UNIVERSITÉ DU QUÉBEC À MONTRÉAL

DYNAMIQUE ET SYLVICULTURE DES PINÈDES À PIN GRIS DE LA CEINTURE D'ARGILE DU NORD-OUEST QUÉBÉCOIS

THÈSE

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PAR

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RÉSUMÉ

La préoccupation des dernières années à l'égard d'un aménagement forestier adapté au site, s'inspirant de la dynamique naturelle ainsi que le manque de connaissances sur l'écologie du pin gris (*Pinus banksiana*) dans la ceinture d'argile du Nord-Ouest québécois et du Nord-Est ontarien ont motivé la présente étude. La thèse, rédigée par articles, porte sur la productivité des sites, la régénération préétablie, les facteurs limitant la régénération naturelle et sur les traitements sylvicoles applicables.

La croissance en hauteur du pin gris dans cette région varie selon trois classes de productivité évaluées à l'aide d'analyses de tiges : faible sur sols minces ou grossiers (12 à 13 m à 50 ans), forte sur till (17,5 à 18,5 m à 50 ans) et très forte sur argile (19 à 20 m à 50 ans). Les faibles différences entre till et argile s'expliquent par les faibles exigences écologiques du pin gris.

La régénération préétablie du pin gris se retrouve presque uniquement sous les peuplements sur sable et en quantité insuffisante pour assurer une régénération adéquate. La régénération préétablie totale (pin gris et autres espèces) ne diffère pas significativement entre les argiles et les tills. Les peuplements sur les sols minces et sur les sables ont des densités plus élevées, bien qu'insuffisantes. L'abondance de la régénération de l'épinette noire (*Picea mariana*) est liée positivement à la proportion de sable dans le dépôt et à un régime hydrique plus sec. L'abondance de la régénération préétablie du sapin baumier (*Abies balsamea*) et de l'épinette blanche (*Picea glauca*) est faiblement limitée par la distance d'une zone préservée du feu contenant des semenciers. Elle est aussi positivement liée à l'abondance du cerisier de Pennsylvanie (*Prunus pensylvanica* L.f.), laquelle est probablement associée à de petites ouvertures dans la canopée. Ces variables, bien que liées de manière significative à l'abondance de la régénération préétablie, n'ont pu donner des prédictions satisfaisantes.

L'étude d'ensemencement du pin gris montre que l'effet positif du scarifiage sur la germination est plus faible sur argile que sur till ou sur sable. Cela s'expliquerait par les températures plus fraîches à la surface du sol et par le taux d'humidité supérieur qui caractérisent les sols argileux. Après deux années de suivi, les semis de pin gris sont plus nombreux sur argile que sur sable. Cependant, la concurrence, principalement celle du tremble (*Populus tremuloides*), pourrait être critique pour la survie et la croissance des semis de pin gris à cause de son abondance et de sa persistance dans le temps.

Lors d'un essai de régénération naturelle du pin gris sur argile au moyen des déchets de coupe, les micro-sites scarifiés comportaient proportionnellement moins de semis que l'humus non perturbé. Ce résultat recoupe celui de l'expérience d'ensemencement, mais peut aussi s'expliquer par l'écartement des déchets de coupe lors du scarifiage. Ce mode de régénération permet d'obtenir un coefficient de distribution relativement bon et constitue une solution de rechange au reboisement du pin gris sur argile. Un regarni et un dégagement de la végétation concurrente pourraient compléter le traitement.

En annexe, un autre essai sylvicole avec le pin sylvestre (*Pinus sylvestris*) dans le sud de la Suède est présenté. Il a révélé qu'avec 200 semenciers à l'hectare, on peut obtenir une régénération naturelle abondante. Ce traitement sylvicole qui vise l'amélioration de la qualité du bois, serait aussi compatible avec la dynamique naturelle de l'espèce.

Les résultats de la présente thèse ont permis d'enrichir les connaissances fondamentales de la dynamique naturelle des peuplements de pin gris de la forêt boréale mixte de l'est du Canada. Ils permettent aussi de jeter les bases de stratégies sylvicoles tenant compte de cette dynamique.

Mots-clés: forêt boréale mixte, classification écologique, productivité, régénération préétablie, lit de germination, scarifiage.

INTRODUCTION GÉNÉRALE

1.1 SUJET

Le pin gris (*Pinus banksiana* Lamb.) est une des principales espèces d'arbre à valeur commerciale au Canada. Ses caractéristiques écologiques et sa sylviculture sont très bien documentées et ont fait l'objet de nombreux symposiums. Cependant, on connaît beaucoup moins bien les peuplements de pin gris de la ceinture d'argile du Nord-Ouest québécois et du Nord-Est ontarien. Ce manque de connaissances, combiné à la préoccupation, ces dernières années, d'adapter la sylviculture et l'aménagement forestier au site ainsi qu'au souci, plus récent, de concevoir des stratégies sylvicoles s'inspirant de la dynamique naturelle (Anonyme, 1995 ; Gouvernement du Québec, 1994), a motivé cette étude.

1.2 PROBLÉMATIQUE

Depuis quelques années, on assiste à un intérêt croissant envers l'aménagement forestier durable. Les six principaux critères d'aménagement forestier durable identifiés par le processus de Montréal lors de l'accord de Santiago (Anonyme 1995) sont les suivants :

1. Préservation de la biodiversité ;
2. Maintien de la santé et des processus ;
3. Maintien de la productivité ;
4. Protection de la qualité des eaux et des sols ;
5. Contribution aux cycles planétaires ;
6. Conservation des usages multiples pour la société.

Bien qu'en général, on s'entende sur ces critères, il existe plusieurs façon de les interpréter. L'aménagement écosystémique apparait être un concept intégrateur intéressant permettant d'intégrer ces différentes préoccupations. L'aménagement écosystémique, c'est l'intégration de la connaissance scientifique des relations écologiques dans un cadre sociopolitique et éthique complexe dans le but général de protéger l'intégrité des écosystèmes naturels à long terme. Ses buts spécifiques sont de maintenir des populations viables de toutes les espèces, de conserver tous les types d'écosystèmes à l'intérieur de leur aire de distribution naturelle, d'aménager sur un horizon temporel suffisant pour maintenir le potentiel évolutif des espèces et des écosystèmes et d'accomoder les besoins de l'homme à l'intérieur des ces contraintes (Salwasser, 1994 ; Hendrickson, 1995 ; Grumbine, 1994). Ce type d'aménagement exige une bonne connaissance de la dynamique des écosystèmes et la connaissances des moyens pour adapter la sylviculture à cette dynamique.

Sur le plan de l'acquisition des connaissances, dans les dernières années, les outils servant de cadre écologique de référence à l'aménagement forestier, tels que la classification et la cartographie écologiques, ont connu un développement important dans l'ensemble du Canada. Cependant, il existe encore trop peu d'informations sous forme de grilles de potentiels et de contraintes permettant d'appliquer concrètement ces outils. Au Québec, la cartographie forestière inclut depuis peu des renseignements issus de la classification écologique. Ce sont principalement le dépôt de surface et la classe de régime hydrique.

Sur le plan des approches sylvicoles adaptées à la dynamique naturelle, au Québec, malgré la tendance récente à favoriser la régénération naturelle, depuis l'élaboration des grands programmes de reboisement des années 1980, la régénération naturelle du pin gris a reçu peu d'attention. Elle n'est habituellement pas considérée comme une solution valable, que ce soit sur les sols à texture grossière ou sur les sols argileux. Par conséquent, les aménagistes forestiers reboisent habituellement le pin gris après coupe.

La question principale qui est posée dans le cadre de la présente thèse est la suivante : L'aménagement écosystémique est-il applicable aux pinèdes à pin gris de la ceinture d'argile du nord-ouest québécois ?

1.3 ÉTAT DES CONNAISSANCES

La dépendance du pin gris envers les feux de forêt pour son maintien dans les paysages naturels est largement reconnue (Gauthier, Bergeron et Simon 1996; Bergeron et Brisson, 1994; Despont et Paillette, 1992; St-Pierre et Gagnon, 1991; St-Pierre, Gagnon et Bellefleur, 1992; Cayford et McRae, 1983; Day et Woods, 1977). De même, les caractéristiques autécologiques impliquées dans cette dépendance ainsi que dans le manque fréquent de régénération naturelle préétablie et de régénération naturelle après coupe sont bien documentées. Elles ont trait à ses cônes sérotineux, à son intolérance à l'ombre (Burns et Honkala, 1990; Chrosciewicz 1990) et au besoin d'un lit de germination adéquat, habituellement de sol minéral mis à nu (Chrosciewicz, 1990). Le sérotinisme des cônes est cependant variable; en Abitibi, Gauthier, Bergeron et Simon (1993) ont montré que le sérotinisme est moins fréquent chez les jeunes arbres de petites tailles. De plus, le pin gris a de faibles exigences nutritionnelles, il peut s'établir sur des sites très secs, sa croissance juvénile est rapide et sa maturité sexuelle est hâtive (Burns et Honkala, 1990).

D'autre part, il existe une quantité considérable d'études portant sur les techniques de régénération naturelle des espèces de pins à cônes sérotineux, dont le pin tordu (*Pinus contorta* Dougl.) (Baumgartner *et al.*, 1985; Alexander, 1986; Cole, 1985; Sheppard et Alexander, 1983; Schabas, 1980; Thompson, 1978; Wang *et al.*, 1992) et le pin gris (Abrams et Dickman, 1982; Ball, 1975; Benzie, 1977; Boisvenue, Arnup et Archibald, 1994; Bowling et Goble, 1994; Bowling et Niznowski, 1991; Bruce et Sims, 1970; Cayford, 1958, 1957; Chrosciewicz, 1992, 1988; McRae, 1979; Riemenschneider, 1982; Sims, 1970; Smith et Brown, 1984; Walker et Sims, 1984; Whittle, Duchesne et Needham, 1997).

Parmi les techniques mentionnées dans les ouvrages sur le sujet, la plus courante consiste à laisser les branches sur le site après coupe, pour ensuite préparer adéquatement le sol (Walker et Sims, 1984; Cayford, 1957). Bruce et Sims (1970) ainsi que Crossley (1956) montrent que pour s'ouvrir, les cônes doivent être le plus près possible du sol sans toutefois être ensevelis sous les déchets de coupe. La chaleur près du sol est alors suffisante pour faire ouvrir les cônes. La technique de scarifiage la plus répandue consiste à tirer des chaînes d'ancre munies de tiges soudées à angle droit souvent accompagnées de barils dentés et lestés (Burns, 1983; Baumgartner *et al.*, 1985; Thompson, 1978). Cette technique permet à la fois d'étendre les déchets de coupe porteurs de cônes, de mélanger les horizons minéraux et organiques ainsi que de créer des placettes de sol minéral exposé. Elle a été utilisée dans les Provinces des Prairies et en Ontario au début des années 1980 (Smith et Brown, 1984) et au Québec dans les années 1970 (Demers, 1970). Le brûlage dirigé sous un couvert d'arbres semenciers est une autre technique utilisée, bien que moins fréquemment (Benzie, 1977).

La plupart des études susmentionnées ont été réalisées sur sable (Abrams, 1984; Walker et Sims, 1984; Riley, 1980, 1975; Chrosciewicz, 1971; Caveney et Rudolph, 1970; Sims, 1970;

Cayford et Hobbs, 1967) ou sur loam sableux (Zasada et Alm, 1970). Cayford (1958 et 1957) ont bien réalisé des essais sylvicoles de régénération naturelle sur argile au Manitoba qui ont eu un certain succès. L'auteur y souligne notamment l'importance de s'assurer que la machinerie utilisée pour le scarifiage n'écarte pas les branches porteuses de cônes à l'extérieur des sites scarifiés. Cependant, des conditions très différentes de celles rencontrées au Québec rendent difficile l'application des résultats; elles ont été réalisées dans une région ou la végétation après coupe est dominée par les graminées et la machinerie utilisée pour le scarifiage du sol, le « athens plough » est inusité au Québec.

La dynamique naturelle de la forêt boréale mixte de l'est du Canada est de mieux en mieux connue grâce, entre autres, aux travaux du Groupe de recherche en écologie forestière interuniversitaire (GREFi). La description du régime des feux de forêt ainsi que la description de la succession végétale constituent la base du modèle de la dynamique naturelle élaborée par Bergeron et Harvey (1997) pour la forêt boréale mixte de l'Est. Ces travaux ont cependant surtout touché la forêt mixte où le tremble et le bouleau sont importants et, outre les travaux de Gauthier et al. (1993), n'ont que peu touché les peuplements de pin gris.

Les peuplements de pin gris de la forêt boréale mixte de l'est du Canada sont caractérisés par la richesse des sols sur lesquels ils poussent et par la présence de strates de sous-bois abondantes. De plus, les peuplements sont purs ou mélangés au bouleau à papier et au peuplier faux tremble, ce qui les distingue de façon marquée des peuplements purs ou ne comportant qu'un sous-étage d'épinette noire que l'on retrouve souvent en forêt boréale sur les sols pauvres et qui supportent généralement un sous-bois ouvert d'éricacées et de mousses hypnacées.

Au delà de ces différences évidentes, on connaissait, au moment d'amorcer nos recherches, peu de choses sur la dynamique naturelle de ces forêts que ce soit sur leur croissance, leur structure, leur régénération ou sur les phénomènes qui influencent l'issue de la compétition entre le bouleau, le tremble et le pin gris. On sait que ces peuplements cèdent graduellement la place à des peuplements dominés par le sapin baumier, le bouleau blanc et les épinettes blanche et noire si aucune perturbation majeure, comme un feu de forêt, ne survient. Dans un contexte d'aménagement écosystémique inspiré de la dynamique naturelle, on ignore s'il est possible de régénérer naturellement le pin gris après coupe à partir de peuplements de début de succession et *a fortiori* à partir de peuplements des stades de succession plus avancés. On ignore aussi s'il est possible, par des traitements sylvicoles appropriés, de simuler le passage des peuplements de pin gris de début de succession à des peuplements mixtes des stades plus avancés tout en récoltant une certaine proportion de pin. On ignore, enfin, dans quelle mesure la sylviculture du pin gris de la forêt boréale mixte de l'Est devra recourir au brûlage dirigé, ou si des traitements sans feu suffiront pour maintenir ces écosystèmes dans un état fonctionnel.

Devant ces lacunes importantes dans nos connaissances, nous visons à répondre aux objectifs décrits dans la prochaine section.

1.4 OBJECTIFS ET HYPOTHÈSES

Notre premier objectif était d'effectuer une évaluation par type écologique de la croissance en hauteur du pin gris. La productivité étant susceptible d'influencer l'ensemble de la dynamique forestière, elle nous est apparue une caractéristique fondamentale des forêts qui mérite investigation. La principale hypothèse qui découle de cet objectif est la suivante : la croissance du pin gris est meilleure sur les sites riches même si cette espèce est réputée peu exigeante.

Le second objectif était d'évaluer la régénération préétablie sous des peuplements de pin gris, par type écologique. Nous supposons que la régénération préétablie du pin gris est quasi absente peu importe la qualité de la station. Nous posons comme hypothèse que l'abondance de la régénération préétablie des autres espèces arborescentes sous les peuplements de pin gris varie selon les exigences de chaque espèce quant à la lumière, à la qualité des sites (type écologique) et selon la distance des zones préservées du feu dont est issu le peuplement de pin gris.

Le troisième objectif était de déterminer les facteurs qui limitent le succès de la régénération naturelle du pin gris. Nous émettons l'hypothèse qu'elle est d'abord limitée par le sérotinisme. Diverses éléments, tel que l'abondance de la litière feuillue et la compacité du sol, nous permettent aussi de penser que la régénération s'établit plus difficilement sur argile que sur les sols à texture plus grossière. Nous tenterons donc de vérifier l'influence des substrats sur la germination et la survie. Enfin, nous supposons que l'établissement est difficile sur les sols argileux en raison de l'importance de la compétition pour la lumière.

Le quatrième objectif était de tester à l'échelle opérationnelle des techniques de régénération naturelle du pin gris, compatibles avec une approche d'aménagement écosystémique. Les hypothèses qui découlent de cet objectif sont les suivantes : i) le scarifiage du sol est essentiel à la régénération naturelle du pin gris en quantité suffisante sur argile; ii) l'ébranchage sur le site devrait permettre une régénération naturelle du pin gris plus abondante que l'ébranchage au chemin.

1.5 STRUCTURE DE LA THÈSE

La présente thèse est constituée de cinq articles dont les quatre premiers forment le coeur de la thèse et le dernier est présenté en annexe:

1. Béland, M. et Y. Bergeron. 1996. Height growth of jack pine (*Pinus banksiana*) in relation to site types in boreal forests of Abitibi, Quebec. *Journal canadien de recherche forestière.* 26 : 2170-2179.

2. Béland, M. et Y. Bergeron. 1993. « Ecological factors affecting abundance of advanced growth in jack pine (*Pinus banksiana* Lamb.) stands of the boreal forest of northwestern Quebec ». *Forestry Chronicle.* 69(5) : 561-568.

3. « Cutting, scarification and competing vegetation affect germination and survival of jack pine seedlings on three soil types of the boreal mixedwood of northwestern Quebec ». Prêt pour publication dans le *Journal canadien de la recherche forestière*.

4. Béland, M. , Y. Bergeron et R. Zarnovican. 1999. « Natural regeneration of jack pine following harvesting and site preparation in the Clay Belt of northwestern Quebec ». *Forestry Chronicle*. 75(5) : 821-831

5. Béland, M., E. Agestam, P.M. Ekö, P.Gemmel et U. Nilsson. 2000. « Scarification and seedfall affect natural regeneration of Scots pine under two shelterwood densities and a clear-cut in southern Sweden ». *Journal scandinave de la recherche forestière*. 15(2) : 247-255.

Le premier article, intitulé en français « Croissance en hauteur du pin gris (*Pinus banksiana*) selon le type écologique dans les forêts boréales de l'Abitibi, au Québec », visait à répondre au premier objectif. Cet article est essentiellement basé sur la comparaison de données de croissance en hauteur provenant d'analyses de tiges réalisées sur trois arbres dominants sur des stations réparties sur les 11 principales combinaisons de dépôt de surface et de classe de régime hydrique où pousse le pin gris dans la région à l'étude. Une extension de ce projet, utilisant la même méthodologie sur le terrain, visait à comparer la croissance en hauteur du pin gris selon la présence d'espèces compagnes telles que le bouleau à papier et le peuplier faux-tremble. Une étudiante de maîtrise, Marie-Hélène Longpré, a rédigé, dans le cadre de ce projet, un article non inclus dans la thèse (Longpré *et al.*, 1994) auquel le candidat a participé comme coauteur.

Le deuxième article, intitulé en français « Facteurs écologiques affectant l'abondance de la régénération préétablie dans les peuplements de pin gris (*Pinus banksiana* Lamb.) de la forêt boréale du nord-ouest du Québec », visait à répondre au deuxième objectif. Nous nous sommes servi du même plan d'échantillonnage que pour le premier article, mais nous avons cherché à comparer l'abondance et la composition de la régénération préétablie haute (1 à 5 cm de diamètre à hauteur de poitrine) entre les mêmes types écologiques. En plus de ces comparaisons, nous avons réalisé des régressions linéaires multiples afin de déterminer l'importance relative des facteurs de sol et des facteurs liés à la composition de la forêt ou à la proximité des semenciers.

Le troisième article, intitulé en français « Effets de la coupe, du scarifiage et de la végétation concurrente sur la germination et la survie de semis de pin gris sur trois dépôts de surface de la forêt boréale mixte du nord-ouest québécois », visait à répondre au troisième objectif. Cet article expose les résultats d'une expérience menée dans des forêts de pin gris où nous avons procédé à un ensemencement contrôlé d'une quantité connue de graines de pin gris dont la germination et l'établissement des semis ont été suivis pendant deux étés après traitement. Cette étude était réalisée à la fois sur argile, sur till et sur sable.

Le quatrième article, intitulé en français « Régénération naturelle du pin gris après coupe et préparation de terrain dans la ceinture d'argile du nord-ouest québécois », visait à répondre au quatrième objectif. Il présente les résultats d'un essai sylvicole réalisé sur sol argileux seulement. Le terrain à l'étude était d'une superficie totale de 36 ha. Il comportait des secteurs ébranchés sur le site et d'autres ébranchés au chemin ainsi que des secteurs qui ont subi soit aucune scarification, soit une ou l'autre des deux techniques de scarification étudiées. La densité et le coefficient de distribution des semis de pin gris ont été suivis pendant deux étés après traitement. En plus des comparaisons entre traitements, le lien entre les lits de germination créés et la hauteur des déchets de coupe, d'une part, et la présence des semis, d'autre part, est étudié.

Le cinquième article, intitulé en français « Le scarifiage et la pluie de graines affectent la régénération naturelle du pin sylvestre sous deux densités de coupe d'ensemencement et dans une coupe à blanc du sud de la Suède », est présenté en annexe. Il a été réalisé lors d'un stage en Suède. L'objectif principal de l'étude était d'évaluer, à l'échelle opérationnelle, l'effet de la densité de pin sylvestre (*Pinus sylvestris*) laissée après une coupe d'ensemencement ainsi que l'effet de la séquence de coupe de l'abri sur la régénération d'une forêt dont le bois serait de meilleure qualité. L'article se concentre sur le succès de la régénération du pin sylvestre quatre années après la coupe initiale. L'inclusion de cette étude dans la thèse visait à illustrer la complémentarité entre une approche sylvicole centrée sur la production ligneuse et une approche sylvicole inspirée de la dynamique naturelle. La réalisation de cette étude visait aussi à aller chercher l'expertise scandinave dans le domaine des études de régénération naturelle. Comme l'article 4, il présente une étude sylvicole qui a aussi permis au candidat de constater les différences et les similitudes entre le pin gris et le pin sylvestre sur le plan de l'écologie et de la sylviculture.

Articles

ARTICLE 1 : CROISSANCE EN HAUTEUR DU PIN GRIS (*PINUS BANKSIANA*) SELON LE TYPE ÉCOLOGIQUE DANS LES FORÊTS BORÉALES DE L'ABITIBI, AU QUÉBEC

Béland, M. et Y. Bergeron. 1996. « Height growth of jack pine (*Pinus banksiana*) in relation to site types in boreal forests of Abitibi, Quebec ». *Journal canadien de la recherche forestière,* vol. 26, p. 2170-2179.

2.1 RÉSUMÉ

Nous avons réalisé une étude stratifiée selon les types écologiques exprimés par une combinaison de dépôt de surface et de régime hydrique afin de tester leur utilité pour prédire la croissance en hauteur du pin gris. Les courbes de hauteur en fonction de l'âge, produites à partir de l'analyse de tiges d'arbres dominants sur 96 stations d'échantillonnage, ont permis de définir trois classes de productivité potentielle du pin gris. La classe de faible productivité comprend les tills minces bien drainés, les sols organiques minces sur roc et les sables à régimes hydriques bon et modéré. La productivité sur les tills profonds de régimes hydriques bon à mauvais et sur les argiles de régimes hydriques bon à imparfait peut être qualifiée respectivement de forte et de très forte. La grande différence sur le plan de la croissance en hauteur entre ces deux derniers types de sol et ceux de la classe de faible productivité ne permet pas de définir une classe de productivité modérée. Les divers types écologiques présentent des courbes de croissance en hauteur très semblables, à l'exception des sables bien drainés, qui montrent un retard de croissance en bas âge. Sur les sites secs, particulièrement sur les tills bien drainés, la densité et la surface terrière sont plus élevées. Les rendements réels des peuplements naturels sur tills et sur argiles seraient donc très semblables, bien que le rendement sur tills puisse être réparti sur un plus grand nombre de tiges que sur argiles. Contrairement à nos attentes, les résultats n'ont montré que de faibles différences entre les tills et les argiles en ce qui concerne l'indice de qualité de station. Nous croyons que les faibles exigences écologiques du pin gris et sa forte capacité d'enracinement font en sorte que la profondeur du sol disponible pour les racines et la facilité avec laquelle celles-ci pénètrent le sol sont des critères plus importants que la richesse du sol. Bien que le type écologique, défini par la combinaison du dépôt de surface et du régime hydrique, a semblé plus détaillé que nécessaire, il a permis une prédiction adéquate de la productivité potentielle des pinèdes à pin gris.

2.2 ABSTRACT

Analysis of jack pine height growth in northwestern Québec was stratified by site type, a combination of surface deposit and moisture regime class, in order to test the utility of site type as a predictor of jack pine growth. Height/age curves produced from stem analyses of dominant trees from 96 sample plots produced three jack pine productivity classes. The low productivity class includes moderately dry shallow tills, shallow organic deposits over bedrock and fluvio-glacial sands with moisture regime classes moderately dry and fresh. Moderately dry to very moist deep tills and moderately dry to moist clays are classified as having high and very high productivity, respectively. The large difference in height growth between these latter two groups and the low productivity class precluded the definition of a "moderate" productivity class. The form of the height-growth curves was very similar among site types except for sandy, moderately dry sites which showed a growth delay at young ages. On dry sites, particularly on well-drained tills, density and basal area were higher than on clay sites. Although volume yield of natural stands on tills and clays would thus be similar, it would likely be spread among a greater number of stems on tills. There was little difference in site index (SI) between natural jack pine growing on clays and tills. The low nutrient and moisture requirements and strong tap root of jack pine may make soil depth and bulk density more important factors than soil richness. Although site type, expressed as a combination of surface deposit and moisture regime class, may be more detailed than necessary, it provided an adequate prediction of potential jack pine productivity.

2.3 INTRODUCTION

One of the principal advantages of an ecological site approach to site classification over the site index concept has been acknowledged for a number of decades (Jameson, 1965): tree height and volume growth patterns vary from site to site, whereas site-index recognized only a family of harmonic curves representing all sites types (Gevorkiantz, 1956 ; Plonski, 1974 ; Heger, 1968). Later studies accounted for the presence of polymorphism (Carmean and Lenthall, 1989 ; Niznowski, 1994 ; Goelz and Burk, 1992 ; Ker and Bowling, 1991). Still, height growth curves are better adapted for showing polymorphism and height growth patterns than are site-index estimation equations which may be more precise for estimating tree height at index age (Carmean, 1975). Jameson (1965) recommended that height age curves and yield tables be developed within the framework of ecological site units, where variability between sites is recognized. Soil moisture regime, nutrient regime and texture were, in his opinion, the primary factors responsible for tree growth.

To facilitate the management of forest cutovers, Cauboue (1988) developed a guide to species selection for plantations based on soil texture and moisture regime by utilizing information found on Québec's site type maps. However, this guide does not indicate the yield expected on different site types. Conversely, yield estimates provided in Québec's forest management handbook (Anon., 1987) and used for allowable cut calculations do not integrate permanent site variables.

The Forest Inventory Service of the Québec Ministry of Natural Resources (MNR) intends to complete a site classification of the entire Abitibi region by the end of the decade, using surface deposit type and moisture regime class as the principal site descriptors. This information will be integrated with forest inventory maps to produce integrated forest ecosystem maps (Bergeron *et al.*, 1992 and Bélanger, Bergeron and Camiré, 1992). Schmidt and Carmean (1988) showed relationships between jack pine (*Pinus banksiana* Lamb.) site index and several specific site variables in north central Ontario. However, we are not certain how these Ontario results apply to the site classification system used by the Québec Ministry of Natural Resources.

Given the high level of investment generally required for softwood establishment on cutovers and the commercial importance of jack pine in Abitibi, a study of jack pine growth stratified by surface deposit and moisture regime class was initiated in 1990. The objectives of this study were 1) to investigate the usefulness of surface deposit type and moisture regime class as permanent site predictors of jack pine productivity in natural stands, and 2) to determine which site types are most suited for intensive management of jack pine. More specifically, we evaluated the effect of moisture regime class, type of surface deposit and depth, forest composition and stand density on jack pine site index and other indicators of actual jack pine productivity in natural, non-managed stands.

2.4 METHODS

2.4.1 Study area

The study area is primarily located in the Hébécourt, Privat and Duparquet Townships (78-79°W, 48°N). All three townships are in the southern part of the clay belt in northwestern Quebec, a large physiographic region characterized by lacustrine clay deposits left by the proglacial lakes Barlow and Ojibway (Vincent and Hardy, 1977). Unlike most of the clay belt to the north and west where poorly drained soils predominate, this area is dominated by moderately dry to fresh lacustrine clay deposits. Coarse-textured deposits include lacustrine sands and reworked tills. Thin, dry organic soils over bedrock and thick, wet organic deposits are also common (Bergeron *et al.*, 1982).

The climate of the region is cold and continental with mean annual temperature and precipitation of 0.4°C and 800-900 mm, respectively (Environment Canada, 1982). The mean number of frost-free days is 64, although occasional frosts during the summer months are not uncommon.

Rowe (1972) places the region within the Missinaibi-Cabonga zone (B.7), dominated by a balsam fir (*Abies balsamea* (L.))-black spruce (*Picea mariana* (Mill.) B.S.P.)-white birch (*Betula papyrifera* Marsh.) climax association. However, probably as a result of the abundance of rich clay deposits, the area is characterized by forests of balsam fir and white birch with more white spruce (*Picea glauca* (Moench) Voss) than black spruce on mesic sites (Bergeron and Bouchard, 1984).

A previous study in the Hébécourt townships in Abitibi has identified a vast area originating following a fire in 1923 (Dansereau and Bergeron, 1993). Brisson (1992) studied jack pine growth in this area along a topographical gradient on reworked till sites. We used the same methodology to extend the sampling to a greater diversity of site types, including clays, shallow tills, and shallow organic soils over bedrock. The site type maps of this township (Béland *et al.*, 1992) allowed almost even distribution of sampling over a variety of site types where jack pine grows (maximum age at time of sampling: 65 years) and allowed random selection of about half of the plots. An extension of the sampling to two other townships (Privat and Duparquet, maximum age: 74 and 84 years, respectively) permitted sampling of fluvio-glacial sands.

Lacustrine clays are compact, very fine-textured deposits, with good water holding capacity and few stones. Virtually all tills in the region were modified to some extent by lake Barlow-Ojibway. They have a texture varying from sandy clay loam to loamy sand, with rather high stoniness and occur at higher elevations than the clay soils. At higher elevations, the tills become shallower and ultimately rock outcrops covered by shallow organic deposits become apparent.

2.4.2 Field data

Ninety six 20 m X 20 m sample plots were located in stands of variable density (Fig. 2.1) but in which more than 50% of the basal area is composed of jack pine (Fig. 2.2). Stems over 1.3 m in height were tallied and DBH was measured so as to determine density and basal area by species.

Soil pits were dug at each plot to identify the surface deposit, its depth and moisture regime class. B horizon samples were taken for subsequent texture analysis. Identification of surface deposits was conducted on the basis of geomorphologic origin as described in Robert and Saucier (1988). Moisture regime classes (1-dry, 2-moderately dry, 3-fresh, 4-moist and 5-very moist) were determined using a field key developed by Brais and Camiré (1992) for the Abitibi-Témiscamingue region. The distribution of sample plots among the different site types is presented in Table 2.1.

2.4.3 Stem analyses

Three dominant jack pines without major defects within the first 97 percentiles of DBH were cut for stem analysis. Disks were collected at stump height, 0.4 m, 1.3 m and every meter up to a minimum stem diameter of 2 cm, as per Zarnovican (1985) and Zarnovican and Ouellet (1986). The size and number of growth rings were measured along 4 radii on every disk. An electronic caliper coupled to the computer program “Analtige”, developed at the Laurentian

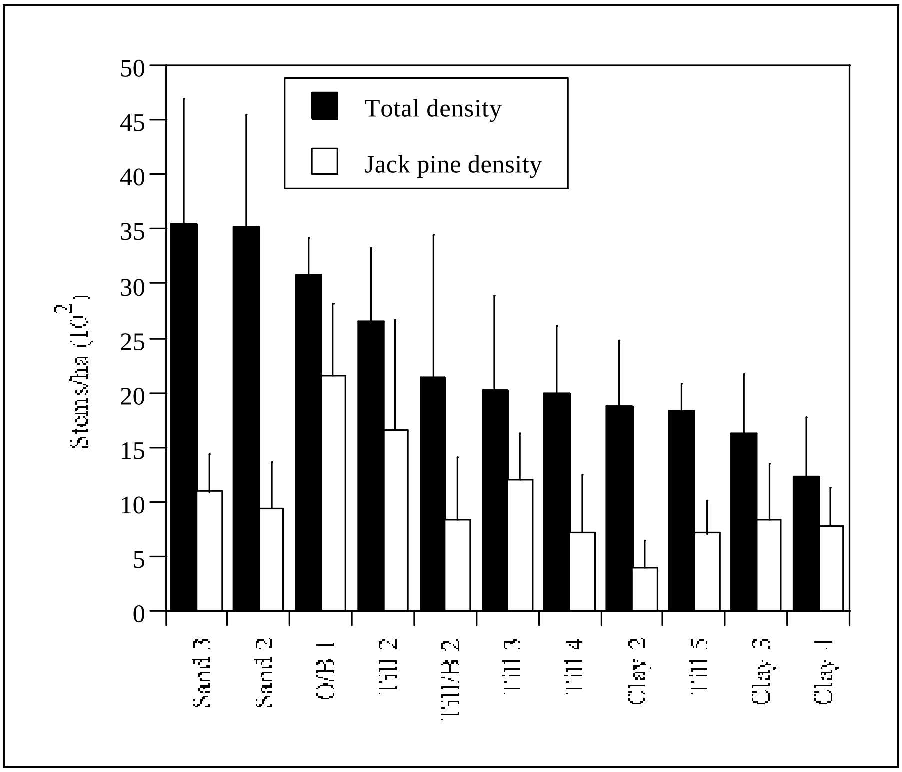

Figure 2.1. Total density and jack pine density for each site type. Surface deposit codes: Till/B = shallow glacial till over bedrock; O/B = shallow organic soil over bedrock.

Forestry Centre (Zarnovican, Ouellet and Gendron, 1988), was used to capture and compile the radial growth data and conduct primary calculations of diameter, height and volume at 5-year intervals. Heights were corrected using methods suggested by Carmean (1972) and Newberry

(1991). Height at the site index (SI) reference stump age of 50 years, was averaged for the three dominant trees on each sample plot.

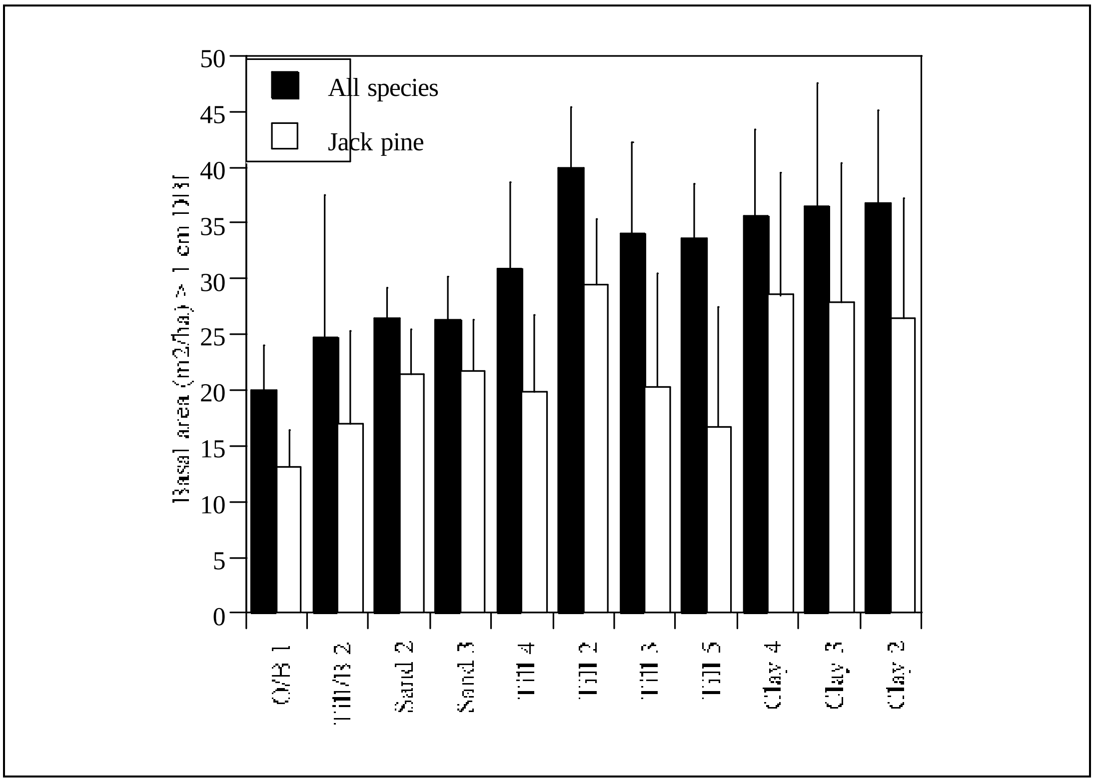

Figure 2.2. Mean total and mean jack pine basal area by site type. Surface deposit codes: Till/B = shallow glacial till over bedrock; O/B = shallow organic soil over bedrock.

Tableau 2.1 Sampling distribution

Site type		
Surface deposit	Moisture regime	Number of plots
Clay	2	9
Clay	3	11
Clay	4	7
Till	2	11
Till	3	16
Till	4	9
Till	5	4
Till/B	2	8
Sand	2	6
Sand	3	9
O/B	1	6
Total:		96

Note: Till/B = Shallow till over bedrock,
O/B = Shallow organic soil over bedrock

Variation in height growth within a stand is partly due to the recruitment of trees of one crown class into another. Thus the selection of trees should be limited to the dominant crown class. Since sampling procedures in the construction and use of site-index curves should be applicable to mixed stands of various densities, sample trees selected by DBH instead of crown class may be the least biased indicators of site quality (Heger, 1968). Additionally, due to the small variability observed between trees growing on the same plot during juvenile growth, and in order to better discriminate the growth patterns associated with the different landforms throughout the life of the tree, no correction was applied to eliminate variation due to stand establishment. Stump age was thus used, despite the recommendations of Heiberg and White (1956), Carmean and Lenthall (1989) and Schmidt and Carmean (1988) to use age at breast height. However, translation of the abscissa towards the right was applied to each of the eleven height-growth curves so they could be plotted as a function of breast-height age for comparisons with other height-growth curves that used breast-height age.

2.4.4 Data analyses

It is well established in the literature that height at a reference age (50 years for most tree species of northeastern North America) is a reliable index of growth potential (Carmean, 1975; Spurr and Barnes, 1980 ; Carmean, Hahn and Jacobs, 1989). The average SI for each site type was first compared using analysis of variance and orthogonal contrasts. Height-growth curves were then formulated using Korf's growth function (Zarnovican, 1979):

[1]

$$\text{Height} = A \exp\left(\frac{-k}{1-n}\,\text{age}^{(1-n)}\right)$$

where A, k and n are parameters of the model. The parameter "A" defines the curve's upper asymptote whereas the parameters "k" and "n" define the position of the inflexion point. Data for height over age were fitted on the Korf's growth equation separately for each site type using the NLIN procedure of the SAS statistical package (SAS, 1985). In order to derive unbiased estimates of the growth curve, data older than the greatest common age for each site type were deleted (Curtis, 1964). Comparison of 95 % confidence intervals for each parameter enabled us to compare the shape of the height-growth curves between site types. An indication of the proportion of the variance explained by the regression was inferred from the correlation (Pearson coefficient) between predicted and observed values of height.

Since textures of tills, shallow tills and fluvio-glacial sands evaluated in the field were considerably more variable than those of clay deposits, these coarse deposits were also analysed in the laboratory using the hydrometer method (Kalra and Maynard, 1991). Consequently, site types on coarse deposits were classified on the basis of their sand content (< 80 % and > 80 %). An additional contrast tested the pertinence of this finer division of deposits in predicting jack pine productivity. We then examined the influence of stand composition on these results.

To estimate standing crop production, total stand basal area was also compared by site type. No correction was applied to basal area of stands on sand due to their advanced age (6 plots 84 years old and 9 plots 74 years old in contrast with 65-67 years old for the other site types). Plonski (1956) showed that basal area starts to reach a maximum at 60 years and remains almost constant for many years afterwards, suggesting that such a correction would have been negligible.

2.5 RESULTS AND DISCUSSION

2.5.1 Comparison of site indices between site types

Analysis of variance revealed that site type explains 65% of observed variability in mean site index (SI) (Table 2.2). Other attempts to test soil-site classifications in regard to predictability of site index have had variable success (Klinka and Carter, 1990 ; LeBlanc and Towill, 1989a). The prime site key developed by Jones (1986) failed to stratify plots into separate ranges of jack pine site productivity (LeBlanc and Towill, 1989a). Considerable site index variation occurred within prime land (sub)classes, except for shallow soils less than 30 cm deep. Klinka and Carter (1990) found significant differences between site indices of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands in British Columbia stratified according to the soil moisture and soil nutrient regime of the biogeoclimatic ecosystem classification.

Tableau 2.2 Analysis of variance of mean jack pine site index by site type.

Source	d.f.	Sum of squares	*F* value	
Site type	10	638.23	15.85	***
Error	85	342.32		
Total	95	980.56	$r^2 = 0.65$	
Contrasts				
Clay *vs* till	1	31.01	7.70	**
Clay 2-3-4 *vs* sand 2-3	1	348.69	86.58	***
Sand *vs* till	1	212.97	52.88	***
Sand *vs* O/B 1	1	3.60	0.89	
Sand *vs* till/B 2	1	0.13	0.03	
Till/B 2 *vs* till 2	1	86.61	21.51	***
Till/B 2 *vs* O/B 1	1	3.98	0.99	
Till *vs* O/B 1	1	156.21	38.79	***
Moisture regime 2 *vs* 3	1	1.69	0.42	
Till 2-3 *vs* till 4-5	1	0.10	0.03	

NOTE: ** $P < 0.01$, *** $P < 0.001$. Till/B = Shallow till over bedrock, O/B = Shallow organic soil over bedrock

Schmidt and Carmean (1988) found a wide range of jack pine site indices within large soil groups, resembling the surface deposits of this study, but did not find any significant differences in mean site index between groups. Relationship of site index to specific site variables was then separately analyzed for each of the soil groups. Multiple regressions showed that site index was closely related to soil depth and coarse fragment content, suggesting these to be the primary factors related to site quality for jack pine; on glacial outwash sands, site index also decreased with increasing slope. LeBlanc and Towill (1989b) tested the equations of Schmidt and Carmean over a larger territory and found that the equations successfully predicted jack pine site index values for stands growing on glacio-fluvial deposits but were not as accurate on shallow soils and on deep morainal sites.

Low mean height (site index) values at 50 years of age (Fig. 2.3) occurred for shallow organic soils, for shallow well-drained tills, and for fluvio-glacial sands (12 and 13 m at 50 years). Orthogonal contrasts confirm that these site-index values are significantly lower than the site-index values for other sites despite the large standard deviations associated with each site type. Lower site indices possibly were a result of the low soil fertility and/or the limited rooting space in shallow soils. This is in accordance with Schmidt and Carmean (1988) who found poor site indices for shallow to bedrock soils, soils having large amounts of coarse fragments, and soils having shallow depths to root restricting layers. Green and Grigal (1979) also found lower jack pine productivity on shallow tills than on deep tills. Schafer (1988a and 1988b) found that effective soil depth was the most reliable predictor of *Pinus elliottii* Engelm. and *Pinus pinaster* Ait. height growth.

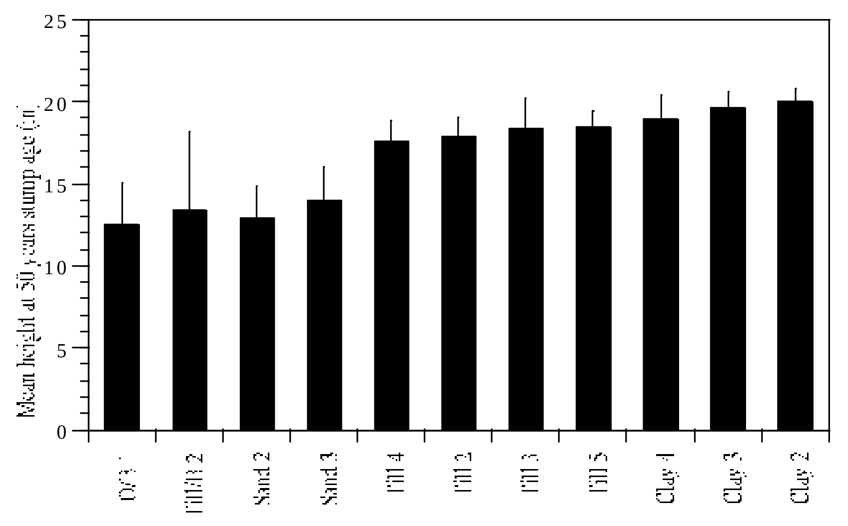

Figure 2.3. Mean jack pine site index by site type. Surface deposit codes: Till/B = shallow glacial till over bedrock; O/B = shallow organic soil over bedrock.

Large differences in site index between tills and clays were expected. Clays are rich, fine-textured soils with little stoniness while tills tend to have considerable variability in soil nutrients and contain variable amounts of coarse fragments. Although differences between site indices on clays (max 19-20 m) and tills (17.5-18.5 m) were statistically significant, they were not as large as expected. Jack pine's low nutrient and water requirements (Pawluk and Arneman, 1961) may partly explain the similarities in height growth. Moreover, Schmidt and Carmean (1988) showed that depth to root restricting layer and coarse fragment content was closely related to site index differences with tills. We attempted to take these factors more into account by separating tills into fine- and coarse-textured classes. This increased the explained variance by only 6% and revealed no further significant difference in jack pine productivity (Table 2.3). Using a sub-set of our data, Brisson (1992) demonstrated that slope length, which influences the degree of lateral drainage (Cartier, Prairie and Bergeron, 1992), may be more important than texture in determining productivity on tills.

Chrosciewicz (1963) found increases in jack pine site index with decreasing particle size on sandy soils. He found that jack pine exhibited peak performance on moist to moderately dry and fresh soils, however, differences were not statistically significant. Similarly, in this study, the effect of moisture regime on site index (differences between classes 2 and 3 and between tills 2-3 and tills 4-5), was not significant.

Site type may have a greater influence on growth of more demanding tree species such as white spruce or aspen (*Populus tremuloides* L.). Hamilton and Krause (1985) state that jack pine has high water-use efficiency and low demand for soil fertility. Their results suggest that a wet moisture regime which restricts rooting depth, is a frequent growth-limiting factor in New Brunswick jack pine plantations.

2.5.2 Influence of stand composition

Actual yield, in contrast to potential yield, might be related to numerous factors such as stand density and composition. Béland and Bergeron (1993) describe ecological factors related to species composition for trees with diameter at breast height (DBH) greater than 5cm. An analysis of covariance (Steel and Torrie, 1980) using the basal area of other tree species on each plot was used as an attempt to remove possible variation caused by stand composition and thus isolate the influence of surface deposit and moisture regime class. However, the contribution of the covariate was too weak to justify their inclusion into the models (Table 2.4). The relationships between the basal area of companion species and jack pine site index also was tested after eliminating variance due to site type. Only the basal area of black spruce (Table 2.4) retained a weak negative residual effect on site index probably related to the poor site quality of stands with black spruce. The negligible effect of companion species might not be representative of natural stands of the region, but rather the result of plot selection biased towards (although far from totally) pure jack pine. Range of variation in stand composition within a site type was not sufficient to show a strong effect. Longpré *et al.* (1994) discuss the question of presence of companion species (white birch and trembling aspen) and the growth of jack pine from the same region.

Tableau 2.3 Analysis of variance of mean site index by site type modified to account for the variable texture of tills.

Source	d.f.	Sum of squares	*F* value	
Site type	14	693.51	13.98	***
Error	81	287.05		
Total	95	980.56	$r^2 = 0.71$	
<u>Contrast</u>				
Coarse-textured tills *vs* fine-textured tills	1	11.73	3.31	n.s.

NOTE: Coarse textured tills < 80% sand; fine-textured tills >80% sand. *** $P < 0.001$

Tableau 2.4 Analysis of covariance of site index between site type with basal area of aspen, black and white spruce, balsam fir and pin cherry (*Prunus pensylvanica* L.f.) as covariates.

Source		d.f.	Sum of squares Type I	*F* value		Sum of squares Type III	*F* value	
Aspen:	Model	11	640.4	14.38	***			
	Error	84	340.1					
	Total	95	980.56	$r^2 = 0.65$				
Site type		10	638.23	15.76	***	572.05	14.13	***
Aspen b.a.		1	2.18	0.54	n.s.	2.18	0.54	n.s.
Black spruce:	Model	11	657.1	15.52	***			
	Error	84	323.4					
	Total	95	980.6	$r^2 = 0.67$				
Site type		10	638.2	16.58	***	504.9	13.11	***
Black spruce b.a.		1	18.9	4.91	*	18.9	4.91	*
White spruce	Model	11	639.2	14.30	***			
	Error	84	341.4					
	Total	95	980.6	$r^2 = 0.65$				
Site type		10	638.2	15.70	***	613.1	15.09	***
White spruce b.a.		1	0.93	0.23	n.s.	0.93	0.23	n.s.
Balsam fir	Model	11	638.7	14.27	***			
	Error	84	341.9					
	Total	95	980.6	$r^2 = 0.65$				
Site type		10	638.2	15.68	***	601.6	14.78	***
Balsam fir b.a.		1	0.46	0.11	n.s.	0.46	0.11	n.s.
Pin cherry:	Model	11	639.7	14.33	***			
	Error	84	340.9					
	Total	95	980.6	$r^2 = 0.65$				
Site type		10	638.2	15.73	***	582.3	14.35	***
Pin cherry b.a.		1	1.4	0.36	n.s.	1.4	0.36	n.s.

Note: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

2.5.3 Form of height-growth curves

In order to see if height at 50 years of age (site index) is representative of tree growth at any age, average curves by site type have been modeled using Korf's growth function (Zarnovican, 1979). The modeled curves (Fig. 2.4) divide into two broad groups. The first group was composed of the clays and deep tills, and the second group was composed of the low productivity site types. The curves of the first group tend to diverge slightly, indicating that small differences between height of tills and clays at 50 years of age may become more important at a more advanced age. The curves for the second group have more variable height-growth patterns since sandy sites show a growth delay in the younger ages. Apart from this obvious difference for dry sandy sites, all of the curves have a similar shape. All equations have R values greater than 0.80 except for shallow tills (R = 0.60) (Table 2.5).

The slight divergence observed among the curves of the high productivity class (Fig. 2.4) is not significant because the confidence intervals of the parameters of Korf's growth function overlap except for the extreme values (Table 2.5). Parameter "A" for moderately dry sands was lower than those for moderately dry and fresh clays, and parameter "n" was higher than those of fresh, moist clays, shallow tills and shallow organic soil over bedrock. Parameter "k" was noticeably higher on moderately dry sand, although all intervals overlap. Results from Korf's function confirm the growth delay observed especially on moderately dry sand where the trend can be considered consistent for all 6 plots since the Pearson correlation coefficient between observed and predicted values is 0.91. These results confirm those of Shea (1973) who noticed that trees on soils with deep root penetration such as sands, had slower initial growth but that growth was sustained longer than on other sites.

Sites of similar (Stansfield, McTague and Lacapa, 1991) as well as sites of different site index (Heiberg and White, 1956) can at times show different age-related growth trends. Both situations seem to happen in the present study where the moderately dry sandy sites show a growth trend different from shallow soils of the same productivity class, and also different from some of the high productivity clays. Considering that the main companion tree species of jack pine on sandy sites is the slower growing black spruce, early suppression of jack pine is probably not responsible for the observed growth delay. On the other hand, the greater depth of the water table or of finer textured layers (Farrish, Doolittle and Gamble, 1990) relative to depth of roots and the slower development of a moss layer on sand are plausible explanations.

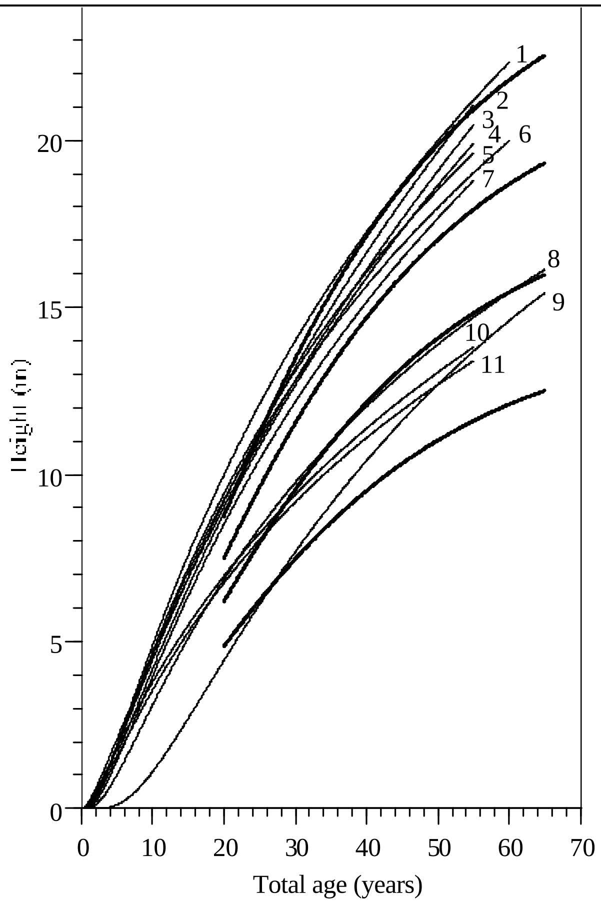

Figure 2.4. Average jack pine height-growth curves for 11 site types modeled using Korf's growth function and the Plonski site-class curves. 1: Moderately dry clay; 2: Fresh clay; 3: Moist clay; 4: Very moist till; 5: Fresh till; 6: Moderately dry till; 7: Moist till; 8: Fresh sand; 9: Moderately dry sand; 10: Moderately dry shallow till on bedrock; 11: Dry shallow organic soil on bedrock. The dark lines indicate the limits of the three site classes of Plonski (1974).

2.5.4 Comparison of height-growth patterns with other jack pine studies

The yield tables used in Quebec for jack pine (Boudoux, 1978) are derived from the balanced harmonized height-growth curves of Gevorkiantz (1956) formulated by Lundgren and Dolid (1970) for the Lake States. These curves are similar to those of Plonski (1974), formulated by Payandeh (1991), for northern Ontario and those of Bella (1968) for Manitoba.

Plonski's curves are anamorphic height-growth curves derived from stem analyses and did not indicate any soil-related information. For the high- and very high-productivity class, height growth in Abitibi is steeper and slightly less curvilinear than the Plonski curves (Fig. 2.4). For the low productivity class, the fit between Plonski's curves and height growth in Abitibi seems poor due to differences in curve shape among the site types.

Tableau 2.5 Coefficients for the Korf (Zarnovican, 1979) model, with 95% confidence limits, for total age curves independently fitted to data for 11 site types

Site type	R	A		k		n	
Sand 2 (6 plots)	0.91	40.75	± 20.705	12.710	± 11.070	1.701	± 0.244
Sand 3 (9 plots)	0.83	47.266	± 30.392	4.233	± 2.989	1.496	± 0.206
Clay 2 (9 plots)	0.97	101.612	± 40.878	2.871	± 0.744	1.388	± 0.077
Clay 3 (10 plots)	0.96	259.6	± 0.0	2.2	± 0.5	1.28	± 0.07
Clay 4 (8 plots)	0.94	527.446	± 1285.7	1.755	± 0.835	1.222	± 0.143
Till 2 (11 plots)	0.96	75.959	± 28.723	3.027	± 0.857	1.415	± 0.085
Till 3 (16 plots)	0.94	88.945	± 40.488	2.828	± 0.822	1.391	± 0.089
Till 4 (9 plots)	0.96	87.178	± 48.016	3.273	± 1.196	1.411	± 0.111
Till 5 (4 plots)	0.98	134.270	± 90.038	2.720	± 0.873	1.350	± 0.097
Till/B 2 (7 plots)	0.60	287.696	± 2741.7	1.55	± 2.0	1.22	± 0.39
O/B 1 (6 plots)	0.80	59.285	± 85.896	2.489	± 2.204	1.374	± 0.2

NOTE: "R" is Pearson's correlation coefficient between observed and predicted values.
Till/B = Shallow till over bedrock, O/B = Shallow organic soil over bedrock

Carmean and Lenthall (1989), in a study about jack pine height-growth curves in north central Ontario, have concluded that curve shape is not related to soil groups but rather to site index. Trees on poor sites showed an almost linear height-growth pattern, but as site index improves, height growth became more curvilinear. Our results do not confirm this because height growth before 65 years of age in the high productivity class in Abitibi seems steeper and much less curvilinear than the curves from Carmean and Lenthall (1989) (Fig. 2.5). Niznowski (1994) extended the study of jack pine height growth throughout northern Ontario using breast-height age and found differences in curves shape that were related to soil groups. However, he judged these differences to be minor and concluded that a single polymorphic set of site-index curves was valid throughout northern Ontario for all mineral soil groups.

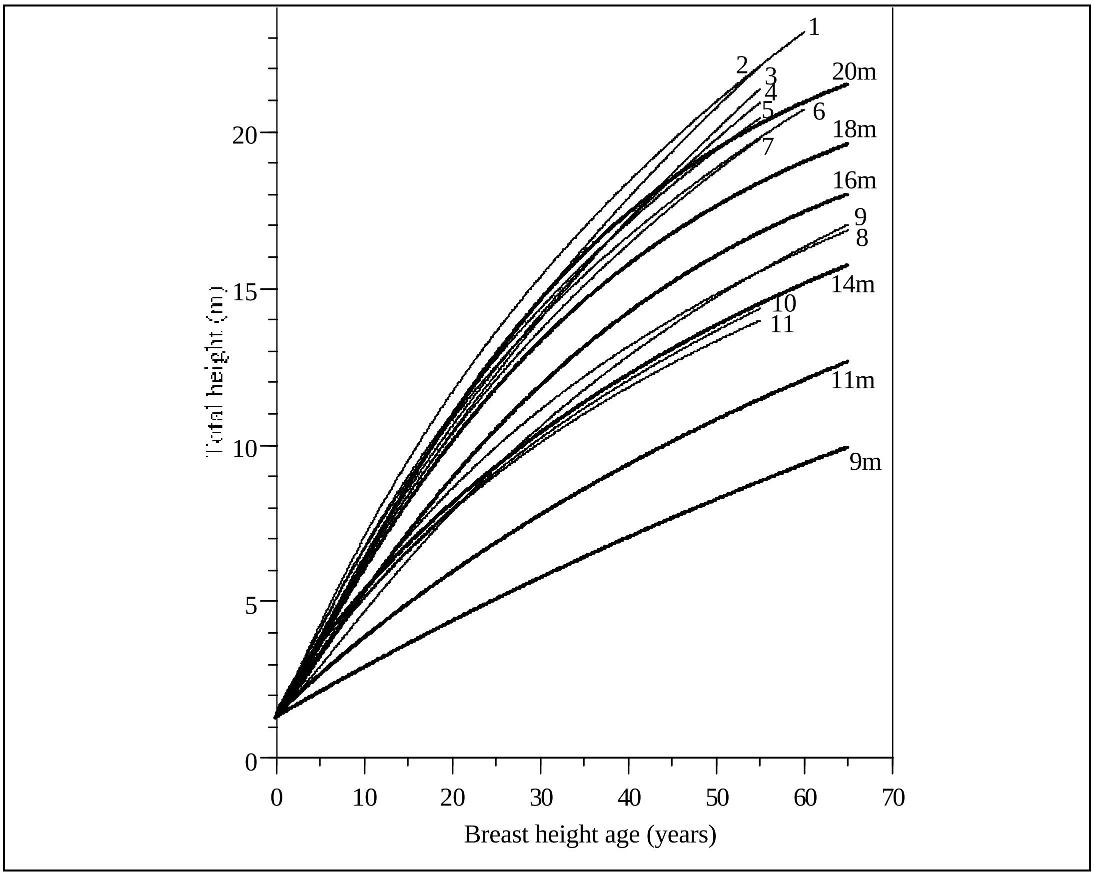

Figure 2.5. Average jack pine height-growth curves by site type modeled using Korf's growth function and average height-growth curves, independently computed for six different site-index classes in Carmean and Lenthall (1989) as a function of breast height age. 1: Moderately dry clay; 2: Fresh clay; 3: Moist clay; 4: Very moist till; 5: Fresh till; 6: Moderately dry till; 7: Moist till; 8: Fresh sand; 9: Moderately dry sand; 10: Moderately dry shallow till on bedrock; 11: Dry shallow organic soil on bedrock. The dark lines indicate the curves drawn from Carmean and Lenthall (1989).

When breast-height age is used instead of total age (Fig. 2.5), the growth delay on moderately dry sands is not apparent. We argue that the use of breast-height age for computing height-age curves for jack pine might have obscured the differences observed between site types in terms of level of site index and in terms of curve shape. Carmean and Lenthall (1989) and Niznowski (1994) suggested, pooling all the soil types of their data set, that site-index curves were more precise when breast-height age was used. They then suggested, using breast-height age, that there were no significant polymorphic height-growth patterns associated with soil types. We think that demonstration of no polymorphic height-growth patterns should be performed using total age. Then, if such patterns appear, the demonstration of the better precision of height-growth and site-index curves when breast-height age is used should be performed separately for each set of data. The argument in favor of the use of breast-height age is the need to eliminate the portions of the tree life below breast height where height growth is slow and erratic. In our opinion, slow early height growth is not a reason for eliminating this portion of tree life. Furthermore, we have no reason to think or any data showing that early height growth in jack pine is erratic when plots compared are from the same site type. According to Carmean and Lenthall (1989), such height growth variations can happen due to non site factors such as early competition and suppression, allelopathic compounds, damage due to frost, mammals, insects and disease or small microsite differences. However, if variations in early height growth are due to varying competition or allelopathic compounds by ericaceous shrubs, a consistent feature of the sandy sites (Bergeron *et al.*, 1983), we should probably consider the growth variations as site dependent. On the other hand, if variations in growth are due to intraspecific competition for light, they should probably be considered as site independent. It is the role of the dendrometrician to try and reveal the relative influence of site factors and non-site factors on growth through every stages of tree life. We do not think that better fit of the models, if better fit there is, justifies the use of breast-height age for height-growth and site-index curves in jack pine.

2.5.5 Comparison of standing crop production

The results presented for site index and height growth are valid in the evaluation of potential jack pine stand productivity. The observed differences in potential productivity are only representative of real differences if stocking is optimal or with similar stocking between site types (Monserud, 1984). Otherwise, indicators of standing crop production of natural stands must be sought among other growth parameters available. According to Mader (1963), volume growth of red pine *(Pinus resinosa* Ait.) plantations is better correlated with environmental factors than height growth although volume data are less precise. If this is true for jack pine, evaluation of volume could lead to an even higher explained variance. Since the heights of trees other than those cut for stem analyses were not measured, estimation of standing crop production in m^3/ha would have to be based on equations drawn from the literature. Because such an estimation may not be indicative of our study area, we have chosen to compare total stand densities, jack pine densities and total basal area.

Stand densities are generally higher on less productive sites types (Fig. 2.1). Moreover, among the site types with high productivity, moderately dry till sites have the highest jack pine densities and total stand densities. Contrary to what was observed for site index, total basal areas (all species combined) on till and clay site types (Fig. 2.2) were not significantly different (Table 2.6). These results suggest that productivity of natural stands on tills, is only slightly lower from that on clays although production may be dispersed among a greater number of stems (Fig. 2.1). Variable densities may be due to better seedling establishment success or to reduced mortality during stand development due to lower herbaceous, shrub and tree competition.

2.6 CONCLUSIONS

Results indicate that among the site types most frequently encountered in the Abitibi region, there are three jack pine potential productivity classes. The low productivity class ($SI < 14$ m) includes well-drained shallow tills, shallow organic deposits over bedrock and fluvio-glacial sands with moisture regime class 2 and 3. Deep tills with moisture regime classes 2 to 5 and clays with moisture regime classes 2 to 4 can be classified as high ($17.5 < SI < 18.5$) and very high ($19 < SI < 20$ m), respectively. They can be considered the best suited site types for intensive management of jack pine in this region. The large height-growth difference between these two classes and the low productivity class precluded the definition of a "moderate" productivity class. Furthermore, the limits of the moderate productivity class of Plonski (1974) coincide with the limits of this gap in productivity. The form of the height-growth curves was very similar among all site types except for the moderately dry sandy sites which showed a growth delay at very young ages.

Tableau 2.6 Analysis of variance of mean total basal area by site type.

Source	d.f.	Sum of squares	*F* value	
Site type	10	3121.11	4.98	***
Error	85	5327.46		
Total	95	8448.57	$r^2 = 0.37$	
<u>Contrasts</u>				
Clay *vs* till	1	58.23	0.93	
Clay 2-3-4 *vs* sand 2-3	1	1009.75	16.11	***
Sand *vs* till	1	695.41	11.10	**
Sand *vs* O/B 1	1	177.09	2.83	
Sand *vs* till/B 2	1	10.13	0.16	
Till/B 2 *vs* till 2	1	997.45	15.91	***
Till/B 2 *vs* O/B 1	1	44.36	0.71	
Till *vs* O/B 1	1	1112.41	17.75	***
Moisture regime 2 *vs* 3	1	55.22	0.88	
Till 2-3 *vs* till 4-5	1	155.05	2.47	

NOTE: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$. Till/B = Shallow till over bedrock, O/B = Shallow organic soil over bedrock

Contrary to our expectations, the significant difference in site index between natural jack pine growing on clays and tills was small. The greatest differences found were on drier sands and shallow tills or organic soils over bedrock. We believe that the low ecological requirements and strong tap root of jack pine make soil depth and bulk density more important than soil richness. Thus, jack pine does not take great advantage of the high growth potential (high nutrient content) of glacio-lacustrine clays.

The small differences in potential productivity observed between clays and tills are probably not representative of differences in actual volume yields in natural stands. On dry sites, particularly on well-drained tills, stand density for jack pine is proportionally higher. Consequently, while actual yield of natural stands on till and on clay may be similar, volume is probably distributed among a greater number of stems on tills.

Carmean (1996) states that accurate estimation of site index using soil survey or ecosystem classification systems can only be accomplished if: (a) the units defined in the system are closely related to site index; (b) these units have relatively little internal variation in site index; and (c) these units accurately identify the full range of site index found for a species in a particular area or region. Site type expressed as a combination of surface deposits and moisture regime (as presented on the site type maps of the Québec Ministry of Natural Resources) satisfactorily meets these requirements and is thus adequate for predicting potential productivity of jack pine stands. Comparisons of height-growth patterns and basal area of the present study have shown that site types, however, probably are too detailed for jack pine which is not so demanding for soil richness. This does not question the appropriateness of the level of detail given by site types for other applications.

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ARTICLE 2 : FACTEURS ÉCOLOGIQUES AFFECTANT L'ABONDANCE DE LA RÉGÉNÉRATION PRÉÉTABLIE DANS LES PEUPLEMENTS DE PIN GRIS (*PINUS BANKSIANA* LAMB.) DE LA FORÊT BORÉALE DU NORD-OUEST DU QUÉBEC

Béland, M. et Y. Bergeron. 1993. « Ecological factors affecting abundance of advanced growth in jack pine (*Pinus banksiana* Lamb.) stands of the boreal forest of northwestern Quebec ». *Forestry Chronicle*, vol. 69, no 5, p. 561-568.

3.1 RÉSUMÉ

Selon la littérature, la régénération naturelle des peuplements de pin gris (*Pinus banksiana* Lamb.) au Québec n'est suffisante que dans 4 % des cas pour les peuplements purs. Cette proportion peut atteindre 33 % pour les peuplements mélangés. Cette étude vise à vérifier l'utilité des types écologiques définis par le Ministère des Forêts du Québec pour prédire l'abondance de la régénération naturelle sous des peuplements de pin gris purs et mélangés de l'Abitibi, dans le nord-ouest du Québec. Les arbres de plus de 1.3 m de hauteur et de moins de 5 cm de diamètre à hauteur de poitrine ont été dénombrés à l'intérieur de 102 placettes de 20 m x 20 m afin d'évaluer la densité de la régénération préétablie. Celle-ci ne diffère pas significativement entre les deux grands types de dépôts de surface de la région, soit les dépôts argileux et les dépôts de tills. Seuls les dépôts organiques et de tills minces sur roc et les dépôts de sables fluvio-glaciaires ont démontré des densités significativement plus élevées. La prédiction de l'abondance de la régénération prétablie peut être facilitée à l'aide de variables écologiques telles que la texture du sol, le régime hydrique, la distance d'une source de graines et la composition du couvert arborescent. L'abondance de la régénération de l'épinette noire (*Picea mariana* (Mill.) B.S.P.) est reliée positivement à la proportion de sable dans le dépôt et à un régime hydrique plus sec tandis que celle du sapin baumier (*Abies balsamea* (L.) Mill.) et de l'épinette blanche (*Picea glauca* (Moench) Voss.) sont reliées négativement à la distance d'une zone préservée du feu contenant des semenciers. L'abondance du cerisier de Pennsylvanie (*Prunus pensylvanica* L.f.), probablement associée à de petites ouvertures dans la canopée, est reliée positivement à l'abondance de la régénération du sapin baumier et de l'épinette blanche. Le pin gris se régénère presque exclusivement dans les peuplements sur sable; une proportion plus élevée de feuillus dans le couvert semble liée négativement à la régénération préétablie du pin gris. Les variables stationnelles étudiées, bien qu'ayant démontré certaines relations significatives avec l'abondance de la régénération préétablie (R^2 maximum de 0.32) qui ont pu être améliorées par l'inclusion des variables de composition du peuplement (R^2 maximum de 0.38), n'ont pu mener à des modèles prédictifs satisfaisants.

3.2 ABSTRACT

Natural regeneration in jack pine (*Pinus banksiana* Lamb.) stands in Quebec is only sufficient 4 % of the time and up to only 33 % of the time in mixed stands. This study evaluates the usefulness of forest ecological types as defined by the Quebec Ministry of Forests in predicting abundance of advanced growth in pure and mixed jack pine stands of the Abitibi region, in northwestern Quebec. Trees above 1.3 m in height and up to 5 cm DBH were tallied in 102 quadrats of 20 X 20 metres to evaluate advanced growth densities. No significant difference in advanced growth densities was observed between the two main types of surficial deposit of the region, lacustrine clays and glacial tills. Only shallow till and organic deposits over bedrock and fluvio-glacial sands showed significantly higher advanced growth densities. Abundance of black spruce (*Picea mariana* (Mill.) B.S.P.) regeneration is positively associated with the proportion of sand in the soil profile and to drier sites; advanced growth of balsam fir (*Abies balsamea* (L.) Mill.) and white spruce (*Picea glauca* (Moench) Voss.) are weakly associated with the distance to a fire-preserved zone containing seed trees. Abundance of pin cherry (*Prunus pensylvanica* L.f.), probably associated with canopy openings, is positively linked with abundance of balsam fir and white spruce advanced growth. Jack pine regeneration by means of advanced growth occurs almost exclusively in jack pine stands on sand; higher proportions of hardwoods in the overstory appear to be negatively linked to jack pine advanced growth. Although the ecological variables studied showed some significant relationships with advanced growth abundance (maximum $R^2 = 0.32$) which were slightly improved with stand composition variables (maximum $R^2 = 0.38$), no satisfactory predictive model could be implemented.

3.3 INTRODUCTION

Clear-cutting methods in much of Quebec have been modified recently to protect advanced growth and minimize site damage by forest machinery. Given these modifications (notably, regularly spaced skidding or forwarding trails) there is an important need to develop ways to predict the amount and quality of advanced regeneration. Most natural regeneration present after clear-cutting of softwood stands in eastern Canada originates from advanced growth (Doucet, 1988).

Over much of its range, jack pine (*Pinus banksiana* Lamb.) has serotinous cones which require high temperatures such as those encountered in forest fires to open and disperse their seeds (Burns and Honkala, 1990). Although some proportion of cones are non-serotinous, the abundant plant competition and the unfavourable seedbeds prevent them from germinating under forest cover (Chrosciewicz, 1990). For some reason, the other boreal tree species also often show poor advanced growth. Consequently, jack pine stands almost always have insufficient total advanced growth (Doucet, 1988). Only 7% of jack pine stands in Quebec have advanced softwood stocking levels over 75% (Ruel, 1991) and only 4% of jack pine stands have adequate advanced growth (Tremblay, 1987). In mixed stands, the proportion may be better (33%), but little is known about the ecological factors that are responsible for higher advanced growth densities. As a result, managers are inclined to use site preparation and planting to regenerate jack pine stands.

Host *et al.* (1987) observed definite patterns of natural regeneration of lower Michigan hardwood trees on different landforms and parent materials. Harvey and Bergeron (1989 , 1990), in their evaluation of advanced growth and natural regeneration after clear-cutting in late-seral balsam fir (*Abies balsamea* (L.) Mill.) – white birch (*Betula papyrifera* Marsh.) – spruce (*Picea* spp.) forests of the same area as the present study found some significant differences between ecological site types. Since the Quebec Ministry of Forests' program of forest ecological type classification of the Abitibi region will be completed by the end of the decade, it was considered pertinent to extend this test of the approach to jack pine stands.

The objective of the present study is to compare coniferous and deciduous advanced growth among ecological types in pure and mixed jack pine stands in an area that had been classified by Bergeron *et al.* (1983) and mapped by the Quebec Ministry of Forests (Béland *et al.*, 1992). Secondly, ecological variables such as texture of B horizon, moisture regime class, composition of the overstory and distance from seed source are evaluated for introduction into a simple predictive linear regression model.

3.4 METHODS

3.4.1 Study area

The study area is located in three townships in northwestern Quebec (Hébécourt, Privat and Duparquet) in the southern part of the Clay Belt (78–79°W, 48°N) (Fig. 3.1), a large physiographic region characterized by lacustrine clay deposits left by proglacial lakes Barlow and Ojibway (Vincent and Hardy, 1977). However, unlike most of the Clay Belt to the north and west where poorly drained soils predominate, this area is dominated by moderately dry to fresh lacustrine clay deposits. Coarse-textured deposits include lacustrine sands, reworked tills and fluvio-glacial deposits. Shallow, dry organic soils over bedrock and thick, wet organic deposits are also common (Bergeron *et al*., 1982).

The climate of the region is cold and continental with a mean annual temperature of 0.4°C and a mean annual precipitation of 800–900 mm (Environment Canada, 1982). The mean number of frost-free days is 64, although occasional frosts during summer months are not uncommon.

Rowe (1972) places the region within the Missinaibi-Cabonga zone (B.7), dominated by a balsam fir – black spruce (*Picea mariana* (Mill.) B.S.P.) – white birch association. However, probably as a result of the abundance of rich clay deposits, the area is characterized by forests of balsam fir and white birch with more white spruce (*Picea glauca* (Moench) Voss) than black spruce on mesic sites (Bergeron and Bouchard, 1984).

Fire history reconstruction by Dansereau and Bergeron (1993) revealed a large area in Hébécourt Township that originated from a fire in 1760. Part of this area burned again in 1923 and has regenerated into jack pine, aspen (*Populus tremuloides* Michx.) and white birch stands as well as into mixed stands.

3.4.2 Field data

The data for this study were gathered from 1988 to 1991 for a study of jack pine productivity on 16 ecological types. Eighty-seven 20 m X 20 m sample plots were located in Hébécourt Township on reworked till deposits, glacio-lacustrine clays and shallow organic soils over bedrock, in a forested area burned in 1923 (maximum age: 65). Fifteen similar sample plots were also located in Privat and Duparquet Townships on fluvio-glacial sands (maximum ages: 74 and 84, respectively). The number of plots per ecological type ranged from one to sixteen.

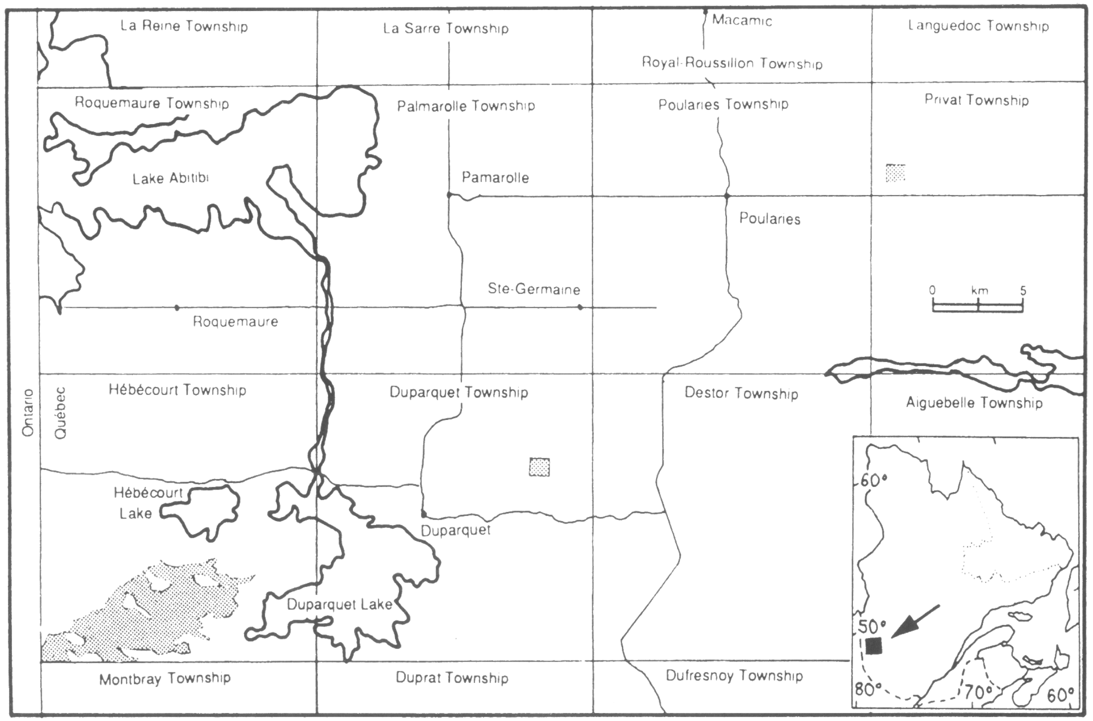

Figure 3.1 Location of the three study areas (shaded) in northwestern Québec.

Stems over 1.3 m in height were tallied for entire sample plots (400 m^2). Soil pits were dug for identification of surficial deposits and moisture regime class and to collect B horizon samples for laboratory textural analysis. Topographic position, slope and aspect were noted. Moisture regime classes (1–dry, 2–moderately dry, 3–fresh, 4–moist and 5–very moist) were evaluated with field keys developed by Brais and Camiré (1992). The ecological type (a relatively homogenous land unit in terms of soil and chronosequence (Jurdant *et al*., 1977)), was identified in the field by determining the type of surficial deposits and the moisture regime class.

3.4.3 Data analysis

Stand composition data on trees larger than 5 cm DBH were analysed in order to group sampled stands according to species and basal area. Cluster analysis using the Steinhaus similarity index and intermediary linkage (cut level = 0.77) was employed (Legendre and Legendre, 1984). Densities of advanced growth were evaluated from counts of stems higher than breast height and with DBH smaller than 5 cm. Multiple comparisons of means of advanced growth densities among ecological types were computed using analysis of variance and Duncan's multiple-range test (Scherrer, 1984). Ecological types with too few sample plots (less than four) were not considered in the analysis. In order to homogenize the variances between ecological types, density data were transformed according to the following equation (Legendre and Legendre, 1984):

$$y' = y^{0.25}$$

Minimum distances to fire-preserved zones were measured using a map of fire limits (Dansereau and Bergeron, 1993) as a possible index of distance to seed source, for all sample plots except those on fluvio-glacial sands, for which fire history was not available. Distances were treated as logarithms to reflect the logarithmic decrease in seed dispersal with distance from the source. Sand, silt and clay proportions in the B horizon were evaluated by the hydrometer method (Kalra and Maynard, 1991) for fluvio-glacial sands and till deposits. A sand value of 0% and a clay value of 100% was assigned to glacio-lacustrine clays and a sand value of 100% and a clay value of 0% has been assigned to shallow organic soils over bedrock for which textural analyses were not done. Multiple linear regressions of advanced growth densities were computed using moisture regime class, sand, silt and clay proportion in the B horizon, slope and distance to fire-preserved zone. In order to test the effect of tree composition, basal area of tree species are afterwards added to the model. The choice of variables to be included in the regression models was done by the *maxr* method (Legendre and Legendre, 1984). Care was taken not to include correlated variables. Since distance to fire-preserved zones was not evaluated for plots on fluvio-glacial sands and since soil texture data, for some sample plots on glacial tills, were missing, computations of multiple linear regressions would be limited to 84 plots. In order to include all possible plots (102 plots), missing values were attributed the value of the mean computed from other plots.

3.5 RESULTS AND DISCUSSION

3.5.1 Description of stand composition

Ten stand composition groups were formed according to similarities in basal areas of trees over 5 cm DBH (cut level = 0.77) (Table 3.1). The most frequently observed stand composition is strongly dominated by jack pine with some proportion of white birch and black spruce and minor proportions of aspen (group 2). A very similar stand composition (group 1) is encountered everywhere except on poor sites such as fluvio-glacial sands, shallow tills and organic soils over bedrock and is only distinguished from group 2 by its slightly larger basal area (Table 3.2).

Stand groups 4 and 8 were also frequently observed. Group 4 is characterized by dominance of jack pine and aspen and is mainly encountered on fresh sands, on fresh to very moist glacial tills and on shallow organic soils over bedrock. Group 8 has a moderate basal area and is characterized by jack pine dominance and presence of white birch and aspen. It is mainly encountered on glacio-lacustrine clays. Groups with the largest proportions of white birch (6, 7, 9, 10) occur mainly on dry shallow organic soils over bedrock.

These latter soils and fresh to moist glacial tills have variable stand compositions as indicated by the rather large number of groups represented (Table 3.2). Apart from varying seed availability, this can be explained by site heterogeneity. Shallow organic soils over bedrock are characterized by a varying topography with pockets of mineral soil or organic matter and patches of exposed bedrock; although moisture regime class is usually identified as dry, pockets of organic matter may be poorly drained. Glacial tills have been deposited directly by the glaciers through erosion of bedrock without major sorting by the melting waters; they thus lead to soil textures and topography that are variable.

Table 3.1 Mean basal area (m^2/ha) by species of trees > 5 cm DBH for each of 10 stands types.

#	Group Description	n	Species										
			Pj	Sb	Bf	Sw	Bw	Pot	Mr	Cp	Pob	Ab	Total
1	Pj, high b.a.	19	36.8	2.2	0.2	0.2	2.9	0.2	0.1	0.0	0	0	42.6
2	Pj, moderate b.a.	45	24.2	2.9	0.0	0.3	3.5	0.7	0.4	0.0	0.1	0.0	32.1
3	Pj and Sb	1	23.4	18.9	0	1.5	1.4	0	0	0	0	0	45.2
4	Pj and Pot	12	13.3	3.9	0.6	0.3	0.6	8.5	0	0	0	0	27.2
5	Sb, Pj and Bw	1	9.17	9.18	0	0	3.0	0	0	0	0	0	21.4
6	Pj, Bw, Sb and Pot	2	11.1	6.3	0	0	10.4	2.2	1.9	0	0	0	31.9
7	Bw, Pj and Mr	1	13.2	0.3	0	0	15.3	1.3	3.4	0	0	1.8	35.3
8	Pj, Bw and Pot, moderate b.a.	10	15.5	2.2	0.0	0.0	4.9	2.9	1.6	0.1	0	0.3	27.5
9	Pj, Bw and Pot, low b.a.	6	9.0	0.5	0	0.5	5.7	2.6	0.6	0	0	0.1	19.0
10	Bw, Pj, Sb and Pot	5	6.7	1.3	0	0.2	10.0	1.1	0.2	0	0	0	19.5

Abbreviations: b.a. = basal area ; Pj = jack pine; Sb= black spruce ; Bf = balsam fir; Sw = white spruce; Bw = white birch; Pot = aspen; Mr = red maple; Cp = *Prunus pensylvanica* L.f.; Pob = *Populus balsamifera* L.; Ab = *Fraxinus nigra* Marsh.

Tableau 3.2 Relative frequency distribution of stand composition groups in each ecological type

			Stand composition group									
Surface deposit	MR class	n	1	2	3	4	5	6	7	8	9	10
FGS	2	6		0.83						0.17		
	3	9		0.78		0.22						
GLC	2	5	0.4	0.4						0.2		
	3	11	0.27	0.36						0.27	0.09	
	4	8	0.38	0.25						0.25	0.13	
GT	2	11	0.27	0.64	0.09							
	3	16	0.13	0.38		0.38		0.06		0.06		
	4	9	0.11	0.44		0.22	0.11			0.11		
	5	4	0.5	0.25		0.25						
T/B	2	6		0.67						0.17	0.17	
O/B	1	6		0.33		0.17		0.17	0.17			0.17

Abbreviations: MR = moisture regime; FGS = fluvio-glacial sand; GLC = glacio-lacustrine clay; GT = glacial till; T/B = shallow glacial till over bedrock; O/B = very shallow organic soil over bedrock.

Other species were too infrequently sampled to allow any valuable conclusion about their site preferences (Table 3.1) : Pin cherry (*Prunus pensylvanica* L.f.), a short-lived, early successional tree, is rarely present in 50-year old stands ; white spruce and balsam fir are late-successional species and are only present as regeneration ; other species are usually associated with rich and very moist sites where jack pine is usually absent (*Fraxinus nigra* Marsh. and *Populus balsamifera* L.) or with warm microclimate (*Acer rubrum* L.) (Bergeron and Bouchard, 1984).

3.5.2 Advanced growth

Density and composition of advanced growth

Levels of advanced growth, for all species studied, differed significantly between ecological types (Table 3.3). Average densities of total advanced growth ranged from 7.7 to 1070.9 stems/ha (Table 3.4). Because sampling did not include seedlings smaller than 1.3 m in height, estimation of real seedling densities has to be completed from field data of Bergeron *et al.* (1983). For equivalent or slightly higher 1–5 cm DBH stem densities (100 to 1 880 stems/ha) in 16 jack pine stands, they found total seedling densities (<5 cm DBH) ranging from 1 240 to 35 270 stems/ha (mean = 15 975 stems/ha).

Tableau 3.3 Analysis of variance summary of mean density of advanced growth (1–5 cm DBH) for each ecological type.

	Total	Bf	Sb	Pj	Sw	Pot	Bw
MS (model)	13.46	7.07	23.08	8.99	2.98	1.98	6.02
df (model)	10	10	10	10	10	10	10
MS (error)	1.86	2.20	1.92	0.51	1.10	0.86	2.20
df (error)	84	84	84	84	84	84	84
F-value	7.25	3.21	12.00	17.56	2.70	2.29	2.74
P	0.000	0.002	0.000	0.000	0.006	0.020	0.006

Note: Statistics computed from transformed values.

Abbreviations : Bf = balsam fir ; Sb = black spruce ; Pj = jack pine ; Sw = white spruce ; Pot = aspen ; Bw = white birch ; MS = mean square ; df = degree of freedom.

Tableau 3.4 Mean density (stems/ha) of advanced growth (1-5 cm DBH) for each ecological type

Total	Bf	Sb	Pj	Sw	Pot	Bw
FGS3	GLC3	O/B1	FGS3	GLC3	FGS3	O/B1
1070.9	41.7	648.1	88.9	6.0	5.0	139.2
O/B1	GLC2	FGS3	O/B1	GT2	O/B1	GLC2
865.1	36.6	488.9	13.4	5.4	0.6	49.7
FGS2	GLC4	FGS2	FGS2	GT5	GLC3	GT2
511.3	14.3	488.7	1.1	0.2	0.2	42.6
GT2	GT2	GT2	GT4	T/B2	GLC2	FGS3
305.8	8.0	74.1	0	0.1	0.03	32.0
GLC2	O/B1	GT5	GLC4	GT3	GT3	GT5
241.5	3.2	14.7	0	0.1	0	16.5
GLC3	T/B2	T/B2	GT2	GLC2	GT2	GLC3
142.2	2.9	2.7	0	0.02	0	11.4
GT5	FGS3	GT3	GT3	GLC4	FGS2	GT4
96.8	1.2	2.3	0	0	0	8.3
GLC4	GT3	GLC2	GLC3	FGS3	GT4	GT3
60.3	0.1	1.9	0	0	0	6.3
GT3	GT4	GT4	GT5	FGS2	GLC4	T/B2
54.9	0.0	0.7	0	0	0	1.8
GT4	FGS2	GLC3	T/B2	GT4	T/B2	GLC4
24.8	0	0.4	0	0	0	0.8
T/B2	GT5	GLC4	GLC2	O/B1	GT5	FGS2
7.7	0	0.3	0	0	0	0

Note : Statistics computed on transformed values. Values in table are however back-trandformed. Vertical lines indicate means that are not significantly different ($P = 0.05$, Duncan's multiple range test). Ecological types are described in terms of surficial deposit (see key on Table 2.2) and moisture regime class (1 = dry, 5 - very moist).

Harvey and Bergeron (1989, 1990), working in the same area as the present study, found an average of 65 000 stems/ha (<5 cm DBH) of advanced softwood growth in fir-birch-spruce forests. This figure more than doubles the 30 000 stems/ha (<7.5 cm DBH) preharvest density threshold of Zelazny and Hayter (1991) necessary to achieve 60% stocking immediately after harvest of spruce-fir stands. It is thus evident from our results that total advanced growth levels found in jack pine stands are much lower than in fir-birch-spruce forests of the same study area and are also too low to achieve sufficient stocking immediately after harvest.

The highest levels of total advanced growth were found on fresh fluvio-glacial sands (mean of 1 070.9 stems/ha) and on dry shallow organic soils over bedrock (mean = 865.1 stems/ha). This advanced growth is composed mainly of black spruce and jack pine and some proportion of white birch in the case of the former, and of black spruce and white birch and some proportion of jack pine in the case of the latter (Table 3.4). These levels are significantly different from other ecological types, except moderately dry fluvio-glacial sands and moderately dry glacial tills, which are intermediate.

The lowest levels of total advanced growth were found on moderately dry shallow tills over bedrock (mean = 7.7 stems/ha). These levels are significantly different from those found on fresh glacio-lacustrine clays, moderately dry glacio-lacustrine clays, glacial tills and fluvio-glacial sands and from dry shallow organic soils over bedrock and fresh fluvio-glacial sands. No significant differences were found between the glacio-lacustrine clay group and the glacial till group (Table 3.4).

The most abundant species present are balsam fir and white birch on glacio-lacustrine clays and on moderately dry shallow glacial tills, and black spruce on fluvio-glacial sands and on moderately dry glacial tills (Table 3.4). These results confirm those of Harvey and Bergeron (1989, 1990) who found no significant difference in total conifer advanced growth between coarse surficial deposits and clay deposits. They also noted that most hardwood advanced growth consisted of white birch.

The multiple linear regression equation selected to predict total advanced growth shows that moisture regime class is the single most important factor, with a negative regression coefficient of -0.55 (R^2 = 0.30), leading to high levels of advanced growth on better-drained sites (Table 3.5). The equation also indicates small negative regression coefficients with the proportion of silt in the B horizon (-0.09). Total basal area (-0.03) and basal area of aspen (0.06) increased the R^2 to 0.38.

Tableau 3.5 Selected simple and multiple linear regression equations to predict advanced growth in jack pine stands of northwestern Québec from site and stand variables

	n	R^2
TOT_{ag}		
5.7 - 0.55 MOIST - 0.09 SILT	102	0.30
6.95 - 0.57 MOIST - 0.08 SILT - 0.06 Pot_{gt5} - 0.03 TOT_{gt5}	102	0.38
Bf_{ag}		
1.68 - 0.33 MOIST + 0.02 CLAY	102	0.20
1.65 + 4.38 Cp_{gt5} - 0.35 MOIST + 0.02 CLAY	102	0.24
Sb_{ag}		
2.47 - 0.61 MOIST + 0.02 SAND	102	0.32
3.23 - 0.70 MOIST - 0.06 $HdWd_{gt5}$ + 0.02 SAND	102	0.36
Pj_{ag}		
- 0.17 + 0.01 SAND	102	0.14
- 1.83 + 2.03 $Cnfr_{rd}$ + 0.01 SAND	102	0.27
Sw_{ag}		
2.77 - 0.37 DIST	102	0.06
3.92 + 4.49 Cp_{gt5} - 1.19 $Cnfr_{rd}$ - 0.42 DIST	102	0.20
Pot_{ag}		
0.51 - 0.02 SILT	102	0.06
Bw_{ag}		
1.47 + 0.10 Bw_{gt5}	102	0.06

NOTE: All regression coefficients are significant ($P < 0.05$). Statistics computed from transformed advanced growth values ($y' = y^{0.25}$). R^2 is proportion of explained variance. y-variables: ag, advanced growth in stems/ha for trees 1–5 cm DBH. x-variables: gt5, stems/ha for trees greater than 5 cm DBH; rd, relative density; TOT, all tree species combined; Bf, balsam fir; Bw, white birch; Sw white spruce; Pj, jack pine; Sb = black spruce; Cp = pin cherry; Pot = aspen; HdWd = hardwoods; Cnfr = conifers, SAND, SILT, CLAY, proportion of sand, silt and clay in B horizon; MOIST, moisture regime class; DIST, log of distance in metres to nearest fire-preserved zone.

Balsam fir

Balsam fir was the most abundant advanced growth species on fresh to moist glacio-lacustrine clays and on moderately dry shallow glacial tills over bedrock, usually slightly more common than black spruce and white birch (Table 3.4). However, the highest balsam fir advanced growth densities were found on moderately dry to fresh glacio-lacustrine clays (mean = 36.6 and 41.7 stems/ha, respectively). These levels are significantly higher than those almost absent on fresh to very moist glacial tills and on moderately dry fluvio-glacial sands. In older fir-birch-spruce forests of the same study area, Harvey and Bergeron (1989, 1990) found that balsam fir made up 97% of conifer advanced growth and dominated on all ecological types sampled. The smaller dominance of balsam fir in the advanced growth of jack pine forests compared to that of fir-birch-spruce forest is explained by delayed invasion; fir is not a fire-adapted species and only trees from outside the limits of the fire or in fire-preserved zones could have seeded into the fire-origin jack pine forests.

The multiple linear regression equation selected for balsam fir indicates that poor moisture regime is limiting balsam fir advanced growth to some extent (regression coefficient = -0.33) and that high proportions of clay in the B horizon also positively influences balsam fir advanced growth (regression coefficient = +0.02). The proportion of the variance explained is only 20%. Adding basal area of pin cherry greater than 5 cm DBH (regression coefficient = +4.38) improves the R^2 to 0.24. We suspect that the presence of pin cherry is not causal of higher levels of balsam fir advanced growth and since pin cherry was not correlated with any of the physical site variables tested, it could simply be associated with better light conditions in small openings of the canopy. Proximity of fire-preserved zones seem to be associated with slightly more abundant balsam fir advanced growth as indicated by a significant correlation coefficient (-0.40 $P = 0.0001$), but collinearity excluded it from the model. Seed source distances to our sample plots ranged from 20 m to 1 140 m (mean = 396 m). Sims, Kershaw and Wickware (1990) observed maximum balsam fir seed dispersal at 160 m, although most seed falls directly beneath the tree; consequently, the relationship with such long distances from seed sources is weak.

Bélanger, Côté and Marchand (1991) found important differences in advanced fir densities between sites on glacial tills having different moisture regimes, highest densities being on imperfectly drained soils. They also found differences between two well-drained ecological types with different ground vegetation characteristics, concluding that observed differences were due to differences in seedbed suitability. Conifer needle or mixed needle-leaf litter is a favourable seedbed; feather mosses, mosses on dead wood or on rocks are neutral seedbeds and hardwood leaf litter or sphagnum are unfavourable seedbeds for fir. The inverse relationship with moisture regime that we observed might be due to different competition patterns in northwestern Québec (Harvey and Bergeron, 1990).

No significant regression coefficients were obtained (Table 3.5) for balsam fir advanced growth using basal area of aspen, white birch or all broad-leaved trees greater than 5 cm DBH. These results do not corroborate those of Place (1955) who found hardwood litter to be an important barrier to establishment of spruce and, to a lesser extent, fir, in mixedwood or hardwood stands.

Black spruce

Black spruce regeneration is denser on dry, shallow organic soils over bedrock and on fluvio-glacial sands than on other ecological types. Black spruce was the most abundant regenerating tree species on fluvio-glacial sands, on dry, shallow organic soils over bedrock and on moderately dry to fresh deep tills (Table 3.4).

The multiple linear regression equations selected for black spruce indicate that the better the moisture regime and the larger the proportion of sand in the B horizon, the greater the black spruce advanced growth (regression coefficient = -0.61, +0.02, respectively) (Table 3.5). The proportion of variance explained is only 0.32. These results confirm those of Harvey and Bergeron (1989, 1990) who found that black spruce showed better advanced growth on coarse-textured deposits, and with those of Racey, Whitfield and Sims (1989) who state that black spruce advanced growth can be common in conifer-dominated, nutrient-poor upland stands on shallow soils with less than 20 cm of mineral soil. The inclusion of basal area of hardwoods in the model improves the R^2 to 0.36.

The absence of a significant relationship with distance from seed source can be explained by black spruce's semi-serotinous cones which readily disperse seed after fire and allowed it to colonize the site from seed close to where adults were present before the fire. Later on, advanced growth establishes itself either from seed or from layerings.

Jack pine

Significantly higher densities of jack pine advanced growth were observed in the following descending order: fresh fluvio-glacial sands, dry shallow organic soils over bedrock and moderately dry fluvio-glacial sands compared to the other ecological types which showed no jack pine regeneration (Table 3.4). These sites, although of lower productivity (Béland and Bergeron, 1991), are of comparable tree basal area (Table 3.1 and 3.2). Thus, one could expect similar light conditions as influenced by tree cover. However, although it was not confirmed by field data, the herb and shrub layer was very different in composition and cover was much sparser.

The selected linear regression equation for jack pine indicates that the proportion of sand in the B horizon is positively related to jack pine regeneration (regression coefficient = +0.01). The proportion of variance explained by this equation is 0.14 (Table 3.5). Adding softwood relative dominance in the canopy to the model improves the R^2 to 0.27. The independence of the variable "distance to fire-preserved zones" may be explained by the fact that adult jack pines do not originate from these zones but rather from burnt trees present before the fire and that advanced growth under these stands is due to adult jack pines of the canopy (Sims, Kershaw and Wickware, 1990). The positive relationship with the relative dominance of softwood in the canopy partly confirms the notion that white birch litter inhibits germination and growth of jack pine seedlings (Sims, Kershaw and Wickware, 1990).

White spruce

White spruce is a minor component of advanced growth in jack pine stands (mean = 6.0 stems/ha) (Table 3.4). According to Bergeron and Dubuc (1989), white spruce produces very little advanced growth between fires in the clay belt, after the initial establishment, and regeneration occurs only when the forest cover or possibly the soil is disturbed. Furthermore, Fox *et al*. (1984) suggested that advanced growth of white spruce before logging was insignificant on upland sites in Alaska and that exposed mineral soil composed a good white spruce seedbed.

Levels of advanced growth were found to be significantly higher on fresh glacio-lacustrine clays and moderately dry glacial tills than on moist glacio-lacustrine clays and glacial tills, fresh and moderately dry fluvio-glacial sands and dry shallow organic soils over bedrock (Table 3.4). According to Sims, Kershaw and Wickware (1990), white spruce requires well or moderately well drained soils for germination and early growth.

The multiple linear regression equation selected for white spruce indicates, as for balsam fir, some minor negative influence of distance to fire-preserved zones (regression coefficient = -0.37 R^2 = 0.06). Heidman (1985) emphasized the importance of adequate seed production in ensuring good natural regeneration. White spruce is solely dependant on seed for its regeneration, but since seed dispersal can extend up to 200 m (Burns and Honkala, 1990), the proportion of the variance explained is low (0.20) (Table 3.5). The positive relationship with basal area of pin cherry and the negative relationship with softwood relative dominance (regression coefficient = +4.49 and - 1.19, respectively) improved the R^2 to 0.20. We suspect this latter relationship to be an indicator of white spruce site preferences that were not adequately measured with the site variables tested.

Aspen

Levels of aspen regeneration were found to be significantly higher on fresh fluvio-glacial sands than on all other ecological types, except dry shallow organic soils over bedrock and fresh glacio-lacustrine clays, which are intermediates (Table 3.4). Some weak negative relationship of aspen advanced growth with proportion of silt in the B horizon was observed (regression coefficient = -0.02) but explained as little as 6% of the variability (Table 3.5). Although aspen is a minor component of advanced growth in jack pine stands (maximum mean = 5.0 stems/ha), natural regeneration from root suckering will most probably maintain aspen after harvest or fire on sites where it is present in the canopy (Sims, Kershaw and Wickware, 1990).

White birch

Levels of white birch advanced growth were found to be significantly higher on dry shallow organic soils over bedrock than on fresh to moist glacial tills, shallow glacial tills over bedrock, moist glacio-lacustrine clays and moderately dry fluvio-glacial sands (Table 3.4). White birch dominates the regeneration on fresh to very moist glacial tills and on moderately dry glacio-lacustrine clays.

Although white birch is a good seed producer that can take advantage of canopy gaps, it reproduces readily by stump sprouting. We suggest that the greater abundance of white birch advanced growth observed on shallow organic soils over bedrock is composed mainly of sprouts and reflects the greater abundance of white birch in the canopy of these sites, as seen earlier and as suggested by the significant regression coefficient of white birch advanced growth (+0.10) with its own basal area in the canopy (R^2 = 6%) (Table 3.5).

3.6 CONCLUSION

The regeneration densities observed in jack pine stands of the present study are too low for achieving sufficient post-harvest natural regeneration. These results suggest that future applied research should be aimed at understanding the dynamics involved in terms of seed production and light and seedbed conditions thus enabling to enhance natural regeneration of these forests through forest management strategies suitable for local ecological conditions.

The comparatively higher levels of jack pine and black spruce advanced growth on fluvio-glacial sands and dry shallow organic soils over bedrock are probably due to sparse herb and shrub cover and more favourable seedbed conditions. However, investigations about the role of canopy openness in controlling the establishment of regeneration still have to be undertaken.

The ecological types were not satisfactory classes for comparison of advanced growth in jack pine stands in our study area. Indeed, only classes on extreme conditions, such as dry, very shallow or very coarse-textured soils, showed significant differences in advanced growth densities. Moreover, the two major surficial deposits of the region, i.e. glacio-lacustrine clays and glacial tills, did not show significant differences in advanced growth between one another.

Among the continuous variables tested, poor moisture regime seemed to have limited balsam fir and black spruce advanced growth. We suspect that the presence of pin cherry is not causal of higher levels of balsam fir and white spruce advanced growth but could simply be associated with better light conditions. The greater relative dominance of hardwoods in the canopy also seemed to have had a negative effect on the abundance of black spruce and jack pine advanced growth. Finally, greater distances to fire-preserved zone seemed to have slightly limited balsam fir and white spruce advanced growth.

It appears that the site variables used to predict abundance of advanced growth in jack pine stands have some significance but due to low maximum R^2 values (<0.38), they are inadequate for making useful predictions. Site history and pre-fire stand composition, in addition to site variables, could improve advanced growth predictions.

3.7 ACKNOWLEDGMENTS

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ARTICLE 3 : EFFETS DE LA COUPE, DU SCARIFIAGE ET DE LA VÉGÉTATION CONCURRENTE SUR LA GERMINATION ET LA SURVIE DE SEMIS DE PIN GRIS SUR TROIS DÉPÔTS DE SURFACE DE LA FORÊT BORÉALE MIXTE DU NORD-OUEST QUÉBÉCOIS

Béland, M., Y. Bergeron, R. Zarnovican. « Cutting, scarification and competing vegetation affect germination and survival of jack pine seedlings on three soil types of the boreal mixedwood of northwestern Quebec. » Prêt pour publication dans le *Journal canadien de la recherche forestière.*

4.1 RÉSUMÉ

Nous avons réalisé une expérience d'ensemencement selon un dispositif en tiroirs subdivisés dans le secteur de la Forêt d'enseignement et de recherche du lac Duparquet pour identifier les facteurs affectant la régénération naturelle du pin gris dans la forêt boréale mixte du nord-ouest du Québec. L'effet positif du scarifiage sur la germination était plus faible sur argile que sur till ou sur sable. Cette différence résulterait du fait que les températures à la surface du sol sont plus basses, probablement à cause d'un taux d'humidité plus élevé. L'absence de couvert arborescent et le contrôle de la végétation concurrente a favorisé la survie des semis de pin gris. Entre 3 et 33 % des graines semées ont survécu au stade de semis après deux saisons de croissance. Une quantité négligeable de graines et de semis de pin gris était issue des arbres semenciers et de la forêt environnante. Rien n'indique que le pin gris aurait plus de difficulté à s'établir sur argile que sur des sables plus typiques de cette espèce. Cependant, la compétition végétale, particulièrement sur argile, principalement celle du tremble, pourrait être un facteur critique pour la survie des semis à cause de son abondance et de sa persistance. La régénération du pin gris après coupe est moins abondante qu'après feu, probablement en raison du délai entre l'ouverture du couvert et la dispersion des graines.

4.2 ABSTRACT

A split-split-plot sowing experiment was undertaken in the area of the Lake Duparquet Teaching and Research Forest to identify which of the seedbed or the competing vegetation is the limiting factor of natural regeneration of jack pine in the boreal mixedwood of northwestern Québec. Between 3 to 33% of sown seeds survived as seedlings after two growing seasons. Negligible jack pine seed or seedling came from seed trees. Scarification had a smaller effect on germination on clay than on till or sand. This difference could be explained by lower soil surface temperatures, probably resulting from more moist conditions. Absence of shrubs and vegetation control had a strong positive effect on seedling survival. Nothing indicates that jack pine regeneration would be more difficult on clay than on more typical coarse-textured sands. However, survival from competing vegetation could be the critical factor because of its abundance and persistence in time (aspen). Jack pine regeneration after cutting is less abundant than after fire, probably because of the delay between the opening of the stand and seed dispersion.

4.3 INTRODUCTION

The dependence of jack pine (*Pinus banksiana* Lamb.) on forest fire for its maintenance in natural landscapes is largely recognized (Cayford and McRae, 1983) and autecological factors involved in this dependence as well as to the frequent lack of natural regeneration after harvesting are well documented. They relate to its serotinous cones, its intolerance of shade (a little shade is beneficial to germination although full sunlight is essential afterwards (Burns and Honkala, 1990 ; Chrosciewicz, 1990)) and to the need for an adequate usually mineral soil seedbed (Chrosciewicz, 1990).

The respect of natural processes including natural regeneration is mentioned as an indicator of ecosystem health in most forest management certification processes (Anonymous, 1995) and has been identified as a key principle in the Forest Protection Strategy of the Province of Québec (Gouvernement du Québec, 1994). This preoccupation is the origin of the recent amphasis on protection of advanced growth by methods of careful logging. The regeneration of species producing little advanced growth recieved less attention.

There is however a considerable body of literature about techniques of natural regeneration of serotinous cone pine species such as lodegepole pine (*Pinus contorta* Dougl.) (Baumgartner *et al.*, 1985 ; Alexander, 1986 ; Cole, 1985 ; Sheppard and Alexander, 1983 ; Schabas, 1980 ; Thompson, 1978 ; Wang *et al.*, 1992) and jack pine (Abrams and Dickman, 1982 ; Ball, 1975 ; Benzie, 1977 ; Boisvenue, Arnup and Archibald, 1994 ; Bowling and Goble, 1994 ; Bowling and Niznowski, 1991 ; Bruce and Sims, 1970 ; Cayford, 1958, 1957 ; Chrosciewicz, 1992, 1988 ; McRae, 1979 ; Riemenschneider, 1982 ; Sims, 1970 ; Smith and Brown, 1984 ; Walker and Sims, 1984 ; Whittle, Duchesne and Needham, 1997). Among the techniques mentioned in the literature, the most common is to leave branches on site and adequately prepare the soil (Walker and Sims, 1984 ; Cayford, 1957). It was also shown that for cones to open, they must be as close to the ground as possible without being buried under slash (Bruce and Sims, 1970 ; Crossley, 1956). Heat near the ground should then be sufficient to open the cones. The most common scarification technique is to pull drags made up of ship anchor chains with pins welded on them at right angles often accompanied by toothed/finned barrels filled with ballast (Burns, 1983 ; Baumgartner *et al.*, 1985 ; Thompson, 1978). These simultaneously spread the cone-bearing slash, mix mineral and organic layers and create patches of mineral soils. Prescribed burning under a cover of seed trees is another but less frequently used alternative (Benzie, 1977). However, most of the above studies occured on sands (Abrams, 1984; Walker and Sims, 1984; Riley, 1980, 1975; Chrosciewicz, 1971; Caveney and Rudolph, 1970; Sims, 1970; Cayford and Hobbs, 1967) or on sandy loams (Zasada and Alm, 1970). Studies taking place on clay soils (Cayford, 1958, 1957) are fewer.

Jack pine stands in the Clay Belt of northwestern Quebec and northeastern Ontario are often mixed with white birch (*Betula papyrifera* Marsh.) and trembling aspen (*Populus tremuloides* Michx.) and grow on glacio-lacustrine clay deposits as well as on more typical, coarse-textured sands. Jack pine stands on clay sites are characteristically productive, reaching 18 to 20 m height at 50 years stump age (Béland and Bergeron, 1996) and comprise very little advanced regeneration (Béland and Bergeron, 1993). However, studies of balsam fir (*Abies balsamea* (L.) Mill.) stands in the study area revealed that clay sites can also be very susceptible to invasion of competing vegetation (Harvey and Bergeron, 1989 ; Harvey, Leduc and Bergeron, 1995). In the long run, the outcome of the competition between jack pine and aspen, i.e. the pure or mixed composition of the post-disturbance forest is probably dependent on initial establishment since they grow at approximately the same rate (Longpré *et al.*, 1994). Gauthier, Bergeron and Simon(1996 ; 1993) suggested that non-serotinous cones occur on some trees of the islands of lake Duparquet, in Abitibi. Occurence of non-serotinous cones and its implications for silviculture on mainland forests of the area remains to be investigated.

In Quebec, for historical reasons, natural regeneration of jack pine has received little attention and is generally not considered a silvicultural option neither on coarse-textured soils nor on clay soils. As a result, forest managers generally plant jack pine after harvesting. In order to eventually test alternative silvicultural methods that could be applicable in Quebec, there is a need to investigate the mechanisms involved in the natural regeneration of jack pine.

The objective of this study was to identify which of seedbed quality or competition for light is the limiting factor involved in the natural regeneration of jack pine in the absence of fire on rich clay, sand and till in the southeastern boreal forest. Specific objectives were to verify the following hypotheses:

? The contribution of jack pine seed trees to seedfall in the absence of fire is very small ;

? Jack pine regeneration success in terms of germination, survival and juvenile growth is better on a scarified soil than on an undisturbed forest floor ;

? Seedbed conditions are more limiting to germination on sands than on till and more so than on clays ;

? Light conditions are more limiting to survival of seedlings on clays than on tills and more so than on sand, reflecting the high abundance of competing vegetation.

4.4 MATERIAL AND METHODS

4.4.1 Study sites

The study area is located in the southeastern boreal forest (79°W, 48°N), approximately fifty kilometers northwest of Rouyn-Noranda (Abitibi, Quebec), in the western balsam fir and white birch bioclimatic domain (Grondin, 1996). The area is characterized by the presence of extensive clay deposits originating from the proglacial Lake Barlow-Ojibway (Veillette, 1994). The climate is cold (annual average temperature 0.8°C) and continental (average annual precipitation 857 mm). The average frost-free period is 64 days although frosts may occur any time during the growing season (Environment Canada, 1993).

Balsam fir is the dominant species of mature forests on mesic sites. It is associated with white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) B.S.P.) and white birch (Bergeron and Dubuc, 1989). Following fire, jack pine, trembling aspen and white birch form a mosaic of forest stands (Bergeron and Bouchard, 1984).

Nine 60 x 120 m plots were located in mature stands whose composition is dominated by jack pine, with secondary paper birch, trembling aspen and black spruce components (Table 4.1). All plots were located on deep surficial deposit of moderate moisture regime (Brais and Camiré, 1992) using forest ecosystem maps. Stands on till and clay, located in the Lake Duparquet Research and Teaching Forest, originated from a fire that burned in 1923 (Dansereau and Bergeron, 1993) and were thus 70 years old at the time of the experiment. The plots on sand were also of fire origin. One of them was 77 years old and was located on nearby public forest under management by Tembec Forest Products whereas the two remaining were 61 years old and were located on forests managed by Norbord Industries.

Tableau 4.1. Average forest composition (density, basal area and mean DBH of stems > 1.3 m) of sub-plots on the three soil types before the experiment (n=6).

Species	Clay			Till			Sand		
	Density (stems/ha)	Basal area (m^2/ha)	Stem diameter (cm)	Density (stems/ha)	Basal area (m^2/ha)	Stem diameter (cm)	Density (stems/ha)	Basal area (m^2/ha)	Stem diameter (cm)
Jack pine	921.9 (134.85)	32.8 (2.25)	20.9 (0.88)	965.6 (260.49)	26.5 (3.88)	18.6 (2.18)	1184.4 (200.73)	29.9 (4.30)	17.4 (1.75)
Paper birch	138.5 (32.46)	2.1 (0.56)	13.5 (1.13)	218.8 (113.12)	3.6 (2.58)	13.6 (1.40)	1.0 (2.55)	0.01 (0.02)	10 (n.a.)
Trembling aspen	19.8 (30.72)	1.1 (1.43)	30.2 (10.30)	26.0 (18.29)	1.4 (1.39)	23.0 (5.66)	3.1 (7.65)	0.04 (0.09)	12.3 (n.a.)
Black spruce	7.3 (9.20)	0.1 (0.12)	11.9 (2.53)	76.0 (58.95)	1.0 (0.73)	12.5 (1.15)	152.1 (218.8)	1.9 (2.78)	11.2 (1.15)
White spruce	1.0 (2.55)	0.03 (0.08)	20.0 (n.a.)	2.1 (5.10)	0.02 (0.04)	10.5 (n.a.)	0	0	
Red maple	0	0		1.0 (2.55)	0.01 (0.02)	10 (n.a.)	0	0	
Balsam fir	0	0		0	0		1.0 (2.55)	0.01 (0.02)	10 (n.a.)
Pin cherry	4.2 (7.57)	0.04 (0.07)	10.3 (0.47)	0	0		0	0	
Total :	1092.7	36.1		1289.6	32.5		1341.7	31.8	1341.7

Note. Standard deviations are shown in parentheses.

4.4.2 Experimental design

The experiment was designed as a split-split-plot (Steel and Torrie, 1980). Surficial material (till, clay or sand) was used to define main plots (three un-blocked repetitions per surficial material).

Cutting treatments (40 x 40 m seed tree cutting cutting and uncut surrounded by 10 m buffer strips) were used as sub-plots in order to have extremes of light levels. Cutting treatments were performed with a chain saw and trees were skidded with a winch from outside the plots and then delimbed to prevent any soil disturbance. Sixteen seed trees per sub-plot were chosen among the largest crowns. Benzie (1977) and Chrosciewicz (1988) recommended between 20 and 25 jack pine seed trees·ha^{-1} for treatments of prescribed burning. Because we expected little seed to fall from seed trees, we left 100 seed trees·ha^{-1}.

Four treatments (10 m x 10 m) repeated four times formed sub-sub-plots. These treatments were arranged as a 2 x 2 factorial. The first factor is soil scarification or no scarification and the second is the periodic competitive vegetation removal or no removal. Scarification was performed in May and early June using La Taupe™, a small rototiller mounted on a brushcutter with expulsion of most of the humus outside the sub-sub-plots. The area was then raked to smooth the surface. In order to homogenize the light levels and facilitate the placement of quadrats at the beginning of the experiment, the whole experiment area was cleared of herbaceous and brush vegetation with a brush cutter and slash was removed manually. Removal of vegetation was performed by hand and with a pair of pruning shears during each subsequent measurement of the seedlings.

Treatments of cutting were randomly assigned to sub-plots, whereas scarification and vegetation removal were randomly assigned to sub-sub-plots. On each of the sub-sub-plots, one 1 m^2 quadrat was sowed with 100 jack pine seed on a 10 x 10 cm grid and another 1 m^2 quadrat received only seeds susceptible to fall from seed trees and from the surrounding forest. Sown seeds were of local origin and obtained through the Quebec Ministry of Natural Resources Berthierville nursery. Viability of seed was estimated by the nursery to vary between 98 and 100% and rate of germination between 72 and 90%. Seeds were sown in mid-June 1994.

4.4.3 Field data

On sown sub-sub-plots, newly germinated seedlings and dead seedlings were recorded four times in 1994 (1 : June 28th to July 7th, 2 : July 7th to 20th, 3 : July 21st to August 3rd and 4 : August 5th to 18th) and three times in 1995 (1 : June 12th to July 5th, 2 : July 13th to 27th and 3 : July 28th to August 7th). A grid was superimposed over the plot to identify the date of emergence of each seedling. For each measurement period, temperature close to the ground was measured using a mercury thermometer laid flat on the plot and shaded from the sun by folded cardboard covered by a reflective layer of aluminium foil. Seedling height was measured once at the last measurement period of 1994 and at the first and last measurement period of 1995. Seedling stem diameter in the cut sub-plots was measured during the last measurement period of 1995 (in the uncut treatments, seedlings were too small to have their diameter measured without risking to damage their stem). On control non-sown sub-sub-plots, only the number of seedlings was recorded to give an estimate of the influence of seed trees and surrounding forest on the results of the sowing experiment. Photosynthetically active radiation (PAR) was measured on overcast days (Messier and Parent 1997) at ground level, below competing vegetation (PAR_{ground}), and above competing vegetation (PAR_{above}) on each sub-sub-plot with a portable Sunfleck™ ceptometer (Decagon Devices, Pullman, Wash.), model SF-80. These measurements as well as one made in the open just after the measurement of each sub-plot (PAR_{open}) were taken in July 1995. In order to estimate competition for light, light interception by vegetation was calculated by the following formula:

$$Interception \; ? \; \frac{(PAR_{above} \; ? \; PAR_{ground})}{PAR_{open}} \; ?100$$

Its value represents an estimation of vegetation cover all species combined (Jobidon, 1994, 1992).

Four circular seed traps of 0.6 m diameter were installed 0.6 m above ground at the beginning of July 1994 on each of the 40 x 40 m sub-plots. Contents were collected at the end of July and August in 1994 and 1995.

4.4.4 Analyses

ANOVA was used to compare treatment effects at a significance level of 0.05 using SAS (SAS Institute, 1985). The model used took into account the structure of the split-split-plot experimental design, i.e. seperate error terms were used for each of the three levels of the split-split-plot. Surficial material (SOIL) was tested against SOIL*REP as an error term whereas cutting treatment (CUT) and SOIL*CUT were tested against SOIL*CUT*REP as an error term. All other terms tested use mean square error as an error term. Interactions between each of the factors were included in the model. All the effects in the model were considered as fixed. Although surficial material could obviously not be assigned randomly to plots (Hurlbert 1984), for the purpose of integrating it in the analyses, it was assumed so. We think it causes little bias in the interpretation of the results for the sites studied because they are from the same bioclimatic domain but acknowledge the limit it imposes on the inference of the results to other sites.

Temperatures close to the ground for the seven periods of measurements were averaged so as to minimize heterogeneity of variance among treatments and thus satisfy this basic assumption of analysis of variance. The record of newly germinated seedlings and dead seedlings enabled the computation of rates of germination and mortality cumulated over the seven periods of measurement using

$$\textit{Cumulative germ rate} \; ? \; \frac{(n_1 \; ? \; n_2 \; ? \; n_3 \; ? \; n_4 \; ? \; n_5 \; ? \; n_6 \; ? \; n_7)}{100}$$

and

$$\textit{Cumulative mortality rate} \; ? \; \frac{(d_1 \; ? \; d_2 \; ? \; d_3 \; ? \; d_4 \; ? \; d_5 \; ? \; d_6 \; ? \; d_7)}{(n_1 \; ? \; n_2 \; ? \; n_3 \; ? \; n_4 \; ? \; n_5 \; ? \; n_6 \; ? \; n_7)}$$

where n_1 to n_7 and d_1 to d_7 are respectively the number of newly germinated and of dead jack pine seedlings observed on each of the measurement periods.

To minimize heteroscedasticity, second and third measurements of seedling height were transformed with the reciprocal of the square root $H_2' \; ? \; \frac{1}{\sqrt{(H_2 \; ? \; 0.5)}}$ and with the log

$H_3' ? \log(H_3 ? 1)$, respectively, before data analysis. The three measurements of height were analysed separately. Height/diameter ratios were transformed with the reciprocal $Ratio' ? ? \frac{1}{Ratio}$.

4.5 RESULTS

4.5.1 Germination

Fig. 4.1 gives an overview of the timing of seedling germination and mortality over the seven periods of measurements. Germination is observed mainly during the 2^nd^ and 3^rd^ period of measurement of the first year (July 7^th^ to August 3^rd^), and mortality is observed mainly during the first period of year two (June 12^th^ to July 5th), although it continues until the end of the measurements. A set of curves corresponding to the uncut treatments exhibited high rates of germination but a higher rates of mortality.

Germination rate cumulated over the seven periods of measurements varied between 10 and 55 % depending on the treatment (Fig. 4.2). It was twice as high in the uncut plots than in the cut plots and higher on scarified plots than on non-scarified plots. However, scarification had a more important effect on sand and till than on clay. Germination rate decreases from clay, to till and to sand (Table 4.2).

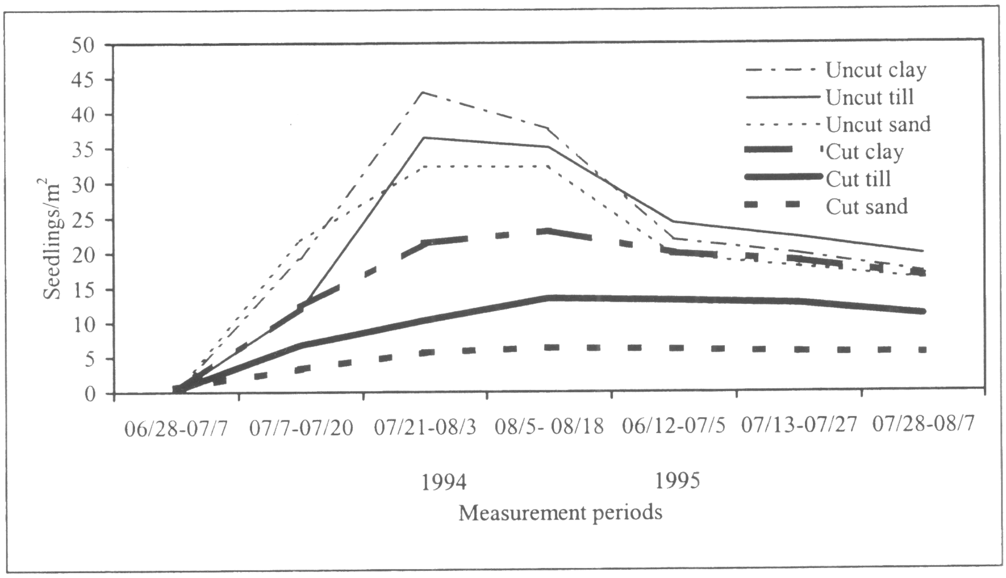

Figure 4.1. Number of seedlings/m^2 at each period of measurement for the various soil types and cutting treatments on sown plots.

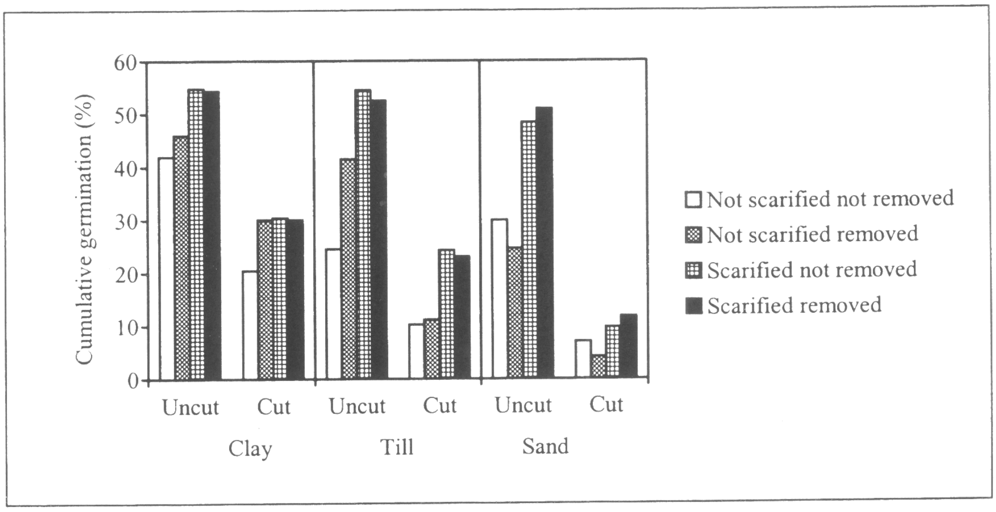

Figure 4.2. Cumulative rate of germination according to treatments.

Tableau 4.2. Analysis of variance of mean cumulative germination and mortality and remaining seedlings/m^2 according to treatments. Cumulative germination and seedlings remaining were square root transformed prior to analysis.

	Cumulative germination			Cumulative mortality			Seedlings remaining		
Source	DF	SS	P > F	DF	SS	P > F	DF	SS	P > F
Sub-subplots	267			266			266		
Subplots	17			17			17		
Main plots	8			8			8		
Soil	2	123.99	**0.0035**	2	0.120	0.74	2	43.14	0.14
Main plot error	6	22.28		6	1.15		6	47.50	
Cut	1	427.16	**0.0001**	1	3.93	**0.012**	1	38.20	0.10
Soil*Cut	2	27.57	0.18	2	0.157	0.79	2	27.76	0.33
Subplot error	6	35.17		6	1.87		6	62.88	
Scarif.	1	92.33	**0.0001**	1	0.890	**0.0001**	1	96.96	**0.0001**
Remov	1	1.90	0.23	1	0.927	**0.0001**	1	26.88	**0.0001**
Scarif.*remov	1	2.30	0.19	1	0.253	**0.012**	1	0.33	0.62
Soil*scarif.	2	9.14	**0.034**	2	0.401	0.0065	2	17.08	**0.002**
Soil*remov	2	2.71	0.36	2	0.090	0.32	2	10.16	**0.024**
Cut*scarif.	1	2.91	0.14	1	0.0199	0.48	1	5.43	**0.044**
Cut*remov	1	0.14	0.74	1	0.0040	0.75	1	3.55	0.10
Cut*scarif.*remov	1	0.29	0.64	1	0.0243	0.43	1	0.08	0.80
Soil*scarif.*remov	2	7.90	0.053	2	0.042	0.59	2	4.37	0.20
Soil*cut*scarif.	2	2.81	0.35	2	0.046	0.55	2	3.40	0.28
Soil*cut*remov	2	3.11	0.31	2	0.074	0.39	2	5.26	0.14
Soil*cut*scarif.*remov	2	2.42	0.40	2	0.101	0.28	2	3.51	0.27
Sub-subplot error	232	308.68		231	9.009		231	308.44	

4.5.2 Natural regeneration

Among the 72 seed traps collected in July and August 1994 and 1995, only one seed trap collected at the end of July 1994 contained one jack pine seed. Balsam fir and paper birch seed was present in more important quantities.

Generally, the number of seedlings in control non sown sub-sub-plots increased gradually during the two years of measurements and varied from 0.0006 to 0.007 per m^2 for the last measurement (Table 4.3). In comparison, the number of seedlings per m^2 in sown sub-sub-plots varied form 5 to 50 (Fig 4.1).

Tableau 4.3. Mean and standard error of seedlings/m^2 in control sub-sub-plots.

Soil type	Cutting treatment	N	Period of measurement 1	2	3	4	5	6	7
Clay	Uncut	48	0	0.0002 (0.001)	0.0002 (0.001)	0.0002 (0.001)	0.003 (0.006)	0.001 (0.003)	0.0006 (0.003)
Clay	Cut	48	0.0006 (0.002)	0.001 (0.004)	0.003 (0.007)	0.003 (0.007)	0.003 (0.006)	0.004 (0.006)	0.003 (0.005)
Till	Uncut	36	0.0006 (0.002)	0	0	0.0003 (0.002)	0.002 (0.005)	0.001 (0.004)	0.002 (0.005)
Till	Cut	48	0.001 (0.005)	0.002 (0.005)	0.003 (0.008)	0.005 (0.01)	0.004 (0.01)	0.004 (0.01)	0.004 (0.01)
Sand	Uncut	44	0.0002 (0.002)	0.0007 (0.003)	0.0005 (0.002)	0.001 (0.004)	0.0005 (0.002)	0.001 (0.004)	0.001 (0.004)
Sand	Cut	44	0.002 (0.007)	0.007 (0.02)	0.006 (0.02)	0.006 (0.02)	0.008 (0.02)	0.008 (0.2)	0.007 (0.02)

4.5.3 Soil surface temperature and competition

Mean soil surface temperatures over the seven periods of measurements varied significantly according to the following effects : SOIL, CUT, SCARIF, treatment of maintenance of vegetation (REMOV), interaction (CUT * REMOV) and interaction SOIL * CUT * SCARIF * REMOV (Table 4.4). Temperature varied between 18 and 28°C (Fig. 4.3a). It was the lowest on clay, intermediate on till and the highest on sand. Temperature was also higher on cut sites that were not scarified and had their vegetation removed than on uncut, scarified and where vegetation was not removed. Moreover, the effect of vegetation control was higher on cut sites compared to uncut site. Finally, the significant interaction involving the four factors was however difficult to interpret since it involved small temperature variations.

Light intercepted by vegetation between 0 and 1 m in 1995 varied significantly according to the following effects : REMOV, interactions SOIL * SCARIF, SOIL * REMOV, CUT * REMOV and SOIL * CUT * REMOV (Table 4.4). It varied from 2 to 45 % of total incident light and was significantly reduced by maintenance of vegetation (Fig. 4.3b). This effect was stronger on cut treatments than on uncut treatments but was much stronger on clay cut treatments where plots that didn't have their vegetation removed exhibited light interception of 45 % whereas all the other treatments never exceeded 20 %. Scarification had a significant reducing effect on light interception only on till.

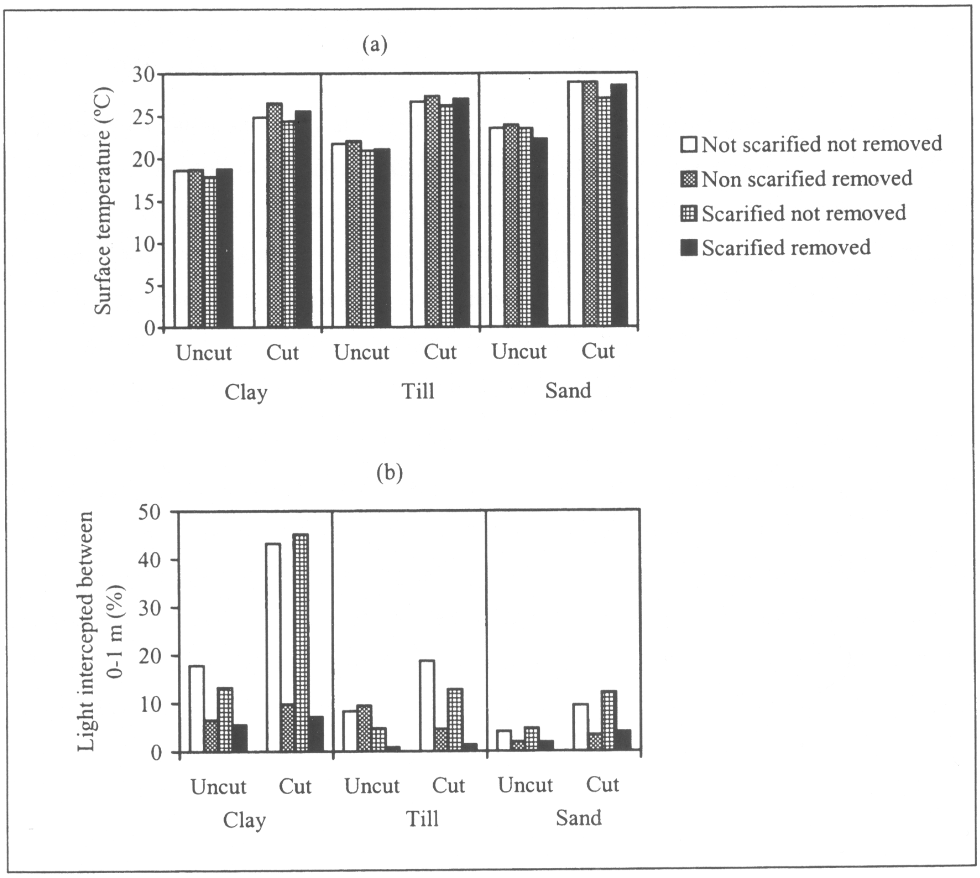

Figure 4.3. Mean soil surface temperatures (a) and percentage of light intercepted by vegetation between 0-1 m (b) according to treatments.

4.5.4 Mortality

Cumulative relative mortality at the end of the periods of measurements varied significantly according to the following effects : CUT, SCARIF, REMOV, interaction SCARIF*REMOV and SOIL*SCARIF (Table 4.2). Mortality varied between 12 and 75 % depending on the treatment and was significantly higher in the uncut treatments than in the cut treatments (Fig. 4.4). It was reduced by scarification and removal of vegetation and these effects were higher when the two treatments were combined as shown by the significant interaction between these two factors, except on clay where scarification had little effect.

At the end of the periods of measurement, the number of seedlings remaining varied significantly according to the following effects : SCARIF, REMOV, interaction SOIL*SCARIF, SOIL*REMOV and CUT*SCARIF (Table 4.2). Between 3 and 33 seedlings/m^2 remained (Fig. 4.5) depending on the treatment. Scarification and removal of vegetation both had a positive effect. The effect of removal of vegetation was stronger on clay than on sand and the effect of scarification was weaker on clay than on the other two surficial materials and was stronger on uncut treatments than on cut treatments.

Tableau 4.4. Analysis of variance of mean soil surface temperature and mean light interception between 0 and 1 m according to treatments.

	Soil surface temperature			Light intercepted 0-1 m		
Source	DF	SS	P > F	DF	SS	P > F
Sub-subplots	266			256		
Subplots	17			17		
Main plots	8			8		
Soil	2	708.94	**0.0354**	2	20.10	0.13
Main plot error	6	346.68		6	7.07	
Cut	1	2161.44	**0.0002**	1	7.93	0.11
Soil*Cut	2	42.25	0.59	2	1.98	0.59
Subplot error	6	216.25		6	4.62	
Scarif.	1	32.61	**0.0001**	1	1.14	0.14
Remov	1	20.69	**0.0015**	1	45.34	**0.0001**
Scarif.*remov	1	0.15	0.79	1	0.16	0.58
Soil*scarif.	2	3.60	0.41	2	7.83	**0.0006**
Soil*remov	2	6.61	0.20	2	4.21	**0.018**
Cut*scarif.	1	0.11	0.82	1	0.17	0.56
Cut*remov	1	11.35	**0.02**	1	8.41	**0.0001**
Cut*scarif.*remov	1	2.05	0.31	1	0.0073	0.91
Soil*scarif.*remov	2	0.05	0.99	2	1.07	0.35
Soil*cut*scarif.	2	1.78	0.64	2	0.14	0.87
Soil*cut*remov	2	2.03	0.60	2	3.61	**0.031**
Soil*cut*scarif.*remov	2	16.78	**0.017**	2	1.33	0.28
Sub-subplot error	231	464.19		227	116.47	

NOTE : SS : Sum of squares

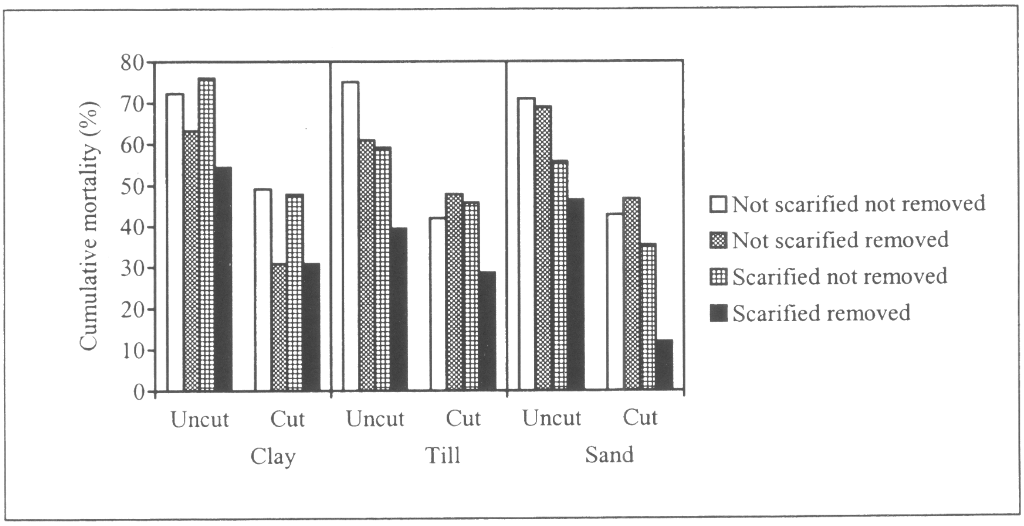

Figure 4.4. Cumulative relative mortality according to treatments.

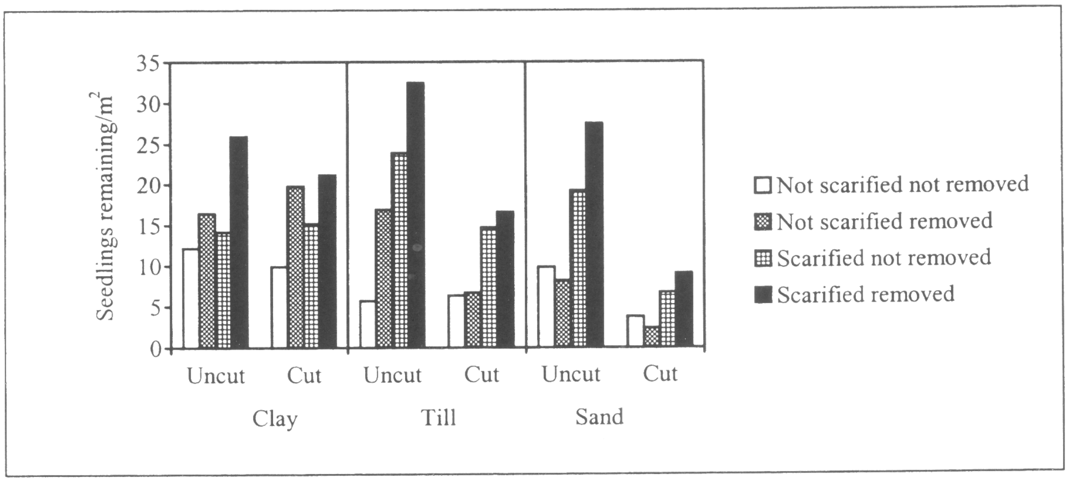

Figure 4.5. Remaining number of seedling/m^2 at the end of the measurements according to treatments.

4.5.5 Seedling growth

Height of jack pine seedlings measured the last time during the first growing season varied significantly according to the following effects : SOIL, SCARIF, REMOV, interaction CUT*SCARIF and CUT*REMOV (Table 4.5). It reached approximately 30 mm and seedlings were slightly taller on clay than on till or sand (Fig. 4.6a). Scarification had a positive but slightly bigger effect on uncut plots than on cut plots. Removal of vegetation had a negative effect on height in general although, on uncut plots, the effect was opposite.

At the second height measurement, taken at the beginning of the second growing season, the seedlings height varied significantly according to the following effects: SOIL, CUT, interaction SOIL*CUT, SCARIF, interaction SOIL*SCARIF and SOIL*CUT*SCARIF (Table 4.5). At this stage, seedlings in the cut plots took off markedly, reaching 40 to 75 mm, whereas it almost stagnated in the uncut plots (Fig. 4.6b). This height growth decrease from clay to till and to sand. The effect of scarification is positive but more so on till and clay than on sand. There was no significant effect of removal of vegetation.

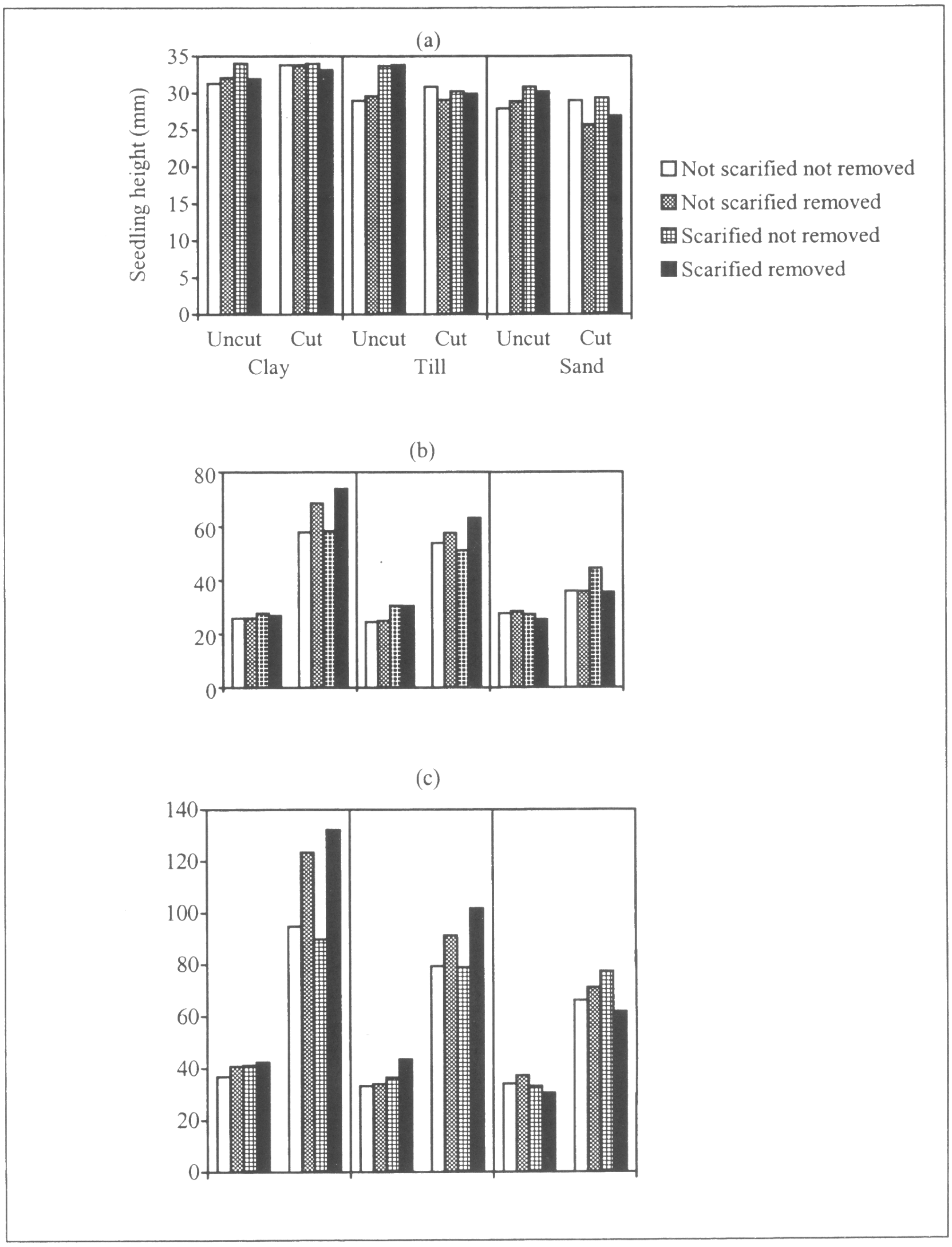

Figure 4.6. Mean seedling height at last measurement of 1994 (a), first measurement of 1995 (b) and last measurement of 1995 (c) according to treatments.

Tableau 4.5. Analysis of variance of three measurements of mean seedling height according to treatments.

	1			2			3		
Source	DF	SS	P > F	DF	SS	P > F	DF	SS	P > F
Sub-subplots	262			249			253		
Subplots	17			17			17		
Main plots	8			8			8		
Soil	2	867.2	**0.001**	2	0.014	**0.002**	2	4.6	**0.003**
Main plot error	6	103.8		6	0.002		6	0.79	
Cut	1	25.9	0.3	1	0.14	**0.0001**	1	43.34	**0.0001**
Soil*Cut	2	132.3	0.1	2	0.019	**0.003**	2	0.72	0.2
Subplot error	6	126.0		6	0.003		6	1.03	
Scarif.	1	128.9	**0.0001**	1	0.0013	**0.02**	1	0.095	0.2
Remov	1	35.6	**0.03**	1	0.00042	0.2	1	0.81	**0.0003**
Scarif.*remov	1	5.74	0.4	1	0.00022	0.34	1	0.015	0.6
Soil*scarif.	2	34.6	0.1	2	0.0016	**0.04**	2	0.31	0.07
Soil*remov	2	12.9	0.4	2	0.0014	0.06	2	0.71	**0.003**
Cut*scarif.	1	97.1	**0.0005**	1	0.00028	0.3	1	0.017	0.6
Cut*remov	1	33.2	**0.04**	1	0.00055	0.1	1	0.16	0.1
Cut*scarif.*remov	1	18.9	0.1	1	0.00018	0.4	1	2.4×10^{-7}	0.998
Soil*scarif.*remov	2	16.0	0.4	2	0.00048	0.4	2	0.32	0.07
Soil*cut*scarif.	2	28.3	0.2	2	0.0019	**0.02**	2	0.057	0.62
Soil*cut*remov	2	30.5	0.1	2	0.0011	0.11	2	0.27	0.11
Soil*cut*scarif.*remov	2	0.27	0.98	2	0.0002	0.59	2	0.091	0.46
Sub-subplot error	227	1758		214	0.052		218	12.94	

At the third and last height measurement, seedling height varied significantly according to the following effects : SOIL, CUT, REMOV, interaction SOIL*REMOV (Table 4.5). The increase in height on clay and till cut plots was further accentuated (Fig. 4.6c). No effect of scarification remains at this stage whereas removal of vegetation has a positive effect on clay and till sites and no significant effect on sandy sites.

Diameter measurements taken at the end of the experiment in 1995 varied significantly according to the following effects : SOIL, interaction SCARIF*REMOV and SOIL*REMOV (Table 4.6). Height/diameter ratio varied significantly according to the following effects : interaction SCARIF*REMOV, SOIL*REMOV and SOIL*SCARIF*REMOV (Table 4.6). Diameter varied between 1 and 1.8 mm and showed a positive effect of maintenance of vegetation but more accentuated on clay than on till and still more so than on sand where the effect was negative on non scarified sites (Fig. 4.7a). The same trends appears when considering height/diameter ratios i.e. ratios are smaller on sites where vegetation was removed except on non scarified sand where the effect seems opposite (Fig. 4.7b).

Tableau 4.6. Analysis of variance of mean seedling stem diameter and height/diameter ratio according to treatments.

		Diameter		Height/diameter ratio	
Source	DF	SS	P > F	SS	P > F
Subplots	93				
Main plots	8				
Soil	2	0.53	**0.033**	7.4×10^{-5}	0.34
Main plot error	6	3.17		1.7×10^{-4}	
Scarif.	1	0.057	0.39	1.1×10^{-7}	0.84
Remov	1	0.19	0.11	6.3×10^{-6}	0.14
Scarif.*remov	1	0.45	**0.016**	2×10^{-5}	**0.0086**
Soil*scarif.	2	0.13	0.42	4.6×10^{-6}	0.44
Soil*remov	2	1.57	**0.0001**	3.5×10^{-5}	**0.0029**
Soil*scarif.*remov	2	0.46	0.051	2.5×10^{-5}	**0.014**
Subplot error	76	5.69		2.1×10^{-4}	

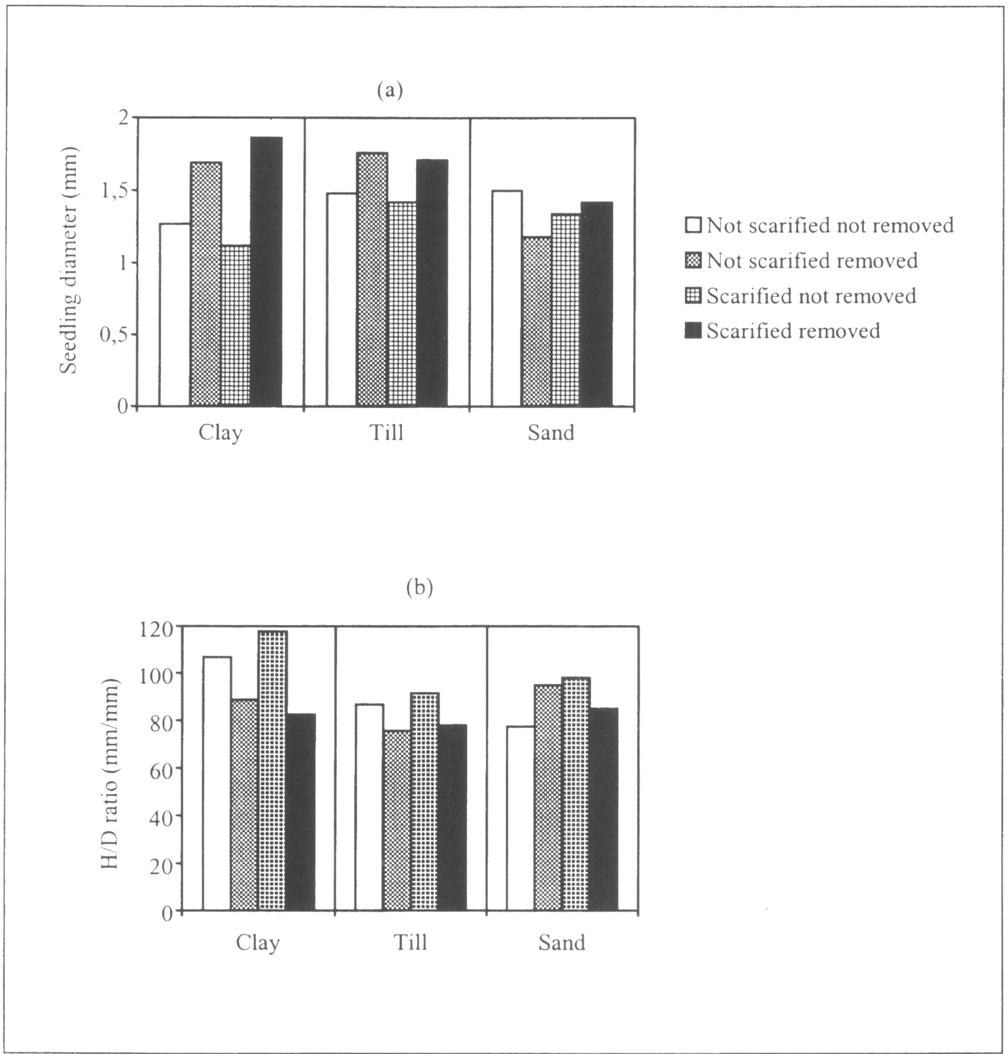

Figure 4.7. Mean seedling stem diameter (a) and height/diameter ratios (b) at last measurement of 1995 according to treatments.

4.6 DISCUSSION

4.6.1 Germination

The contribution of seed trees and of the surrounding forest to jack pine seedfall and the number of seedlings in non-sown sub-sub-plots are both negligible compared to those that germinated on sown sub-sub-plots and also very low when considered on a per hectare basis (corresponds to 6 to 70 seedlings$\cdot$ha^{-1}). This confirms that seed dispersal and natural regeneration from standing trees in the absence of fire is too scarce to ensure forest renewal and that we can consider germination rates measured for this experiment with confidence since they were not influenced by natural regeneration.

The germination of most jack pine seedlings during the first season confirms that jack pine seed is ordinarily not dormant and, given adequate conditions, is a fast germinant (Roe, 1963). It is however possible that absence of treatments of pregermination or absence of seed coverage might have delayed the germination of some seeds after August 18th of the first year (Krugman and Jenkinson, 1974 ; Burns and Honkala, 1990). If so, only some of these seedlings were observed the next spring, the remaining would have died and disappeared during the winter, confirming the low ability of late germinants to survive during the winter. Moreover, the higher germination rate in uncut, scarified plots and the gradient from clay to sand is consistent with the lower soil surface temperature on clay than on coarse-textured soils and on uncut, scarified plots than on cut, unscarified plots. The measurement of soil surface temperature can be interpreted in two opposite ways. High temperatures can speed physico-chemical reactions involved in the growth of plants (seedlings or competing vegetation) but can also be a sign that the substrate for growth has dried out. Bergeron and Brisson (1993) related the high abundance of jack pine regeneration on rock outcrops during the twentieth century to abundant precipitations and low temperatures. The authors explain their results by the difficulty of seedlings to establish during dry summers and when the winter had a low snow cover. Similarly, greenhouse experiment suggested that jack pine seedling emergence was severely reduced by a slight reduction in watering (Herr and Duchesne, 1995) Consequently, we assumed that low temperatures would not be a limiting factor for jack pine regeneration and that soil surface temperature could be an adequate indicator of moisture stress. This assumption allowed us to circumvent, the difficulty to adequately measure soil surface moisture, considering the large number of sampling plots.

The high values of light interception between 0 and 1 m in the cut treatments especially on clay where vegetation was not eliminated reflects the high abundance of competing vegetation. Canopy and lower vegetation shades the heat of the sun and protects from desiccation. Scarification allows better contact of seedlings with moisture of lower soil horizons. Clays have more water holding capacity (Bernier, 1992) and support more vegetation.

Moreover, humus on soils of the till and clay sites is composed of needles and leaves whereas humus on coniferous sandy sites are thicker and comprise larger amounts of mosses. Therefore, humus on clay sites is probably heated and desiccated more slowly on clay and till than on sand. Taking this in consideration, the cooling effect of vegetation cover and the effect of scarification observed in our study can all be interpreted as increased levels of soil surface moisture.

In an operational test of on-site delimbing and scarification to regenerate jack pine on clay, Béland, Bergeron and Zarnovican (1999) observed proportionally more jack pine seedlings on undisturbed humus than on scarified soil. This result, contrary to what is generally reported in the literature was explained either by the fairly humid conditions, favourable to germination and seedling establishment, occurring on clay sites or by the scarifier spreading the cone-bearing slash outward. In the present study, the fact that scarification had a smaller but significant effect on germination and mortality on clay than on sand or till suggests that favourable moisture conditions on clay were probably encountered but that they can nevertheless be improved by scarification. The summer of 1994 and 1995 both had favourable weather (frequent rain) for seed germination. Drier weather might result in a stronger effect of scarification (Chrosciewicz, 1990).

4.6.2 Seedling growth

The strong effect of the cover of trees and of competing vegetation on height and diameter growth and the consequent slendering of the seedlings reflect the inability of jack pine to strive in the shade. It is also consistent with the higher mortality observed on these treatments and allows to foresee that later survival of the seedlings will depend upon the removal of the vegetation. However, if most of the mortality is due to lack of stem lignification, seedlings will probably have less difficulty in the future now that their first winter is behind them. For the present study, jack pine seedlings were followed for only two years. On the other hand, Longpré *et al*. (1994) studied the effect of competition from paper birch and aspen on jack pine growth on clay on the same area as the present study in mature stands. They could not find any significant effect of the presence of aspen on the height growth of jack pine. There is however a need to fill the gap and document the competition on jack pine seedlings on a longer time period of juvenile growth.

The better height growth on clays than on tills and than on sands reflects the relative fertility of the various surficial materials (Béland and Bergeron, 1996). The positive effect of scarification being significant only during the two first measurements of height and the reversal in the effects of vegetation control leads us to think that young seedlings depend on the moisture of the superficial soil horizons exposed by the scarification, which facilitates root penetration, and are protected from dessication by vegetation. However, as time goes and their roots penetrate further in the soil, they rely more on the water and nutrients of the lower soil horizons and suffer increasingly from the shade.

4.6.3 Seedling mortality

Mortality observed at the first measurement period of the second year indicates mortality that occured between August 18th 1994 and May 1995. Seedlings that germinated too late in the summer 1994, may not have adequately lignified their stem and get prepared for the winter. We have no reason to think that absence of treatment pregermination or lack of seed coverage had a more important effect on uncut treatmens than cut treatments or on plots where vegetation was not removed than where it was removed. This factor thus cannot explain the higher mortality rates observed on these treatments. One the other hand, the low levels of light associated with these treatments, may have slowed the growth of seedlings which could have impaired their preparation for the winter. No significant difference in height measured at the end of first season between cut and uncut treatments could confirm this. Such differences in height occurred only after the winter. However, diameter was probably smaller but could not be measured at this stage because it was too small and measurements could have broken the stems.

Lower mortality for scarified plots reflects the positive effect that scarification has on seedling growth probably due to better contact of the seedlings with soil moisture or to the possible control that the scarification treatment may have exerted on competing vegetation as shown by the significant effect of scarification on light interception on tills.

4.6.4 Consequences for forest management

Seed stored in the crowns of jack pine stands in Minnesota varies from 560 000 to 1 900 000 viable seed·ha^{-1} (Roe, 1963). With a regeneration success between 3 to 33 %, as observed in the present study, this would mean approximately 30 000 to 300 000 seedling·ha^{-1}. We can thus assume that seed production and early establishment are probably not limiting the regeneration of jack pine. However, seed production could vary between surficial materials and with stand age because of differences in stand density and structure (Popovich, Demers and Gagnon, 1970) since the larger the tree crown, the bigger the seed production. These variations in seed production could have a significant impact on the success of natural regeneration. Nevertheless, the results of an operational silvicultural test of on-site delimbing and scarification on clay indicated up to 10 000 jack pine seedlings·ha^{-1} after two years (Béland, Bergeron and Zarnovican, 1999).

The results of the present study also stress the importance of scarification for initial establishement, mainly on coarse-textured soils but its limited effects on clay. Using no scarification for natural regeneration of jack pine on clay, apart from saving the cost of the operation (about 300$·ha^{-1}), might help reduce the invasion of non indigenous ruderal plant species (Durand, Bergeron and Harvey, 1988). This could be an additional argument for the integration of the approach to ecosystem management strategies.

Although aspen is rather short-lived compared to jack pine, it can maintain its presence over up to three cohorts or over 225 years after fire (Bergeron, 2000). The amount of aspen present before fire necessary to reproduce a pure aspen stand through root suckering can be very small (Lavertu, Mauffette and Bergeron, 1994). However, this might be in places where jack pine was historically not present (Greene and Johnson 1999). If this scenario is true, then aspen competition will be a major problem for the silviculture of jack pine natural regeneration and will at best produce mixed stands of the two species. The proportion between pure aspen, pure jack pine and mixed stands of the two species might have to be regulated at the landscape level by some proportion of plantation or vegetation clearing.

The better knowledge of limiting factors in natural regeneration of jack pine obtained by this study could be used to improve silvicultural strategies applicable on the three main surficial materials where it grows in the Clay Belt of Northwestern Quebec and Northeastern Ontario. The results do not permit so far to state on which alternative, prescribed burning under seed trees or scarification with on-site delimbing, will give the best results. For that matter, prescribed burning will have to be experimented. Moreover, little is known of factors involved in the developement of the mixed-wood forests. Some field observations suggest that mesic clay soils of the region can lead to forests with very different understory vegetation and probably very different stand dynamics to that observed on clay soils in the present study (Légaré, 2000). Among the factors susceptible to be involved are a colder climate, history of tree colonization and regional variations in nutrient richness of clays. The success of silvicultural treatment aiming natural regeneration in such different jack pine forests, especially the intensity of competition could differ substantially.

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ARTICLE 4 : RÉGÉNÉRATION NATURELLE DU PIN GRIS APRÈS COUPE ET PRÉPARATION DE TERRAIN DANS LA CEINTURE D'ARGILE DU NORD-OUEST QUÉBÉCOIS

Béland, M. , Y. Bergeron et R. Zarnovican. 1999. « Natural regeneration of jack pine following harvesting and site preparation in the Clay Belt of northwestern Quebec ». *Forestry Chronicle*, vol. 75, no. 5, p. 821-831.

5.1 RÉSUMÉ

Nous avons réalisé une expérience afin d'évaluer l'efficacité de la coupe avec ébranchage sur le site combinée au scarifiage pour régénérer naturellement les pinèdes à pin gris sur argile du nord-ouest québécois. Bien que les différences d'un traitement à l'autre n'étaient pas significatives, nous avons tout de même noté que le scarifiage effectué à l'aide du scarificateur à cônes Wadell™ de Silva, combiné à l'ébranchage sur le site, donnait, au bout de deux ans, les meilleurs résultats du point de vue de la densité (jusqu'à 10 000 semis·ha^{-1}) et de la distribution (50 % des placettes de 1 m^2 avec au moins un semis, correspondant à 94 % avec des placettes de 4 m^2). Cependant, les micro-sites scarifiés comportaient proportionnellement moins de semis que l'humus non perturbé, ce qui est contraire aux résultats publiés jusqu'à présent. Cela peut s'expliquer par les conditions d'humidité favorables à la germination, retrouvées sur les sites argileux, ou par l'écartement des déchets de coupe par le scarificateur. L'abondance des semis de pin gris et leur coefficient de distribution ont augmenté substantiellement de la première à la deuxième année après traitement. Même si la distribution inégale des branches à travers le parterre de coupe a limité le succès de la régénération, la régénération du pin gris à partir des branches laissées au sol permet d'obtenir un coefficient de distribution des semis relativement élevé et constitue une solution de rechange au reboisement du pin gris sur argile. Un regarni et le dégagement de la végétation concurrente pourraient compléter le traitement.

5.2 ABSTRACT

A 36-ha experiment was carried out to assess the possibility of naturally regenerating jack pine stands following harvesting on clay soils of northwestern Quebec. Although differences between treatments were not statistically significant, there was a trend toward a positive effect of one treatment combining on-site delimbing and scarification with the Silva Wadell™ cone scarifier on jack pine seedling density (up to 10 000 seedlings·ha^{-1}) and distribution (50% of 1 m^2 plots with at least one seedling, corresponding to 94% with 4 m^2 plots), two years after harvest. However, scarified microsites contained fewer seedlings than expected and undisturbed humus contained more seedlings than expected. This result, contrary to what is generally reported in the literature may be explained either by the fairly humid conditions, favorable to germination and seedling establishment, occurring on clay sites or by the scarifier spreading the cone-bearing slash outward. Seedling abundance and distribution improved substantially from the first year to the second year following treatment. Although the irregular branch distribution over the cutover area appears to have limited regeneration success, combining on-site delimbing with soil scarification could lead to relatively good stocking of jack pine regeneration that could be enhanced by some fill-planting. This regeneration method could constitute an alternative to planting jack pine on clay. However, vegetation control to remove aspen competition might be necessary.

5.3 INTRODUCTION

The dependence of jack pine (*Pinus banksiana* Lamb.) on forest fire for its maintenance in boreal Canada is largely recognized (Cayford and McRae, 1983). Autecological factors involved in this dependence (serotinous cones (Beaufait, 1960), shade intolerance (Burns and Honkala, 1990 ; Chrosciewicz, 1990) and the need for an adequate (usually mineral soil) seedbed (Chrosciewicz, 1990)) are well documented.

Due regard for natural processes, including natural regeneration, is mentioned as an indicator of ecosystem health in most forest management certification processes (Anonymous, 1995) and has been identified as a key principle in the Forest Protection Strategy of the Province of Quebec (Government of Quebec, 1994). There is a considerable body of literature about natural regeneration techniques of serotinous cone pine species such as lodgepole pine (*Pinus contorta* Dougl.) (Baumgartner *et al.*, 1985 ; Alexander, 1986 ; Cole, 1985 ; Sheppard and Alexander, 1983 ; Schabas, 1980 ; Thompson, 1978 ; Wang *et al.*, 1992) and jack pine (Abrams and Dickman, 1982 ; Ball, 1975 ; Benzie, 1977 ; Boisvenue, Arnup and Archibald, 1994 ; Bowling and Goble, 1994 ; Bowling and Niznowski, 1991 ; Bruce and Sims, 1970 ; Cayford, 1958, 1957 ; Chrosciewicz, 1992, 1988 ; McRae, 1979 ; Riemenschneider, 1982 ; Sims, 1970 ; Smith and Brown, 1984 ; Walker and Sims, 1984 ; Whittle, Duchesne and Needham, 1997). However, in Quebec, for historical reasons, natural regeneration of jack pine has received little attention and is generally not considered a silvicultural option. As a result, forest managers systematically plant jack pine after harvesting. There is thus a need to test alternative silvicultural methods to regenerate jack pine in Quebec.

Among the techniques mentioned in the literature, the most common is to leave branches on site and adequately prepare the soil surface (Walker and Sims, 1984 ; Cayford, 1957). These studies show that for cones to open, they must be as close to the ground as possible without being buried under slash (Bruce and Sims, 1970 ; Crossley, 1956). Heat near the ground should thus be sufficient to open the cones. The most common scarification technique is to pull drags made of ship anchor chains with pins welded on them at right angles often accompanied by toothed/finned barrels filled with ballast (Burns, 1983 ; Baumgartner *et al.*, 1985 ; Thompson, 1978). These simultaneously spread the cone-bearing slash, mix mineral and organic layers and create patches of mineral soil. Prescribed burning under seed trees is another but less frequently used alternative to promote jack pine natural regeneration (Benzie, 1977 ; Chrosciewicz, 1988). However, most of the above studies were undertaken on sandy soils (Abrams, 1984; Walker and Sims, 1984; Riley, 1980, 1975; Caveney and Rudolph, 1970; Sims, 1970; Cayford, 1957) or on sandy loams (Zasada and Alm, 1970). Studies taking place on clay soils (Cayford, 1958, 1957) are fewer.

Jack pine stands in the Clay Belt (northern clay section (Rowe, 1972)) of northwestern Quebec and northeastern Ontario are often mixed with white birch (*Betula papyrifera* Marsh.) and trembling aspen (*Populus tremuloides* Michx.) and grow on glacio-lacustrine clay deposits as well as on coarse-textured soils. Jack pine stands on clay sites are characteristically productive, reaching 18 to 20 m tall at 50 years stump age (Béland and Bergeron, 1996) and contain very small amounts of advanced regeneration in the understorey (Béland and Bergeron, 1993). Studies of balsam fir (*Abies balsamea* (L.) Mill.) stands in the study area have revealed that these productive sites can also be very susceptible to invasion of competing vegetation (Harvey and Bergeron, 1989 ; Harvey, Leduc and Bergeron, 1995).

The objective of this study was to examine the operational feasibility of naturally regenerating jack pine in the absence of fire on clay sites in the southeastern boreal forest. The method used is a final cutting with on-site delimbing or road-side delimbing combined with soil scarification. Specific objectives were to:

• Evaluate the contribution of jack pine seed trees to seedfall in the absence of fire and the risk of windthrow of these seed trees growing on clay soils;

• Compare the effect of on-site delimbing (tree-length harvesting) and road-side delimbing (full-tree harvesting) on abundance of natural jack pine regeneration on clay soils;

• Compare the effect of scarification methods on slash pile reduction, dispersal of cone-bearing branches and preparation of seedbeds for jack pine;

• Measure the effect of competing vegetation on natural regeneration of jack pine on clay soils.

5.4 METHODS

5.4.1 Study sites

The study area is located in the southeastern boreal forest, in Hebecourt township (79°W, 48°N), approximately fifty kilometres northwest of Rouyn-Noranda (Abitibi, Quebec), in the western part of the Amos Lowlands ecological region (Thibault and Hotte, 1985). The study is located in the Lake Duparquet Research and Teaching Forest and on adjacent public forest under management by Tembec Forest Products and Norbord Industries. The area is characterized by the presence of extensive clay deposits originating from the proglacial Lake Barlow-Ojibway (Veillette, 1994). The climate is cold (annual average temperature 0.8°C) and continental (average annual precipitation 857 mm). The average frost-free period is 64 days although frosts may occur any time during the growing season (Environment Canada, 1993).

Balsam fir is the dominant species of mature forests on mesic sites. It is associated with white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) B.S.P.) and white birch (Bergeron and Dubuc, 1989). Following fire, jack pine, trembling aspen and white birch form a mosaic of forest stands (Bergeron and Bouchard, 1984). Jack pine stands on clay sites were located from earlier studies on the geomorphology, vegetation and fire history (Dansereau and Bergeron, 1993 ; Bergeron and Bouchard, 1984; Bergeron *et al*., 1982, 1983; Béland *et al.*, 1992), from forest inventory maps and from aerial photographs. Eighteen 2-ha plots were established on mesic clay sites in mature jack pine stands that originated from a fire in 1923. Care was taken to have stands as pure as possible in jack pine but a small component of white birch and trembling aspen was also present. Soils that typically develop on these sites are grey luvisols (Bergeron *et al*., 1982). Understorey vegetation was characterized by the abundance of *Acer spicatum* Lam., *Diervilla lonicera* Mill., *Rubus idaeus* L., *Aster macrophyllus* L. and *Aralia nudicaulis* L.

5.4.2 Pre-harvest survey

Forest composition was surveyed using the point-centered quarter method (Barbour, Burk and Pitts, 1987) on 20 sampling points spaced systematically within each 2-ha plot in order to estimate density and basal area of the different tree species. White birch density estimates are biased by the point-centered quarter method due to the clustered distribution of stump sprouts. For this reason, white birch stumps were tallied over the entire 2-ha plot after harvest and DBH was estimated using equation no. 34 from Honer, Ker and Alemdag (1983). Cover of seedbed types was also evaluated inside temporary circular 4 m^2 plots at each sample point using the following class intervals : 0 - 0.9%, 1 - 4.9%, 5 - 9.9%, 10-24.9%, 25-49.9%, 50-74.9%, 75-100%.

5.4.3 Cutting and scarification treatments

A factorial randomized complete block design was used for the experiment. The 18 plots were grouped into three blocks of 6 plots. Each block contained one repetition of each combination of two types of harvesting and three types of scarification. Harvesting treatments, performed in fall 1993, included (1) clear felling with chain saws with top and branches of the merchantable part of stems left on site, and (2) seed tree cutting (25 seed trees/ha) with delimbing performed at the road-side. In both cases, cable skidder circulation was limited to regularly spaced skidding trails in order to limit soil disturbance.

Scarification treatments, performed in May and early June 1994, were (1) scarification using a Silva Wadell™ cone scarifier, (2) scarification with La Taupe™, and (3) no scarification (control). The Wadell™ scarifier consists of two rotating toothed cones mounted on a skidder. The Wadell™ scarifier was equipped with a hydraulic system to control the pressure of the machine's cones. Consequently, the machine was able to scarify a large proportion of the clear-cut area without being hindered by slash piles and without penetrating too deeply into the mineral soil. The granular-structured A horizon of the clay soils could be exposed without exposing the more compact B and C horizons. Drags made up of barrels and chains like those mentioned in the introduction were not available in the region at the time of establishing the experiment.

La Taupe™ is a three-toothed disc mounted on a motorized portable brush-saw. It was chosen for its utility in scarifying upper soil horizons and exposing seedbeds of rotten wood, humus-mineral soil mixture and disturbed humus. The treatment consisted of 2 m-wide bands (the reach of the machine), spaced 10 m apart.

5.4.4 Post-harvest survey

Four circular seed traps of 0.6 m diameter were installed 0.6 m above ground at the beginning of July 1994 on each of the 2-ha plots. Contents were collected at the end of July and August in 1994 and 1995. Seed trees that were broken or uprooted were measured in summer 1994. Measurements included DBH, total height, crown length, dimensions of the uprooted earth mass, topographic situation and type of blowdown (uprooting or breakage).

Fourty 1-m^2 permanent sample plots were distributed on each 2-ha plots with a semi-random sampling strategy : ten parallel transects were distributed randomly in each 2-ha plot and four sample plots were located randomly along each transect. Presence of seedlings, seedbed type and slash thickness were recorded in 10 cm x 10 cm squares inside each sample plot. Seedbed types noted were: exposed mineral soil, exposed bedrock, disturbed humus (including rotten wood and mixture of mineral soil and humus), woody debris, needles and leaves, mosses, lichens and water.

Photosynthetically active radiation (PAR) was measured on overcast days (Messier and Parent, 1997) in August 1996 at ground level (below competing vegetation) and above competing vegetation. Light interception by vegetation was calculated by the following formula:

$$\text{Interception} = (PAR_{above} - PAR_{ground})/PAR_{above} \times 100$$

Its value represents an estimation of vegetation cover for all species combined (Jobidon, 1994 et 1992).

5.4.5 Analyses

Treatment effects (type of harvesting and type of scarification) on regeneration parameters (seedling distribution and density), seedbed type, slash thickness and light interception by vegetation were compared using analysis of variance. The analysis was performed using the mean value for each 2-ha plot. Seedling preferences for different seedbed types (all treatments combined) were analyzed using Chi-square goodness of fit tests specifying fixed expected frequencies based on seedbed type percent cover (Simard, Bergeron and Sirois, 1998). The analysis was done on each 1 dm^2 (10 cm x 10 cm) sub-plot. Seedbed types (rock, water, lichens) that were very rare (< 5% cover) were excluded from the analysis. Mean percent cover of seedbed types for each treatment were calculated from the mean frequency over the 2-ha plot of the seedbed types observed in each 1 dm^2 square sub-plot. Linear regression between maximum slash height for each number of seedling/m^2 was computed to express the limit imposed by slash height on jack pine regeneration.

5.5 RESULTS AND DISCUSSION

5.5.1 Preharvest survey

Undisturbed forest litter of needles and leaves was the dominant seedbed prior to harvest (Table 5.1). A small proportion of cover was also occupied by mosses, rotten wood and woody debris. Other seedbed types were virtually absent. Seedbeds frequency among treatments were not significantly different prior to treatments (Table 5.2).

Forest composition did not vary significantly among treatment plots prior to treatments (Fig. 5.1, Table 5.2). Therefore, variations in pre-harvest forest composition were not considered to influence treatment effects.

Tableau 5.1 Mean cover and standard deviation of different seedbeds on plots prior to harvest.

		Mosses		Rotten wood		Woody debris		Needles and leaves	
Delimbing	Scarification	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
On-site	La Taupe™	7.1	1.5	7.9	0.8	7.0	2.4	78.0	3.1
	Control	7.6	2.2	10.2	1.7	5.4	0.3	76.8	4.0
	Wadell™	9.2	2.4	12.8	2.8	6.9	1.6	71.1	3.7
Road-side	La Taupe™	7.2	2.6	12.1	3.5	6.8	2.4	73.9	3.7
	Control	9.5	1.2	10.3	2.6	6.0	1.8	74.2	1.7
	Wadell™	8.8	5.2	9.9	3.7	7.3	0.8	74.0	7.5

The average over the 2-ha plot of the midpoint of each class was used as an observation, n=3.

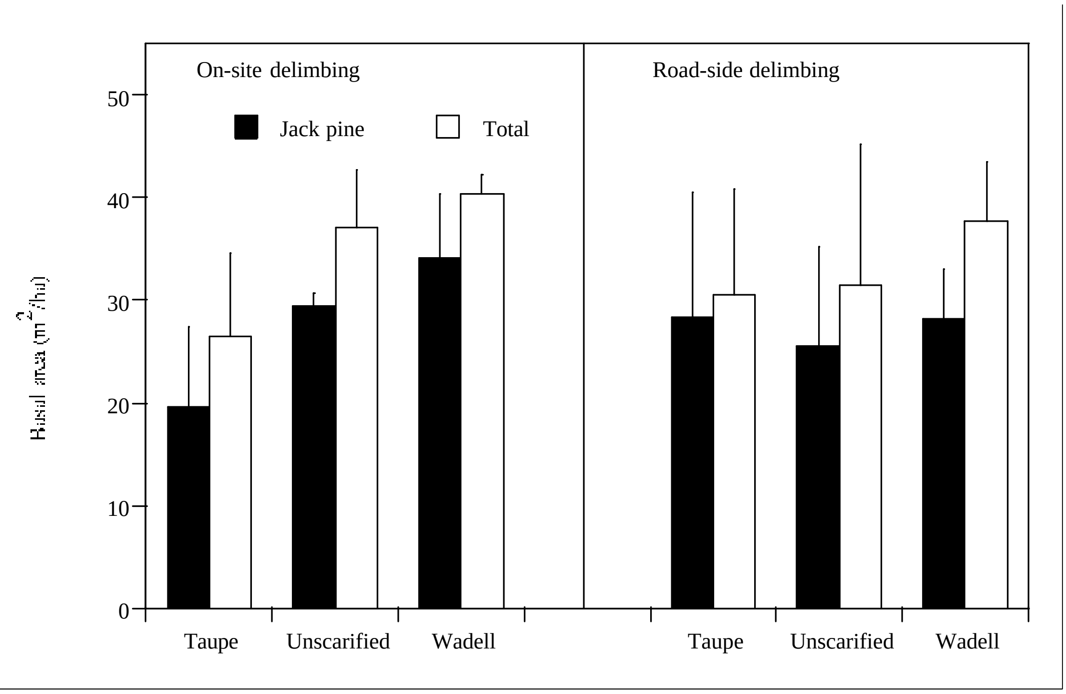

Figure 5.1. Total and jack pine basal area (m^2/ha) (mean and standard deviation) on plots prior to harvest.

Tableau 5.2 Analysis of variance of various dependent variables according to treatments.

Dependent variable	Source of variation	Degrees of freedom	Sum of squares	*P>F*
Mosses percent Cover in 1993	Delimbing	1	1.3×10^{-4}	0.72
	Scarification	2	1.1×10^{-3}	0.58
	Delimbing X scarification	2	4.7×10^{-4}	0.78
	Block	2	2.6×10^{-4}	0.87
	Error	10	9.4×10^{-3}	
Rotten wood percent Cover in 1993	Delimbing	1	8.9×10^{-5}	0.74
	Scarification	2	6.3×10^{-4}	0.68
	Delimbing X scarification	2	3.9×10^{-3}	0.13
	Block	2	1.0×10^{-3}	0.55
	Error	10	7.8×10^{-3}	
Woody debris percent Cover in 1993	Delimbing	1	4.7×10^{-5}	0.72
	Scarification	2	6.7×10^{-4}	0.40
	Delimbing X scarification	2	4.6×10^{-5}	0.94
	Block	2	2.4×10^{-4}	0.71
	Error	10	3.3×10^{-3}	
Needles and leaves percent cover in 1993	Delimbing	1	7.6×10^{-4}	0.57
	Scarification	2	4.0×10^{-3}	0.44
	Delimbing X scarification	2	4.1×10^{-3}	0.43
	Block	2	8.2×10^{-5}	0.98
	Error	10	0.022	
Jack pine basal area before harvesting	Delimbing	1	2.2×10^{-7}	1.00
	Scarification	2	1.92	0.27
	Delimbing X scarification	2	1.64	0.33
	Block	2	0.80	0.56
	Error	10	6.53	
Mineral soil percent cover in 1994	Delimbing	1	151.73	**0.0008**
	Scarification	2	1137.61	**0.0001**
	Delimbing X scarification	2	131.17	**0.0047**
	Block	2	39.51	0.10
	Error	10	68.19	
	La Taupe™ vs control	1	0.299	0.84
	Wadell™ vs control	1	869.02	**0.0001**
Disturbed seedbed percent cover in 1994	Delimbing	1	312.94	**0.024**
	Scarification	2	2066.65	**0.0002**
	Delimbing X scarification	2	2.38	0.97
	Block	2	251.29	0.10
	Error	10	438.75	
	La Taupe™ vs control	1	81.67	0.20
	Wadell™ vs control	1	1857.84	**0.0001**
Woody debris percent Cover in 1994	Delimbing	1	718.84	**0.0499**
	Scarification	2	1574.40	**0.025**
	Delimbing X scarification	2	82.67	0.76
	Block	2	449.94	0.26
	Error	10	1446.86	
	La Taupe™ vs control	1	10.79	0.79
	Wadell™ vs control	1	1062.92	**0.02**

Tableau 5.2 suite

Needles and leaves percent cover in 1994	Delimbing	1	10.22	0.79
	Scarification	2	1665.96	**0.0185**
	Delimbing X scarification	2	484.82	0.22
	Block	2	530.20	0.19
	Error	10	1364.94	
	La Taupe™ vs control	1	165.59	0.30
	Wadell™ vs control	1	1598.34	**0.006**
Jack pine seedling Density in 1994	Delimbing	1	14.2×10^6	0.19
	Scarification	2	4.5×10^6	0.74
	Delimbing X scarification	2	6.6×10^6	0.65
	Block	2	13.2×10^6	0.43
	Error	10	112.1×10^6	
Jack pine seedling Density in 1995	Delimbing	1	14.8×10^6	0.36
	Scarification	2	14.0×10^6	0.66
	Delimbing X scarification	2	36.5×10^6	0.36
	Block	2	25.4×10^6	0.48
	Error	10	162.5×10^6	
Jack pine stocking Coefficient in 1994	Delimbing	1	0.0090	0.44
	Scarification	2	0.0028	0.90
	Delimbing X scarification	2	0.078	0.104
	Block	2	0.0080	0.75
	Error	10	0.14	
Jack pine stocking Coefficient in 1995	Delimbing	1	0.0069	0.60
	Scarification	2	0.023	0.62
	Delimbing X scarification	2	0.17	0.060
	Block	2	0.028	0.57
	Error	10	0.23	
White birch stocking Coefficient in 1995	Delimbing	1	0.12	**0.002**
	Scarification	2	0.0005	0.96
	Delimbing X scarification	2	0.011	0.47
	Block	2	0.079	**0.02**
	Error	10	0.066	
Balsam fir stocking Coefficient in 1995	Delimbing	1	0.0006	0.45
	Scarification	2	0.002	0.39
	Delimbing X scarification	2	0.002	0.34
	Block	2	0.001	0.47
	Error	10	0.009	
Trembling aspen stocking Coefficient in 1995	Delimbing	1	0.003	0.76
	Scarification	2	0.03	0.58
	Delimbing X scarification	2	0.02	0.70
	Block	2	0.017	0.75
	Error	10	0.29	
Balsam poplar stocking Coefficient in 1995	Delimbing	1	0.0006	0.51
	Scarification	2	0.002	0.47
	Delimbing X scarification	2	0.004	0.26
	Block	2	0.003	0.89
	Error	10	0.012	

Tableau 5.2 suite

Light intercepted by Vegetation in 1996 (%)	Delimbing	1	0.0028	0.24
	Scarification	2	0.034	**0.0054**
	Delimbing X scarification	2	0.0037	0.41
	Block	2	0.010	0.11
	Error	10	0.019	
	La Taupe™ vs control	1	0.0035	0.20
	Wadell™ vs control	1	0.015	**0.018**
Seedling height (mm) In 1995	Delimbing	1	7.91	0.84
	Scarification	2	231.96	0.55
	Delimbing X scarification	2	306.67	0.47
	Block	2	299.85	0.47
	Error	7	2154.59	
Slash height In 1994	Delimbing	1	0.054	0.34
	Scarification	2	0.41	0.06
	Delimbing X scarification	2	0.003	0.97
	Block	2	0.085	0.49
	Error	10	0.552	

Note. Jack pine basal area and density before harvesting were square-root transformed;.arcsin transformation was performed on stocking coefficient of jack pine and log transformation on slash height.

5.5.2 Seed trees

The number of seed trees (total of 50 per plot) that were windthrown varied from 4 to 35 ($\bar{x}$ = 16.2) per plot in mid summer 1994, i.e. one year after harvest. The Wadell™ scarifier did not cause any supplementary windthrow compared to the two other treatments. Plots most exposed to prevailing winds suffered the highest frequency of windthrow. A large proportion of seed trees fell roughly in the direction of prevailing northwestern winds (32% fell between 135° and 180°). A number of factors suggest that rooting potential did not limit physical stability of seed trees : 1) 20% of windthrows were due to breakage; and 2) for the remaining 80% of trees which were uprooted, the size of the earth mass lifted by the roots indicates that roots reached up to 3 m deep (mean of 1.26 m). This shows that jack pine roots had no major difficulty to penetrate deep into clay soils. Consequently, windthrow was probably caused by a high height/diameter ratio (Ruel, 1995). Crown length averaged 35% of total length of trees that were uprooted or broken. If stands were thinned a few years before, it would be possible to improve resistance of seed trees to windthrow (Ruel, 1992).

Seed traps contained many white birch seeds but no jack pine seeds. This result confirms work by Cayford (1957) and Gauthier, Bergeron and Simon (1993, 1996) who found high proportions of serotinous cones in jack pine stands. Seed-tree cutting as a means of naturally regenerating jack pine may only be successful if applied in combination with a prescribed burn to open cones and disperse seeds. Because seed trees did not contribute to the seedfall, the two harvesting treatments performed in the present study can be assumed to be similar to clear-cutting with on-site and road-side delimbing.

5.5.3 Regeneration

Full-tree harvesting significantly reduced the percent cover of cone-bearing woody debris compared to harvesting with delimbing at stump (Figure 5.2, Table 5.2). However, this did not lead to lower regeneration success as could be suggested by the trend in Fig. 5.3, since there was no significant differences in jack pine stocking or density between the two harvesting systems (Table 5.2). Overall, mean jack pine seedling density varied from about 3000 to 12 000 seedlings/ha two years after harvest. On-site delimbing followed by scarification by the Wadell™ appeared to provide the best results (Fig. 5.3). However, because of large within-treatment variations (n=3), there were no significant differences between treatments (Table 5.2) thus precluding any definitive conclusion concerning the most appropriate scarification treatment. Second-year stocking coefficient followed the same trends as seedling density; almost half of 1 m^2 plots in the on-site delimbing Wadell™ treatments had at least one seedling, whereas jack pine stocking varied around 20-35% on other treatments (Fig. 5.4). Seedling density and stocking increased from 1994 to 1995 (Fig. 5.3 and 5.4).

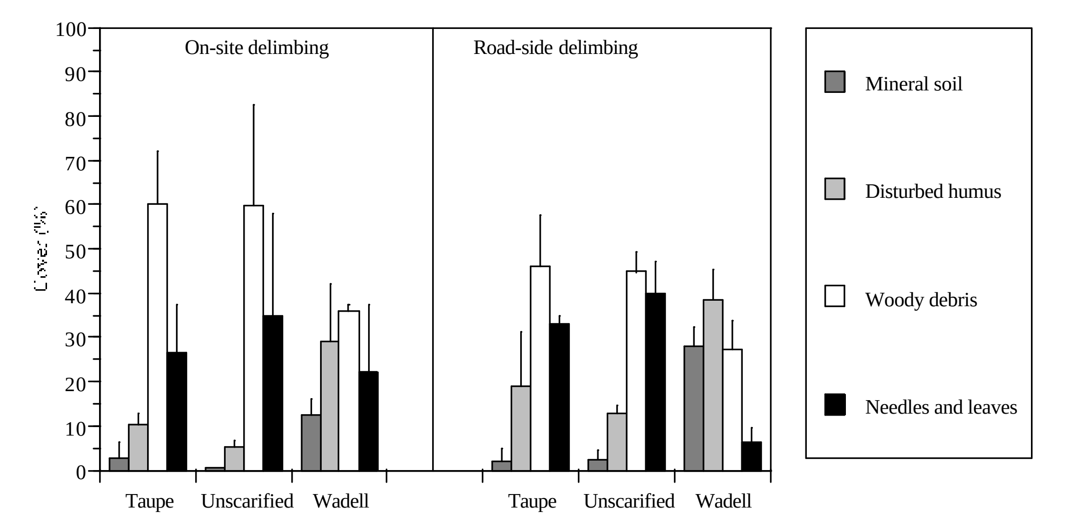

Figure 5.2. Mean cover (%) and standard deviation of different seedbeds following site preparation.

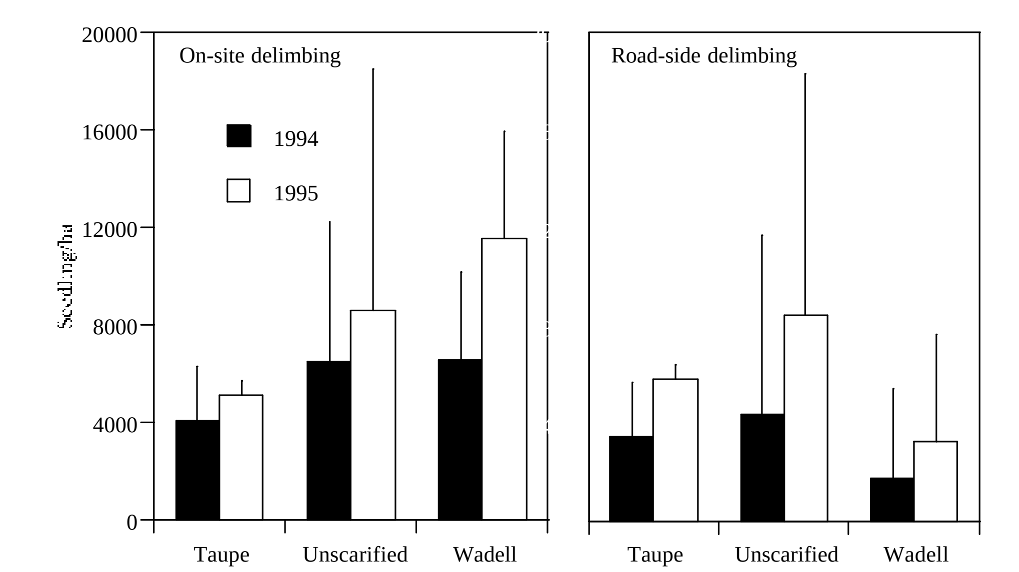

Figure 5.3. Jack pine seedling density (seedlings/ha)(mean and standard deviation) in 1994 and 1995 on each treatment.

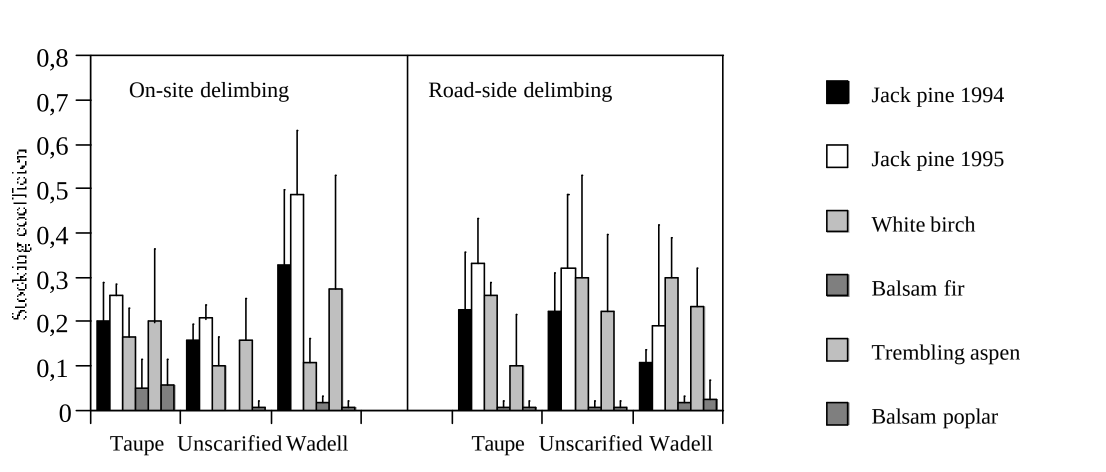

Figure 5.4. Stocking coefficient (mean and standard deviation) of jack pine in 1994 and 1995 and of the other tree species in 1995 on each treatment.

The observed difference in cover of cone-bearing woody debris among on site and road-side delimbing is similar to that observed by Bowling and Goble (1994) in northwestern Ontario. The lack of effect of this decrease on regeneration can be caused by : 1) cones left on the ground during on-site delimbing may be so badly distributed that they cannot fully contribute to regenerate the site, and 2) on whole-tree harvested plots, cones left on site with broken branches were no doubt less obstructed by logging slash. Stocking values may seem low but, if stocking was evaluated for 4 m^2 plots, as suggested by the Quebec Ministry of Natural Resources (Walsh, Rhéaume and Marotte, 1997), the figures would be much higher. An approximate conversion from stocking of 1 m^2 plots (S1) to stocking of 4 m^2 plots (S4) is as follows :

$$S4 = 1 - (1 - S1)^4$$

It is deduced by assuming that the probabilities of four 1 m^2 plots to be unstocked are independent. Thus, the probability for these plots to be simultaneously unstocked is the product of each of these probabilities. Using this formula, we obtain 94% for the on-site delimbing Wadell™ treatment and 59-82% for the other treatments, showing satisfactory jack pine stocking. The progress of regeneration from 1994 to 1995 suggests that cones in the slash continued to open. According to St-Pierre, Gagnon and Bellefleur (1992), 95% of seedlings establish during the first three years following fire. However cone opening might occur more slowly after harvest thus delaying the regeneration. This is supported by the studies of Ball (1975), Bowling, Niznowski and Maley (1997) and Symons (1996).

5.5.4 Effect of scarification

Seedlings do not establish in appropriate scarification or harvesting treatments *per se*, but on appropriate substrates. It is thus essential to evaluate the real effect of treatments on seedbeds. In this experiment, the scarifying effect of the treatments is confounded with their effect on logging slash distribution. This is one reason why « slash » was one of the seedbed types recorded.

In comparison, with the other scarification treatments, the Wadell™ reduced the slash cover and the proportion of needles and leaves and increased exposed mineral soil and mixtures of humus and mineral soil (Fig. 5.2, Table 5.2).

Scarification using La Taupe™ was tedious for workers and its effectiveness was hindered by slash piles and as expected, it did not have any significant effect on cover of different seedbeds (Fig. 5.2). Moreover, the superficial nature of the treatment resulted in its effects being rather short-lived; as early as the end of the first year, treated bands were indistinguishable from the rest of the plot. Finally, because the treatment could not be applied over the entire area but only on 17 % of the 2-ha plots, it is difficult to compare with other treatments.

When all treatments are combined, there is a strong association ($P < 0.001$), both in 1994 and 1995, between the presence of jack pine seedlings and the type of seedbed. Jack pine seedlings were more abundant on undisturbed seedbeds of needles and leaves than expected from the frequency of this seedbed (Fig. 5.5). In contrast, slash was less preferred. The seedbeds that are generally presumed to be most appropriate (exposed mineral soil, disturbed humus and rotten wood) showed little relationship with abundance of jack pine seedlings.

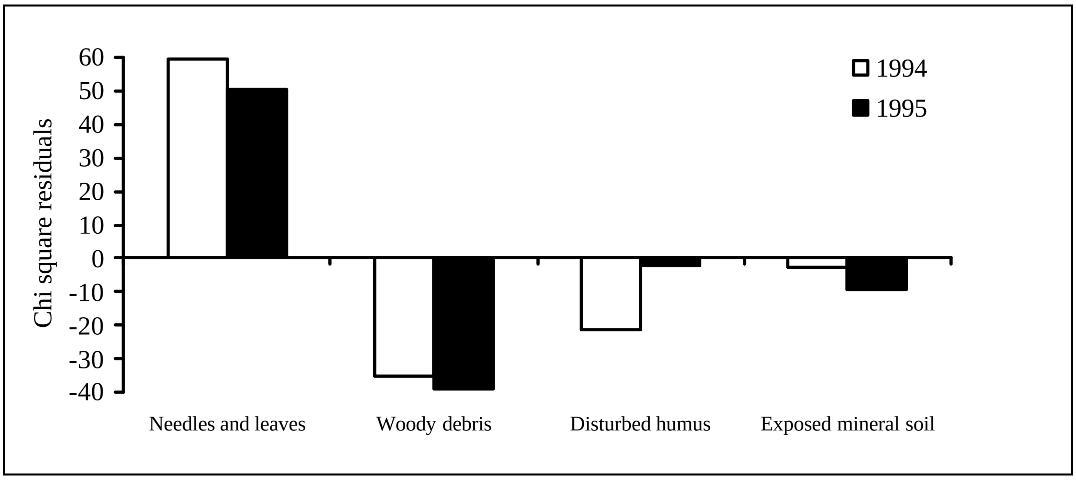

Figure 5.5. Seedbed preferences of jack pine seedlings in 1994 and 1995 shown by Chi squared residuals. Positive values indicate a higher frequency of seedlings than that predicted by abundance of seedbed.

Slash thickness was almost significantly reduced (P = 0.06) from a mean of approximately 20 cm for the control and the La Taupe™ to 14 cm for the Wadell™ (Fig. 5.6) whereas, surprisingly, it was not significantly affected by type of harvesting. The density of jack pine seedlings in each 1 m^2 sample plots in 1994 and 1995 varied from 0 to 12 and showed significant (P = 0.08 in 1994 and P = 0.0067 in 1995) linear relationships

$$Density\ in\ 1994\ ?\ ?5.09\ ?\ (\log_{10}(maximum\ slash\ height\ ?\ 1))\ ?\ 11.84$$

$$Density\ in\ 1995\ ?\ ?8.59\ ?\ (\log_{10}(maximum\ slash\ height\ ?\ 1))\ ?\ 17.77$$

with the log of maximum slash height (Fig. 5.7), showing the limit imposed by slash height on the success of regeneration. These results suggest that the utility of the Wadell™ is more in reducing slash height and improving distribution of slash than in scarifying the soil as such. They also provide some explanation as to why regeneration success is variable.

Several hypotheses may be proposed to explain why jack pine regeneration observed on undisturbed litter was proportionally more abundant than on mineral soil or disturbed humus. First, the cones and seeds on scarified sites may be more visible to seed-eating rodents than on unscarified sites. However, according to Martell, Macaulay and Crook (1995), jack pine seeds do not form a major part of the diet of deer mice (*Peromyscus maniculatus* Wagner) or southern red-backed voles (*Clethrionomys gapperi* Vigor), two of the most common small mammals in our study area (Drapeau *et al.*, 1996). As well, although red squirrels (*Tamiasciurus hudsonicus*) and chipmunks (*Tamias striatus*) do feed mainly on seeds from cones and could have a more important impact, they generally do not frequent open areas (Banfield, 1974).

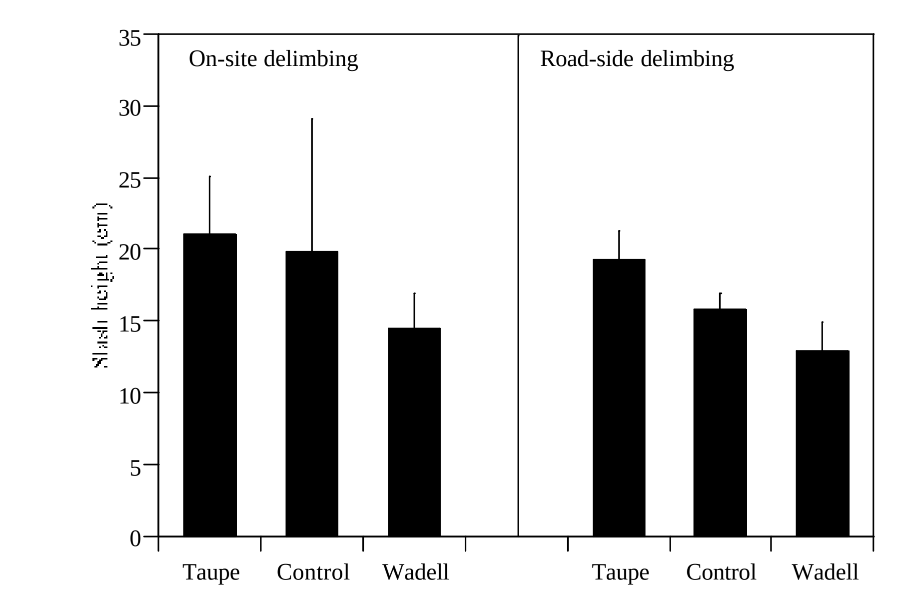

Figure 5.6. Slash height (cm)(mean and standard deviation) following site preparation.

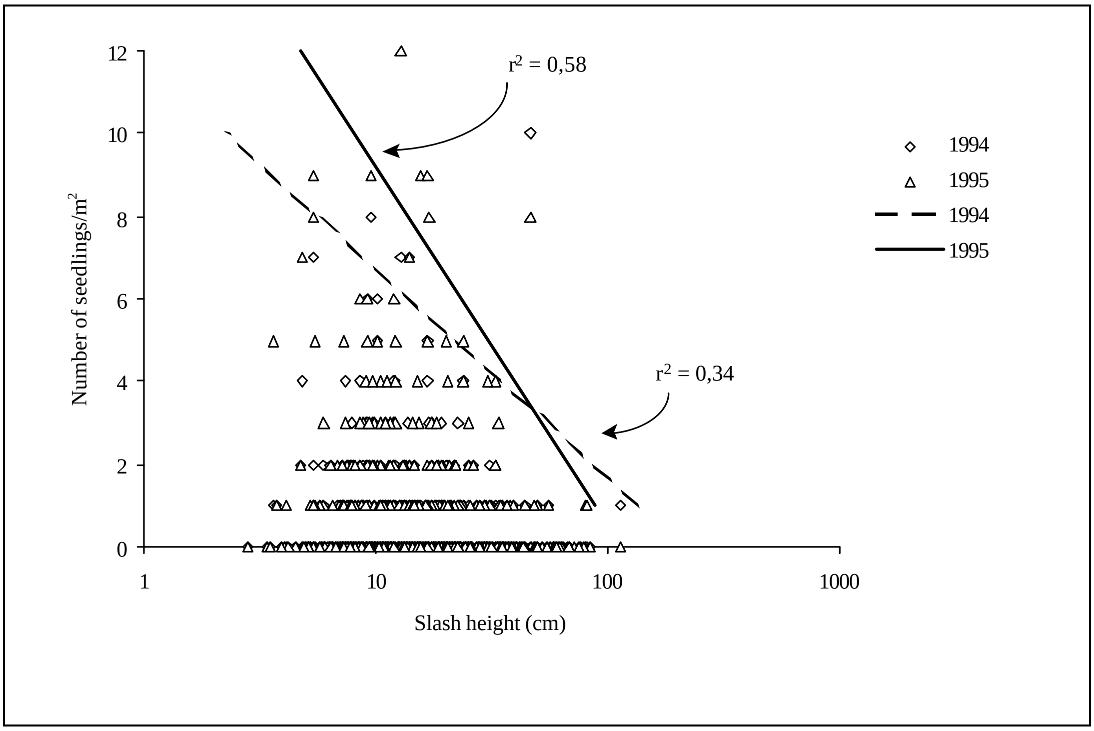

Figure 5.7. Density of jack pine seedlings (seedlings/m^2) in 1994 and 1995 in relation to slash height after treatments for each of the 1 m^2 sample plots. Linear regression lines between maximum slash height for each seedling density are shown.

Secondly, although we assumed the Wadell™ treatment with its rotating cones would have mixed and spread rather evenly the slash on the cutover area, it may have spread the material outward thus removing the cones and cone-bearing slash from above the prepared areas. However, our observations in the field confirmed that this happened on part of the sites but that slash was still adequately positioned in most cases. Nonetheless, it is possible that the different surface temperature between litter and mineral soil surfaces (Béland, Bergeron and Zarnovican, unpublished data) may have affected cone opening.

While these hypotheses refer to the presence of seed on an appropriate seedbed, it is possible that undisturbed seedbeds composed of fine leaf and needle litter may actually be the preferred substrate of jack pine on clay soils. Bulley and Bowling (1996) observed similar results in an unreplicated jack pine aerial seeding trial in northwestern Ontario. Regeneration success was higher on humus than on exposed mineral soil on clay sites and inversely on sandy sites. In another study, Fleming *et al.* (1995) observed on dry coarse-textured soils high black spruce regeneration rates on exposed mineral soil whereas in more moist conditions, maximum regeneration rate was found on seedbeds composed of surface soil. Some similarity may be drawn between moisture and texture gradients; as such, on fine-textured soils, like on more moist sites, undisturbed humus may provide the best temperature and moisture conditions for germination and seedling establishment.

On coarse-textured or sandy soils, forest floors are usually thick and fibric and are mainly composed of ericaceous shrubs, mosses and lichens that dry out rapidly when moisture conditions are dry. However, organic layers on mesic clay soils are generally shallow and humic, and probably dry out more slowly. Because clay soils have a higher water retention capacity than sandy soils, drying time of humus is probably longer on these soils. In contrast, exposed clay is generally compact and tends to harden when dry, making the substrate virtually impenetrable to seedling roots.

5.5.5 Competing vegetation

Competing vegetation was more abundant on non-scarified control plots and on plots scarified with La Taupe™ than on plots scarified with the Wadell™. Mean light interception by competing vegetation ranged from 75 % to about 90 % (Table 5.2 and 5.3). Field observations indicated that the Wadell™ reduced the amount of shrubs and increased the abundance of grasses and sedges.

We measured the effect of competing vegetation on the presence of jack pine seedlings by comparing the light intercepted by vegetation on 1 m^2 plots where at least one jack pine seedling was present to light intercepted on plots with no seedlings. Both were close to 0.83. No significant difference was revealed by analysis of variance (Table 5.4), indicating that differences in competing vegetation observed between treatments did not influence abundance of natural regeneration in the first two years. Seedling height was not significantly different between treatments (Table 5.2). Since jack pine seedlings reached a height of approximately 10 cm in 1995 (Table 5.3) compared to over a meter for aspen suckers at the same period, seedling growth may be affected in the future by strong competition from aspen suckers.

Tableau 5.3 Light intercepted by competing vegetation in 1996 and jack pine seedling height in 1995 (mean and standard deviation) for each treatment.

		Light interception (%)		Jack pine seedling height (mm)	
Delimbing	Scarification	Mean	Standard deviation	Mean	Standard deviation
On-site	La Taupe™	88.7	0.036	103.79	12.54
	Control	85.0	0.070	84.88	3.76
	Wadell™	80.4	0.010	99.37	0.57
Road-side	La Taupe™	86.8	0.047	86.62	17.47
	Control	84.7	0.059	90.31	10.39
	Wadell™	74.1	0.050	94.22	16.80

Tableau 5.4 Analysis of variance of light intercepted by competing vegetation according to presence or absence of at least one jack pine seedling in each 1 m^2 plot in 1994 and 1995.

		1994		*1995*	
Source	Degrees of freedom	Sum of squares	*P>F*	Sum of squares	*P>F*
Block	2	0.35308455	0.09	0.35775094	0.13
Presence	1	0.00143144	0.8	0.02045233	0.48
Error	2	0.03432323		0.05667727	

5.5.6 Regeneration of other species

Post-harvest stocking for white birch was higher in plots delimbed at the road side than in those delimbed on site (Fig. 5.3). This might simply be due to more surface area free of slash. Stocking of balsam fir, aspen and balsam poplar (*Populus balsamifera* L.) were not significantly different between treatments. Overall, stocking levels suggest that, unless fill planting and hardwood control are undertaken, stands evolving from the experiment will have a mixed (deciduous-conifer) composition.

5.6 CONCLUSIONS

The irregular distribution of slash during on-site delimbing limited the contribution of cones contained in slash to regeneration. Consequently, on-site delimbing did not result in higher jack pine seedling densities than road-side delimbing. Soil scarification did not significantly improve jack pine regeneration on clay soils. Scarification treatments had more impact on distribution and thickness of slash than on seedbed quality for germination. The cost of scarification by the Wadell™ (215 $/ha, Parent (1996)) is difficult to justify given these results.

Thick accumulations of slash produced inadequate seedbeds. Cayford (1958) stressed the importance of adequate branch dispersal to obtain good jack pine regeneration and Bruce and Sims (1970) suggested shredding slash as a means of getting the cones closer to the ground. A simpler method of ensuring better branch distribution and avoiding thick slash accumulations would be to delimb trees completely rather than only up to the end of their merchantable portion. When followed by a light site preparation to distribute branches over the cutover and, in year three, fill planting, this prescription could assure adequate regeneration density on these sites.

It should be mentioned, however, that competing vegetation was very abundant in the experiment and that vegetation control will probably be necessary to successfully bring seedlings to free-to-grow. Further monitoring of competition, seedling survival and growth is necessary to evaluate this effect.

Jack pine seed trees did not readily disperse seeds in the absence of fire. However, the conservation of seed trees in combination with prescribed burning could conceivably be used to naturally regenerate jack pine. If the site is protected form prevailing winds and if stands were previously thinned, windthrow could be limited.

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CONCLUSION GÉNÉRALE

6.1 PRINCIPAUX RÉSULTATS

L'objet de la présente thèse était, d'une part, de recueillir des informations de base susceptibles de servir au développement de la sylviculture des peuplements de pin gris retrouvés sur les différents types de sols de la ceinture d'argile abitibienne et, d'autre part, de tester des techniques sylvicoles applicables pour y favoriser la régénération naturelle du pin gris après coupe. L'originalité de la thèse réside principalement dans cette double approche expérimentale. Nous croyons que les deux volets de cette approche se complètent, se valident mutuellement et donnent plus de force aux conclusions et recommandations que l'on peut tirer de la thèse. Les résultats de la thèse profitent également de leur inscription dans le cadre plus vaste de l'approche d'aménagement écosystémique. L'autre aspect original est de nature circonstancielle. En effet, les peuplements de pin gris sur argile de l'Abitibi avaient assez peu attiré l'attention des chercheurs québécois avant la présente recherche malgré l'importance de la superficie couverte par ces forêts.

Avant de discuter des conséquences de nos résultats sur l'aménagement des peuplements de pin gris, nous réviserons les principaux résultats obtenus.

Les résultats de l'article 1 ont permis de définir trois classes de productivité du pin gris : une classe de faible productivité où l'on retrouve les sables et les dépôts (organiques ou de till) minces sur roc, une classe de forte productivité représentée par les tills et une classe de très forte productivité représentée par les argiles. Bien qu'il soit peu exigeant, le pin gris bénéficie de la richesse des sols argileux. L'analyse des formes de courbes de croissance en hauteur a aussi révélé que les peuplements sur sables bien drainés accusent un retard de croissance en hauteur pendant les premières années de vie par rapport aux peuplements sur sables modérément bien drainés. Par contre, ce retard ne se traduit pas, à maturité, par une productivité différente de celle des sables modérément bien drainés. La prise en compte du régime hydrique ne permettrait donc pas de déterminer avec plus de précision la productivité du pin gris.

Les résultats de l'article 2 ont permis de constater que la régénération haute préétablie sous les peuplements de pin gris diffère surtout entre les sables, les dépôts minces et les dépôts d'argile ou de till. De plus, malgré les différences qu'ils présentent du point de vue de la croissance, les peuplements de pin gris sur till et sur argile ont une régénération préétablie similaire. Le type de sol n'est pas la seule variable influençant la régénération préétablie sous les peuplements de pin gris. Il semble que la proximité des arbres semenciers soit un autre facteur important, du moins pour le sapin baumier et l'épinette blanche (Galipeau, Kneeshaw et Bergeron, 1997). Le régime hydrique n'apparait pas comme une variable qui permette de discriminer davantage les types de sol sur le plan de la régénération préétablie et de la croissance en hauteur du pin gris.

Les résultats de l'expérience d'ensemencement (article 3) indiquent que les conditions de germination sont meilleures sur argile que sur till ou sur sable. Le scarifiage du sol est utile à la germination des semis de pin gris; cette utilité décroît lorsque l'on passe des sables aux tills et des tills aux argiles. Les régimes de température et d'humidité du sol, conséquences de la grande capacité de rétention d'eau et de l'abondante végétation concurrente sur argile peuvent expliquer ces résultats. Ceci nous porte à croire que le pin gris n'a pas plus de difficulté à s'établir sur argile que sur des sables plus typiques de cette espèce. Le contrôle de la végétation concurrente a eu un effet positif sur la survie et la croissance en diamètre des semis de pin gris au terme des deux années de suivi. Cet effet est plus grand sur les sols argileux. Par ailleurs, la croissance en hauteur était peu affectée. Ainsi, l'abondance et la persistance de la végétation concurrente (principalement le tremble) pourrait être un facteur critique pour la survie et le développement des semis de pin gris à plus long terme.

Les résultats des articles 3 et 4 confirment que la dispersion des graines de pin gris à partir des arbres semenciers et de la forêt environnante ne contribue pratiquement pas à la régénération du pin gris à cause du caractère sérotineux de ses cônes dans les conditions retrouvées dans le secteur à l'étude. Cependant, des observations faites sur le terrain suggèrent que l'ouverture des cônes au sol ne limitent pas la régénération du pin gris dans les conditions qui existent sur le territoire à l'étude ; en général, les écailles des cônes de pin gris sur le sol se détachent les unes des autres sur au moins un des côtés, peu importe le type de dépôt de surface. Les résultats positifs de l'essai sylvicole réalisé sur argile (article 4) confirment cette hypothèse.

Les résultats de l'essai de régénération du pin gris par ébranchage sur le site et scarifiage (article 4) montrent que ces techniques, élaborées dans le reste du Canada, sont également applicables dans le secteur à l'étude, sur les sols argileux de l'Abitibi. En effet, la densité et le coefficient de distribution de semis de pin gris obtenus après deux saisons de croissance sont le signe d'une régénération suffisante pour assurer, à tout le moins, l'établissement de peuplements mélangés de pin gris et de peuplier faux-tremble. Par contre, les techniques utilisées pour le scarifiage et l'ébranchage sur le site n'ont pas amélioré la régénération du pin gris autant qu'on s'y attendait et pourraient encore être optimisées. L'utilisation de semenciers dans les dispositifs des articles 3 et 4 a permis de constater que les semenciers pourraient rester debout suffisamment longtemps pour réaliser un brûlage dirigé sous couvert de semenciers.

Les résultats de l'article 5, présenté en annexe, montrent que les coupes d'ensemencement avec conservation de 200 tiges·ha^{-1} de pin sylvestre réalisées dans le sud de la Suède pour obtenir des peuplements denses, et ainsi améliorer la qualité du bois (défilement, densité du bois, etc.), favorisent une régénération naturelle du pin sylvestre très abondante dont le succès à court ou à moyen terme est quasi assuré.

6.3 DYNAMIQUE DES PEUPLEMENTS DE PIN GRIS

Le Tableau 6.1 résume les caractéristiques des peuplements de pin gris sur les trois principaux dépôts de surface de la forêt boréale mixte de l'Est.

Tableau 6.1. Résumé des caractéristiques des peuplements de pin gris sur les trois principaux dépôts de surface de la forêt boréale mixte de l'Est.

Thème		Sable	Till	Argile
Productivité du pin gris		Faible	Forte	Très forte
Régénération préétablie				
(tiges·ha^{-1})	Pin gris	40	0	0
	Épinette noire	490	23	1
	Épinette blanche	0	1	2
	Bouleau à papier	16	18	21
	Sapin baumier	1	2	31
Température au sol		+++	++	+
Compétition		-	+	++
Impact du scarifiage		+++	++	+
Espèces compagnes		PIMA	BEPA, POTR	BEPA, POTR
Substrat dominant		Mousses hypnacées	Litière feuilles et aiguilles	Litière feuilles et aiguilles

Note : PIMA, épinette noire, BEPA, bouleau à papier, POTR, peuplier faux-tremble.

La croissance très rapide du pin gris sur les sols argileux de l'Abitibi (Béland et Bergeron, 1996) illustre bien la richesse du sol et le grand potentiel de croissance que celui-ci peut offrir, non seulement pour le pin gris, mais aussi pour les autres espèces arborescentes et de sous-bois avec lesquelles il partage le milieu. C'est donc cette forte productivité qui rend la dynamique naturelle sur sol argileux plus complexe que celle sur sable. En effet, sur les sols à texture grossière de la forêt boréale, où se retrouve principalement le pin gris, les mécanismes de succession sont simples. À la suite d'un feu de forêt, le pin gris s'installe rapidement en compagnie d'une quantité variable d'épinette noire. Comme le pin gris pousse plus vite que l'épinette noire, il domine le début de la succession. Par contre, si le feu de forêt suivant ne se produit qu'au-delà de la longévité du pin gris, l'épinette noire prend le relais. Le sous-bois de ces forêts est généralement dominé par des mousses et des éricacées qui laissent percer une lumière abondante jusqu'au sol.

À l'opposé, les peuplements de pin gris sur argile sont caractérisés par une régénération préétablie moins abondante mais plus diversifiée que celle sur sable (Béland et Bergeron, 1993) et par une composition mixte et variable à l'échelle du paysage (Longpré *et al.*, 1994). De plus, un sous-bois plus riche (De Grandpré, Gagnon et Bergeron, 1993 ; Légaré, 2000), plus dense et une faible quantité de lumière au sol (D'Astous et Messier, 1999) sont d'autres caractéristiques qui découlent de la forte productivité de ces sites. C'est d'ailleurs la présence du bouleau et surtout, celle du peuplier faux-tremble, qui rend les mécanismes de succession complexes puisqu'elle crée une incertitude quant à l'issue de celle-ci. Toutefois, les résultats de la présente étude ne permettent pas de se prononcer sur les facteurs qui déterminent la prédominance du tremble ou du pin gris. L'intensité des feux et la composition forestière avant feu (Greene et Johnson, 1999) figurent parmi les facteurs susceptibles de jouer un rôle dans ce processus. Les résultats confirment néanmoins la faisabilité de la régénération naturelle du pin gris après coupe sur argile.

6.4 IMPLICATIONS POUR L'AMÉNAGEMENT DES PEUPLEMENTS DE PIN GRIS SELON UNE APPROCHE ÉCOSYSTÉMIQUE

Les résultats de l'article 1 soulignent l'importance de tenir compte du type de sol dans le calcul des rendements des peuplements de pin gris et dans la planification de leur sylviculture. L'utilisation de l'âge total plutôt que l'âge à hauteur de poitrine paraît plus appropriée car ce dernier masque les différences de niveau et de forme de courbe de croissance en hauteur entre les dépôts.

La présence du pin gris parmi les trois principales essences forestières présentes après feu dans la forêt boréale mixte de l'est du Canada est mentionnée par Bergeron et Harvey (1997). Le pin gris fait partie, au même titre que le peuplier faux-tremble et que le bouleau à papier, du premier des trois stades de succession à survenir après feu sur argile. Afin que le paysage aménagé soit représentatif d'un paysage soumis au régime de perturbations naturelles, il est nécessaire de maintenir la représentation du pin gris parmi les peuplements de ce premier stade et de maintenir la représentation du premier stade à l'échelle de la forêt.

Pour ce faire, on ne peut pas compter sur la régénération préétablie, comme nous l’indiquent les résultats de l’article 2 puisqu’elle est présente en trop faible quantité. Les articles 3 et 4 éclairent l’aménagiste sur la façon de régénérer naturellement les peuplements purs de pin gris après coupe. Ils permettent de croire que les techniques présentées assureraient le retour, sinon de peuplements purs de pin gris, du moins de peuplements mixtes comportant une certaine proportion de peuplier et de bouleau. Le recour au regarni, lorsque nécessaire, ou au dégagement de la régénération naturelle en pin gris, quelques années après la coupe, permettrait d’atteindre les objectifs en matière de composition relative en peuplier, en bouleau, en pin gris et en peuplements mixtes de ces essences à l’intérieur des peuplements de début de succession. Au besoin, on pourrait procéder, dans une certaine proportion du territoire, à la plantation ou à l’ensemencement artificiel de pin gris surtout si l’on souhaite régénérer un peuplement de pin gris à partir d’un peuplement de succession plus avancée dans lequel la proportion de pin gris est faible. Cependant des expériences de régénération du pin gris par brûlage dirigé sous couvert de semenciers pourraient nous permettre un jour de régénérer ces peuplements à partir de semenciers isolés.

D’ici là, il est préférable de privilégier les peuplements de début de succession pour assurer le retour du pin gris. De plus, il faudrait planifier l’ensemble de la récolte des peuplements de début de succession de façon à favoriser le pin gris, puisque ce dernier semble plus difficile à régénérer que le peuplier ou le bouleau.

Afin d’assurer la présence d’un maximum de semences de pin gris sur le parterre de coupe, nous suggérons de réaliser l’ébranchage sur le site et de disperser les branches avec une chaîne à débroussailler ou une débusqueuse munie d’un peigne. Le scarifiage serait nécessaire pour garantir la régénération du pin gris sur sable et sur till, mais il serait probablement superflu sur argile. N’ayant pas à effectuer cette opération, l’aménagiste réaliserait des économies et éviterait en partie que le site soit envahi par des espèces végétales rudérales.

Pour ce qui est de faire évoluer une certaine proportion de peuplements de pin gris vers les stades intermédiaire et éventuellement de fin de succession, on devrait pouvoir utiliser des coupes partielles pour réduire l’importance du tremble et favoriser la régénération préétablie, comme l’ont suggéré Harvey *et al.* (2000) pour les peuplements de peuplier faux-tremble. Par, ailleurs, puisque le pin gris a une longévité supérieure à celle du peuplier faux-tremble, il est plausible qu'un certain nombre de pin gris survivent jusqu'au stade intermédiaire.

La présente thèse a été réalisée dans le but de contribuer au développement d'une stratégie d'aménagement des peuplements de pin gris qui s'intègre à la dynamique naturelle des écosystèmes. Rien n'indique que ces pratiques aient des conséquences négatives sur l'exploitation de la matière ligneuse dans ces peuplements. L'article 5, présenté en annexe, est un autre exemple de cette compatibilité entre aménagement intensif et aménagement écosystémique. Ainsi, les coupes d'ensemencement avec conservation de 200 tiges$\cdot$ha^{-1} de pin sylvestre, réalisées dans le sud de la Suède, constituent un changement important dans les méthodes employées par les aménagistes suédois. Ce type de traitement sylvicole, qui permet d'obtenir des peuplements denses et éventuellement d'améliorer la qualité du bois, a été conçu au départ dans un contexte d'aménagement intensif qui visait essentiellement la production ligneuse. Toutefois, il pourrait très bien s'inscrire dans une démarche plus vaste d'aménagement écosystémique puisqu'il est *a priori* compatible avec l'écologie de l'espèce. Il offre un compromis qui permettra, d'une part, de satisfaire les besoins de l'industrie en matière ligneuse et, d'autre part, de répondre aux préoccupations de plus en plus grandes liées à la préservation de la biodiversité et au maintien de l'intégrité écologique des écosystèmes.

6.5 PISTES DE RECHERCHE PROPOSÉES

Nous diviserons en deux thèmes les pistes de recherche qui pourraient découler de la présente thèse. Le premier concerne les aspects fondamentaux qui permettraient d'explorer davantage les processus impliqués dans la régénération naturelle du pin gris. Le second concerne des essais sylvicoles.

Parmi les aspects fondamentaux, les données inédites recueillies lors des travaux sur le terrain entrepris dans le cadre de cette thèse permettraient d'établir des liens entre, d'une part, la structure des peuplements de pin gris selon le type de sol et l'âge du peuplement et, d'autre part, la production de cônes et de graines. Ces données permettraient notamment d'étudier l'influence de la structure des peuplements sur l'évolution, avec l'âge, du coefficient de forme des tiges de pin gris selon le type de dépôt de surface. Cela permettrait de mieux prévoir le résultat des traitements sylvicoles visant la régénération naturelle du pin gris et éventuellement de proposer des traitements pour augmenter la production de graines.

Selon les observations de Longpré *et al.* (1994), la présence d'espèces compagnes n'aurait aucun effet sur la croissance moyenne en hauteur du pin gris. Par contre, une analyse plus fine de la structure de taille des arbres, basée sur les théories de Weiner (1995a,1995b), permettrait de mieux comprendre les mécanismes en jeu dans la compétition entre le pin gris, le bouleau et le tremble.

Il serait intéressant de mieux définir les propriétés des humus qu'on retrouve sur les différents types de sol et les différents types de composition forestière, et d'établir des liens entre ces caractéristiques et le régime de température et d'humidité à la surface du sol. Ces renseignements permettraient de vérifier pourquoi le scarifiage sur argile est apparemment peu utile.

Du côté des essais sylvicoles, il serait intéressant de tester différentes techniques permettant d'accroître la quantité de graines dispersées et d'améliorer leur distribution lors d'opérations visant la régénération naturelle du pin gris à partir des déchets de coupe. Parmi les techniques qui pouuraient être employées, mentionnons l'ébranchage jusqu'au fin bout et le déchiquetage des déchets de coupe.

Les résultats de la présente thèse indiquent qu'une opération de brûlage dirigé sous couvert d'arbres semenciers visant la régénération naturelle du pin gris pourrait être réalisable puisque les arbres semenciers ont de bonnes chances de rester debout assez longtemps pour assurer la dispersion des graines. De plus, il est possible que la régénération naturelle du pin gris puisse s'établir plus rapidement par cette technique qu'à partir des déchets de coupe. Il serait intéressant de vérifier si l'élimination de ce délai favorise le pin gris dans la lutte qui l'oppose au peuplier pour la dominance du peuplement. Enfin, la faible concentration de nitrates retrouvée après feu favoriserait le pin gris, puisqu'il utilise surtout l'azote sous forme d'ammoniaque alors que le tremble et plusieurs autres espèces végétales concurrentes l'assimilent plutôt sous forme de nitrates (Ste-Marie et Paré, 1999). Si les résultats de telles expériences s'avéraient positifs avec des peuplements dominés par le pin gris, on pourrait reprendre les expériences des peuplements de stade intermédiaire de succession dans lesquels seules quelques tiges de pin gris subsistent.

L'éclaircie commerciale des peuplements de pin gris est un traitement intermédiaire qui gagne en popularité au Québec. Par contre, les avantages sur le plan des gains en volume marchand de ce type de traitement sylvicole sont encore incertains compte tenu de l'état actuel des forêts; la plupart des peuplements susceptibles d'être éclaircis sont d'origine naturelle et ont rarement subi d'éclarcie précommerciale. Par contre, s'il était possible de favoriser la régénération naturelle par l'éclaircie commerciale, cela ajouterait un second objectif justifiant de poursuivre les expérimentations.

Nous croyons qu'il serait opportun de faire un suivi de dégagement des semis de pin gris pour évaluer l'effet de la compétition végétale sur la croissance et la survie des semis de pin gris établis par régénération naturelle par rapport à des semis issus de plantations, mais également pour vérifier si l'on peut ainsi influencer la composition des forêts régénérées.

On pourrait en outre étudier les communautés de plantes retrouvées dans les peuplements de pin gris issus de plantations et dans ceux provenant de la régénération naturelle, avec et sans scarifiage, afin d'évaluer l'impact des pratiques suggérées dans cette thèse sur la préservation de la biodiversité.

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ANNEXE : LE SCARIFIAGE ET LA PLUIE DE GRAINES AFFECTENT LA RÉGÉNÉRATION NATURELLE DU PIN SYLVESTRE SOUS DEUX DENSITÉS DE COUPE D'ENSEMENCEMENT ET DANS UNE COUPE À BLANC DU SUD DE LA SUÈDE

Martin Béland, Eric Agestam, Per Magnus Ekö, Pelle Gemmel et Urban Nilsson. 2000. « Scarification and seedfall affects natural regeneration of Scots pine under two shelterwood densities and a clear-cut in southern Sweden ». *Scandinavian Journal of Forest Research*. 15(2) : 247-255.

A.1 RÉSUMÉ

Nous avons réalisé une étude afin d'évaluer l'effet de la densité du pin sylvestre (*Pinus sylvestris*) laissé après une coupe d'ensemencement ainsi que l'effet de la séquence de coupe des tiges résiduelles sur la régénération d'une forêt dont le bois serait de meilleure qualité. Le présent article porte sur l'effet du scarifiage et de la pluie de graines sur la régénération du pin sylvestre sous deux densités de coupe d'ensemencement et dans une coupe à blanc. Les effets sur la qualité du bois seront traités ultérieurement. Après quatre années, la régénération naturelle du pin sylvestre a atteint 90 000 semis·ha^{-1} sous un abri de 200 tiges·ha^{-1}, 53 000 semis·ha^{-1} sous un abri de 160 tiges·ha^{-1} et 3 700 semis·ha^{-1} dans une coupe à blanc. La grande abondance de régénération naturelle sous l'abri le plus dense résulte d'une forte pluie de graines, d'une invasion plus lente de la végétation concurrente, d'une période de recrutement conséquemment prolongée et d'une faible mortalité. Comme la mortalité a fortement diminué dans les deux densités d'abri et puisque le recrutement semble se poursuivre, nous nous attendons à ce que le succès de la régénération se maintienne dans le futur si des opérations de dégagement appropriées de l'abri sont effectuées. Ces opérations pourraient commencer dès que les semis atteindront 0.5 m de hauteur et se poursuivre de façon à conserver un couvert jusqu'à ce qu'ils atteignent une hauteur d'environ 6 m. Il semble possible d'utiliser des abris de 200 tiges·ha^{-1} de pin sylvestre dans le sud de la Suède pour obtenir des peuplements denses et ainsi améliorer la qualité du bois (défilement, densité du bois, etc.).

A.2 ABSTRACT

A study was undertaken to evaluate the effect of Scots pine (*Pinus sylvestris*) shelterwood density and timing of removal on the regeneration of forests with improved wood quality. This paper focuses on the effect of scarification and seedfall on success of natural regeneration of Scots pine under two shelterwood densities and in a clear-cut. Wood quality aspects will be addressed later in the study. After four years, natural regeneration of Scots pine under a 200 stems·ha^{-1} shelterwood reached 90 000 seedlings·ha^{-1}, 53 000 under a 160 stems·ha^{-1} shelterwood and 3 700 in a clear-cut. The high natural regeneration under the densest shelterwood resulted from a high seedfall, slower invasion by competing vegetation, consequent prolonged recruitment and low mortality. Since mortality largely decreased for both shelterwood densities and since recruitment seems to continue, we expect the success of regeneration to maintain in the future if proper release operations are conducted. The latter could begin when seedlings get to about 0.5 m high and the cover should be maintained until they get to about 6 m high. Using 200 stems·ha^{-1} Scots pine shelterwoods in southern Sweden to get dense stands and by that improve wood quality (stem taper, wood density, etc.) might thus be possible.

A.3 INTRODUCTION

Regeneration of Scots pine (*Pinus sylvestris* L.) in southern Sweden is mainly accomplished through planting, with plantation densities commonly varying from 2 000 to 4 000 seedlings·ha^{-1} and, to a smaller extent, through natural regeneration with shelterwood cutting. Planting, especially with wide spacings, leads to poor wood quality (Persson, 1976). Shelterwood cutting in combination with soil scarification has been used in Sweden for a long time. It is a fair approximation of the natural dynamics of Scots pine which is largely influenced by the fire regime (Bradshaw, Tolonen and Tolonen, 1997, Zackrisson *et al.*, 1995) : soil scarification replaces fire for seedbed preparation and residual trees simulate the survival of some trees to a surface fire. This method has the advantage of protecting seedlings from frost damage (Hagner, 1962), pine weevil (*Hylobius abietis* (L.)) attacks (von Sydow & Örlander, 1994) and, desiccation (Hagner, 1962). The shading of a shelterwood may also protect seedlings from frost heaving (Goulet, 1995). We know from spacing experiments that seedling densities (in planted stands) of 10 000 seedlings·ha^{-1} sometimes are not enough to ensure good wood quality (Persson, 1977). Therefore, densities above 10 000 seedlings·ha^{-1} (at the height of about 1 m) are probably needed in natural regeneration since the seedlings most often are less evenly distributed than in planted stands. Commonly used shelter tree densities vary from 20 to 160 stems·ha^{-1}. The use of shelterwoods with a high density of shelter trees maintained for long periods of time is expected to lead to high seedling densities and to give sufficient shade to slightly slow the growth of seedlings. High seedling densities contribute to lower the stem taper and slow growth favors an homogenous wood density, both properties leading to better wood quality of the new forest (Ekö & Agestam, 1994 ; Agestam, Ekö and Johansson, 1998). High density of shelter trees could also lower the risk of shelter trees being windthrown (Hagner, 1962) and could increase the quantity of high quality wood harvested from the shelter trees. However, the optimal design of shelterwood systems for forest regeneration remains to be determined (von Sydow and Örlander, 1994).

Soil scarification is known to increase soil surface moisture availability and to favor seed germination (Hagner, 1962). Raw forest humus is a poor seedbed for germination (Fleming *et al.*, 1995 ; Riley, 1980, Chrosciewicz, 1990). Soil scarification is thus a standard practice used in combination with shelterwood regeneration of Scots pine. However, the extent of scarification effect in dense shelterwoods is unknown. Scots pine seed production is known to vary from year to year and is mainly dependent on the climate conditions three years before seedfall (Sarvas, 1962). This variation could affect the increased availability of seeds expected in a dense shelterwood. Ground vegetation gradually invades prepared seedbeds but this colonization is probably slowed by dense shelterwoods. Scarified sites may therefore be open to seedfall for longer periods of time in dense shelterwoods compared to sparse ones.

A study was thus undertaken to evaluate the effect of Scots pine shelterwood density and timing of removal on the regeneration of forests with improved wood quality. This study focuses on the success of natural regeneration (germination and survival) of Scots pine under two shelter tree densities and in a clear-cut in combination with soil scarification. Wood quality aspects are to be addressed at a later stage in the study.

The hypotheses that were tested are: (i) Scots pine germination is greater on scarified than on undisturbed seedbeds and Scots pine germination declines after prepared seedbed invasion by ground vegetation; (ii) Prepared seedbed invasion by ground vegetation takes a longer period of time in dense shelterwoods than in more open ones; (iii) Scots pine regeneration success under a 200 stems$\cdot$ha^{-1} shelterwood is similar to that under a 160 stems$\cdot$ha^{-1} shelterwood.

A.4 MATERIAL & METHODS

The experiment was conducted in the Linnebjörke Forest (57°00'N, 15°10'E, altitude 225 m a.s.l.), belonging to the Swedish University of Agricultural Sciences, Asa Experimental Forest, about 30 km north-east of Växjö in southern Sweden. The stand chosen for the experiment had 573 stems$\cdot$ha^{-1} and was about 78 years old at the time of shelterwood establishment. A smaller component of Norway spruce (*Picea abies* (L.) Karst.) was also present (Table A.1). The soil is a relatively fertile (site index = 27 m dominant height at age 100 years, Hägglund, 1974) sandy loam moraine. The experiment was about 10 ha surrounded by a fence to avoid browsing by deer and moose (Fig. A.1). The experiment is organized in three shelterwood densities; (1). Clear-cut, (2). Shelterwood cut, about 160 shelter trees$\cdot$ha^{-1}, (3). Shelterwood cut, about 200 shelter trees$\cdot$ha^{-1} (Table A.1). The cutting was done in January and February, 1992. The Norway spruce were all cut except when no Scots pine shelter tree was present. Due to the cost of establishing the experiment, treatments of shelterwood densities were not replicated. Care was taken to avoid any source of variability that could affect the results apart from the treatments. Therefore, the three treatments were contiguous and placed on a flat terrain of uniform soil composition and stand composition.

Tableau A. 1. Stand characteristics before cutting and in the two shelterwood treatments.

	Site Index (m)	Age (yr)	Height (m)	Density (stems·ha^{-1})	Basal area (m^2·ha^{-1})	Mean DBH (cm)	Stem volume (m^3·ha^{-1})
Before shelterwood establishment							
Scots pine	27	78	24	230	15.9	29.7	174
Norway spruce				343	13.8	22.6	110
After shelterwood establishment, 160 stems·ha^{-1}							
Scots pine				150	11.3	31.0	123
Norway spruce				4	0.3	30.9	1
After shelterwood establishment, 200 stems·ha^{-1}							
Scots pine				189	13.8	30.5	151
Norway spruce				19	1.2	28.4	7

Note: Age and height are averages for the 100 largest dominant pine trees.

The slash was left on the ground but was spread out by a forwarder in July 1992. Scarification (disc trenching) with a Donaren 870H was done at the end of October 1992 in two perpendicular passes. The scarifier created patches 200 x 50 cm.

Another scarification experiment was also conducted inside the same area to compare ground vegetation invasion and seedling establishment during successive years on freshly scarified seedbeds. Two scarification treatments were done in the autumn each year from 1992 to 1995. These treatments were (i) exposing mineral soil on 0.16 m^2, and (ii) mixing 5 dm^3 of humus with mineral soil on 0.16 m^2. Each combination of year and type of scarification was repeated and randomized within 10 blocks in the clear-cut and in the densest shelterwood. Number of seedlings were tallied each fall of the years following scarification until the end of 1996. The extent of prepared seedbed invasion by vegetation was recorded in percent cover in the fall of 1996.

Air temperature 1.7 m above ground (thermocouple. Cu-Co Ø=0.05 mm) and precipitation (rain gauge, Environmental Instruments Ltd. UK) were measured at the experimental site. Both the thermocouple and the rain gauge were connected to a Campbell CR10 datalogger (Campbell Scientific Inc.). Measurements were taken each minute and average (air temperature) and sum (precipitation) values were stored each day. During eight days in May 1992, quantum sensors (Model LI190SA, LiCor Inc. Lincoln, NE, USA) were used to measure photosynthetic active radiation in each shelterwood. One quantum sensor was placed in each shelterwood and was connected to a Campbell CR10 datalogger. Measurements were taken each minute and summed each day ($mol{\cdot}m^{2}{\cdot}day^{-1}$).

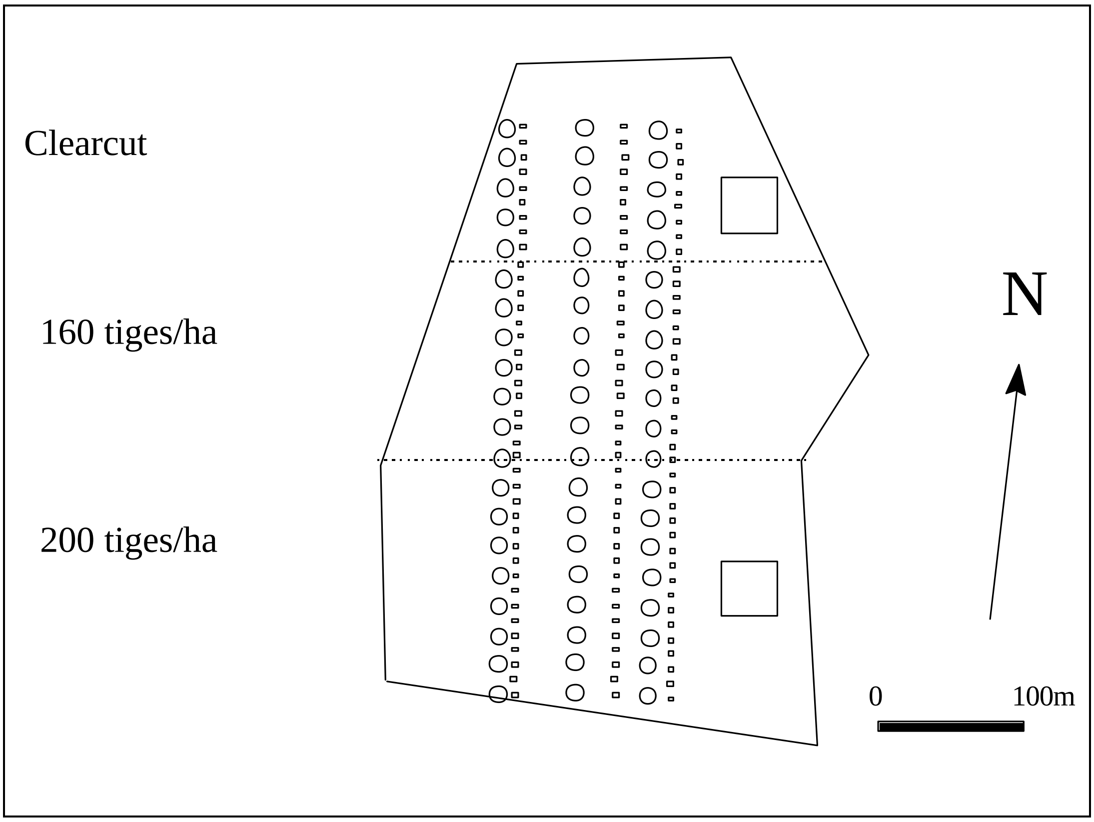

Figure A.1. Map of the experimental design. Small squares : sample plots ; circles : seed traps ; large squares : location of the small scarification experiment ; dashed lines : limits of treatments and full line : fence.

On 1 m^2 sample plots, systematically distributed along three transects (39 on each), the degree of disturbance to the ground by the scarification was assessed during the spring following the treatments, and was described on a map of each subplot. The areal extent of each seedbed type (mineral soil, mixture of mineral soil and humus, undisturbed seedbed and other) was measured by superimposing a grid on each map. On the same plots, the number of seedlings (new, old, mortality) was registered once each spring and autumn from 1993 to 1996. Because it is difficult to differentiate the species (Norway spruce or Scots pine) of the seedlings when they are very young, identification was done only in the last seedling inventory in the autumn of 1996. The seedfall has been sampled every year between 1992-1996. Seed traps of 0.25 m^2 each were set along three lines (20 traps along each line), running through the various shelterwood treatments (Fig. A.1). Scots pine and Norway spruce seeds without their wings are difficult to distinguish. Therefore, seedwings without seeds and seeds without wings were counted separately from the intact seeds.

The evaluation of the number of Scots pine seedlings was done by giving the same proportion of Scots pine and Norway spruce as the one observed in the remaining live seedlings observed in the last inventory (proportion ranging from 0 to 33 % Norway spruce). This was done by assuming the same rate of mortality for the two species. The seedfall assigned to each plot was the average number of Scots pine seeds in neighbouring seedtraps. Species of seeds without wings were assumed to be in the same proportion as that of Scots pine seed wings. The rate of germination on each sample plot was computed by calculating the percentage of newly germinated seedlings per m^2 over the seed fall per m^2. Since each seedling was mapped in the field, we could determine the year of origin of each of them and compute a cumulative rate of mortality for each cohort of seedlings. The different means were compared using two-sample t-tests with pooled variance (Snedecor & Cochran, 1967). A significance level of 0.05 was used.

A.5 RESULTS

Climate measurements indicated that the year 1993 had a rather cold and wet summer, whereas there was a severe drought and high temperatures in middle summer 1994 and a relatively wet spring in 1995 (Fig. A.2). The measurements of photosynthetic active radiation (PAR) in the various cuttings in May 1992 showed that PAR at ground level was reduced by about 35 % in the 160 stems·ha^{-1} shelterwood and by about 53 % in the 200 stems·ha^{-1} shelterwood.

In the scarification-year experiment, the percent cover of vegetation increased with increasing time since scarification (Fig. A.3), showing the gradual invasion of ground vegetation. This invasion occurred significantly faster in the clear-cut than in the 200 stems·ha^{-1} shelterwood (? < 0.05). There was no significant difference between the mixed treatment and the mineral soil treatment. The most common species of competing ground vegetation found on the experiment were *Deschampsia flexuosa* and *Caluna vulgaris.* In the clear-cut, germination rate (ratio of germinated seeds) on freshly scarified soil stayed approximately the same in 1993 and 1994, decreased in 1995 and, in 1996, increased to a significantly higher level than 1993, whereas, in the dense shelterwood, germination rate decreased in 1994, increased somewhat in 1995, and then increased greatly in 1996 (? < 0.05) (Fig. A.4). All years considered, the germination rate was significantly higher on mineral soil than on mixed humus and mineral soil (? < 0.05).

In the main experiment, the scarificator created a significantly lower proportion of mineral soil seedbeds than of humus mixed with mineral soil (? < 0.05) (Table A.2). There was no significant difference in the seedbed type proportion between the shelter treatments. Years 1993 and 1995 were good seed years for Scots pine compared to 1994 and 1996 (? < 0.05) (Table A.3). Seedfall was significantly lower on the clear-cut than in the shelterwood and higher in the 200 stems·ha^{-1} shelterwood than in the 160 stems·ha^{-1} shelterwood (Table A.3).

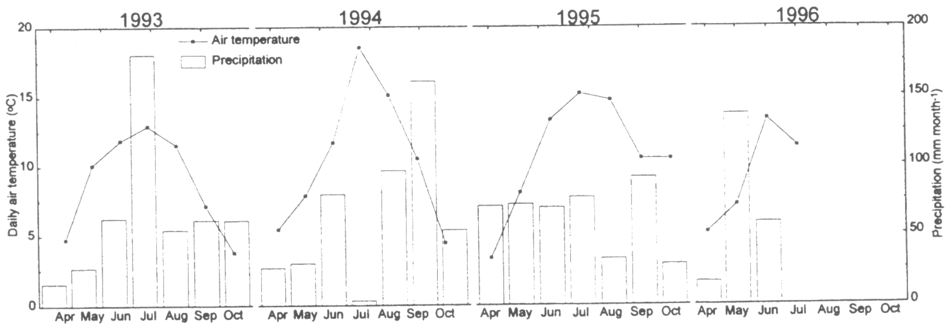

Figure A.2. Daily air temperature 1.7 m above the ground (lines) and total monthly precipitation (bars) at the study site from 1993 to 1996.

All cutting treatments and years considered, germination was significantly better on mineral soil compared to humus mixed with mineral soil and undisturbed seedbeds (Fig. A.5). Only few seedlings were recorded to have germinated in the slash. Germination rate was highest and approximately the same during the first year (1993) in all shelterwood treatments. During the following years, the rate of germination decreased strongly in the clear-cut so that germination rate was almost zero in 1995 and 1996 (Fig. A.5a). In the shelterwoods, germination rates decreased during the second year but were still much higher than in the clear-cut, largely due to the decrease with time in the clear-cut. These differences were significant. Germination rates decreased only slightly in the shelterwoods after the second year (Fig. A.5b, c).

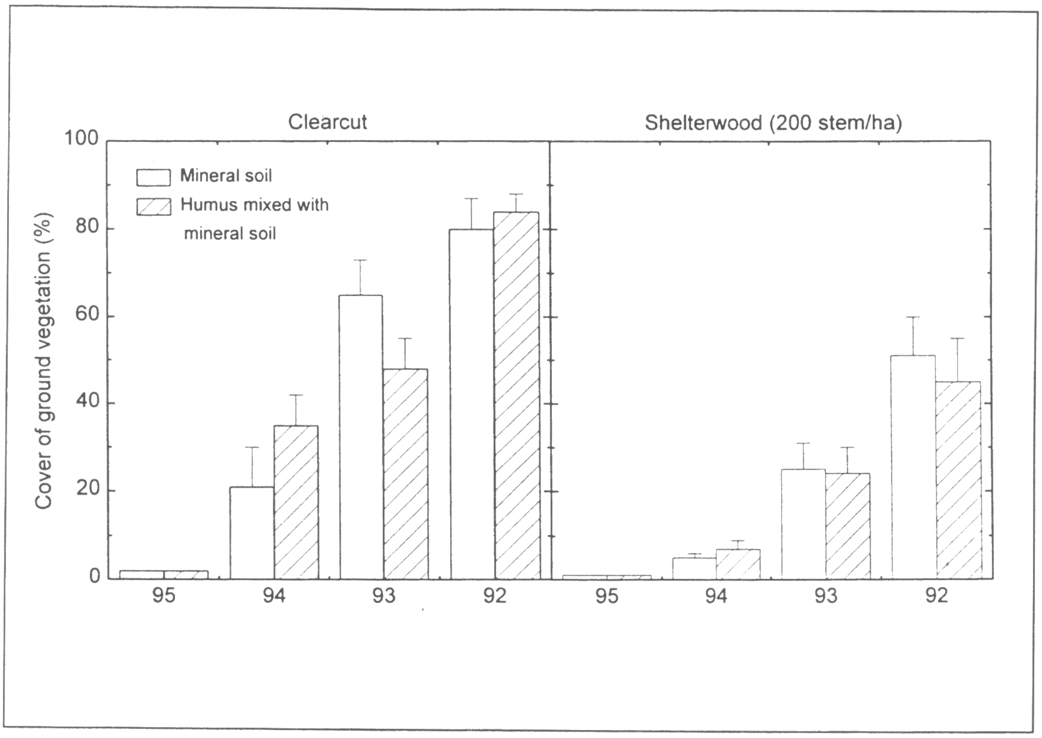

Figure A.3. Percent cover of ground vegetation on seedbeds prepared on four consecutive years a) in the clear-cut and b) under the 200 stems·ha⁻¹ shelter. Error bars indicate one standard error of the mean.

Tableau A.2. Proportion of the surface of each seedbed type within the three shelter treatments after scarification. Standard error of the means are shown within parenthesis.

Shelter density (stems·ha⁻¹)	Seedbed types							
	Undisturbed		Mixed humus-mineral		Mineral		Slash and other	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
0	0.288	0.051	0.489	0.058	0.042	0.014	0.182	0.047
160	0.379	0.052	0.460	0.052	0.052	0.015	0.109	0.035
200	0.385	0.058	0.429	0.059	0.081	0.029	0.105	0.043

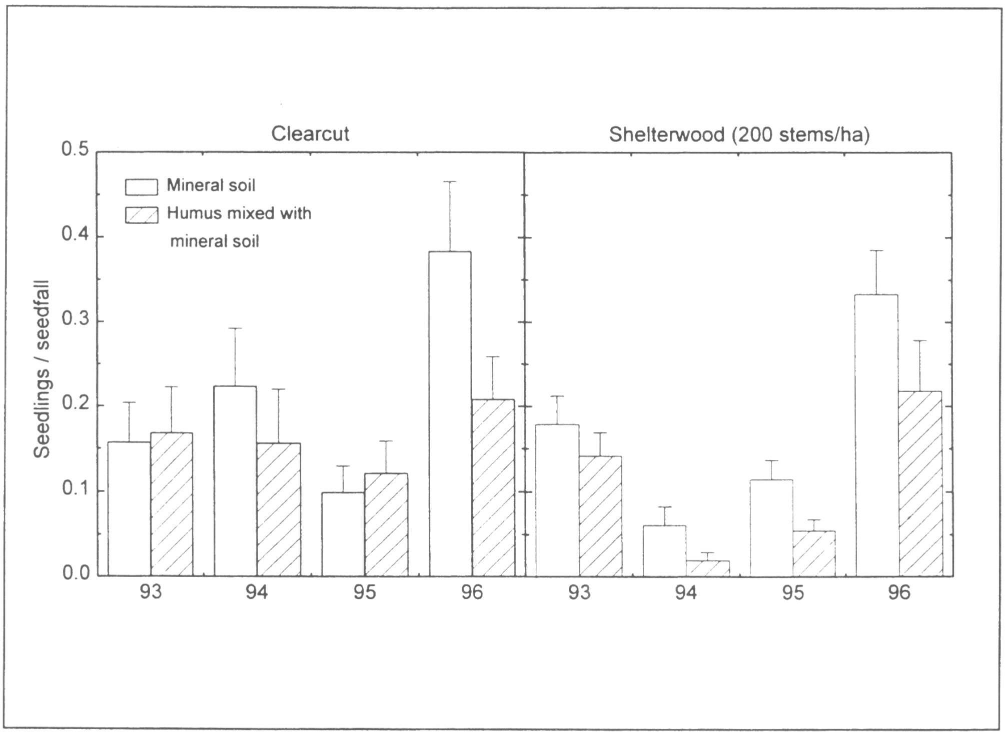

Figure A.4. Germination rate on plots scarified at different years a) in the clear-cut and b) in the 200 stems·ha^{-1} shelterwood. Error bars indicate one standard error of the mean.

Tableau A. 3. Average Scots pine seedfall per m^2 recorded each year from 1993 to 1996 in each shelterwood density. Standard error of the means are shown within parenthesis.

Shelter density	Year							
(stems·ha^{-1})	1993		1994		1995		1996	
0	51.61	8.94	14.78	2.89	27.99	5.19	29.40	3.28
160	128.55	7.71	42.88	4.45	117.69	9.74	90.59	8.10
200	209.12	16.75	104.78	6.79	238.28	13.11	146.80	14.31

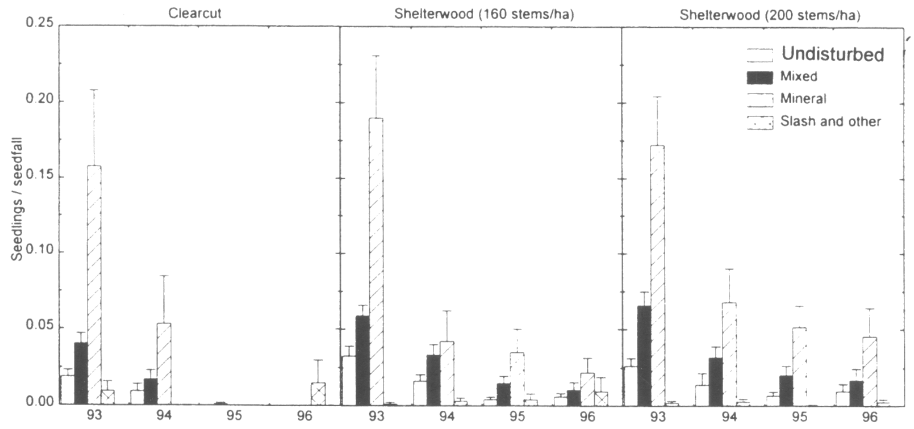

Figure A.5. Germination rate on different seedbed types from 1993 to 1996 a) in the clear-cut, b) in the 160 stems·ha^{-1} shelterwood and c) in the 200 stems·ha^{-1} shelterwood. Error bars indicate one standard error of the mean.

For seedlings germinating in 1993 (the first year after treatment), the rate of mortality was significantly higher during the first year after germination than in subsequent years (Fig. A.6). This was particularly true in the clear-cut area. Year of germination seemed to be unimportant, because the rate of mortality was similar among cohorts germinating in 1993, 1994 or 1995 (Fig. A.6). All cohorts and years considered, mortality was significantly higher in the clear-cut (Fig. A.6a) than in the shelterwoods (Fig. A.6b, c). There was no significant difference in the rate of mortality between seedbed types.

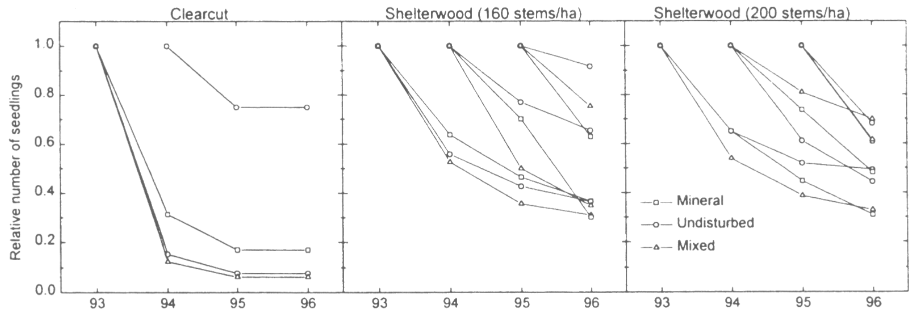

Figure A.6. Relative number of seedlings from each seedling-year origin on various seedbed types and shelter treatments from 1993 to 1996. a) clear-cut, b) 160 stems·ha^{-1} shelterwood, c) 200 stems·ha^{-1} shelterwood.

The seedlings still alive in 1996 that germinated in 1993 were significantly more abundant than those originating from any of the three following years (Fig. A.7), i.e. nearly half of the seedlings alive in 1996 originated from the 1993 generation. The 200 stems·ha^{-1} shelterwood had the highest number of living seedlings in 1996 (ca. 90 000 stems·ha^{-1}; Fig. A.7c) and the clear-cut had the lowest (approx. 2 000 stems·ha^{-1}; Fig. A.7a). These differences were significant. The proportion of plots with at least one seedling in 1996 follows the same pattern and was very high (ca. 90 %) in the 200 stems·ha^{-1} shelter, slightly lower (ca. 80 %) in the 160 stems·ha^{-1} shelter and much lower (ca. 10 %) in the clear-cut (Table A.4).

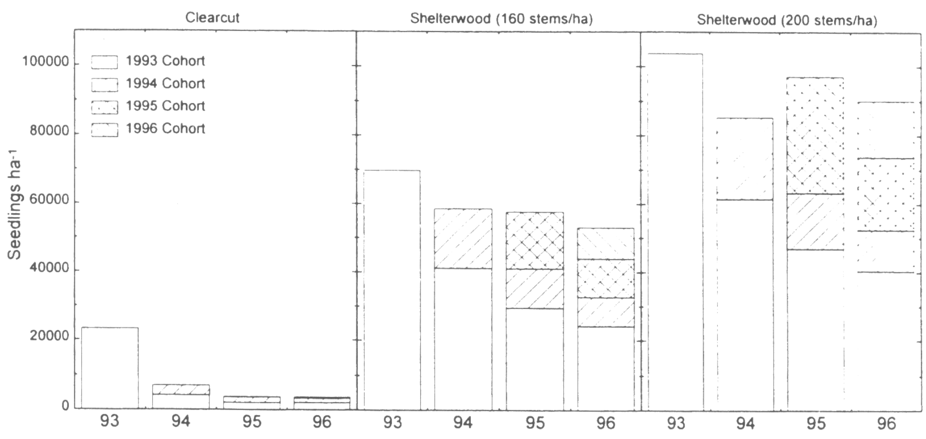

Figure A.7. Number of seedlings·ha⁻¹ from different year origin from 1993 to 1996. a) clear-cut, b) 160 stems·ha⁻¹ shelterwood, c) 200 stems·ha⁻¹ shelterwood.

Tableau A. 4. Changes in stocking coefficient (proportion of plots with at least one seedling) on the three shelter densities from 1993 to 1996.

Shelter density (stems·ha⁻¹)	Year 1993	1994	1995	1996
0	0.615	0.154	0.077	0.077
160	0.949	0.872	0.795	0.769
200	0.949	0.897	0.897	0.923

A.6 DISCUSSION

Many aspects of the site conditions that are liable to influence Scots pine regeneration were expected to differ substantially in a clear-cut, in a 160 stems·ha^{-1} Scots pine shelter and in a 200 stems·ha^{-1} shelter. The much higher rate of invasion of ground vegetation in prepared seedbeds in the clear-cut than in the 200 stems·ha^{-1} shelter, was probably due to both higher light exposition and reduced below ground competition from shelter trees. Moreover, the seedfall measured in this experiment was of course positively correlated to the abundance of shelter trees and was about the same level as reported by Hagner (1965). Even though seedlings that germinated after 1993 only made up less than half of the total seedling number, they might be very important for the future stand. Without these additional seedlings, the proportion of plots without seedlings would probably have been higher. Moreover, seedlings from 1994-1996 may produce the best timber quality since competition from larger seedlings from 1993 will reduce branch size (Agestam, Ekö and Johansson, 1998).

The scarificator used in this experiment created relatively few mineral soil seedbeds. Nevertheless, this seedbed contributed substantially to the success of the natural regeneration. This result is consistent with many other studies that have shown that exposed mineral soil is the best seedbed for germination because it allows a better water conductivity than organic matter (Chrosciewicz, 1990 ; Fleming *et al.*, 1995 ; Örlander, Gemmel and Hunt, 1990 ; Riley, 1980). If the scarification had prepared a larger proportion of mineral seedbeds, the success of natural regeneration might have been even better. However, it is important to reduce the depth of the trench so the root systems of the shelter trees are damaged as little as possible.

We think that the decreases in germination rate observed the second year after cutting is mainly due to gradual invasion of ground vegetation over prepared seedbed as suggested by Hagner (1962). The sharper decrease in germination rate observed in the clear-cut is consistent with this interpretation since vegetation also grew faster in the clear-cut. The growth of vegetation could have two effects on the quality of the seedbed. The first is to cut the contact of the falling seed with the moisture of the mineral soil and the second might be to decrease mineral nutrient availability, as suggested by Nilsson, Steijlen and Zackrisson (1996). The works of Bjor (1971) indicated that the quality of exposed mineral soil as a seedbed might reside in the capacity of the seed to take advantage of the micro erosion that occurs when rain drops falling to the ground project soil particles over the seed and thus allows even better contact with soil moisture. This phenomenon would have a rapidly decreasing intensity as time after scarification increases which is consistent with the decrease of germination rates observed in the present study. There was a very dry summer in 1994. The drought conditions might have been more severe in the clear-cut than in the shelterwoods. This could also explain the low germination rate in the clear-cut. However, since the germination rate does not increase again in 1995, we think that climate is not the only factor involved.

Severe frost heaving was observed on the Scots pine seedlings but most dead seedlings were simply not found afterwards, leaving no means to distinguish the different causes of mortality. However, we suspect the higher rate of mortality observed in the clear-cut to be caused by frost heaving, frost damage and pine weevil damage. The presence of the shelter probably also protected the seedlings against high temperature variation. Our hypothesis that mixed seedbed could be better for survival was not supported by the results. The rates of mortality largely decreased and are approximately the same for the 160 stems·ha^{-1} shelterwood as for the 200 stems·ha^{-1} shelterwood. We thus think that without any catastrophic event, the success of regeneration should be maintained in the future.

This study was done in a fertile Scots pine stand. Conclusions drawn from this study should therefore only be valid for this type of site. Furthermore, this experiment should be repeated in the future to see if the conclusions are correct and to investigate the effect of a 200 stems·ha^{-1} shelter on the different causes of mortality into more details. However, considering the marked differences observed between shelterwood treatments in regard to most of the variables compared, we are confident that results could be generalized and that the use of dense shelterwoods (200 stems·ha^{-1}), to regenerate Scots pine for the purpose of improving wood quality on a fertile Scots pine site, produces sufficient regeneration both in terms of number of seedlings·ha^{-1} and in terms of seedling distribution.

The slightly better results obtained in the 200 stems·ha^{-1} shelter than in the 160 stems·ha^{-1} shelter are probably caused both by more abundant seedfall and by the slower rate of competing vegetation invasion and consequent better rate of germination and survival. After four years of measurements, the proportion of Norway spruce seedlings varied from 0 to 33 % depending on seedbed and year of origin.

It is thus possible to recommend to the forest manager the use of dense shelterwoods provided that a schedule of cuttings be planned to gradually remove the overwood and release the new stand. For the sake of the experiment, the normal shelter will be removed in one operation in winter 1999 (normal operation for regeneration under shelterwoods in southern Sweden) and the dense shelter will be removed in 2 or 3 operations beginning in 1999 with removal of approximately 50-60% of trees, the final cutting not being performed until the regeneration has reached about 6 m.

This study was undertaken making the hypotheses that increasing wood quality requires a high density of seedlings and a dense shelter. Follow up of seedling growth and of wood properties of the regenerating stand will tell if these conditions were sufficient.

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