	1.0	15–18
	HEBC	N48.145 W71.589	992.9	-12.1/17.9		51.3 ±9	15.8	48.3			15–18
2	LB95	N48.033 W72.33	1012.7	-16.8/17.3	1995	81.9 ±27	14.7	33.1	13.1	1.4	15–18
	LBC	N48.032 W72.334	1012.7	-16.8/17.3		67.1 ±23	14.6	17.2			15–18
3	LC96	N48.143 W71.879	1036.7	-11.7/19.3	1996	56.3 ±6	15.1	44.8	39.6	1.3	18–21
	LCC	N48.143 W71.878	1036.7	-11.7/19.3		54.9 ±13	20.7	35.2			18–21
4	LJ96	N48.983 W72.738	919.8	-18.4/17.6	1996	46.8 ±6	13.6	42.3	52.5	0.8	15–18
	LJC	N48.983 W72.741	919.8	-18.4/17.6		53.1 ±7	12.3	48.9			12–15
5	MV95	N48.794 W70.544	1187.3	-16.1/17.5	1995	60.9 ±11	14.1	40	39.7	1.3	12–15
	MV96	N48.76 W70.551	1187.3	-16.1/17.5	1996	59.5 ±8	12.9	33	30.8	1.3	12–15
	MVC	N48.764 W70.55	1187.3	-16.1/17.5		52.8 ±12	14.6	49.8			15–18
6	SL97	N48.874 W71.747	1061.4	-11.7/18.2	1997	57.1 ±7	17.1	40	37.4	1.3	18–21
	SLC	N48.874 W71.475	1061.4	-11.7/18.2		50.2 ±7	15.5	34			18–21
Mean for CT stand						58	14.7	38.5	30.5	1.2	
Mean for C stands						55	15.6	38.9			

TY = thinning year, Dbh = diameter at breast high, G = basal area, RES = residual stem, THI = thinned stem.

Grey line = control, ± = standard deviation.

Table 5.2: Rings characteristics and MOE variation by stand.

Site	RW variation (%)	Variation in EWW proportion (%)	Variation in LWW proportion (%)	RD variation (%)	MOE variation (%)
HEB95	97.6	101.9	95.6	98.6	115.8
HEB96-1	113.0	90.0	112.0	94.6	107.1
HEB96-2	105.7	99.8	96.0	102.3	106.3
HEBC	96.8	96.7	105.2	101.6	103.8
LB95	109.0	101.4	90.6	95.2	110.8
LBC	91.4	94.1	115.3	96.5	94.9
LC96	96.9	94.9	107.8	97.3	101.7
LCC	123.1	94.4	95.4	97.7	108.2
LJ96	110.3	99.4	103.0	100.1	116.2
LJC	86.7	93.3	115.7	98.0	108.0
MV95	99.5	199.2	125.8	97.0	112.6
MV96	175.6	54.2	62.3	98.2	113.6
MVC	79.3	110.6	114.8	102.4	94.0
SL97	97.8	105.4	101.2	95.0	118.7
SLC	107.4	86.6	148.5	100.6	107.7
Mean for CT stand	111.7	105.1	99.3	97.6	111.4
Mean for C stands	97.5	95.9	115.8	99.5	102.8

RW = ring width

EWW = early-wood width, LWW = late-wood width, RD = ring density, MOE = modulus of elasticity.

CT = commercial thinning, C = controls.

Table 5.3: ANOVA for treatment and temporal effects on a) ring width (RW), b) early-wood width (EWW), c) latewood width (LWW), d) ring density (RD), e) average ring density (average RD) and f) modulus of elasticity (MOE).

Test		Source	DF	DFDen	*F* ratio	Prob. > *F*
a)	RW	Block	5	8.053	1.1338	0.4150
		Time	19	111.2	1.4952	0.1008
		Treatment	1	8.007	0.1730	0.6884
		Treatment*Time	19	5218	4.3948	<.0001*
b)	EWW	Block	5	8.016	0.7728	0.5951
		Time	19	163.4	1.1319	0.3240
		Treatment	1	8.021	0.1359	0.7220
		Treatment*Time	19	4571	3.4621	<.0001*
c)	LWW	Block	5	7.966	3.1198	0.0746
		Time	19	125.4	4.3980	<.0001*
		Treatment	1	7.949	0.5350	0.4855
		Treatment*Time	19	4302	2.7691	<.0001*
d)	RD	Block	5	8.037	5.3825	0.0182*
		Time	19	150.5	2.5324	0.0009*
		Treatment	1	8.08	0.5050	0.4973
		Treatment*Time	19	5108	1.2618	0.1977
e)	Average RD	Block	5	8.095	3.3857	0.0606
		Time	1	6.304	2.7135	0.1482
		Treatment	1	8.197	0.9046	0.3688
		Treatment*Time	1	5.692	1.2326	0.3116
f)	MOE	Block	5	9.352	1.5920	0.2533
		Time	1	5.308	18.9200	0.0064*
		Treatment	1	8.301	11.2674	0.0095*
		Treatment*Time	1	6.246	5.1138	0.0627

Table 5.4: Effect from analysis of variance (ANOVA) for a) average ring density (Average RD) and b) modulus of elasticity (MOE) before and after thinning: analysis with tree height.

Test		Source	DF	DFDen	*F* ratio	Prob. > *F*
a)	Average RD	Block	5	8.582	2.9700	0.0777
		Time	1	6.392	0.2651	0.6239
		Height	3	52.07	8.1499	0.0002*
		Height*Time	3	51.67	0.1598	0.9229
		Treatment	1	8.348	1.1791	0.3079
		Treatment*Height	3	57.46	0.9396	0.4275
		Treatment*Time	1	61.41	1.7286	0.1935
		Treatment*Time*Height	3	57.03	0.1548	0.9262
b)	MOE	Block	5	9.752	1.7427	0.2145
		Time	1	5.459	15.0628	0.0098*
		Height	3	40.63	5.0721	0.0045*
		Height*Time	3	40.51	0.1414	0.9346
		Treatment	1	9.833	11.4396	0.0071*
		Treatment*Height	3	42.95	0.4213	0.7387
		Treatment*Time	1	44.73	2.6997	0.1074
		Treatment*Time*Height	3	42.81	0.2410	0.8673

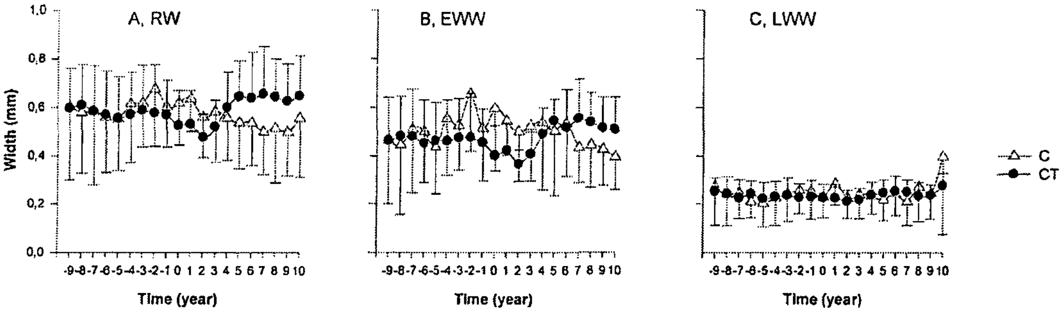

Figure 5.1: Change before and after thinning year (time = 0) in A) ring width (RW, mm) B) early-wood width (EWW, mm) and C) latewood width (LWW, mm) for both thinned (CT, black circle) and control (C, white triangle) stands.

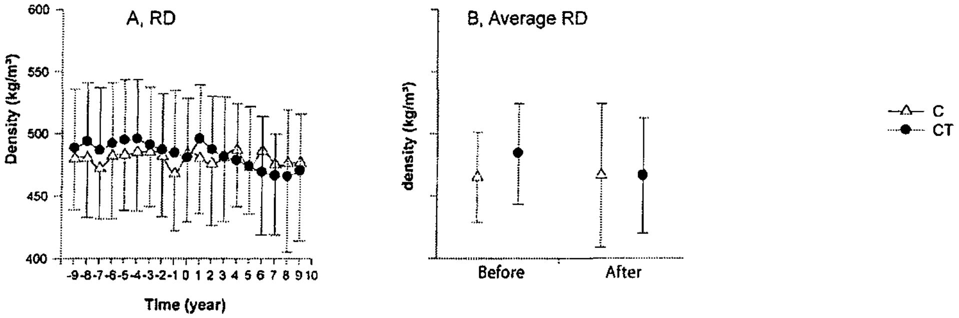

Figure 5.2: Change before and after thinning year (time = 0) in A) ring density (RD, kg/m³) and B) average ring density (Average RD, kg/m³) for both thinned (CT, black circle) and control (C, white triangle) stands.

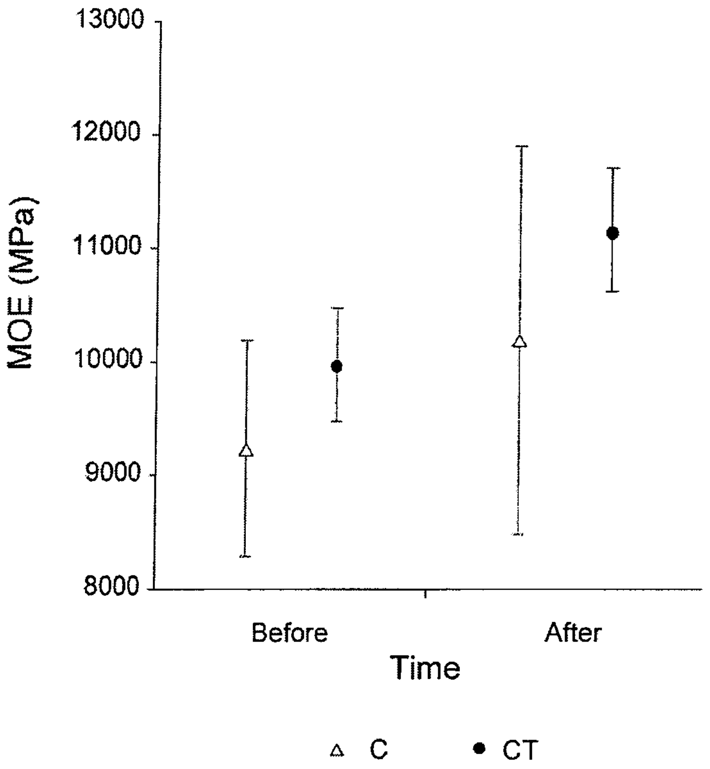

Figure 5.3: Variation in modulus of elasticity (MOE, GPa) for both thinned (CT, black circle) and control (C, white triangle) stands.

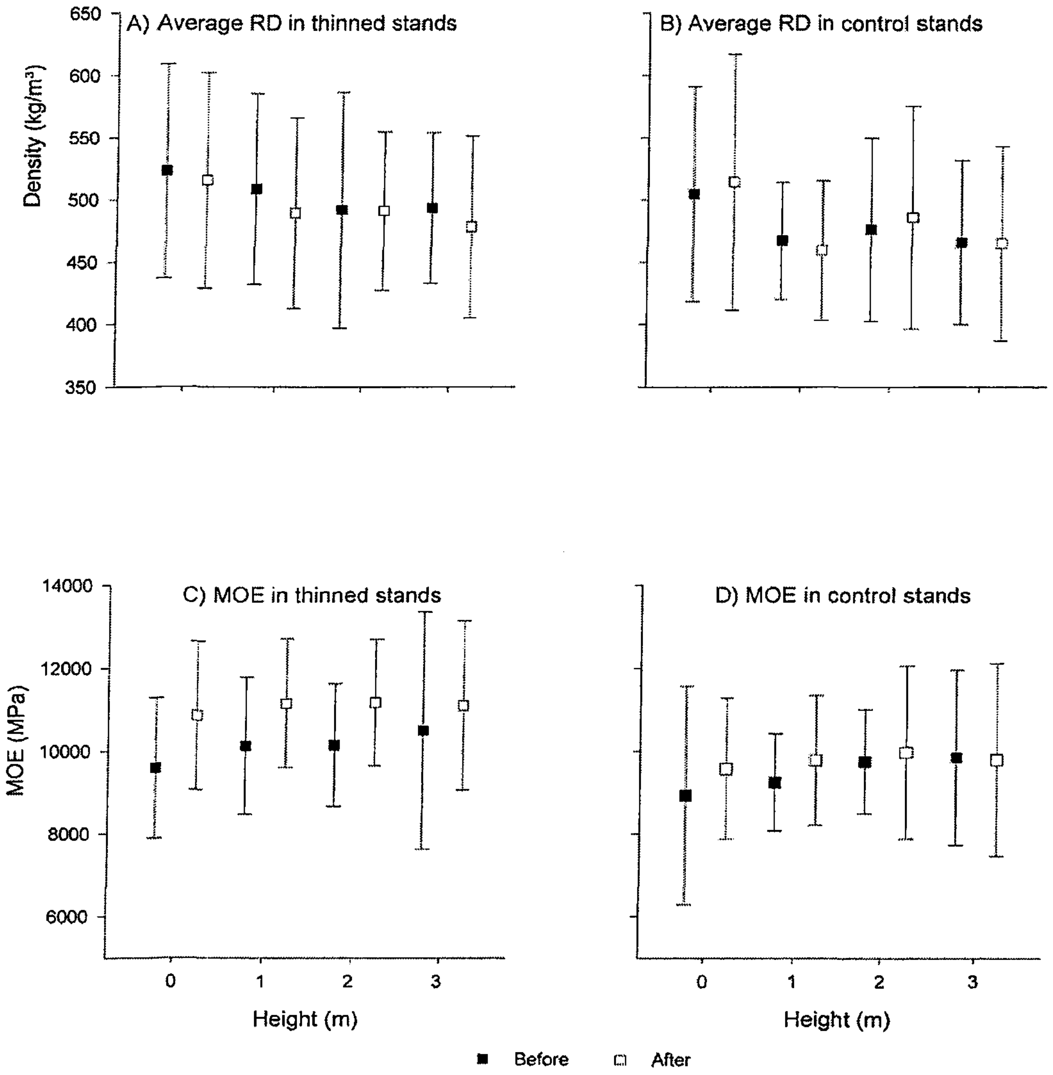

Figure 5.4: Change along the first four metres of stem in A) average ring density (Average RD) for thinned stands, B) Average RD for control stands, C) modulus of elasticity (MOE) for thinned stands and D) MOE for control stands, before (black square) and after (white square) thinning year.

CHAPITRE 6

DOES TIMING MAKE A DIFFERENCE IN THE PROFITABILITY OF COMMERCIAL THINNING IN THE BOREAL FOREST?

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Keywords: *black spruce; commercial thinning; products recovery; Net Present Value (NPV).*

CHAPITRE 6

DOES TIMING MAKE THE DIFFERENCE ON THE PROFITABILITY OF COMMERCIAL THINNING IN THE BOREAL FOREST?

6.1. ABSTRACT

The profitability of commercial thinning in low-productivity boreal black spruce stands is often questioned. This article evaluates the hypothesis that commercial thinning can be used in periods of favorable market conditions to increase the profitability of the stand for future total harvest, when the market conditions are less favorable. Based on nine thinned and six untreated stands, this research tests the effect of the timing of thinning and market conditions on the Net Present Value (*NPV*) of commercial thinning (CT) and final felling. Type, number and grade of timber products from both thinned and residual stems were assessed using simulations from the Optitek sawing simulator. Two multivariate regression models built with lumber market conditions during CT and final harvest and thinned and control stands characteristics explained about 58% of the *NPV* variations of thinned stand variations ($p < 0.0001$) and about 73% of the *NPV* variations for controls stands. Compared with *NPV* variations for control stands, it appears that CT in natural black spruce stands 10 years before final harvest may be profitable when the lumber market was high during CT and low or lower during final harvest. A retrospective analysis based on historical lumber prices series from 1981 to 2009 demonstrated that for a 10-year lag period between CT and final harvest, CT could have been a profitable operation in 42% of cases. Despite the fact that this percentage may decrease when an

increasing time horizon is considered, these results may be very relevant in the context of a critical timber supply.

6.2. INTRODUCTION

Black spruce (*Picea mariana* (Mill.) B.) is the most important commercial and reforested species in Eastern Canada (Parent and Fortin, 2008; Zhang and Koubaa, 2009). The current silviculture systems used in black spruce stands is the clear-cutting system (with plantation), or the natural shelterwood system, using careful logging around advance growth (CLAAG) (Groot *et al.*, 2005). In Quebec, the reduced land base for fiber production (Coulombe *et al.*, 2004) coupled with increasing global competition in the forestry industry has led to the development of new strategies to increase wood productivity. Partial cutting such as commercial thinning (CT) could be a sound choice to attain sustainable development within global market constraints while still achieving maximum value (Zhang *et al.*, 2006; Thorpe and Thomas, 2007; Thorpe *et al.,* 2007).

Usually CT is performed preferably in plantations but it also can be done in natural, unmanaged stands (OMNR, 1997; Gouvernement du Québec, 2003). In the Canadian boreal forest, thinning from below is usually practiced in order to 1) salvage dead or low-vigor trees that could be lost by self-thinning before final harvest (Thiffault *et al.*, 2003); 2) provide an early financial return from managed stands (Kellog *et al.*, 1996; Brazee and Bulte, 2000), and 3) increase stand value while eliminating lower quality stems and keeping larger trees with improved growth (Johnstone, 1997). When diameter growth increment of residual stems is significant, CT leads to a decrease in processing costs and a diversification of available wood products (Bulley, 1999; Duchesne and Swift, 2009).

However, in boreal black spruce, these advantages are often questioned: Lussier *et al.* (2002) showed that self-thinning in black spruce affected mostly sapling and small pole-size trees without any economic value, so there is no significant salvage in the economic sense. Moreover, despite that radial growth increment can double in some stands 10 years after CT (Soucy, 2003; Vincent *et al.*, 2009), increment is very low in absolute terms as stem diameter only increases at best by one or two centimeters after treatment.

Short-term profitability of CT is sometimes questioned because immediate harvest costs surpass timber value (Brazee and Bulte, 2000; Cameron, 2002), in particular with thinning from below in pole stands.

Thinning could be a profitable investment if the increase of residual stand value at the time of final felling exceeded net CT costs. Because stem wood volume value depends on tree size and market price fluctuations (Brazee and Bulte, 2000), we hypothesize that CT could be profitable in boreal black spruce by restricting the application of thinning to high price conditions, while the future final felling is done during a low price condition. We assume here that during low prices periods, only the largest trees in a typical black spruce stand have a positive merchantable value. In this case, thinning from below could be a method to remove trees with a marginal or negative value at time of final felling.

The objectives were 1) to estimate *NPV* of thinned and control stands based on recovery products available after CT and final harvest (FINAL); 2) build a multivariate linear regression model to estimate *NPV* based on stands characteristics and market price index; 3) Evaluate market and stand conditions where thinned stands present a higher *NPV* value than unthinned stands.

6.3. STUDY AREA

The study was based on nine commercially thinned stands and their associated controls in the boreal forest of Quebec, Canada. Latitudes ranged from 47.9° N to 49° N, longitudes from 70.5° W to 72.7° W and altitudes from 210 to 671 m (Table 6.1). The region is characterized by cold winter temperatures and short growing seasons. Over the past 30 years, the average minimum temperature was −18.4 °C during the coldest month and the average maximum was 17.9 °C during the warmest month. Average annual precipitation varies from 920 to 1187 cm in the studied stands (Environment Canada, 2008). Stand selection was based on two main criteria: (i) thinning had to be done 10 – 12 years before sampling in unmanaged natural stands and (ii) stands had to have similar characteristics. Stands had to be located close to a road to be accessible by truck. Typically, commercial thinnings in boreal black spruce for that region and this period were thinning from below with a 30-40% removal of basal area, with an increase of at least 5% of the average diameter at breast high (Dbh) (Gouvernement du Québec, 2003).

Essentially pure unmanaged natural black spruce stands were selected according to Quebec Ministry of Natural Resources and Wildlife data. The mean age of the stands at thinning year varied from 48 to 82 years. Merchantable stand density, evaluated within a 20 × 20 m quadrat, was between 950 and 3 900 trees ha^{-1}, with a basal area of 17-50 m^2/ha (Table 6.1). The herbaceous and moss layers are mainly composed of *Pleurozium schreberi* (Brid.) Mitt., *polytrichum sp.*, *Ptilium crista-castrensis* (Hedw.) De Not., *Ledum groenlandicum* Oeder, *Vaccinium angustifolium* Ait. and *Kalmia angustifolia* L. All study stands are mesic black spruce sites, imperfectly to well drained.

6.4. DATA

In each stand a 20 × 20 quadrat was selected comprising at least 35 black spruces (Dbh > 9 cm). The stand characteristics of each quadrat, such as vegetation composition, topography and depth to mineral soil, were determined in order to check homogeneity among stands. Each tree within the quadrat was measured for height (H), Dbh, diameter at stump height (Dsh, ≈ 10 cm), and stem height at the lowest living branch (Table 6.1). Stump circumferences of cut trees and their positions within the quadrat were also determined. An increment core was taken from each living tree at 25 cm above the ground along the north-south direction to determine tree age and radial growth variations after thinning (Vincent *et al.*, 2009). Stem volume was calculated with volume tables for black spruce trees as a function of stem Dbh and H (Perron, 1985). The average stem volume (AVS) and volume by hectare (V) were calculated at year of thinning (AVS_{CT}, V_{CT}, m^3) and at the final harvest year (AVS_{FINAL}, V_{FINAL}, m^3) for both thinned and control stands (Table 6.2).

Because the studied stands are even-aged, harvested tree height was assessed with stumps of residual stems of similar diameter within and close to the quadrat.

In the rest of the text, thinned stems (appearing as stumps inside the quadrat) are referred to THI whereas residual stems, to be harvested in due course as RES.

6.5. METHODS

6.5.1. Prediction of product recovery

The Optitek database (Goulet, 2009) was used to assess type, number and grade of products that could be produced from both RES and THI stems. This database is the result of simulations performed with the Optitek sawing simulator on a sample of 1312 softwoods stems, (FPInnovation, Forintek division, Quebec), which was adjusted to simulate the typical sawmill processes used in Eastern Canada (Goulet, 2009).

Each stem (RES and THI) of the studied stands was matched (according to Dbh, Dsh, H) to a corresponding tree sample from the Optitek database. Product recovery from the studied stems was assumed to be equal to that simulated by Optitek for the associated stem.

6.5.2. Economic analysis

A financial analysis was performed with the Net Present Value at the time of the final harvest (*NPV*, CAN2009$, profitability analysis) (Gélinas *et al.*, 2009) as indicator of profitability on a per-hectare basis. For the purpose of the analysis, stands were considered ready for final felling at the year of sampling. The analysis was done at the scale of the whole value chain, from the woodlot owner to the markets, including the wood processing business units. In short, the net value per ha is equal to the income from the sale of the products of the primary processing, minus the cost of silviculture and wood transformation. Distribution of net profit among the business units of the value chain is not considered. The value chain is composed of five business units: a forest owner, a sawmill, a pulpmill (processing residual chips from the sawmill), a pulp market and a timber market. To optimize available data, we assumed that: (i) the time horizon was 10 years (ie. CT is followed by a clearcut 10 years later) and (ii) the net actualization rate (nominal rate –inflation rate) was chosen to be equal to 4% (Natural Resources of

Canada, Gélinas *et al.*, 2009). Because studied stands were unmanaged before CT, no stand regeneration or tending investments were considered.

Transportation costs from the forest to the mill and from the mill to the markets were not considered in the *NPV* calculation. We assume the perfect scenario when sawmill is located really close to the thinned stands.

Thinning costs (C_{CT}) were calculated according to Meek (2000) equation (1):

$$C_{CT} = 1.529V^{-0.9211} \qquad (1),$$

where C_{CT} is the cost of CT ($CAN/m^3) and V the mean of total thinned volume by stand (m^3/stem harvested). Hauling (8$CAN/m^3), supervision and general fees (~20%) were added to C_{CT} according to Meek's information on typical CT operations (Meek, personal communication). The cost of final harvest (C_{FINAL}) essentially depends on volume harvested (20$CAN/m^3), since variations of final harvest costs in relation to tree size are negligible. Table 2 presents stand characteristics used to calculate C_{CT} and C_{FINAL}. Transformation costs such as sawing (15 $CAN/m^3), planing (25 $CAN/1000FBM) and drying costs (8 $CAN /1000FBM), were added in *NPV* calculation according to Goulet (2009) information. Every price was reduced by a constant $CAN2009.

The incomes I at the year y, I_y, depend on product recovery determined with the Optitek database and can be expressed as follows (equation 2):

$$I_y = \sum_{j=1}^{z} \sum_{k=1}^{n} xP_{k,j}(y) \qquad (2),$$

where j is the number of residual or thinned stems, k the number of different product types, x the number of product types k by tree j, P the price (value) of the product types k at year y. It was noticed by Tong *et al.* (2005), that virtual trees produce more lumber recovery than a real one of the same Dbh and H, but because we compare thinned with controls stands we did not correct this overestimation.

With the above assumptions *NPV* was calculated by equation 3:

$$NPV_y = I_{CT} + \frac{I_{FINAL}}{(1+i)^{10}} - C_{CT} - \frac{C_{FINAL}}{(1+i)^{10}} \qquad (3)$$

where I_{CT} are the incomes from THI stems, I_{FINAL} the incomes from RES stems (or final harvested stems), C_{CT} the costs of CT, and C_{FINAL}, final harvest costs.

6.5.3. *Influence of lumber price fluctuations*

The Pribec composite lumber price market (Pribec) was used to measure historical lumber price fluctuation from 1981 to 2009. Composite prices were converted in 2009 dollars, considering an average annual inflation rate of 3.08% (from 1981 to 2009, Bank of Canada, 2010). Working with detrended composite price series, five percentiles (10th, 25th, 50th, 75th and 90th) were determined with residual values of detrended series to represent different market conditions (from low to high market values, Figure 6.2). To evaluate the influence of market price fluctuations on final incomes, *NPV* ($CAN2009) was calculated with CT and FINAL realized for each possible combination of market condition, (PP_{CT} =percentile of price for CT; PP_{FINAL}= percentile of price for final harvest). For each percentile of the composite price, corresponding prices of single lumber products were used to estimate the value of the product basket.

Eventually, *NPV* estimated for CT stands according to their characteristics was compared with the mean of *NPV* calculated for controls stands for the different percentiles of price values in order to determine the percentile of price combinations when NPV_{CT} was higher than NPV_C defined as “winning conditions”.

6.5.4. *Retrospective analysis*

The last part of the study is a retrospective analysis based on composite price series. Occurrence of percentile price combinations has been computed considering a 10-year lag between thinning and the final harvest, using the historical Pribec series.

6.5.5. *Statistical analyses*

Multiple regression analysis was performed between NPV_{CT} and four independent variables that could be correlated with NPV_{CT} fluctuations and their interactions: V_{CT}, V_{FINAL}, AVS_{CT} and AVS_{FINAL}. To assess the influence of lumber market conditions, in improving NPV_{CT} value PP_{CT} and PP_{FINAL} were also added to the multiple regression model (equation 4). A complementary multiple regression analysis was also performed between NPV_C and V_{FINAL}, AVS_{FINAL} and PP_{FINAL} (equation 5).

$$NPV_{CT} = a_0 + a_1(PP_{CT}) + a_2(PP_{FINAL}) + a_3(V_{CT}) + a_4(V_{FINAL}) + a_5(AVS_{CT}) + a_6(AVS_{FINAL}) + a_7(V_{CT} * PP_{CT}) + a_8(V_{FINAL} * PP_{FINAL}) + a_9(V_{FINAL} * V_{CT}) + a_{10}(AVS_{CT} * V_{CT}) + a_{11}(AVS_{CT} * V_{FINAL}) + a_{12}(AVS_{FINAL} * AVS_{CT}) \quad (4)$$

$$NPV_C = b_0 + b_1(PP_{FINAL}) + b_2(V_{FINAL}) + b_3(AVS_{FINAL}) + b_4(V_{FINAL} * PP_{FINAL}) \ (5)$$

The best model was automated selected with the glmulti procedure on R. Glmulti provides a general wrapper for glm and related functions (Calcagno and Mazancourt, 2010).

6.6. RESULTS

6.6.1. *Lumber Products recovery*

Figure 6.1 presents individual stem value according to their classes for the five studied percentiles of prices. It appears that for low market conditions (PP = 10 and PP = 25 and PP = 50 at final harvest), harvesting stems in Dbh classes 10 to 12 cm is wasteful.

Regarding types and number of products available from both THI and RES stems, most products belonged to the "studs" category, for about 65% of total products produced. The "Studs" category also represented about 65% of the products issued from controls stands. On a per hectare basis, the number of lumber pieces obtained from RES stems was about twice the one from THI stems for the three categories "boards", "studs" and "utility #3", whereas "specified length 1&2" and "economy" pieces were four times more numerous for RES than THI stems. The average lumber recovery by THI stem was about 5.7 lumber units per tree, whereas it was about 9.2 by RES stem. A mean of 8.7 products was produced per stem in unthinned stands at the time of final felling.

6.6.2. NPV prediction

The historical average for each cost and income and *NPV* is presented in Table 6.3.

Fitting Equation 4 using glmulti procedure resulted in a model that explained approximately 88% of the NPV_{CT} variations (Table 6.4).

Fitting Equation 5 using glmulti procedure resulted in a model that explained approximately 85% of NPV_C variations (Table 6.5).

Figure 6.3 illustrates *NPV* evolution for both thinned and control stands (NPV_{CT}, NPV_C). NPV_{CT} was calculated according to equations defined in the multiple regression model with V_{FINAL}, AVS_{FINAL}, V_{CT} and AVS_{CT} set as the mean for each variable of all thinned stands. NPV_C was calculated from equation 5.

According to Figure 6.3, when the price index is above the 90th percentile at the time of thinning and when it is lower than the 50th percentiles it is more profitable to thin. In these conditions, the benefit of thinning increases as a proportion to the difference in the price index between thinning and final harvest.

Moreover, in comparison to unthinned stands, thinning appears to temper the fluctuation of NPV of stands in response to variations in the price index (Figure 6.3).

6.6.3. *Retrospective analysis*

Frequencies of combined observations of price index with a 10-year lag between 1981 and 2009 are presented in Table 6.5. "Winning conditions" (eg. when NPV of thinned stands is larger than unthinned ones) occurred in 26% out of the 19 possible year pairs (last 30 years).

6.7. DISCUSSION

6.7.1. *Product recovery*

Of all the products available from black spruce stands after CT, some were widely available from both THI and RES stems (such as "studs", "boards" and "utility #3"), whereas other products were scarcer from THI stems, ("economy" and "specified length"). Moreover, belongs the tree stands presenting a lowest historical mean of *NPV* (HEB95, HEB96-1 and MV96) (Table 6.3), HEB95 and MV96 presented the lowest V harvested during both CT and final harvest and the smallest AVS_{CT} (Table 6.3) and HEB96-1 presented a thinning intensity very low. Stem volume may influence the number of product recovery but also the type of volume recovery. Logically, the biggest stems may produce some products with larger dimensions and thus higher value but also, products of lower quality that increase final profitability. Aubry *et al.* (1998) working on coastal Douglas fir (*Pseudotsuga menziessii* (Mirb.) Franco) reported that the size of stems determined the number of boards per log (diameter effect) and the number of logs per tree (height effect). When CT increases the proportion of big trees within CT stands, it also increases final profitability of the stand. On the other hand, the profitability of thinning is less important than only one final harvest and the way to enhance this profitability is to manage with market fluctuations.

6.7.2. Thinning Profitability

According to the multiple regression models developed in this paper, CT may enhance stand profitability when specific lumber market conditions are met for both CT and final harvests. To increase stand productivity it seems that CT should be conducted during periods of high market prices (Figure 6.3). A further study demonstrated the importance of stumpage price fluctuations in harvesting decisions (Brazee and Bulte, 2000) but no study to our knowledge dealt with the importance of lumber market fluctuations on thinning profitability. This study also demonstrated that CT regularizes annual fluctuations of *NPV* in comparison with a scenario with only one final harvest. CT appears to temper NPV fluctuations in response to variations in the price index.

Regarding retrospective data, it appears that "winning conditions" were met about 26% of the studied years (Table 6.5). However, if market price evolution keeps following the same negative trend, the probabilities to meet "winning conditions" for final harvest may increase over the next years.

6.7.3. Limits analysis

Many assumptions were made to develop this analysis. The method used to determine CT profitability over time is questionable because it compared real financial data over time (lumber value) with data adjusted only with a constant inflation rate (treatment costs). In reality, C_{CT} and C_{CLAAG} also follow annual variations, such as wood industry activity, gas costs etc. and so the relative influence of the costs on the final income may vary. Nevertheless, we may assume that these variations are somehow linked with lumber price fluctuations.

Some important costs and incomes were not considered in this study: carriage costs, chips and sawdust incomes and others. To enhance model efficiency, it will be important to integrate these income sources (chips and sawdust) to calculate final profitability given the increasing use of these materials in the wood industry (Ericsson *et al.*, 2005; Zerbe, 2006). These costs and incomes were not included to simplify the analysis.

The transportation costs essentially depend on the distance between stands and sawmills, such that sawmills nearest to the stands are usually chosen to limit these costs. According to Tong *et al.* (2005) who set it as a constant, it is about 12.83 $\$/m^3$ in Quebec. According to stands data about 69.2m^3/ha were harvested at the thinning year and about 153m^3/ha during final harvest whereas 243m^2/ha were harvest from control stands (Table 6.2). Taking into account net actualization rate, transportation cost was around 3100 $ on a hectare basis for both CT and control stands. However, carriage costs may have an indirect impact on CT profitability by determining the available sawmill technology and thus types of products.

To take advantage of the available data, the time horizon was set at 10 years. Although this choice may appear short, to our knowledge, no financial analyses based on longer periods are currently available in the literature for naturally regenerated stands. However, it may amplify and/or understate the relative importance of RES and THI incomes. Specifically, the major disadvantage of using *NPV* is the difficulty in choosing appropriate discount rate (Smith and Oerlemans, 1988). Impact of discount rate on *NPV* will be even more important on a longer time horizon.

The model developed in this study presented a questionable result while $\mathrm{AVS_{CT}}$ and $\mathrm{AVS_{FINAL}}$ were negatively correlated with *NPV* calculation for thinned stands (Table 6.4). This result is inconsistent with the method used to calculate $\mathrm{C_{CT}}$ (equation 1) and with the lumber recovery resulting from the Optitek simulation. The studied stands characteristics may explain this result. Indeed, according to Tables 6.2 and 6.3, some stands (HEB96-1, LB95 and SL97) presented a low historical *NPV* while $\mathrm{AVS_{CT}}$ and above all $\mathrm{AVS_{FINAL}}$ were quite high compared to other stands with higher historical *NPV*. In the same way, these three stands presented a low $\mathrm{V_{CT}}$ (especially HEB96-1 and LB95) that may explain the *NPV* observed. In these cases it seems that total volume thinned by stand influenced more CT profitability than $\mathrm{AVS_{CT}}$. A transformation of the $\mathrm{AVS_{CT}}$ factor to better assess its effect on *NPV* before including it in the stepwise procedure may be necessary to enhance model predictability.

This study is based on the assumption that THI stems were harvested for lumber use and thus assumed that pulpwood value was constant. It is obvious that profitability would change under other use of thinned stems such as pulp production. Nevertheless, to increase CT profitability it is important that THI stems are considered as much as possible as lumber resources.

6.8. CONCLUSION

Although thinning of even-age single species stands in order to increase volume increment in individual stems and the final stand value is a standard silvicultural practice, there have been few treatments of thinning to optimize forest management with fluctuating lumber prices. In this article we present new results after conducting thinning to take advantage of the lumber market. These results may be useful for informing decisions during critical periods of supply.

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6.10. LITERATURE

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Table 6.1: Stand characteristics

Site	Location	Annual precipitation (mm)	Temperature (average min/average max, °C)	TY	Stand Age at TY	Dbh at TY (cm)	G at TY (RES+THI m^2/ha)	Merchantable Thinning intensity (%)	Dbh$_{RES}$ at TY / Dbh$_{THI}$ at TY
HEB95	N47.887 W71.464	992.9	-12.1/17.9	1995	48.4 ±10	13.0	29.2	19.6	1,4
HEB96-1	N48.315 W71.679	992.9	-12.1/17.9	1996	58.7 ±9	15.4	23.8	9.7	1,0
HEB96-2	N48.279 W71.683	992.9	-12.1/17.9	1996	53.2 ±8	16.6	41	31.8	1,0
LB95	N48.033 W72.33	1012.7	-16.8/17.3	1995	81.9 ±27	14.7	33.1	13.1	1,4
LC96	N48.143 W71.879	1036.7	-11.7/19.3	1996	56.3 ±6	15.1	44.8	39.6	1,3
LJ96	N48.983 W72.738	919.8	-18.4/17.6	1996	46.8 ±6	13.6	42.3	52.5	0,8
MV95	N48.794 W70.544	1187.3	-16.1/17.5	1995	60.9 ±11	14.1	40	39.7	1,3
MV96	N48.76 W70.551	1187.3	-16.1/17.5	1996	59.5 ±8	12.9	33	30.8	1,3
SL97	N48.874 W71.747	1061.4	-11.7/18.2	1997	57.1 ±7	17.1	40	37.4	1,3
HEBC	N48.145 W71.589	992.9	-12.1/17.9		51.3 ±9	15.8	48.3		
LBC	N48.032 W72.334	1012.7	-16.8/17.3		67.1 ±23	14.6	17.2		
LCC	N48.143 W71.878	1036.7	-11.7/19.3		54.9 ±13	20.7	35.2		
LJC	N48.983 W72.741	919.8	-18.4/17.6		53.1 ±7	12.3	48.9		
MVC	N48.764 W70.55	1187.3	-16.1/17.5		52.8 ±12	14.6	49.8		
SLC	N48.874 W71.475	1061.4	-11.7/18.2		50.2 ±7	15.5	34		
Mean for CT stand					58	14,7	38.5	30.5	1.2
Mean for C stands					55	15.6	38.9		

TY = Thinning Year, CT = Commercial Thinning, C = Controls

G = basal area

RES = residual stems, THI = thinned stems

Table 6.2: Stand characteristics and parameters, used to calculate commercial thinning (CT) and final harvest (FINAL) costs and incomes.

Stands	V_{CT} (m^3/ha)	V_{FINAL} (m^3/ha)	AVS_{CT} (m^3)	AVS_{FINAL} (m^3)
HEB95	19.3	69.5	0.04	0.104
HEB96-1	21.2	204.3	0.121	0.215
HEB96-2	81.5	182.2	0.142	0.152
LB95	29.1	187.8	0.078	0.163
LC96	114.2	180.2	0.095	0.185
LJ96	134.1	125.0	0.112	0.076
MV95	76.7	124.8	0.139	0.111
MV96	51.7	120.4	0.045	0.102
SL97	94.7	183.8	0.118	0.223
HEBC	0	306.0	0	0.136
LBC	0	110.4	0	0.116
LCC	0	237.4	0	0.264
LJC	0	298.1	0	0.076
MVC	0	280.4	0	0.102
SLC	0	225.4	0	0.145
Mean for CT stands	69.17	153.1	0.10	0.15
Mean for C stands	0	243.0	0	0.14

V = stand volume

AVS = Average volume per stem

C = control, CT = Commercial thinning

Table 6.3 : Mean of historical prices from 1981 to 2009 for commercial thinning (CT) and final harvest (FINAL) costs (C_{CT}, C_{FINAL}), stumpage fees, transformation costs, incomes (I_{CT}, I_{FINAL}) and Net Present Value (*NPV*) in $CAN2009, CT data are discounted to fit in *NPV* calculation. Costs and Incomes are given by hectare for each stand.

Stands	I_{CT}	I_{FINAL}	C_{CT}	C_{FINAL}	Transformation costs for CT	Transformation costs for FINAL	NPV
HEB95	3832	13783	1346	2203	4126	1537	8403
HEB96-1	2205	19360	236	2881	5157	772	12519
HEB96-2	14488	22986	1180	3854	7036	4598	20806
LB95	4910	22780	734	3974	7150	1617	14216
LC96	18760	22371	2386	3811	6849	6238	21848
LJ96	24165	13207	2416	2644	4746	7490	20075
MV95	12737	27831	2489	2639	4808	4389	26243
MV96	12737	27831	2489	2639	4808	4389	26243
SL97	15428	19801	1618	3888	6656	5241	17826
HEBC	0	36699	0	6474	0	11558	18668
LBC	0	12998	0	2336	0	4179	6483
LCC	0	29685	0	5022	0	8695	15969
LJC	0	32685	0	6295	0	11466	14924
MVC	0	32813	0	5932	0	10690	16190
SLC	0	19913	0	4768	0	7196	7949
Mean for CT stands	12140	21106	1655	3170	4030	5704	18687
Mean for C stands	0	27466	0	5138	0	8964	13364

C = control stands

Table 6.4 : A) NPV_{CT} model of the multivariate regression resulting from the glmulti procedure and B) independent variables.

A) WHOLE MODEL

Source	DF	Sum of squares	Mean square	*F* ratio
Model	11	8.09e+9	7.35e+8	139.9750
Error	213	1.12e+9	5.25e+7	**Prob. > F**
C. Total	224	9.2e+9		<.0001*

B) INDEPENDENT VARIABLES

Term	Estimate	SE	*t* ratio	**Prob. > F**	Standard β
Constante	84132,6	508	16,5	4,7448e-40	0
PP_{FINAL}	15,2	1,4	10,8	4,3672e-22	0,3
PP_{CT}	10,7	1,4	7,6	8,8124e-13	0,2
V_{FINAL}	-539,1	36,2	-14,9	6,7713e-35	-3,6
V_{CT}	-296,1	23,8	-12,4	5,3366e-27	-1,8
VMT_{FINAL}	-10073,1	9146,4	-1,1	0,27200335	-0,1
VMT_{CT}	554851,91	32467,5	17,1	8,3571e-42	3
$(PP_{CT} -531,217)*(V_{CT} -69,1677)$	0,1	0,04	3,8	0,00018455	0,1
$(PP_{FINAL} -531,217)*(V_{FINAL} -153,097)$	0,04	0,03	1,3	0,21100793	0,03
$(V_{FINAL} -153,097)*(V_{CT} -69,1677)$	10,81	0,6	19,2	2,1979e-48	3,1
$(V_{CT} -69,1677)*(AVS_{CT} -0,08997)$	-15009	691,9	-21,7	7,6604e-56	-2,4
$(V_{FINAL} -153,097)*(AVS_{CT} -0,08997)$	-17659,4	1012,9	-17,4	6,9017e-43	-3,7

V = Volume harvested (thinned or final harvest) on a per hectare basis, CT = Commercial Thinning, FINAL = final harvest; AVS = average volume per stem, PP = Percentile of Price.

Table 6.5 : A) NPV_C model of the multivariate regression resulting from glmulti procedure and B) independent variables.

A) WHOLE MODEL

Source	DF	Sum of squares	Mean square	*F* ratio
Model	4	4.25e+9	1.06e+9	211.42
Error	145	7.29e+8	5.03e+6	**Prob. > F**
C. Total	149	4.98e+9		<.0001*

B) INDEPENDENT VARIABLES

Term	Estimate	SE	*t* ratio	Prob. > F	Standard β
Constant	-36907.039	1874.583	-19.688	<.0001*	0
PP_{FINAL}	24.375	1.684	14.459	<.0001*	0.459384
V_{FINAL}	125.127	5.0556	24.750	<.0001*	0.920813
AVS_{FINAL}	39880,480	3618.713	11.021	<.0001*	0.139624

Results from stepwise regression using the forward procedure with AIC as indicator, ΔAIC (ΔAIC = AIC before enter – AIC after enter) has to be positive to enter.

V = Volume by stand at thinning year, FINAL = final harvest; AVS = average volume per stem, PP = Percentile of Price.

Table 6.6 : Percentiles of price combinations observed during the last 30 years for a 10-year lag period between CT and final harvest (FINAL). Grey cases correspond to "winning conditions" as defined in the text ($NPV_{CT} > NPV_{C}$)

PP_{FINAL} PP_{CT}	10	25	50	75	90
10	0 %	0 %	0 %	5 %	0 %
25	0 %	0 %	5 %	11 %	5 %
50	0 %	0 %	5 %	5 %	26 %
75	0 %	0 %	5 %	0 %	0 %
90	16 %	5 %	5 %	0 %	5 %

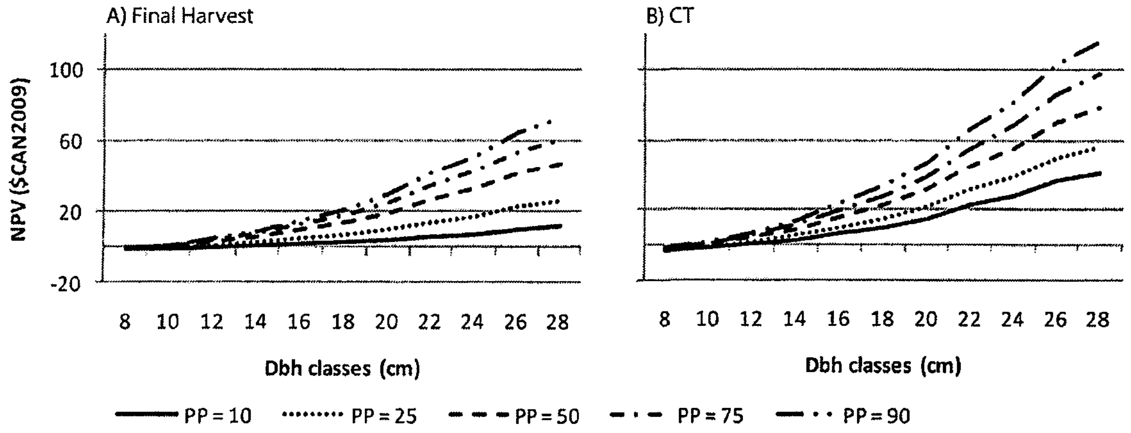

Figure 6.1 : Individual stem value according to Dbh classes for the five percentiles of prices (PP). A) At final harvest, B) when thinned. Thinned values were discounted.

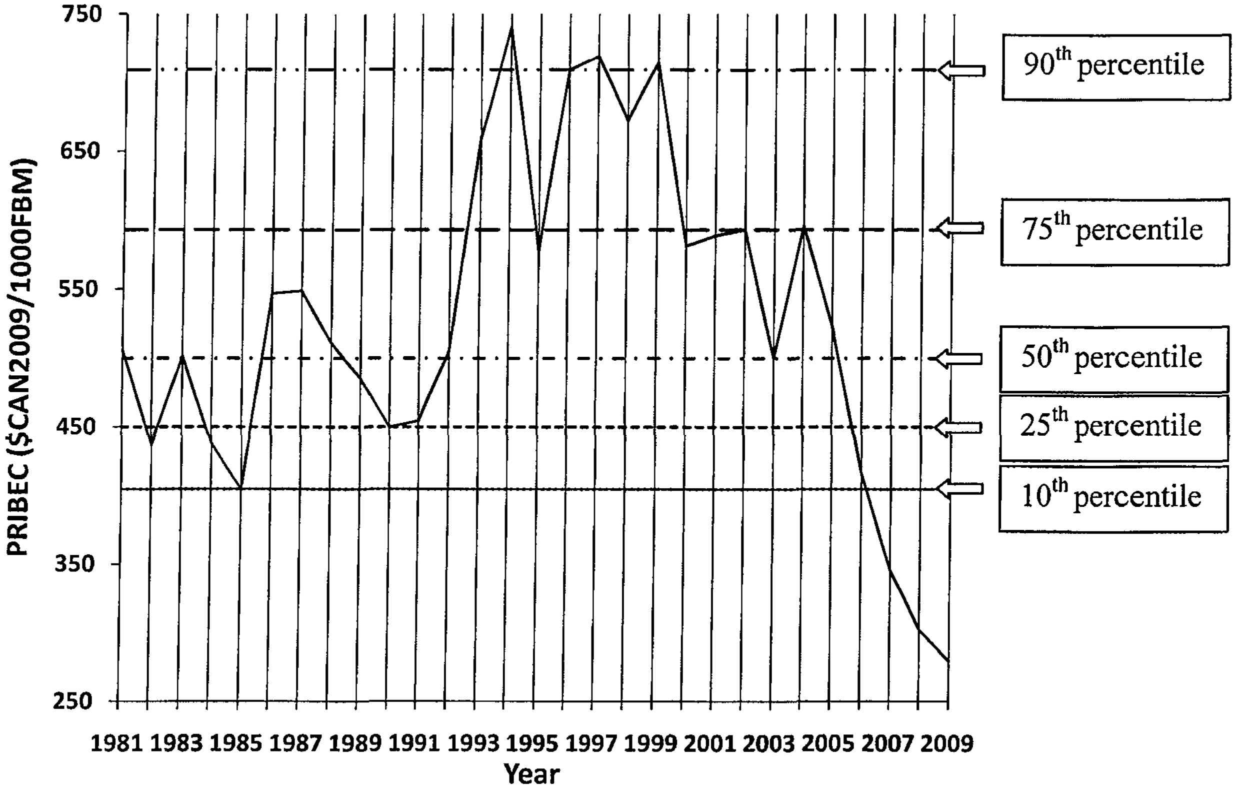

Figure 6.2: PRIBEC series ($CAN2009) from 1981 to 2009 embraced with percentile of prices. The five horizontal lines correspond to the five selected percentiles from the 10th (bottom solid line) to the 90th (upper dash line) and including 25th, 50th and 75th percentile of prices.

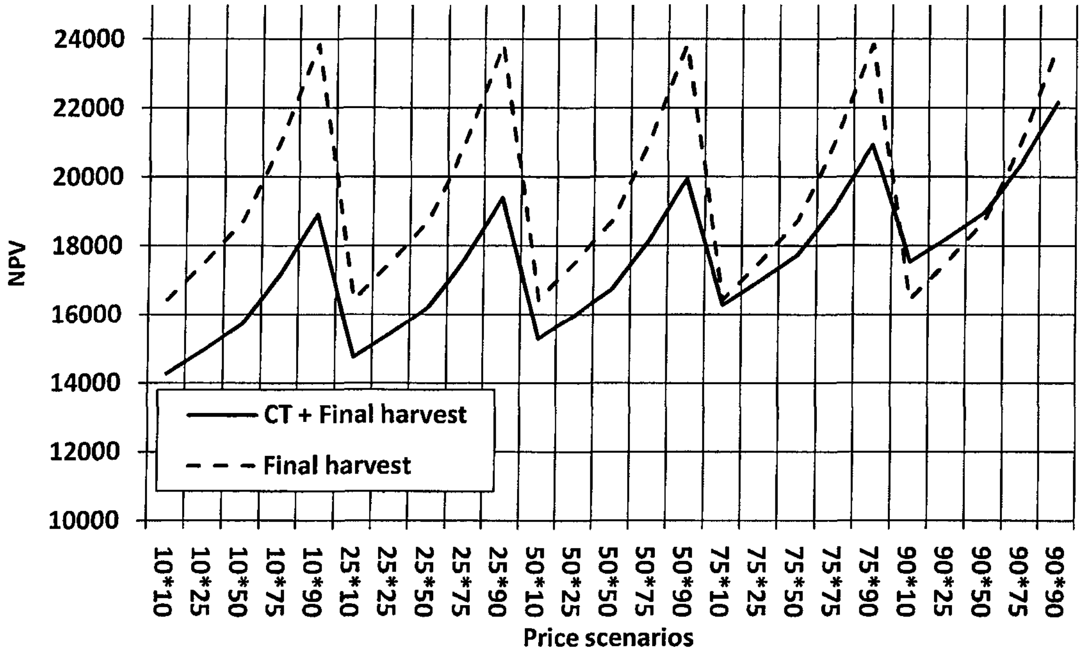

Figure 6.3 : Net Present Value (*NPV*, left-hand side) estimated for CT (NPV_{CT} solid line) and control stands (NPV_C, dash line) for different percentile of prices combinations.

CHAPITRE 7

CONCLUSION GENERALE

Cette thèse présente plusieurs avancées vers une meilleure compréhension de l'éclaircie commerciale (EC) et de son influence sur la croissance des tiges d'épinettes noires (*Picea mariana* (Mill.) BSP.) (Epn) en forêt boréale. Cette recherche est à notre connaissance la première traitant des effets d'un tel traitement dans les peuplements naturels non éduqués d'Epn. Bien que cette pratique sylvicole soit peu utilisée à l'heure actuelle dans ces peuplements, nous avons démontré plusieurs résultats intéressants pouvant se regrouper sous quatre thèmes : croissance des peuplements, rôle des racines, qualité de la tige et des produits bois et premières retombées économiques.

7.1. IMPLICATIONS SYLVICOLES

7.1.1. Éclaircie commerciale et croissance des peuplements

De façon générale, les individus répondent positivement au traitement, car la croissance radiale des arbres augmente significativement après l'EC. Cet accroissement relatif des arbres résiduels postérieur au traitement d'EC se correspond à celui observé pour d'autres essences de résineux (Chapitre 2). Ainsi, chez le pin gris (Bella et de Francesci, 1974), le sapin Baumier (Pape, 1999) ou encore le sapin Douglas (Aussenac et Granier, 1988) l'accroissement radial augmente de 30 à 100 % après l'EC. Il est néanmoins important de mentionner qu'il s'agit de croissance relative, ainsi les résultats en termes de croissance absolue sont plus mitigés. En effet, lorsque de petits arbres présentent un fort accroissement relatif après le traitement, la quantité de bois produite reste faible (Morris et Forslund, 1992). En l'occurrence, dans les peuplements étudiés, les petits arbres répondent mieux au traitement d'EC que les gros arbres (Chapitre 2). Les résultats de notre étude suggèreraient donc de modifier cette façon de faire en intégrant une certaine portion d'arbre de belle dimension et de belle qualité, contrairement aux pratiques en vigueur au Québec où les EC sont essentiellement réalisées par le bas, c'est-à-dire en supprimant les petits arbres.

Le rôle des racines abordé au chapitre 2 mériterait être développé d'avantage, mais une corrélation positive entre les arbres présentant une bonne réponse au traitement et leurs racines a été mise en évidence (Chapitre 2). Il a été démontré que le développement proche de la tige assurait le rôle de soutien tandis que le développement des racines éloignées impliquait un développement de la nutrition et de la conduction de l'eau (Ruel *et al.*, 2003; Pothier et Margolis, 1991). Dans notre cas les racines proches semblent se développer mieux que les racines loin et joueraient donc un rôle de stabilisation. Cependant une comparaison entre la croissance des tiges et celle des racines proches et loin serait importante pour appuyer cette hypothèse.

En termes de volume de bois produit, les résultats obtenus corroborent les différentes études sur le sujet (e.g. Bella and De Franceschi, 1974; Curtis and Marshall, 2002). Le volume total du peuplement n'augmente pas après le traitement, seul le volume par tige est affecté (Chapitre 3). Finalement le volume marchand des peuplements éclaircis n'est pas supérieur à celui des peuplements témoin 10 ans après le traitement.

7.1.2. Éclaircie commerciale et qualité du bois

L'accroissement radial après l'EC est localisé sur les deux tiers inférieurs de la tige alors que les témoins présentent une croissance radiale plus importante au sommet de l'arbre (chapitre 4). Cet accroissement localisé n'influence cependant pas le défilement et la forme de la tige puisqu'aucune variation significative de ces deux paramètres n'a été observée 10 ans après le traitement. En ce qui concerne les propriétés physiques et mécaniques que sont la densité et le module d'élasticité du bois des tiges résiduelles, celles-ci ne sont pas modifiées avec le traitement (Chapitre 5). Les échantillons testés présentaient un MOE supérieur à celui relevé par d'autres études (Zhang and Koubaa, 2009) au Québec. Cette particularité qui peut être perçue comme une caractéristique des Epn de la forêt boréale du nord du Québec, inhérente à leurs conditions de croissance (St-Germain et Krause, 2008) et au type de peuplement étudié, pourrait servir l'argumentation en faveur de l'EC. Ce résultat appuie donc l'utilisation de l'EC dans les peuplements d'épinettes noires d'origine naturelle. Une diminution significative du MOE a été observée après la réalisation d'éclaircies précommerciales (Koga *et al.*, 2002) qui pourraient s'expliquer par la présence de bois juvénile, aux propriétés particulières dans les tiges des peuplements traités. Ces résultats suggèrent d'éclaircir commercialement les peuplements d'origine naturelle d'Epn sans que ceux-ci aient subi au préalable une ou des éclaircies précommerciales.

Finalement l'étude démontre que contrairement la densité initiale de peuplement qui influence positivement le module d'élasticité des tiges (Zhang *et al.*, 2002), la diminution de la densité de peuplement par l'éclaircie commerciale n'entraine pas de diminution du MOE (Chapitre 5). Cela suggère qu'un traitement sylvicole tel que l'EC pourrait être préférable pour les propriétés mécaniques des billes qu'une faible densité initiale imposée lors de la plantation d'épinettes noires.

7.1.3. Implication économique

«Bien que les forêts soient avant tout des entités biologiques complexes qui n'évoluent pas en fonction de critères financiers, elles constituent également des ressources économiques parce qu'elles sont utilisées pour produire des biens et des services. Le principal objectif de la foresterie est d'aménager la ressource pour combler les besoins de la société» (Gélinas *et al.,* 2009). S'il a déjà été démontré que l'accroissement du volume des tiges d'un peuplement pouvait influencer le panier de produits et les coûts associés à la transformation des billes (Aubry *et al.*, 1998 ; Briggs et Fight, 1992), l'influence du marché du sciage sur la rentabilité du traitement d'éclaircie est encore peu étudié. Notre étude a permis de démontrer que sous certaines conditions de marché, l'EC pouvait augmenter la valeur des peuplements traités par rapport aux peuplements témoins (Chapitre 6). Le type de produits créés influence ainsi le rendement du traitement. Le nombre et surtout la possibilité de produire des planches de meilleure et de moins bonnes qualités à partir des tiges éclaircies améliorent la rentabilité du traitement. Cependant, bien que l'éclaircie commerciale puisse être plus rentable qu'une seule récolte finale sous certaines conditions de marché, le cas contraire est rencontré dans la majorité des cas (Chapitre 6). La possibilité de déterminer les conditions gagnantes pour que l'EC soit un traitement rentable offre plusieurs avantages sylvicoles. À l'échelle de la forêt, cela permet d'utiliser stratégiquement l'EC pour répondre à court terme aux besoins d'approvisionnement en bois (Jamnick *et al.*, 1994).

7.2. CONTRIBUTION SCIENTIFIQUE ET ORIGINALITÉ DE L'ÉTUDE

Bien que l'EC soit une méthode éprouvée depuis de nombreuses années dans les forêts européennes et nord-américaines (Worthington et Staebler, 1961; Bella et De Franceschi, 1974), son utilisation en forêt boréale québécoise est plus récente, notamment dans les pessières noires (Lussier, 2001). La particularité de cette étude est qu'elle porte sur la réalisation d'EC dans des peuplements d'épinettes noires non éduqués (avant EC), une première à notre connaissance. Le plan expérimental de l'étude original a permis d'étudier à la fois les variations avant/après traitement — donc l'effet direct de l'EC sur le peuplement — mais aussi de vérifier que cet effet n'était pas spécifique d'un peuplement donné par comparaison avec des témoins.

Dans ce sens, cette étude propose un regard nouveau sur l'utilisation de ce traitement sylvicole comme une opportunité pour répondre aux attentes sociétales d'aujourd'hui.

L'étude des racines au chapitre 2, comme élément déterminant de la réaction à l'EC apporte des informations pertinentes sur le sujet. En effet, l'EC est parfois critiquée parce qu'elle peut rendre les peuplements traités susceptibles aux chablis (Cameron, 2002), les racines sont donc un facteur important de la réussite du traitement puisqu'elles assurent la stabilité des individus. Notre étude s'est penchée sur l'influence des racines sur la croissance radiale de la tige suite à l'EC et sur la relation tige/racine. Cette approche est une étape dans l'explication des mécanismes de réaction à l'ouverture de la canopée notamment pour une espèce tolérante à l'ombre comme l'Epn.

Si le gain en volume reste une priorité, la variation de la résistance mécanique du bois de résineux possible après une augmentation de croissance doit aussi être considérée. Cette étude est la première à notre connaissance à quantifier cette variation au niveau de la densité annuelle de cernes et du MOE pour l'Epn. Le chapitre 5 est d'autant plus important que l'Epn est une essence très utilisée comme bois d'œuvre et donc ses propriétés mécaniques sont essentielles.

Finalement, l'approche économique est novatrice, car rarement associée à ce type de projet. L'analyse temporelle de rentabilité du traitement n'avait pas été présentée antérieurement. Elle permet d'ouvrir l'étude vers d'autres perspectives et de créer un lien entre la recherche fondamentale et la recherche appliquée. Elle peut par la suite servir l'argumentaire des décisionnaires.

7.3. PERSPECTIVES DE RECHERCHES

L'étude présente la particularité de regrouper un grand nombre de sites exclusivement localisés dans la région du Saguenay-Lac-Saint-Jean. Ce choix logistique et méthodologique assure une homogénéité des sites tout en étant représentatif du domaine de la pessière noire caractéristique de la forêt boréale canadienne. Une étude plus restreinte au niveau du nombre de sites mais avec plus d'arbres récoltés par site, aurait par contre permis un design expérimental équilibré et plus représentatif de chaque site. La recherche est limitée 10 ans après le traitement, mais une analyse à long terme apporterait des informations complémentaires et permettrait de réaliser des tests mécaniques plus réalistes. Il est en effet difficile de limiter les cernes avant et après traitement dans des échantillons de petite taille (chapitre 5). De plus, quel que soit le traitement, la croissance de l'Epn en forêt boréale est très lente et donc la quantité de bois produit en 10 ans est très faible et insuffisante pour fabriquer une planche aux dimensions du marché. Une analyse supplémentaire à long terme apporterait des informations complémentaires pour ces premiers résultats. De plus, une étude basée sur des produits aux dimensions industrielles permettrait d'une part de connaitre le panier de produits disponibles à partir de nos peuplements et d'autre part, d'effectuer des tests MSR et un classement MSR de ces produits.

Le cas de chablis dans les peuplements éclaircis n'a pas été abordé dans l'étude. Ors c'est un élément important à prendre en compte que ce soit pour déterminer le volume du peuplement, l'influence réelle des compétiteurs, le rôle et le développement des racines suite au traitement. Une étude plus spécifique sur le sujet serait pertinente pour préciser les résultats obtenus.

Finalement de nouveaux enjeux émergent aujourd'hui qui pourraient contribuer à l'intensification de l'EC dans les peuplements naturels et créer de la valeur ajoutée au traitement d'EC. De récentes études ont par exemple démontré que les peuplements d'Epn productifs éclaircis séquestraient plus de carbone que les peuplements témoins (Keyser, 2010). La pression grandissante exercée sur les entreprises pour l'utilisation de la biomasse forestière pourrait aussi contribuer à l'intensification de l'EC et améliorer sa rentabilité suite à la prise de valeur des copeaux et des sciures (Zerbe, 2006).

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