UNIVERSITÉ DU QUÉBEC À MONTRÉAL

ESTIMATION OPÉRATIONNELLE DE LA FERTILITÉ DES SOLS ET ÉVALUATION DES INDICES FOLIAIRES COMME INDICATEUR DE SUIVI DES RÉSERVOIRS NUTRITIFS DES SOLS DE LA FORÊT BORÉALE

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RÉSUMÉ

Les pluies acides, la plantation d'arbres à croissance rapide, des rotations plus courtes et la récolte par arbres entiers accentuent la pression sur les sols forestiers, et pourraient en diminuer la fertilité à long terme. Afin d'assurer le maintien de la productivité des stations forestières, les sites vulnérables à la déplétion de leurs nutriments doivent être identifiés afin d'y limiter l'extraction de biomasse forestière. Par la suite, un suivi devrait être effectué afin de vérifier l'efficacité des mesures mises en place.

Le premier chapitre de ce mémoire évalue le potentiel de la nutrition foliaire comme indicateur de suivi de la fertilité des sols. Cent quatre-vingt-onze stations furent échantillonnées pour déterminer les relations entre la nutrition, la fertilité du sol et la productivité. La nutrition du sapin baumier (*Abies balsamea*), de l'épinette noire (*Picea mariana*), de l'épinette blanche (*Picea glauca*) et du pin gris (*Pinus banksiana*) a été évaluée à l'échelle de la forêt boréale québécoise. Chaque essence s'est avérée avoir un profil nutritionnel distinct. La nutrition foliaire du sapin baumier, de l'épinette blanche et du pin gris répondait davantage aux gradients de fertilité du sol que celle de l'épinette noire. La capacité d'échange cationique (CEC) et le pH du sol ont démontré de plus fortes et consistantes corrélations avec la nutrition foliaire que les variables physiques du sol (texture, surface spécifique et profondeur). Entre la concentration en nutriments des aiguilles, le contenu en nutriments de 100 aiguilles et les ratios multivariés des concentrations foliaires (CND), la dernière méthode semble plus fortement liée à la fertilité des sols. L'âge du peuplement, la densité et les variables climatiques ont des effets variés sur la nutrition foliaire, mais souvent faibles et limités, suggérant la possibilité d'utiliser la nutrition foliaire comme indicateur sur de larges gradients environnementaux. Des normes CND établies avec la méthode « boundary-line » indiquent que la nutrition d'une importante proportion de peuplement est déjà déficiente en calcium et potassium. Donc, le suivi des réservoirs nutritionnels devraient figurer parmi les enjeux importants d'aménagement forestier.

Dans le second chapitre, la productivité de plus de 400 sites déterminée à l'aide de l'indice de qualité de station (IQS), de la surface terrière et de la végétation indicatrice de sous-bois, a été mise en relation avec des variables climatiques et pédologiques. À une échelle régionale, les concentrations en cations basiques du sol évaluées à l'aide de 80 000 échantillons de sédiments de lacs et rivières provenant de la prospection minière sont faiblement corrélées à la productivité dans les modèles testés. La position sur la pente, le drainage, le dépôt de surface, le nombre de degrées-jours et les précipitations utiles formaient le modèle le plus apte à prédire la productivité. Un peuplement sur un dépôt à texture grossière, dépôt mince ou sur un affleurement rocheux a respectivement 6,1, 7,7 et 21,5 fois moins de chance qu'un site sur dépôt argileux d'être dans une classe de bonne productivité. Les sites en haut de pente à bon drainage ainsi que les sites présentant un drainage imparfait ont aussi été identifiés comme étant moins productifs. Ces résultats suggèrent que des sites vulnérables à la récolte de la biomasse forestière pourraient être facilement identifiés à l'aide de variables cartographiées comme le dépôt de surface, la position sur la pente et le drainage.

MOTS-CLÉS : forêt boréale, fertilité des sols, productivité, nutrition foliaire.

INTRODUCTION

Aménagement durable des sols

Dans le cadre de la Conférence des Nations Unies sur l'Environnement et le Développement en 1992, le Canada a reconnu l'importance de l'aménagement forestier durable et signé la Déclaration de principe sur les forêts. Suite à cette conférence, le Conseil Canadien des Ministres des Forêts (CCMF) a développé des critères et indicateurs permettant de suivre l'évolution de l'aménagement durable des forêts (CCMF, 2003). Le Ministère des Ressources Naturelles et de la Faune du Québec (MRNFQ), suivant la démarche du CCMF, a adopté une liste de six critères d'aménagement forestier durable. Le maintien de la fertilité des sols, une composante incontournable de la foresterie durable, est mis de l'avant à travers ces critères. De plus, la venue des « Objectifs de protection et de mise en valeur des ressources du milieu forestier » définis par le MRNFQ a fait en sorte que les plans généraux d'aménagement forestier doivent désormais viser à réduire l'impact des activités anthropiques sur les sols (MRNFQ, 2006). La préservation de la fertilité des sols est aussi une partie importante du processus de certification forestière. Les normes du « Forest Stewardship Council (FSC) » et du « Canadian Standards Association (CSA) » indiquent clairement l'importance de maintenir la fertilité des sols pour avoir accès à ces certifications (FSC, 2004 ; CSA, 2002).

Vulnérabilité des sols forestiers

Par contre, avec les pluies acides et l'intensification des pratiques sylvicoles, comme la plantation d'arbres à croissance rapide, des rotations plus courtes et la récolte par arbres entiers, les pressions sur les sols forestiers se font grandissantes.

Les pluies acides, principalement causées par l'activité anthropique, apportent sur le territoire forestier des quantités importantes d'acide sulfurique (H_2SO_4) et nitrique (HNO_3). Ces acides se dissocient et augmentent les concentrations de H^+ dans le sol. L'acidité du sol sera en partie tamponnée par la dissolution des complexes Al-OH en Al^{3+} et H_2O. Les H^+ et Al^{3+} libres peuvent déplacer les cations basiques (Ca^{2+}, Mg^{2+}, K^+ et Na^{2+}) des sites d'échanges, causant le lessivage de ces derniers (Bélanger, 2000; Galloway *et al.*, 1983; DeHayes *et al.*, 1999). Les cations basiques ainsi lessivés dans les bassins versants peuvent être supérieurs aux apports de cations par altération de la roche mère et par déposition atmosphérique, pouvant ainsi causer une perte nette de cations basiques hors l'écosystème. Cet appauvrissement des sols a été observé sur certains sites de la forêt boréale (Duchesne et Houle, 2006). De plus, lorsque l'apport de H+ dans un écosystème est supérieur au pouvoir neutralisant de son sol, une acidification nette du sol peut se produire. Les pluies acides peuvent donc appauvrir les sols forestiers en acidifiant le sol et en lessivant une partie des cations basiques présents.

Les arbres à croissance rapide cultivés au Québec peuvent augmenter sensiblement la production de la biomasse forestière sur certains sites. Par exemple, le peuplier hybride, en conditions normales moyennes, a un accroissement annuel moyen (AAM) de $11{,}6 m^3 \cdot ha^{-1} \cdot an^{-1}$, comparativement à $3{,}3 m^3 \cdot ha^{-1} \cdot an^{-1}$ pour le peuplier faux-tremble et $1{,}8\ m^3 \cdot ha^{-1} \cdot an^{-1}$ pour l'épinette noire (Ménétrier, 2008). Cette production accrue de biomasse entraîne une exportation plus élevée de nutriments lors de la récolte (Adegbidi *et al.*, 2001). De surcroît, la diminution de la période entre deux récoltes, observée sur l'ensemble du Québec, réduit l'âge moyen des arbres récoltés (Cyr *et al.*, 2009). Les arbres plus jeunes, moins efficaces dans leur utilisation de nutriments, produisent une biomasse avec des concentrations nutritionnelles plus élevées (Paré *et al.*, 2002 ; Adegbidi *et al.*, 2002). Conséquemment, les arbres à croissance rapide et les rotations écourtées amplifient l'exportation de nutriments en augmentant le volume de bois récolté et les concentrations nutritionnelles de ce bois.

De plus, la croissance des arbres entraîne une acidification des sols, ce qui peut augmenter le lessivage des cations basiques hors de l'écosystème forestier. Les racines des arbres relâchent des ions H^+ lors de l'absorbtion de cations basiques et d'ammonium (NH^{4+}) (Bélanger, 2000 ; Nilsson *et al.*, 1982 ; Matzner et Ulrich, 1987). Normallement, cette augmentation de H^+ est contrebalancée par la décomposition d'arbres arrivés à maturité qui retournent les cations basiques dans le sol. Par contre, la récolte forestière vient briser ce cycle, pouvant entraîner les mêmes conséquences qu'énumérées précédemment pour les pluies acides (Federer *et al.*, 1989).

La nitrification, processus par lequel certains micro-organismes oxydent l'ammoniac en nitrate, libère des H^+ dans le sol. La nitrification est favorisée par une augmentation de la température et de l'humidité du sol. La récolte forestière favorise ces conditions et cause ainsi une augmentation de la nitrification, de l'acidification des sols et du lessivage des cations basiques (Dahlgren et Driscoll, 1994).

Cependant, certaines études ont démontré qu'une augmentation de la croissance des arbres peut parfois s'accompagner d'une augmentation à court terme de la disponibilité des cations basiques dans le sol (Bélanger *et al.*, 2004 ; Quideau *et al.*, 1996). Ce phénomèene pourrait être expliqué par le fait que certaines espèces d'arbres peuvent augmenter la libération des cations basiques par l'altération des roches et augmenter la rétention des cations basiques dans le sol (Bélanger *et al.*, 2004). Les arbres peuvent avoir une influence importante sur les sols selon la qualité de leur litière, l'étendue et la profondeur de leurs racines ou encore selon leur rhizosphère (Augusto *et al.*, 2002). Par contre, même si la croissance rapide de certaines espèces peut être bénéfique à court terme au niveau de la capicité d'échange cationique, probablement que cette augmentation se fait au détriment des réservoirs à long terme de cations basiques dans le sol (Quideau *et al.*, 1996).

La coupe forestière entraine une exportation nette de nutriments beaucoup plus importante que les feux de forêts ou autres perturbations naturelles (Thiffault *et al.*, 2007). La récolte par arbres entiers exporte une quantité plus élevée de nutriments que les méthodes par troncs entiers (Paré *et al.*, 2002; Weetman et Webber, 1972). Étant donné les concentration nutritionnelles élevées dans les branches et le feuillage, l'exportation de nutriments découlant de la récolte par arbres entiers est de deux à quatre fois supérieure à celle engendrée par une coupe par troncs entiers (Paré *et al.*, 2002). Les pertes causées par la récolte par arbres entiers dépendent de la distribution de la biomasse dans les différentes parties de l'arbre, et peuvent donc varier d'une espèce à l'autre. Par exemple, Paré *et al.* (2002) suggèerent que les pertes sont plus importantes pour les peuplements de sapin baumier que de pin gris.

Les réservoirs en cations basiques sont probablement plus sensibles à l'exportation de la biomasse que l'azote et le phosphore (Fisher *et* Binkley, 2000; voir §3.1.4), puisque l'apport en cations basiques par déposition atmosphérique est faible par rapport èa l'azote (Grigal, 2000). La récolte par arbres entiers peut ainsi diminuer les réservoirs nutritifs basiques des sols (e.g. Brais *et al.*, 1995; Bélanger *et al.*, 2003 ; Pennock et Kessel, 1997; Olsson *et al.*, 1996 ; Duchesne et Houle, 2006) et éventuellement, les acidifier (Bélanger *et al.*, 2003). Ces changements pédologiques sont susçeptibles d'affecter la vigueur des arbres, leur résistance aux stress environnementaux comme le gel (DeHayes *et al.*, 1999) et les maladies (McLaughlin et Wimmer, 1999), ainsi que leur nutrition (Thiffault *et al.* 2006). Finalement, les changements pédologiques induits par la récolte par arbres entiers peuvent entraîner une réduction de la croissance des arbres et de la productivité des peuplements (Egnell et Valinger, 2003 ; Mann *et al.*, 1988).

Avenir de la récolte de la biomasse forestière

Des efforts ont été consentis à diminuer la récolte par arbres entiers dans la dernière décennie, et celle-ci est passée d'environ 92% des surfaces récoltées à seulement 49% en 2004 (MRNFQ, 2008). Par contre, dans les dernières années, cette tendance semble s'inverser. Avec l'augmentation des prix du pétrole, et avec la recherche de sources stables et renouvelables d'énergie, il devient profitable d'exploiter le contenu énergétique des branches et du feuillage. Ces résidus forestiers, présentement laissés sur les sites de coupes, pourraient être utilisés dans des usines de cogénération, ou pourraient même servir à synthétiser des biocarburants dans un avenir rapproché. En effet, il est désormais possible de développer des biocarburants à partir des branches, des feuilles et même des souches des arbres (Robert, 2007). De nouvelles usines expérimentales dédiées à la conversion de cette biomasse forestière sont présentement fonctionnelles et en construction en Amérique du Nord, et cette avenue est financée massivement par les gouvernements (Schubert, 2007). Cette technologie se développera probablement rapidement au cours des prochaines années, engendrant une demande pour les résidus forestiers. Avec l'augmentation de la récolte par arbres entiers en vue de satisfaire ces besoins énergétiques, la pression sur les sols forestiers risque de s'accroître.

Le plan d'action vers la valorisation de la biomasse forestière, déposé récemment par le MRNFQ, oriente clairement la foresterie vers cette avenue (MRNFQ, 2009) :

> « *Le plan d'action visant la valorisation de la biomasse forestière pourrait permettre l'utilisation de 1,5 million de tma de biomasse forestière par année, soit 22,6% du volume disponible, et entraînera la création de 850 emplois dans les régions du Québec, dont 680 en forêt.* »

Dans ce contexte, il devient essentiel de mettre en place des directives permettant d'encadrer la récolte de la biomasse forestière, et d'effectuer un suivi de la fertilité des sols du Québec. Les directives devront être opérationnelles pour l'ensemble de la province, facilement applicables pour l'industrie, et devront se baser sur les meilleures données et connaissances disponibles.

Il sera donc nécessaire d'identifier les sites forestiers vulnérables à une diminution de leur fertilité par l'exportation de leur biomasse forestière et de développer des indicateurs de suivi de la fertilité des sols.

Objectifs

Ce projet comporte deux objectifs principaux correspondant à deux chapitres distincts du mémoire:

(1) Identifier des indices foliaires sensibles aux variations de la fertilité des sols et pouvant servir d'indicateurs des impacts de la récolte de la biomasse sur les réservoirs nutritifs.

(2) Développer un outil opérationnel à l'échelle de la province pouvant servir à identifier les sites vulnérables à une exportation accrue de nutriments.

CHAPITRE I

EVALUATION OF FOLIAR INDICATORS AS A TOOL TO MONITOR FOREST SOIL FERTILITY

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1.1 Abstract

Acid rain, intensive forest management practices and forest biomass industry development apply significant pressure on forest soils and may deplete forest soil base cation pools. It becomes important to identify sites vulnerable to fertility decline and develop operational indicators to monitor soil fertility on provincial scale.In order to evaluate and monitor base cation pool status, foliar indicators have been evaluated for 4 conifer species (balsam fir, black spruce, jack pine and white spruce) on a wide geographical and soil fertility range of Eastern Canadian boreal forest. Each species had a distinct nutrition profile, and was analysed separately. Cationic exchange capacity (CEC) and pH displayed stronger and more consistent correlations with foliar indicators than physical variables (e.g. percentage of fine texture material, soil specific surface and depth). Between foliar nutrient concentrations, nutrient content in 100 needles and compositional nutrient diagnostic (CND) ratios, the latter had the strongest fit with soil fertility variables. White spruce, jack pine and balsam fir foliar CND ratios were more strongly correlated with soil fertility than black spruce foliar nutrients. Stand age, density and climatic variables had conflicting effects on nutrition that were often weak and limited, suggesting the possible use of foliar indicators on a wide environmental range. Foliar CND norms established with a boundary-line approach gave results comparable with other similar studies. Those norms indicate that an important proportion of stands are already Ca or K deficient. Consequently, monitoring soil base cations should become an important forest management issue in the future.

Keywords: foliar nutrition , DRIS, CND, concentration content, soil fertility, productivity, base cations, black spruce, white spruce, balsam fir, jack pine.

1.2 Introduction

Preservation of soil fertility is a key issue of sustainable forest management and a prerequisite to obtain forest certifications such as the Forest Stewardship Council and the Canadian Standards Association certifications (FSC, 2004; CSA, 2002). However, acid rain, shorter rotation, plantation of fast growing species and whole tree harvesting (WTH) accentuate pressures on forest soils and may jeopardize their long term fertility.

Intensification of silviculture practices can increase ecosystem nutrient losses by increasing nutrient uptake by vegetation and rate of harvesting. For example, plantation of hybrid poplars - with a mean annual increment rate three to seven times higher than those of trembling aspen and black spruce (Ménétrier, 2008) - dramatically enhances soil nutrient immobilization by tree biomass. In addition, with the growing bio fuels industry, harvesting of leaves, branches and tree tops (WTH) for energy conversion will probably increase (MRNF, 2009). The higher nutrient concentrations in branches and leaves (Mann *et al.*, 1988) augment 2 to 3 folds WTH nutrient exportation in comparison to stem only harvesting (SOH) (Paré *et al.*, 2002; Yanai, 1998; Foster and Morrison, 1987). Increased biomass harvesting and increase in biomass nutrient concentrations both require more nutrients from forest soils. Finally, acid rain can increase leaching of soil bases cations by replacing them with H+ on exchange sites (Driscoll *et al.*, 2001; DeHayes *et al.,* 1999).

Many studies in the boreal forest have reported nutrient outputs following harvesting exceeding current atmospheric and weathering inputs (Sverdrup and Rosen, 1998; Duchesne and Houle, 2008; Duchesne and Houle, 2006), suggesting a possible upcoming depletion of those nutrients in forest soils. The negative balance between input and output seems to be more acute for base cations than nitrogen and phosphorus (Fisher and Binkley, 2000; Morris, 1997).

In this context, it is important to monitor soil fertility and ensure that our current practices are sustainable. We need to identify indicators that reflect soil fertility, sensitive to changes induced by anthropogenic or natural disturbance, valid on a wide variety of sites, easy to measure and inexpensive to sample (Schoenholtz *et al.*, 2000). Foliar nutrient concentrations of trees could possess those criterions, and they present the advantage of integrating a large soil volume influencing the capacity of trees to access soil nutrients (Fisher and Binkley 2000).

The objective of this study is to evaluate the potential of foliar nutrient concentrations as indicators of forest soil fertility within Quebec's boreal forest. Several steps will be taken in order to achieve this objective. Needles from balsam fir (*Abies balsamea*), black spruce (*Picea mariana*), white spruce (*Picea glauca*) and jack pine (*Pinus banksiana*) will be sampled and analysed with different expressions of foliar concentrations and ratios : absolute foliar nutrient concentration, foliar nutrient content (Walworth and Summer, 1988), Diagnosis and Recommendation Integrated System (DRIS) (Beaufils 1973), and Compositional Nutrient Diagnostic (CND) (Parent and Dafir 1992). The four tree species were chosen because of their abundance in Eastern Canadian boreal forest and their nutrition requirement differences. The differences will first be highlighted by comparing foliar nutrient means between species.

Species and foliar analytical techniques will be evaluated individually in order to identify which one constitutes the best soil fertility indicator. A good indicator will have to be sensitive to soil fertility variation and usable on a wide range of environment conditions. Simple correlations between foliar indicators and environmental variables will be performed and redundancy analysis will be used to evaluate the global fitness between different indicators and soil fertility variables. The foliar nutrient analysis technique that will give the best results will be used to develop foliar indicators. The effects of soil on this indicator will be analysed more closely by evaluating with multiple regressions the relationship between different soil fertility models and foliar nutrition. Finally, the relationship between foliar nutrition and productivity will be assessed with a boundary line approach (Vizcayno-Soto and Côté, 2004; Quesnel *et al.*, 2006) in order to establish norms that could indicate stands with or close to nutrient deficiencies. The boundary-line approach is useful to establish foliar nutrition standards in varying environment.

1.3 Methodology

Study area

The study was conducted in the balsam fir / paper birch and the black spruce / moss domains of Quebec's boreal forest. The two domains differ by the species' composition of late successionnal stages. Each of them is subdivided in 2 sub-domains (Table 1.1). The balsam fir / paper birch east sub-domain receives more precipitation and has a rougher landscape than its western counterpart. East and West black spruce / moss sub-domains differ also by their annual precipitation, which results in longer fire cycles in the East (Saucier *et al.*, 1998). The study area covers part of the Precambrian shield and Appalachian geologic region. The bedrock is covered with Quaternary deposits (Landry and Mercier, 1992). Quaternary deposits vary from sandy to clay soils and from rock outcrop to deep loose soil. Surface deposit distribution is unequal, with regions predominantly on fine texture deposits, like the clay belt region (Vincent and Hardy, 1977), and regions composed mostly of tills and coarse texture deposits like Quebec's Nort Shore region. Plots were sampled between 47.8° - 51.2° north, and 64.6° - 79.3° west. Annual temperature varies from -2,3°C to 3,3°C and the total precipitation from 863 mm to 1223 mm.

Table 1.1. Study site characteristics

	Balsam fir / paper birch		Black spruce / moss	
	East	West	East	West
Latitude (min and max)	48.181 °N 49.722 °N	47.823 °N 48.989 °N	49.132 °N 51.228 °N	48.90 °N 49.58 °N
Longitude (min and max)	64.61 °W 69.38 °W	73.54 °W 79.28 °W	68.06 °W 69.79 °W	75.81 °W 78.87 °W
Ecological regions ID	5g, 5h, 5i	5a, 5b, 5c	6h, 6i, 6k	6a, 6c
Average precipitation (mm)	1076.8	1008.8	1023.5	945.2
Average Degree-Days	1197.7	1244.7	1064.5	1252.6
Species sampled	BF, BS, JP, WS	BF, BS, JP, WS	BF, BS, JP, WS	BF, BS, JP
# of stands sampled	52	66	49	24

Longitude, latitude, and climatic variables statistics were determined from sampled stands. Ecological region ID corresponds to Quebec's ecological classification (Saucier *et al.*, 1998). Only ecological regions with at least one sampled stand are presented in this table. Species sampled were balsam fir (BF), black spruce (BS), jack pine (JP) and white spruce (WS).

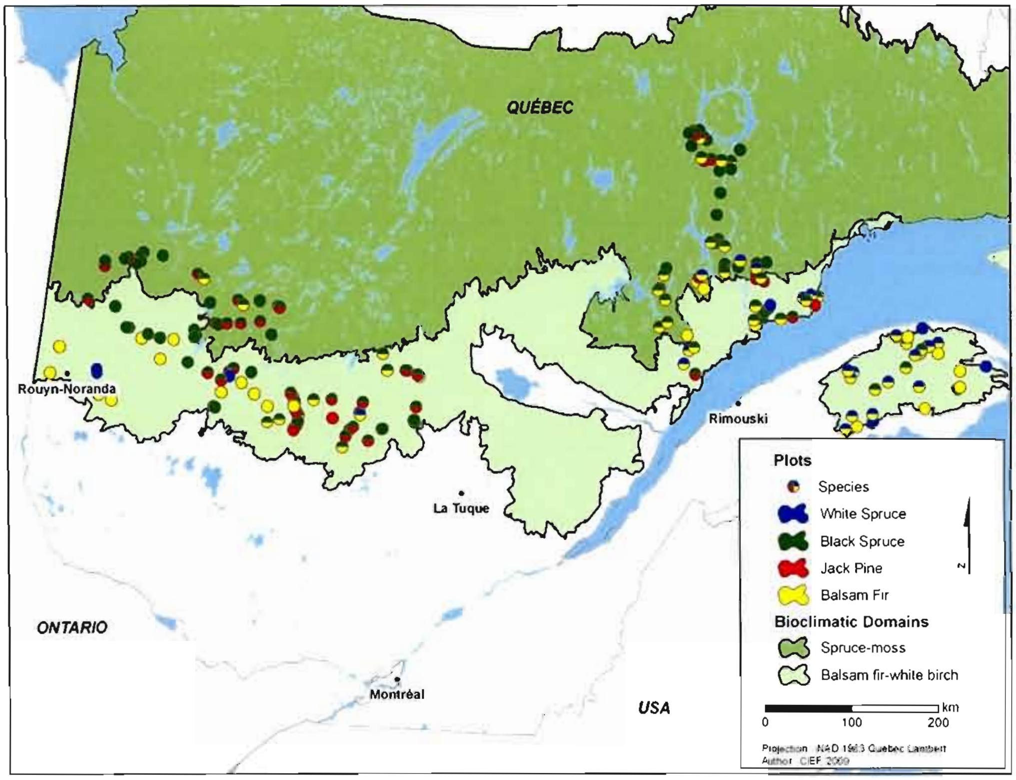

Figure 1.1. Stand location and species sampled.

Stand selection

Using Quebec's ecological classification (Saucier *et al.*, 1998), 191 stands were selected to represent the main physical (topography, texture and drainage) and biological (forest cover and potential vegetation) characteristics of their ecological region. The selected sites covered 22 different geological units (MRN, 2001) and a wide array of surface deposits representing a large soil fertility gradient. Stands supported by organic deposits have not been selected for this study. All stands were at least 50 years old and preferably more than 70 years old. Forest cover density was over 40%, and slope inclination inferior to 50%. Most sites had a mesic to sub-xeric water regime.

Field methods

Geographical coordinates, altitude, slope and aspect were noted for each stand. A sampling plot ($400m^2$) was located and all trees with a diameter at breast height (DBH) over 9 cm were numbered by species. Five or more dominant trees per species were harvested for stem analyses. Only straight trees with no apparent default and of at least 50 years were retained for the analysis. Each selected tree was cut and disks were taken at 0.15m, 0.60m, 1.0m, 1.3m, 3.0m and at each additional 2 meters until the apex of the stem. On most plots, two different species were sampled. Additionnal details on sampling methods are given in the forest inventory manual of the Quebec government (MRNF, 2006).

Surface deposit origin and depth were noted (MRNF, 2006). For each plot, three soil samples were collected with an auger between 20 and 30 centimetres in the mineral soil. Samples were pooled in the same bag. For podzolic soils with a Ae horizon, soil samples were always taken beneath the eluviate horizon.

Foliage sampling took place in the autumn of 2008. To limit seasonal variability in nutrient concentrations, foliar samples were taken after tree hardening (UN/ECE-EC, 2000). On each plot, 5 dominant and healthy trees per species were selected. Foliage samples of current year needles were collected with a shotgun from three branches of the upper third of the crown. Foliage was collected from all species sampled for stem analyses and samples of the same species were pooled for each stand.

Laboratory methods

Growth measurements were taken with binoculars and digitized with WinDendro software on four radiuses for the first 4 disks and on 2 radiuses for the following ones (Zarnovican, 1985). Height and diameter growth was then reconstructed using the ANATI software (MRNF, 2006). Growth delays caused by external factors, like spruce budworm or oppression, were corrected following the methodology described in Quebec's forest inventory standards (MRNF, 2006). A mean site index (SI) was attributed by species for each plot based on average height at age 50 of all sampled trees. From a total of 191 plots, SI was obtained from 87 balsam fir plots, 132 black spruce plots, 31 white spruce plots and 56 jack pine plots. The age of the stand was estimated from mean age of the dominant trees.

Mineral soil samples were dried at room temperature and sieved (2mm). The relative proportion of clay (<0,002mm), silt (>0,002mm and <0,05mm) and sand (>0,05mm and <2mm) was determined by granulometric analysis (Carter 1993). Mineral soil specific surface was calculated according to Jönsson *et al.*, (1995):

$$Se = 0{,}003*sand + 0{,}022*silt + 0{,}08*clay \quad (1)$$

Mineral soil pH in distilled water (pH_{water}) was determined with a glass electrode-calomel system using 1 part of soil for 2 parts of solution. Exchangeable cations were determined following an extraction with an unbuffered $BaCl_2$ solution (Hendershot *et al.*, 1993). To measure the proportion of Ca, Mg and K that is not readily available to trees but that could be released from soil mineral weathering, we used a weak digestion. Thus, soil samples were leached for one hour in a 10% HNO_3 solution and hot HCl. Potassium was determined by atomic emission, and Calcium and Magnesium by atomic absorption on a Varian AA spectrometer.

Foliage samples were dried at 60°C for 48 hours. Afterwards, 100 needles of each sample were weighted and mass per needle was determined. Total cations and P were determined following calcination at 500°C and dilution with hydrochloric acid (Miller, 1988). Cations were analysed by atomic absorption and P by colorimetry (Lachat Instruments, Milwaukee, Wisconsin). Total N was measured by a CNS analyzer.

Average nutrient content in 100 needles was calculated for each sample from foliar concentrations and needle mass. Also, DRIS bivariate ratios were calculated for each sample (Beaufils, 1973; Walwort and Summer, 1987). DRIS technique uses all possible ratios between the mass of two elements:

$$\frac{\text{Element } x_1 \text{ mass Drymattermass}}{\text{Element } x_2 \text{ mass Drymattermass}} = \frac{\text{Element } x_1 \text{ mass}}{\text{Element } x_2 \text{ mass}} \quad (2)$$

With DRIS ratios, deficiencies are not calculated by the absolute concentration of an element, but by imbalance of a nutrient compared to another. Finally, CND ratios were established following Parent and Dafir (1992) method:

$$R = 1000 - (N + P + K + Ca + Mg) \quad (3)$$

Where R is the filling value and where nutrients are in g/kg.

$$g = (N * P * K * Ca * Mg * R)^{1/6} \quad (4)$$

Where g is the geometric mean of foliar nutrients

$$CND_{(Ca)} = \ln (ca/g) \quad (5)$$

Where $CND_{(Ca)}$ is the CND ratio for Ca, a log centered multivariate ratio.

Degree-days and available precipitation are believed to be important climatic factors influencing productivity (Hamel *et al.*, 2004; Pinno, 2009; Ung *et al.*, 2001). Both variables were derived from stand longitude, latitude, elevation, slope and aspect using BIOSIM (Régnière 1996). BIOSIM matches geographical coordinates of a given site to climatic data from 1965 to 1998 collected in 120 Quebec stations. This data is then adjusted to specified elevation, slope and aspect. Using climatic data generated by BIOSIM has the advantage of keeping models simple while capturing the most important information from climate proxies like longitude, latitude, elevation, slope and aspect.

Statistical analysis

Tukey-Kramer tests were used to compare foliar nutrients mean between species. Due to the important foliar nutrition differences between species, the following analyses were conducted on individual species. Complementarity and divergence between different foliar nutrition indices were assessed by means of Pearson correlations. Also, correlations between foliar indices and stand density, age, degree-days and available precipitation were performed to evaluate the validity of foliar indices on a large variety of sites.

For each species and each nutritional index, the link between soil fertility and foliar base cations was explored with redundancy analysis (RDA) (ter Braak and Smilauer 1998). Redundancy analysis is an extension of multiple regressions, with a set of response variables correlated to a set of explanatory variables (Legendre and Legendre, 1998). The different variables used to describe soil fertility were soil texture, soil specific surface area, soil depth, $pH_{(water)}$, exchangeable cations (Ca_{CEC}, Mg_{CEC} and K_{CEC}) and HNO_3- leached cations (Ca_{HNO3}, Mg_{HNO3} and K_{HNO3}).

To understand the influence of soil characteristics on individual indices of tree nutrition, different soil fertility models were constructed (Table 1.2) and tested with multiple regressions - the first model being the general model containing all variables and the other model subsets of the general model. Each model was a combination of variables from five groups of variables: base cations short-term availability (exchangeable cations and pH), acid extractable base cations (base cations HNO_3), soil texture (% of silt, % of clay), soil specific surface, and presence/absence of a soil depth of less than 50cm. Except for the general model, no model had two variables from similar groups of variables. For example, base cations short-term availability and acid extractable base cations are two different estimators of soil nutrients and consequently, those variables were never included in the same model. The same was true for texture and soil specific surface.

Table 1.2. Models ID and their respective variables.

Model ID	Model variables
1	Ca_{CEC} * pH $_{(water)}$ * Ca_{HNO3} * % silt * % clay * specific surface * depth
2	Ca_{CEC} * pH $_{(water)}$ * % silt * % clay * depth
3	Ca_{CEC} * pH $_{(water)}$ * specific surface * depth
4	Ca_{CEC} * pH $_{(water)}$ * % silt * % clay
5	Ca_{CEC} * pH $_{(water)}$ * specific surface
6	Ca_{CEC} * pH $_{(water)}$ * depth
7	Ca_{CEC} * pH $_{(water)}$
8	Ca_{HNO3} * % silt * % clay * depth
9	Ca_{HNO3} * specific surface * depth
10	Ca_{HNO3} * % silt * % clay
11	Ca_{HNO3} * specific surface
12	Ca_{HNO3} * depth
13	Ca_{HNO3}
14	% silt * % clay * depth
15	% silt * % clay
16	specific surface * depth
17	specific surface
18	Depth

In those models, foliar Ca CND ratios is the response variable, but the same set of models were used for foliar CND Mg and K

Models were tested separately for each tree species and nutrient CND ratios (Ca, Mg and K) by means of linear regressions.

Model selection was based on Akaike's Information Criterion (AIC) where:

$$AIC = -2(\text{log-likelihood}) + 2K \quad (6)$$

and k is the number of parameters used in the model.

The Akaike weight was then calculated to compare models between them:

$$\Delta_i = AIC_i - \min AIC \quad (7)$$

$$w_i = \exp(-\Delta_i/2) / \sum_{r=1} \exp(-\Delta_r/2) \quad (8)$$

where Δ_i is a relative measure of model *i* compare with the best model (min AIC), w_i is the Akaike weight which provides a measure of strength of the model *i* relative to the whole set of models *r*. This method allows comparing different soil fertility models based on their ability to predict foliar nutrition as well as their simplicity (Burnham and Anderson, 2002).

Critical concentrations assessment by the boundary line approach

In order to efficiently establish the link between foliar nutrition and stand productivity for a wide study area including a large variation in soils conditions, a boundary line-approach can be used (Vizcayno-Soto and Côté, 2004; Quesnel *et al.*, 2006). This method was performed separately for each species and nutrients CND ratio (N, P, Ca, Mg and K).

Each nutrient range was first divided in 11 segments of equal length. The number of segments had to be large enough to calculate a boundary layer curve, but small enough to avoid having sub-optimal nutrition points. In each segment, only the stand with maximum SI was retained, while other stands were considered as having sub-optimal growth, limited by a factor other than nutrition. Due to limited sample size, it is possible that some of the 11 stands retained still show sub-optimal growth for a nutrient level. To detect and eliminate those points, the following criterion was used:

$$Y_i < Y_{i-n} \text{ and } Y_{i+n} \text{ and } Y/[(Y_{i-n} + Y_{i+n})/2] < 90\% \quad (9)$$

Where Y_i is the SI of the segment i, and Y_{i-n} and Y_{i+n} the SI of adjacent segments if n=1, and of the second adjacent points for n=2.

A quadratic regression of SI as a function of each nutrient CND ratio was then computed with the remaining boundary points:

$$Y = ax^2 + bx + c \qquad (10)$$

Where Y is the SI and x is the CND ratio.

The optimum nutrient CND ratio was determined with this equation:

$$\text{Optimum} = -b/2a \qquad (11)$$

The optimum nutrition range was bounded by the two points corresponding to 90% of the maximum growth (Fig. 1.2). Stands under that range were considered as having a nutrient deficiency, while stands with a nutrient CND ratio over that range were considered as having an unbalanced nutrition negatively affecting productivity. A nutrient range was not computed if the quadratic regression had a p value under 0.10, the deficiency level was not computed if no stand was beneath the optimum range, and the unbalanced level was not computed if no stand was above the optimum range.

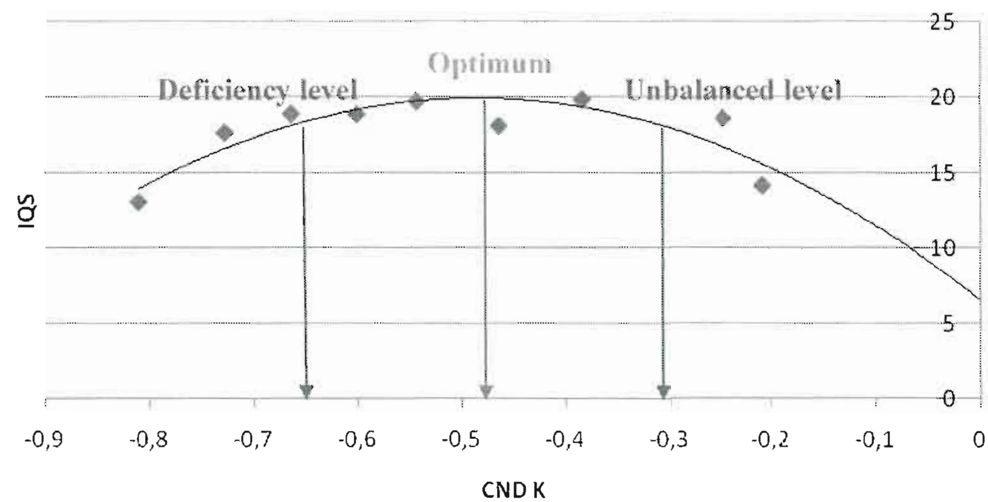

Figure 1.2. Optimum, deficiency and unbalanced level determination with the boundary line approach: example with Balsam fir's K CND ratio and SI.

1.4 Results

Stand characteristics

Based on surficial geology, about 45% of sampled stands grew on medium texture soil (till deposits), 20% on fine texture soil (glaciolacustrine deposits), 20% on coarse texture soil (fluvioglacial deposits) and 15% on shallow till deposit or bedrock. A large variation in dominant tree age and in tree density was observed (Table 1.3). There was also a large variation in stand potential productivity, with the largest variation observed for white spruce (Table 1.3). Soils pH ranged from acid (3.7) to neutral (6.8).

Table 1.3. Stand characteristics

	Minimum	Mean	Maximum	Standard deviation
Stem age (years)				
Balsam fir	62	119	212	36.4
Black spruce	54	107	212	30.4
Jack pine	54	90	128	18.2
White spruce	63	118	197	38.2
Site Index (m)				
Balsam fir	7.9	13.9	20.0	3.2
Black spruce	7.5	12.9	17.5	2.2
Jack pine	7.6	13.7	19.2	2.5
White spruce	8.1	15.5	23.0	3.7
Density (trees/ha)				
Balsam fir	450	1725	4025	679
Black spruce	450	1769	3275	635
Jack pine	475	1644	2900	616
White spruce	700	1710	4025	720
Soil pH	3.74	4.66	6.82	0.39

Correlations between foliar indicators

Strong correlations between CND ratios and DRIS bivariate ratios were found (Table 1.4, results with Mg and K are similar to those of Ca but not shown). Because of DRIS's ratios high dimensionality and their strong correlations with CND, DRIS ratios were not retained for the rest of this study. Strong correlations between CND ratios, foliar nutrient concentrations and contents were also observed (Table 1.5, results with black spruce, jack pine and white spruce are similar to those of balsam fir but not shown). The strongest correlations were between CND ratios and foliar nutrient concentrations.

Table 1.4. Correlations between Ca CND ratios and DRIS bivariate ratios containing Ca, by species

		N/Ca	P/Ca	Mg/Ca	K/Ca	Ca/N	Ca/P	Ca/Mg	Ca/K
Ca CND	Balsam fir	-0.92	-0.87	-0.87	-0.91	0.89	0.80	0.80	0.89
	Black spruce	-0.88	-0.83	-0.81	-0.90	0.90	0.82	0.80	0.89
	Jack pine	-0.94	-0.94	-0.86	-0.91	0.93	0.94	0.81	0.91
	White spruce	-0.91	-0.91	-0.87	-0.93	0.93	0.84	0.84	0.84

*All correlations are highly significant (p<0.001).

Table 1.5. Correlations between CND ratios, nutrient concentrations and nutrient contents for balsam fir

	Concentration (g/kg) vs content (g/100 needles)	Concentration (g/kg) vs CND ratio	Content (g/100 needles) vs CND ratio
N	0.659**	0.683**	0.331*
P	0.867**	0.951**	0.812**
Ca	0.832**	0.927**	0.735**
Mg	0.749**	0.869**	0.551**
K	0.710**	0.835**	0.482**

*Significant correlations (p<0.05)
**Highly significant correlations (p<0:001)

Variability of foliar indicators

Nutrition differences between species were evaluated by comparing means by nutrient, by species and by foliair indicator. Significant nutritional differences were found between species. Average weight of 100 needles for black spruce was 0.202g, compared to 1.038g for jack pine, 0.395g for balsam fir and 0.329g for white spruce (Table 1.6). Also, jack pine had significantly (Tukey-Kramer with p<0.05) lower needle base cation concentrations than other conifers, and balsam fir had significantly higher N, Ca and Mg concentrations in its needles. Black spruce had significantly lower N concentrations in its needles than other species.

Table 1.6. Mean nutrient concentrations (mg/g), contents (g/100 needles), and CND ratios by species.

		Balsam fir	Black spruce	Jack Pine	White spruce
Concentration	N	13.266 (A)	9.869 (C)	11.682 (B)	11.468 (B)
	P	1.605 (A)	1.311 (B)	0.990 (C)	1.646 (A)
	Ca	5.216 (A)	3.012 (C)	1.852 (D)	3.404 (B)
	Mg	1.158 (A)	1.070 (B)	0.842 (D)	1.000 (C)
	K	5.705 (B)	5.844 (B)	3.856 (C)	6.276 (A)
Content	Weight	0.395 (B)	0.202 (D)	1.038 (A)	0.329 (C)
	N	5.262 (B)	1.989 (D)	12.170 (A)	3.793 (C)
	P	0.639 (B)	0.265 (D)	1.030 (A)	0.535 (C)
	Ca	2.075 (A)	0.608 (D)	1.920 (B)	1.129 (C)
	Mg	0.457 (B)	0.216 (D)	0.876 (A)	0.333 (C)
	K	2.261 (B)	1.177 (D)	4.012 (A)	2.029 (C)
CND score	N	0.348 (B)	0.234 (C)	0.610 (A)	0.313 (B)
	P	-1.788 (B)	-1.799 (B)	-1.859 (C)	-1.667 (A)
	Ca	-0.606 (A)	-0.981 (B)	-1.267 (C)	-0.950 (B)
	Mg	-2.101 (B)	-1.992 (A)	-2.026 (A)	-2.141 (B)
	K	-0.502 (B)	-0.299 (A)	-0.505 (B)	-0.319 (A)

A, B, C and D exponents indicate significantly (<0.05) different means between species determined by Tukey-Kramer.

Relationship between environmental factors and foliar indicators

Weak correlations were found between foliar indicators and stand age, density, degree-days and available precipitation (Table 1.7). CND ratios had lower correlation with stand age than other foliar indicators. Stand density was generally negatively correlated with black spruce and balsam fir nutrition, while it was positively correlated for white spruce. Degree-days were positively correlated with balsam fir Ca nutrition, negatively with black spruce nutrient content and showed both positive and negative correlations with jack pine and white spruce nutrition. Available precipitation generally affects all species and nutrients negatively. For all species and foliar indicators, Ca was significantly negatively correlated with available precipitation. Calcium presented more significant correlations with tested variables than all other nutrients (Table 1.8).

Table 1.7. Pearson r correlations by species between foliar indicators and stand age, density, degree-days and available precipitation, where only significant (p<0.05) correlations are shown

			Stand Age	Density	Degree-days	Available precipitation
Balsam fir	Concentration (g/kg)	N	0.228			
		P				
		Ca		-0.256	0.249	-0.279
		Mg				
		K		0.250		
	Content (g/100 needles)	Weight				
		N				
		P				
		Ca		-0.256		-0.311
		Mg				
		K				
	CND ratio	N				
		P				
		Ca		-0.292	0.248	-0.236
		Mg	-0.334			
		K		0.243		
Black spruce	Concentration (g/kg)	N	0.180			-0.216
		P	0.286*			0.180
		Ca	0.260			-0.348*
		Mg				-0.238
		K	0.277			
	Content (g/100 needles)	Weight		-0.335*	-0.243	
		N		-0.259		
		P	0.196	-0.193	-0.202	
		Ca	0.202	-0.207		-0260
		Mg		-0.263	-0.262	
		K	0.187	-0.123	-0.238	
	CND ratio	N			0.210	
		P				
		Ca	0.194			-0.287*
		Mg				
		K				

			Stand Age	Density	Degree-days	Available precipitation
Jack Pine	Concentration (g/kg)	N	-0.456*		0.358	
		P				
		Ca			-0.420	-0.454*
		Mg				-0.407
		K				
	Content (g/100	Weight			0.308	
		N	-0.317		0.416	
		P				
		Ca				-0.363
		Mg				
		K				
	CND ratio	N	-0.426		0.512*	
		P				0.457*
		Ca			-0.483	-0.425
		Mg				
		K				
White spruce	Concentration (g/kg)	N			-0.518	0.429
		P	--	0.423		
		Ca			0.368	-0.435
		Mg				
		K				
	Content (g/100 needles)	Weight				
		N				
		P		0.395	0.370	
		Ca				
		Mg				
		K				
	CND ratio	N			-0.414	0.542
		P		0.385		
		Ca			0.409	-0.428
		Mg				
		K				

* Highly significant correlations ($p<0.001$)

Assessment of relationship between soil fertility and foliar indicators by means of redundancy analyses

Redundancy analysis evaluates the fit between a set of explanatory variables with a set of response variables. Soil fertility variables were used to explain the variability in foliar indicators (Table 1.8).

Table 1.8. RDA r^2 of 1st and the 1st + 2nd axis by species and foliar indicator, with base cation nutrition explained by soil cation exchange capacity (CEC), $pH_{(water)}$, base cation HNO_3, % of silt, % of clay, specific surface area and presence/absence of a soil depth of less then 50cm. The p values of the first canonical axis was assessed with a Monte-Carlo test.

		r^2 1st axis	1st axis p	r^2 1st + 2nd axis
Balsam fir	Concentration (g/kg)	0.312	0.006	0.430
	Content (g/100 needles)	0.248	0.078	0.320
	CND ratios	0.319	0.004	0.374
Black spruce	Concentration (g/kg)	0.096	0.082	0.167
	Content (g/100 needles)	0.134	0.014	0.180
	CND ratios	0.147	0.002	0.197
Jack pine	Concentration (g/kg)	0.312	0.006	0.430
	Content (g/100 needles)	0.248	0.162	0.320
	CND ratios	0.319	0.004	0.374
White spruce	Concentration (g/kg)	0.308	0.198	0.486
	Content (g/100 needles)	0.364	0.018	0.518
	CND ratios	0.446	0.016	0.582

Black spruce has the smallest r square, suggesting that its foliar nutrition is less correlated to soil fertility than other species (Table 1.8). For all species, the CND r square of the 1st axis and its corresponding p value are stronger than other foliar indicators. For that reason, the following analysis will only concern CND foliar indicator.

Assessment of relationship between soil fertility and foliar indicators by multiple regressions

For balsam fir and white spruce, Akaike's weight of regressions models between soil variables and CND ratios are stronger for Ca than Mg and K (annexe 1). Jack pine shows higher r square with K while black spruce shows a stronger link with Mg, followed closely by Ca for both species. Generally, models r^2 of relationships between soil fertility and CND are stronger with white spruce, followed respectively by jack pine, balsam fir and black spruce (annexe 1). In general, relationships between soil variables and foliar CND ratios are weak for the tested models.

Best models determined by AIC for each species and nutrient gives further insight on links between foliar nutrient and soil fertility. For Ca CND ratios, $pH_{(water)}$ is present in 2 of the 4 best models presented, for balsam fir and white spruce (Table 1.9). In those models, $pH_{(water)}$ is positively correlated with foliar Ca nutrition. Ca_{HNO3} is the only variable in the jack pine best model, and it has a positive effect on Ca CND ratio. Ca_{HNO3} is also present in the black spruce best model (Table 1.9). Percentage of silt and percentage of clay have a negative effect on foliar Ca^{-} CND ratios in the majority of the models.

Table 1.9. Best models by species and nutrient explaining Ca CND ratios with soil fertility variables

Model ID	Specie	w_i	Model variables (t ratio, prob.>|t|)
Ca CND			
5	B. fir	0.26	-Ca_{CEC} (-0.87, 0.39), pH (2.64, 0.01), specific surface (1.48, 0.14)
10	B. spruce	0.25	Ca_{HNO3} (1.92, 0.058), -% silt (-2.06, 0.04), -% clay (-1.24, 0.22)
13	J. pine	0.25	Ca_{HNO3} (2.5, 0.02)
4	W. spruce	0.43	Ca_{CEC} (0.13, 0.9), pH (1.5, 0.16), % silt (1.75, 0.1), -% clay (-1.81, 0.09)
Mg CND			
6	B. spruce	0.29	-Mg_{CEC} (-3.51, <0.001), pH (1.91, 0.06), depth (2.01, 0.046)
4	W. spruce	0.32	-Mg_{CEC} (-0.4, 0.7), -pH (-1.6, 0.13), % silt (2.0, 0.06), -% clay (-0.7, 0.5)
K CND			
5	B. fir	0.12	K_{CEC} (1.25, 0.22), -pH (-1.51, 0.14), -specific surface (-1.46, 0.15)
7	B. spruce	0.18	K_{CEC} (2.30, 0.02), -pH (-1.56, 0.12)
7	J. pine	0.34	-K_{CEC} (-0.87, 0.39), -pH (-3.46, 0.001)
15	W. spruce	0.57	-% silt (-2.65, 0.017), % clay (1.56, 0.14)

w_i is the Akaike weigth.

Regressions between soil fertility variables and Mg CND ratios were very weak for balsam fir and jack pine. For both species, the best model only contained depth of the profile, which had a low r square ($r^2 < 0.03$). Soil depth in the black spruce model (Table 1.9) is positively correlated with the Mg CND ratio. $pH_{(water)}$ has a positive influence on black spruce nutrition. For white spruce, silt is positively correlated with Mg CND ratios.

$pH_{(water)}$ is present in 3 of the 4 best K models presented, for balsam fir (Table 1.9), black spruce and jack pine. In all the models, $pH_{(water)}$ is negatively correlated with foliar K nutrition. K_{CEC} is also present in those 3 models and is positively correlated with black spruce and jack pine nutrition. Percentage of silt has a negative effect on the white spruce CND Mg ratio. Percentage of clay is positive in this model, but not significant.

Relationships between foliar indicators and productivity by the boundary line-approach

A boundary line could not be assessed for balsam fir and jack pine P due to a convex quadratic regression. Also, due to low quadratic regression p value, black spruce N and balsam fir Ca boundary line are not considered. Because of the lack of samples beneath the deficiency level, Mg deficiency level could not be estimated for all sampled species.

Table 1.10. Nutrition standard by species, determined by the boundary layer approach

		CND Optimum	CND deficiency level	CND Unbalanced level	r^2	Deficient samples (%)	Max productivity loss (%)
Balsam fir	N	0.4121	0.2139	0.6103	0.739	4.6	18.7
	P	N.A.	N.A.	N.A.	N.A.	-	-
	Ca	-0.6751⁺	-1.1503⁺	-0.1999⁺	0.074⁺	-	-
	Mg	-2.0522	-2.2614*	-1.8430	0.911	0*	-
	K	-0.4683	-0.6684	-0.2682	0.747	10.3	29.1
Black spruce	N	0.2196⁺	-0.0382⁺	0.4774⁺	0.145⁺	-	-
	P	-1.7967	-2.0782	-1.5152	0.595	5.3	12.9
	Ca	-0.7892	-1.1433	-0.4350	0.748	17.4	28.3
	Mg	-2.0336	-2.1987*	-1.8686	0.956	0*	-
	K	-0.3352	-0.6872	0.0169	0.586	0.8	10.7
Jack pine	N	0.6304	0.5060	0.7548	0.875	17.9	40.3
	P	N.A.	N.A.	N.A.	N.A.	-	-
	Ca	-1.2526	-1.5198	-0.9855	0.912	14.3	38.3
	Mg	-2.0303	-2.1525*	-1.9080	0.688	0*	-
	K	-0.5189	-0.6366	-0.4011	0.928	12.5	27.3
White spruce	N	0.2936	0.1820	0.4033	0.819	12.9	14.4
	P	-1.5109	-1.7878	-1.2340	0.868	25.8	26.8
	Ca	-1.0732	-1.4155	-0.7309	0.832	9.7	17.1
	Mg	-2.2870	-2.5078*	-2.0662	0.870	0*	-
	K	-0.2260	-0.3570	-0.0950	0.853	29.0	28.3

Nutrition optimum corresponds to the boundary-line CND ratio where productivity is at its highest, while CND deficiency and unbalanced level correspond respectively to the point where productivity is at 90% due to low or high CND ratios. The r^2 is the r square of the quadratic regression. Deficient samples correspond to the proportion of samples which have a lower CND ratio than its corresponding CND deficiency level. Max productivity loss corresponds to the lowest CND ratio sample plotted on the quadratic regression.

*Calculation of CND deficiency level is not possible due to the lack of observation with nutrient deficiency.

⁺Determination of CND optimum and nutrition range is not possible due to the low p value ($p<0.10$) of regression of boundary line points.

N.A. Determination of boundary line characteristics is not possible due to a convex quadratic regression.

Of the 306 foliar samples, 222 had no deficiencies, 75 had one nutrient under the deficiency level and only 9 had two nutrient deficiencies. More stands were limited by base cation deficiencies than N or P deficiencies, as 34 stands had a Ca CND ratio under the deficiency level, 26 for K, 18 for N and 15 for P. However, the highest productivity loss has been observed with low N CND ratios on a sampled jack pine.

1.5 Discussion

As mentioned in the introduction, developing foliar indicators of stand nutrient status for large geographical areas involved many steps: comparison of different expression of foliar concentrations, testing indicator sensitivity to species, soil conditions and productivity as well as their applicability to a wide range of environmental conditions.

Differences between species

Fast growing species generally respond more to a change in soil fertility than conservative species (Chapin, 1980). Redundancy analysis showed that the relationship between soil and foliar nutrition was stronger for balsam fir, white spruce and jack pine than black spruce. The first three species are indeed fast growing species (jack pine) or nutrient demanding species (balsam fir and white spruce), while black spruce is more conservative (Thiffault, 2006). Black spruce needles also had low nutrient content and concentrations, jack pine had low nutrient concentration but high content, while balsam fir needles had high nutrient concentration. Differences in needle nutrient concentrations between species may be caused by species intrinsic charectheristics and/or by their different distribution. Jack pine was mainly found on fluvioglacial deposits and till, while white spruce was mainly sampled on lacustrine deposits and till.

This difference between species is less apparent with CND ratios, suggesting that nutrient ratios are more constant between species than foliar concentrations (Ericsson, 1994). Conservative species are usually well adapted for scarcer resources and are more effective in their use of nutrients, which can explain lower black spruce needle concentration (Chapin, 1980). The link between productivity and foliar nutrition, underlined by the boundary-line approach, also shows that black spruce experiences less foliar deficiencies than other species for all nutrients except Ca.

Compared to other species, white spruce foliar nutrition displays higher coefficient regressions with soil model for all nutrients. However, since fewer white spruce trees were sampled, those coefficients may be biased by the small white spruce sample size. Black spruce needles weakly reflect soil fertility for all nutrients. Jack pine Ca and K CND ratios and balsam fir foliar Ca are good indicators of soil fertility. Thiffault *et al.* (2006) also observed that those species where more sensitive to soil changes.

Difference between indicators

CND offers many advantages over DRIS. The first technique takes into account higher order interaction and interrelationships between all nutrients, as one nutrient cannot vary without affecting all CND ratios (Parent and Dafir, 1992). Also, CND multivariate ratios are free of the unit-sum constraints of DRIS and offer more statistical possibilities. Despite those differences, Parent and Dafir (1992) demonstrated that there is a strong relationship between the two indicators, which was apparent in the correlations observed in this study. However, CND ratios are less affected by stand age than foliar concentrations and contents. Indeed, in Walworth and Sumner (1988) review on foliar indicators, they observed that ratios tend to be more stable to seasonal and annual variation than nutrient concentrations.

Applicability to a wide range of environemetal conditions

Nutrient ratios are usually less affected by external variables (Walworth and Sumner, 1988) than concentrations. The influence of stand age, density, degree-days and available precipitation had comparable effects on all foliar indicators except for black spruce CND ratios which display less significant correlations than other foliar indicators. Although stands were sampled on large geographical and climatic scales, the large majority of correlations were not significant or had a low Pearson coefficient (Table 1.7). This suggests that foliar indicators, particularly CND ratios, could be valid on a large scale and on a wide variety of sites.

However, available precipitation and degree day were correlated with some indicators - the direction of the relationship varied. Water stress can significantly limit tree growth. When photosynthesis is more limited than nutrient uptake, it is possible to observe foliar concentrations increase. Van den Driessche (1974) reviewed a large number of studies where drought or low water table resulted in an increase for N, P and K, and no effect or a positive effect on Ca and Mg. However, transport of Ca and Mg to root occurs by mass flow and water absorption (Palomäki, 1994). The negative correlations between foliar Ca concentrations and available precipitation observed in our study may reflect a dilution effect.

Soil fertility variables

The relationship between CND ratios and soil nutrient status remain weak as showed by the low Akaike weight of all tested models. Similar results were observed in other mature boreal stands (Wang and Klinka, 1997). Weaker relationships between soil and foliar nutrients are expected in mature stands when compared with younger stands because of nutrient retranslocation and lower nutrient requirements (Hamburg *et al.*, 2003; Radwan and Harrington, 1986). Also, it has been observed that boreal conifers have extended lateral root systems and can take up to 75% of their base cations requirements in the forest floor (Finér *et al.*, 1997; Bélanger *et al.*, 2003). For those reasons, forest floor properties are often better correlated to foliar nutrition or growth than mineral soil properties (Hamel *et al.*, 2004).

Nonetheless, our study underlines the importance of mineral soil pH for base cation foliar nutrition. Kayahara *et al.*, (1995) have reported similar results. Soil pH is included in 7 of the 10 best models presented above. According to these models, an increase in acidity has a negative impact on foliar Ca CND, a mixed effect on Mg and a positive impact on foliar K CND. As opposed to Mg and Ca, specific channels in plasma membrane facilitate K transports across the steep pH gradient between the cytoplasm and the external cell membrane where a 3 to 4 magnitude H^+ concentration difference is observed (Marschner, 1991). This mechanism maintains K uptake in soils with high concentrations of Mn or Al (Rengel and Robinson, 1989; Marschner, 1991). This could explain differences observed in this study between Mg and Ca CND on one side and K CND on the other, in relation with soil pH.

Soil acidity plays a key role in many biological and chemical soil processes, such as base saturation, root growth, decomposition rate and earthworm activity (Schoenholtz *et al.*, 2000; Brierly *et al.*, 2004; Marschner, 1991). A lower pH usually has a negative effect on soil base cations (Adams *et al.*, 2000; Adams *et al.*, 1997). Since pH has an important effect on forest ecosystems and since forest management can have important impacts on soil pH (*e.g.* Bélanger *et al.*, 2003; Brais *et al.*, 1995), this variable should be considered has an important indicator of soil fertility.

Mineral soil base cations still had some effects on foliar nutrition, nine out of the 10 best models included soil cation exchange capacity (CEC) or acid extractable base cations (HNO_3). Apart from one model (Table 1.9), there is a positive relationship between soil cations and foliar CND in all models where those soil variables are significant ($p<0.05$) or marginally significant ($p<0.10$). Exchangeable cations seem to be a better predictor of foliar nutrition than base cations measured by the HNO_3 extraction. Exchangeable cations give information on nutrients readily accessible to trees, while the HNO_3 extraction reflects nutrients that will become available via soil mineral weathering.

Relation between growth and foliar nutrition

Optimum nutrition ranges (Table 1.10) showed that tree nutrient deficiencies were mostly caused by low Ca or K. This is in contradiction with many previous studies that have identified N has the most limited nutrient in the boreal forests (Fisher and Binkley, 2000; Wang and Klinka, 1997). However, atmospheric deposition, which supplies forests in NO_3^- while decreasing soil base cations, is reversing this trend as more and more stands will be limited by Ca, Mg or K (Federer *et al.*, 1989; Duchesne and Houle, 2008).

We compared CND ratios developed for white spruce from a range of studies (Table 1.11). Among others, Quesnel *et al.*, (2006) used the boundary-line approach in northern Ontario and Abitibi to established CND norms. Two sites were selected, one with stands ranging from 51 to 125 years old and the other with a 17 years old white spruce plantation.

Table 1.11. White spruce trees optimum CND ratio and nutrition range of current-year needles compared with published results and standards

References		N	P	Ca	Mg	K
This study	Critic	0.18	-1.79	-1.42	-	-0.36
	Optimal	0.29	-1.51	-1.07	-	-0.23
	Unbalanced	0.40	-1.23	-0.73	-	-0.10
Quesnel *et al.*, 2006	Critic	0.02	-1.77	-0.63	-	-0.63
	Optimal	0.17	-1.65	-0.30	-	-0.40
	Unbalanced	0.31	-1.53	-	-2.16	-0.17
Swan , 1971	Critic	-	-	-	-	-
	Optimal	0.69	-1.43	-1.61	-2.01	-0.51
	Unbalanced	-	-	-	-	-
Ballard and Carter, 1986	Critic	0.64	-1.63	-1.40	-1.91	-0.49
	Optimal	-	-	-	-	-
	Unbalanced	-	-	-	-	-
Wang and Klinka, 1997	Critic	0.16	-1.41	-0.74	-2.07	-0.49
	Optimal	-	-	-	-	-
	Unbalanced	-	-	-	-	-
Average of above studies	Critic	0.12	-1.65	-1.05	-1.99	-0.49
	Optimal	0.38	-1.53	-0.99	-2.01	-0.38
	Unbalanced	0.36	-1.38	-0.73	-2.16	-0.14

Modified from Quesnel *et al.* (2006).

Our optimal CND ratios for all nutrients are within the range of optimal CND ratios presented in Table 1.11. However, our optimal range for Ca is wider than the average, due to a low critical CND ratio compared to other studies (Quesnel *et al.*, 2006; Wang and Klinka, 1997). While Ballard and Carter (1986) critical Ca CND ratio is close to ours, the estimated critical ratio of Quesnel *et al.* (2006) would result in 84% of our sampled stands to be considered Ca deficient. Similarly, using Wang and Klinka (1997) critical ratio, 81% of our sampled stands would be considered Ca deficient. This may be caused by regional specificity or stand age differences between studies. The general convergence between white spruce norms resulting form our study and results from other studies was surprising given white spruce small sample size (n=31).

The boundary-line approach selects sites with high productivity to calculate the relationship between foliar nutrition and productivity. Therefore, sites that were selected for this study were mostly situated in high temperature zones. Following Liebig's law which states that growth is limited by the nutrient in least supply, forest stand productivity should be correlated with base cation pools when those pools are a limiting factor (Sverdrup and Rosen, 1998). Because temperature does not restrain their growth, stands with favourable climatic conditions may be more susceptible to be limited by soil nutrient pools, and so generate more accurate results in the boundary-line approach.

1.6 Conclusion

Developing operational indicators of stand nutrient status for large geographical regions raises numerous challenges. Foliar indicators are easy to understand and sampling is quite simple. They could be used over large environmental gradients, and the boundary approach ~~with CND could~~ yield meaningful indicators. However, the relationship between soil fertility and foliar nutrition remains weak. A better understanding of mechanisms of nutrient uptake is crucial. Younger stands could be targeted for monitoring purposes yielding better results.

Results from the boundary-line approach suggested that many stands from the Quebec boreal forest suffer from Ca or K deficiency. Such deficiencies could be accentuated by acid rain or intensification of forest harvesting. These results emphasize the need for large scale soil fertility monitoring programs and the information gathered in this study could contribute to such a program.

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CHAPITRE II

OPERATIONAL TOOL FOR ASSESSING SITES VULNERABILITY OF QUEBEC'S BOREAL FOREST TO BIOMASS EXTRACTION

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2.1 Abstract

In the context of increased biomass harvesting from forests, province wide tools for identifying adequate sites are required. Forest sites with low base cation pools are the most vulnerable to nutrient depletion caused by biomass harvesting. The productivity of more than 400 sites distributed throughout Quebec's boreal forest was determined by a combination of key understory vegetation, site index and basal area. Each site was classified as low or highly productive, and productivity classes were compared with a set of models containing soil and climate variables by Akaike's information criterion. Base cation concentrations estimated from more than 80 000 lakes and rivers sediments sampled for mining prospection were not strong variables in models tested. Surface deposit, position on the slope, drainage and degree-days composed the strongest model, with a pseudo r^2 of 0,415. The odds of a stand growing on a fine texture deposit of being in the high productivity class are 21.5 times larger than stands growing on rock outcrop, 7.7 times than shallow deposits, 6.1 times than coarse texture deposits and 3.4 times larger than medium texture deposits. The odds of stands on top of a slope to be in the low productivity class are 4.0 times higher than stand on middle of slopes, 2.3 times higher than stand on bottom of slope and 1.4 times higher than stands growing on level ground, while the odds of a moderately drained stand to be in the high productivity class are 3.6 times higher than imperfectly drained stands and 1.5 times higher than well drained sites. Those results suggest that a number of vulnerable sites to biomass harvesting can quickly be identified from mapped data like surface deposit, position on the slope and drainage.

Keywords: soil fertility, productivity, base cations, black spruce, white spruce, balsam fir, jack pine, boreal forest.

2.2 Introduction

With large fluctuations in fossil fuels prices, growing concerns over climate change and the search for stable and renewable energy sources, forest biomass as energetic sources gains more and more attention in Quebec, Canada. Quebec aims at harvesting annually 1.5 million anhydrous metric tons of forest biomass by 2016 to produce electricity, heating and potentially biofuels (MRNF, 2009). This forest biomass will mainly come from stems of low industrial value and logging residues (Gouvernement du Québec, 2008).

Logging residues are constituted of tree tops, branches and foliage that can either be left on site by stem only harvesting (SOH), or removed with the stems by whole tree harvesting (WTH). Because of the higher nutrient concentration in branches and leaves (Mann *et al.*, 1988), WTH exports 2 to 3 times more nutrients from the ecosystem than SOH (Paré *et al.*, 2002; Yanai, 1998; Foster and Morrison, 1987). Many studies in the boreal forest observed that, for some nutrients, outputs caused by WTH and leaching exceed current atmospheric and weathering inputs (*e.g.* Sverdrup and Rosen, 1998; Duchesne and Houle, 2008; Duchesne and Houle, 2006), suggesting a depletion of those nutrients in forest soils in the long term.

The negative balance between input and output seems to be more acute for base cations than nitrogen and phosphorus (Fisher and Binkley, 2000; Morris, 1997). Whole tree harvesting has empirically been associated with a reduction of soil base cation pools (e.g. Brais *et al.*, 1995; Pennock and Kessel, 1997; Olsson *et al.*, 1996) and soil acidification (Bélanger *et al.*, 2003), which lead on some sites to a decrease of tree foliar nutrient content (Thiffault *et al.* 2006), and to a lower site productivity (Egnell and Valinger, 2003 ; Mann *et al.*, 1988). In addition, decreases in soil base cation pools may reduce tree resistance to environmental stresses and diseases (DeHayes *et al.*, 1999; McLaughlin and Wimmer, 1999).

In order to protect long term productivity of boreal ecosystems, vulnerable sites to WTH must first be identified. The objective of this study is to develop a province scale operational tool to assess soil base cation pools using currently available information throughout Quebec. Liebig's law states that growth is limited by the nutrient in least supply. Following Liebig's law, forest stand productivity should be correlated with base cation pools only when those pools are a limiting factor (Sverdrup and Rosen, 1998). In order to validate the base cation pools estimation, the link between productivity and base cations pools will be evaluated.

In the Quebec boreal forest, where soils have evolved from quaternary deposits, sites on shallow surface deposits and glaciofluvial sands are expected to be the most vulnerable to WTH (Paré *et al.*, 2002). Due to their small soil volume or weak nutrient retention capacity, a considerable proportion of their nutrients is contained in the harvestable biomass (Morris, 1997), and WTH should have a larger impact on those sites. Soil mineralogy can also significantly influence soil nutrient content (Lahdenperä *et al.*, 2001, Neff *et al.*, 2006). Soils derived from base cation rich rock formations will contain larger amounts of those elements and soil fertility may be less affected by WTH (Thiffault *et al.*, 2006). Sites on soils with limited cation pools are probably already affected by low nutrient availability, and are therefore more vulnerable to an additional exportation of nutrients caused by WTH. In this paper we explore the link between soil fertility variables and potential productivity.

2.3 Methodology

Study area

This study (47,1° to 51,3°N and 64,5° to 79,3° W) was conducted in the two climatic domains of Quebec's boreal forest: balsam fir / paper birch and the black spruce / moss domain. Domains differ by the nature of late successionnal stand composition. Each domain is subdivided in 2 sub-domains. The balsam fir / paper birch east sub-domain receives more precipitation and has a rougher landscape then its western counterpart. East and west black spruce / moss sub-domains differ also by their annual precipitation, which results in longer fire cycles in the east (Saucier el al., 1998). Mean annual temperature varies from -2,3°C to 3,3°C and total precipitations range from 825 mm to 1573 mm.

Table 2.1. Study site characteristics

	Balsam fir / paper birch		Black spruce / moss	
	East	West	East	West
Ecological regions ID	5e, 5f, 5g, 5h, 5i	5a, 5b, 5c, 5d	6i, 6k	6a, 6c
Latitude (Min and Max)	47.128 °N 50.077 °N	47.545 °N 49.628 °N	49.13 °N 51.23 °N	48.90 °N 50.55 °N
Longitude (Min and Max)	64.55 °W 71.68 °W	70.89 °W 79.28 °W	68.02 °W 71.96 °W	74.28 °W 78.87 °W
Average precipitation	1165.3	1016.8	1018.1	930.8
Average Degree-Days	1142.1	1252.7	1077.1	1213.7
Surface deposits	RO, SS, CT, MT, FT	RO, SS, CT, MT, FT	RO, SS, CT, MT,	SS, CT, MT
Species sampled	BF, BS, JP, WS	BF, BS, JP, WS	BF, BS, JP, WS	BF, BS, JP
# of stands sampled	168	137	85	49

Only ecological regions with at least one sampled stand are presented in this table, and ecological regions ID correspond to Quebec's ecological classification (Saucier *et al.*, 1998). Longitude, latitude, and climatic variables statistics were determined with sampled stands. Surface deposits classification is presented in Table 2.2. Species sampled were balsam fir (BF), black spruce (BS), jack pine (JP) and white spruce (WS).

The area is located within the Grenville and Superior provinces of the Precambrian shield as well as the Appalachian orogenic belt. Those three geological provinces are subdivided in 105 geological units (MRN, 2001) which represent different formations and mineralogy. Soils have evolved from unconsolidated material of quaternary origin - till of variable thickness, fluvioglacial, lacustrine or alteration deposits. Stands growing on organic deposits were excluded from the study.

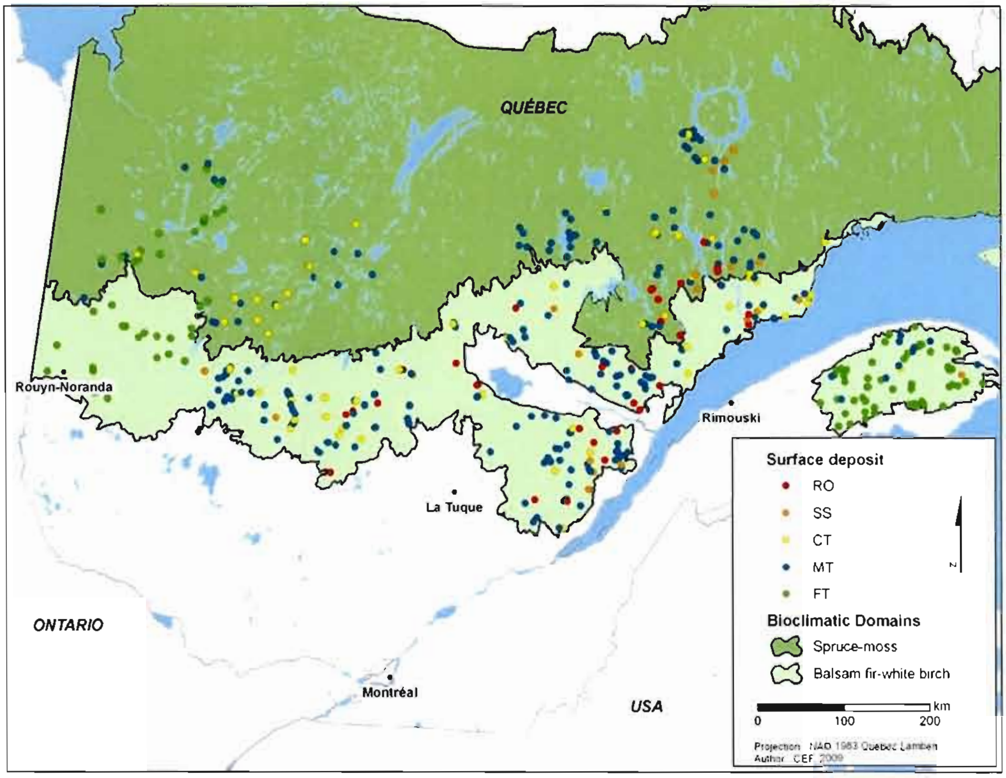

Figure 2.1. Stand location and their respective surface deposit (Abbreviations are as follows: RO, rock outcrop; SS, shallow surface deposit; CT, coarse texture deposit; MT, medium texture deposit; FT, fine texture deposit).

Stand characteristics

Stands were chosen to represent the main physical (topography, texture and moisture regime) and biological (forest cover and potential vegetation) characteristics of their ecological region (Saucier *et al.*, 1998). All sampled stands were at least 50 years-old and preferably more than 70 years old in order to calculate site index (SI). Surface deposit and moisture regime were characterized based on understory vegetation, soil texture, stoniness, and water table depth (MRNF, 2006). A 400m^2 sampling plot was established. All trees $\geqslant$ 9 cm DBH were indentified and measured for basal area estimation. The main understory vegetation was assessed with key herbaceous and shrubs species, which depends on ecological region (MRNF, 2003a).

For example, in the Abitibi plains ecological region, *Kalmia angustifolia L.* is mainly present on poor soils while *Clintonia borealis Raf.* typically grows on rich soils. Finally, at least 5 dominant trees of the same species were selected for stem analyses. On most plots, two different tree species were sampled. Only straight trees with no apparent default and of at least 50 years old were retained for the analysis. Each selected tree was cut and disks were taken at 0.15m, 0.60m, 1.0m, 1.3m, 3.0m and at each additional 2 meters until the apex of the stem.

In the laboratory, growth measures were taken with binoculars and digitized with WinDendro software on four radiuses for the first 4 disks and on 2 radiuses for the following ones (Zarnovican, 1985). Growth in height and diameter was then reconstructed with ANATI software (MRNF, 2006). Growth delays caused by external factors, like spruce budworms or oppression, were corrected following the methodology described in Quebecs' forest inventory standards (MRNF, 2006). Within each sampled stand, a mean 50 years height (site index 50) was calculated for each dominant species present in the stand. Mean SI50 was preferred to stand maximum SI50 in order to avoid potential productivity overestimation that could be caused by microsite differences that can vary over very short distances (Lavoie *et al.*, 2007). We obtained 244 mean SI50 for balsam fir (*Abies balsamea*), 277 for black spruce (*Picea mariana*), 93 for white spruce (*Picea glauca*) and 101 for jack pine (*Pinus banksiana*).

Pothier and Savard (1998) productivity tables were used to correct basal area of each site and set it to a reference age of 75 years for all our stands. Taking into account the ecological region, each understory vegetation community was assigned a richness class from 1 to 5 following Quebec's ecological classification (*e.g.* MRNF, 2002).

Soil richness and base cation pools estimation

Base cation pools were assessed from soil depth, stoniness, bulk density, clay and silt content, and cation concentrations according to the following formula:

$$X_{pool} = [X] * Density * Thickness * (1 - stoniness/100) * (\% fine texture/100) * 100 \quad (1)$$

where X_{pool} is the pool for nutrient X, [X] the concentration of X in the soil, Thickness is the depth of the soil, stoniness the % of the soil occupied by gravel and rocks, and % of fine texture is the fraction of silt and clay in the mineral soil. The estimation is based on two components: the quality of the pool described by the concentration of the element in the soil, and the size of the pool which is the soil volume accessible to tree roots.

Base cation concentrations were derived from the e-sigeom data base (MRNF, 2003b). The data base contains over 82 000 lake sediments, river sediments and soil samples taken by mining prospectors and is the most comprehensive geological data base available in Quebec. The base cation concentrations has been measured by processing the fine texture portion of the sediment (<0,2mm) with nitric acid and by analyzing the extraction by atomic absorption spectrometry (Gagné, 1990). For each nutrient, the median concentration value of all sample points in a particular geological unit (MRN, 2001) have been attributed to all stands on that geological unit. This method was preferred over interpolation techniques due to the large distance between some of the sampled stands and sediment samples, which could reach 100 kilometres.

An average value of thickness, stoniness and % of silt and clay in the B horizon was derived from Quebec's' ecological inventory for each combination of surface deposit – moisture regime and ecological region and apply to each of our stands within a given region. Soil bulk density was set at 1.0 Mg m^{-3} for all soils. Soils from the boreal forest contain little organic matter and bulk density values usually range from 0.8 to 1.2 Mg m^{-3} (Brais, 2001; Thiffault *et al.*, 2007b).

Stand position on slope (top, middle, bottom and level ground) and drainage (imperfect, moderate and good) were also considered indicators of soil nutrient availability. Position on slope can influence stand nutrition by increasing leaching output of stands located in the upper part of slopes, while increasing nutrient inputs by seepage for stands at the bottom of a slope (Bélanger *et al.*, 1995; Fisher and Binkley, 2000). Insufficient drainage can reduce nutrient availability (Morris, 1997), while an excessive drainage can cause significant leaching out of the soil profile. Both variables were assessed in the field (Brais and Camiré, 1992) and were used as an alternative to e-sigeom base cation concentrations.

Since surface deposits are often characterized by the soil texture, thickness and stoniness, surface deposit was also considered an approximation of soil volume. In order to reduce the number of classes, surface deposits were grouped according to their depth and texture classes (Table 2.2).

Table 2.2. Surface deposit classification and number of stands in each class.

Classes	Surface deposit	n
Rock outcrop (RO)	R, R1A, M1A	26
Shallow soil (SS)	1AM, 8AR	19
Coarse texture (CT)	2A, 2BE, 4GS, 9S, 3AN, 5S	44
Medium texture (MT)	1AY, 1A	136
Fine texture (FT)	1AA, 4GA, 8A, 8AY, 8AM, 8C	58

Surface deposit descriptions are given in MRNFs' forest inventory standards (MRNF, 2006).

Stand productivity classification

Site index (SI50), basal area and understory vegetation are three measures of site richness and each has its drawbacks (Skovsgaard and Vanclay 2008). Site index is commonly used as an indicator of site potential productivity (*e.g.* Hamel *et al.*, 2004; Pinno *et al.*, 2009). However, the relationship between tree height and yield is not always straightforward (Richardson *et al.*, 1999) and can vary as a function of climate, density, provenance or soil (Skovsgaard and Vanclay 2008; Williams *et al.*, 1991; Pothier and Savard, 1998).

In order to have a higher confidence level on stand productivity, the three indicators were used to classify the stands of relatively "high productivity" or of relatively "low productivity". A stand was classified in the "high productivity" group when its mean SI by species, for all sampled tree species in that stand, was above the median SI of all SI measured in this study for that particular species. In addition, this stand mean basal area must be higher than the median basal area of all stands with similar species composition. Finally, a site could not be considered as highly productive if its understory vegetation community was classified in the poorest group. The opposite process was followed to classify stands with relatively "low productivity". This process lead to the classification of 142 stands showing a low productivity compared to 141 stands having a high productivity. 156 stands have been rejected in reason of a mixed diagnosis.

Climate variables

At the regional scale, climatic variables are usually the predominant factors influencing productivity (Ung *et al.* 2001; Chen *et al.*, 2002). It is only at the local scale that the influence of soil variables on productivity becomes apparent (Pinno, 2008). Degree-days and available precipitation are two variables recognized as important factors influencing productivity (Hamel *et al.*, 2004; Pinno, 2009; Ung *et al.*, 2001). Geographical coordinates, altitude, slope and aspect of each stand were noted and used to estimate degree-days and available precipitation with the BIOSIM model (Régnière 1996). BIOSIM matches geographical coordinates of a given site to climatic data from 1965 to 1998 collected in 120 Quebec stations. This data is then adjusted to specified elevation, slope and aspect. Using weather data generated by BIOSIM has the advantage of keeping models simple while capturing the most important information from climate proxies like longitude, latitude, elevation, slope and aspect.

Statistical analysis

In order to validate soil base cations pools, the relationship between productivity (high or low) and base cations pools was assessed using logistic regressions. Each tested model (Table 2.3) is a combination of 2 groups of variables: climatic variables and base cations pool variables. Base cations pool variables were estimated by four different means: base cation concentrations estimated from geological units, base cation availability based on drainage and position on the slope, cation pool size based on combinations of surface deposit/drainage/ecological region, and finally, cation pool size using surface deposit as an indicator. The first model (ID = 1) is a general model containing all variables and the other models are subsets of this general model. Except for the general model, each model was built in order to avoid having two groups of variables estimating the same factor (*i.e.* the two different methods used to estimate pool size cannot be represented in the same model).

Table 2.3. Models ID and their respective variables

Model ID	Model variables
1	%silt %clay Stoni thick deposit geoCa geoK geoMg drain position av_prec DD
2	%silt %clay Stoni thick geoCa geoK geoMg av_prec DD
3	%silt %clay Stoni thick geoCa geoK geoMg
4	%silt %clay Stoni thick drain position av_prec DD
5	%silt %clay Stoni thick drain position
6	%silt %clay Stoni thick av_prec DD
7	%silt %clay Stoni thick
8	deposit geoCa geoK geoMg av_prec DD
9	deposit geoCa geoK geoMg
10	deposit drain position av_prec DD
11	deposit drain position
12	deposit av_prec DD
13	Deposit
14	geoCa geoK geoMg av_prec DD
15	geoCa geoK geoMg
16	drain position av_prec DD
17	drain position
18	av_prec DD

Where %silt is the percentage of silt in the B horizon, % clay is the percentage of clay in the B horizon, stoni is soil stoniness, thick is soil thickness, deposit is surface deposit, geoCa, geoK and geoMg is the concentration of those elements estimated with geological unit, drain is the drainage, position is the position on the slope, av_prec is the available precipitation, and DD is the degree-days.

Model selection was based on Akaike's Information Criterion (AIC) and derived measures (Burnham and Anderson, 2002). The AIC penalizes models with many variables, favouring simple and parsimonious models. Model selection based on AIC is an interesting approach for descriptive studies involving large numbers of explanatory variables (Burnham and Anderson, 2002).

For each model, AIC was calculated:

$$AIC = -2(\text{log-likelihood}) + 2K \quad (2)$$

where k is the number of parameters used in the model.

The Akaike weight was then calculated to compare models between them:

$$\Delta_i = AIC_i - \min AIC \quad (3)$$

$$w_i = \exp(-\Delta_i/2) / \sum_{r=1} \exp(-\Delta_r/2) \quad (4)$$

where Δ_i is a relative measure of the model *i* compare with the best (min AIC), w_i is the Akaike weight which provides a measure of strength of the model *i* relative to the whole set of model *r*.

Finally, the max-rescaled r^2 was computed for each model based on the following equation:

$$r^2 = [\ 1 - \exp(2(\log L(M) - \log L(0)) / n)\ ] / [1 - \exp(2 \log L(0) / n)\ ] \quad (5)$$

where logL(M) and logL(0) are respectively the maximized log likelihood for the fitted model and the "null" model containing only an intercept term, and n is the sample size.

The max-rescaled r^2 is a measure of the change in the likelihood function between an intercept only model and a model that contains a set of independent variables.

2.4 Results

Stand characteristics

A total of 439 stands, 134 in the black spruce / moss domain and 305 stands in the balsam fir / paper birch domain were sampled. Those stands covered 26 different geological units, including extrusive as well as intrusive, metamorphic and sedimentary rock formations (Table 2.4). The Témiscouata formation – composed of shale, sandstone, limestone and slate - was one of the poorest geological units sampled, with lake / river sediments containing an average of 6.4 milliequivalents of Ca per 100g of dry soil. On the other end of the spectrum, calc-silicate rocks, marble, dolostone, schist and quartzite formation were base cations rich, with an average of 36.6 mEq/100g of Ca in sediments. More than half of the sampled stands were growing on till of variable thickness, and the other half on fluvioglacial, lacustrine or alteration deposits. Fine texture deposits were more frequent in the balsam fir / paper birch domain.

Table 2.4. Main geological units where stands were sampled (MRN, 2001)

Geological Unit	% of sites		Mean (mEq/100g)	Std
Grey gneiss with quartz, plagioclase, biotite and/or hornblende, mafic gneiss with hornblende and/or biotite, and amphibolite	19	Ca	14.8	12.6
		Mg	6.3	6.8
		K	3.7	6.3
Charnockitic gneiss and orthopyroxene bearing granitoids	12	Ca	21.5	18.3
		Mg	4.6	5.1
		K	3.5	8.2
Orthopyroxene bearing granitoids: charnockite, mangerite, jotunite and hypersthene syenite	11	Ca	15.7	12.4
		Mg	4.2	3.8
		K	2.0	1.8
Limestone, mudrock, sandstone and conglomerate (Matapédia, Honorat and Cabano groups)	8	Ca	12.6	33.4
		Mg	40.4	14.2
		K	12.0	8.1
Pre- to syn-tectonic granitoids: tonalitic and trondhjemitic gneisses; undivided gneiss; minor diorite	7	Ca	11.0	17.5
		Mg	4.7	4.0
		K	2.1	2.1

The most common understory species encountered was *Pleurozium shreberi*, a feather moss species indicating intermediate stand richness, with about half the stands harboring this feather moss on more than 25% of their ground surface. Sheep-laurel (*Kalmia angustifolia*) was also a common understory species and is an indicator of low soil fertility. Rich sampled stands commonly had understory characterized by mountain maple (*Acer spicatum*) or canadian dwarf cornel (*Cornus canadensis*).

Of 439 stands, 32% were classified as highly productive (141 stands), 32% as poor (142 sites), and 36% of stands were not classified as one or more of the productivity class criterion were not met. Basal area at 75 years old on poor productivity class sites ranged from 4 to 33 m^2/ha with an average of 23 m^2/ha, while rich sites basal area ranged from 27 to 80 m^2/ha with an average 41 m^2/ha.

There was a sharp SI50 difference between rich and poor productivity classes (Table 2.5) with no overlapping in site index values between classes. Rich stands were found more often on fine texture deposit and poor stands on rock outcrop, shallow or coarse texture deposit.

Table 2.5. SI and surface deposit by ecological domain, sampled species and productivity classes

Domain	Species	Productivity class	IQS (m) Min	IQS (m) Mean	IQS (m) Max	Surface deposit (# of occurrence) RO	SS	CT	MT	FT
Balsam fir / Paper brich domain	BF	Low	8.86	11.64	13.90	9	5	2	24	6
		High	13.93	16.74	20.04	1	3	-	31	25
	BS	Low	9.11	11.80	13.09	10	6	8	18	5
		High	13.11	14.89	17.76	3	2	9	19	9
	JP	Low	8.64	12.17	13.68	2	3	6	3	-
		High	14.09	16.18	19.16	3	-	9	15	-
	WS	Low	8.14	12.52	15.25	2	2	-	7	1
		High	15.47	17.98	23.03	-	-	-	16	10
Black spruce / moss domain	BF	Low	7.98	10.99	13.83	7	2	-	9	-
		High	14.00	15.11	16.94	-	-	-	9	-
	BS	Low	7.51	10.75	13.01	4	5	17	28	1
		High	13.23	14.41	17.57	1	-	2	8	11
	JP	Low	7.64	11.02	13.60	-	-	14	6	-
		High	14.54	15.26	16.57	-	-	3	3	-
	WS	Low	-	-	-	-	-	-	-	-
		High	-	-	-	-	-	-	-	-

Abbreviations are as follows: BF, Balsam fir; BS, Black spruce; JP, jackp pine; WS, white spruce; RO, Rock outcrop; SS, shallow surface deposit; CT, coarse texture deposit; MT, medium texture deposit; FT, fine texture deposit.

Among retained 283 stands, 48% were on a medium texture deposit, 20% were on fine texture deposit, 16% on coarse texture deposit, 9% on rock outcrop and 7% on shallow deposit (Table 2.2). 17% of the stands were on level ground, as many were on top of a slope, 53% were in the middle of a slope and 12% were at the bottom of a slope. Finally, the majority of stands retained for the analysis were moderately drained (59%), while 26% had an imperfect drainage and 15% a good drainage class.

Link between nutrient pools and productivity classes

Model AICs ranged from 311 to 378. Model 10 had the lowest AIC and its Akaike weight (w_i) of 0.914 makes it by far the most probable model - the model is about 18 times more likely than its closest alternative, model 4 based on average clay and silt content. Model 10 included surface deposit, drainage, stand position on slope, available precipitation, and degree-days. The productivity class predicted by this model is the same as the observed productivity class in 75% of the cases.

Table 2.6. Akaike's information criterion and derived measures of logistic regression models for site productivity

Model ID	AIC	Δ_i	w_i	r^2
1	317.439	6.568	0.034	0.439
2	335.914	25.043	0.000	0.315
3	366.141	55.270	0.000	0.185
4	316.666	5.795	0.050	0.396
5	349.113	38.242	0.000	0.267
6	333.654	22.783	0.000	0.302
7	368.538	57.667	0.000	0.150
8	324.953	14.082	0.001	0.354
9	359.081	48.210	0.000	0.213
10	310.871	0.000	**0.914**	0.415
11	348.297	37.426	0.000	0.270
12	320.433	9.562	0.008	0.349
13	357.546	46.675	0.000	0.195
14	339.305	28.434	0.000	0.274
15	367.081	56.210	0.000	0.148
16	329.803	18.932	0.000	0.323
17	378.770	67.899	0.000	0.115
18	349.350	38.479	0.000	0.212

For model ID refer to Table 2.2. AIC = Akaike's Information Criterion, Δ_i = delta AIC, w_i = Akaike weight, and r^2 is the max-rescaled r^2 from the logistic regression.

The average model was not estimated because model 10, with an Akaike's weight of 91.4%, is largely superior than all other models (Table 2.7).

Table 2.7. Best model: model 10.

Parameter	Estimation	Unconditional SE
Intercept	-9,59370	2,74620
Available precipitation	-0,00022	0,00428
Degree-Days	0,00872	0,00159
Surface deposit: outcrop	-3,23090	0,72560
Surface deposit: thin soil	-2,15760	0,74730
Surface deposit: coarse texture	-1,87920	0,59280
Surface deposit: medium texture	-1,31410	0,47430
Surface deposit: fine texture	-	-
Drainage: imperfect	0,89400	0,58290
Drainage: moderate	1,09030	0,49540
Drainage: good	-	-
Situation on the slope: level ground	-0,63970	0,57100
Situation on the slope: top	-0,81300	0,56800
Situation on the slope: middle	0,35610	0,45680
Situation on the slope: bottom	-	-

Surface deposit was retained in the most probable model (model 10), and resulted in a stronger r^2 and AIC when added to a model solely composed of climatic variables (model 18 vs model 12). A contingency table (Table 2.8) shows that generally, higher SI are found on fine texture deposits and low SI are common on rock outcrop, shallow or coarse surface deposits. Jack pine is the only specie where the lowest SI are not found on rock outcrop deposits.

Table 2.8. Minimum, maximum and mean SI50 by species as a function of surface deposit

		n	SI50 (m)		
			Min	Mean	Max
Balsam fir	Rock outcrop	17	8.4	11.0	15.3
	Shallow deposit	10	10.0	12.8	16.0
	Coarse texture deposit	2	11.4	12.5	13.6
	Medium texture deposit	73	8.0	14.1	19.9
	Fine texture deposit	31	8.9	16.1	20.0
Black spruce	Rock outcrop	18	9.6	12.0	14.9
	Shallow deposit	13	10.9	12.1	15.4
	Coarse texture deposit	36	8.9	12.2	16.7
	Medium texture deposit	73	7.5	12.5	17.8
	Fine texture deposit	26	10.5	13.9	17.5
Jack pine	Rock outcrop	5	10.2	14.7	16.0
	Shallow deposit	3	9.9	13.2	13.4
	Coarse texture deposit	32	7.6	13.3	19.2
	Medium texture deposit	27	9.0	14.4	18.4
	Fine texture deposit	-	-	-	-
White spruce	Rock outcrop	2	12.3	12.8	13.3
	Shallow deposit	2	12.7	13.7	14.6
	Coarse texture deposit	-	-	-	-
	Medium texture deposit	22	10.6	16.2	20.9
	Fine texture deposit	11	8.1	17.9	23.0

Base cation pool concentrations estimated from sediment sample means for a given geological unit were weak predictors of productivity class and were not found in any model with an Akaike's weight higher than 0.001. Model 15 (Tables 2.2 and 2.3), containing only base cation concentrations (Ca, Mg and K) estimated with the sediment samples mean in a given geological unit had the second lowest r^2 (0.148) and the third lowest AIC (367.081).

Model 18, which uses only climatic variables (degree-days and available precipitation) to predict productivity, has an r^2 of 0.21 and an AIC of 349. When surface deposit is added to those variables (model 12), the r^2 (0.349) and AIC (320.433) become stronger. Finally, when drainage and position on the slope are added (model 10), we obtained the best AIC (310.871) and the strongest r^2 (0.415). Position on the slope and drainage added more information to climatic variables and surface deposit than base cation concentrations estimated by sediment samples (model 10 vs model 8).

Based on the best model odd ratios (model 10), the odds of stands on top of a slope to be in the low productivity class are 4.0 times higher than stand on middle of slopes, 2.3 times higher than stand on bottom of slope and 1.4 times higher than stands growing on level ground, all others factors considered have been fixed or controled. Based on the same model, the odds of a moderately drained stand to be in the high productivity class are 3.6 times higher than imperfectly drained stands and 1.5 times higher than well drained sites.

The occurrence of shallow deposits and rock outcrops is more frequent on top of slopes, while less fine texture deposit are observed (Table 2.9). Consequently, the difference in productivity observed on top of slopes could be the results of surface deposit variation. However, if the analysis is circumscribed only to tills to eliminate the influence of surface deposit, we still see a significant (khi square test $p<0.05$) difference with 76% of tills on top of slope in the low productivity class while only 45% of stands are in this class on middle of the slope, bottom of the slope or on flat surface.

Table 2.9. Contingency table of the proportion of sites on different surface deposits as a function of slope position

	Rock outcrop (%)	Shallow deposit (%)	Fine texture deposit (%)	Medium texture deposit (%)	Coarse texture deposit (%)
Top of the slope	22	16	10	35	16
All stands	9	7	20	48	16

Degree-days and available precipitation were present in all models with an Akaike's weight over 0.001, suggesting a strong influence of climatic variables on productivity. This influence was driven by degree-days, as the link between productivity and available precipitation was weak and not significant in each of the model tested.

2.5 Discussion

Large scale cation pools estimation

This study aims to develop operational provincial tools to identify vulnerable sites to soil nutrient deficiencies, a tool that could subsequently be used to limit intensive forest practices such as whole tree harvesting, on these more vulnerable sites. Nutrient pools were estimated with available mapped variables at the provincial scale (surface deposit, drainage, position on slope and sediment samples) and this estimation was validated with potential productivity measures.

The relation between soil pools and potential productivity can be hidden by other variables. At a large scale, climatic variables are considered as the main driver influencing stand productivity (Pinno, 2008; Ung *et al.*, 2001; Chen *et al.*, 1998). Those variables can explain a large proportion of tree growth variability. It is only at the local scale that growth models are dominated by soil factors (Edmonds and Chappell, 1993; Béland *et al.*, 1993). To achieve the objective of this study and analyse soil influences at a provincial scale, climatic variables must be taken into account and a good sampling stratification with a sufficient sample size is necessary. Those two requirements were met in this study. Models used in this study showed that while climate is a good indicator of potential productivity, soil variables can add significant information to climatic variables. The large-scale study by Grondin *et al.* (1999, 2000) estimated soil fertility of Quebec's balsam fir /white birch ecological domain with potential vegetation. The principal variables used to explain the observed fertility gradient were texture, depth of the mineral soil and drainage. These variables can be estimated from surficial geology.The fertility class distribution obtained, derived by Paré *et al.* (2002), is similar to the one observed in the present study (Table 2.10).

Table 2.10. Comparison between this study and Grondin *et al.* (1999, 2000) of fertility class distribution as a function of surface deposits

Deposit	Study	Fertility class (%)		
		Poor	Medium	High
Shallow soil and roc	Grondin *et al.* (1999, 2000)	49-67	33-47	0-4
	This study	81	-	19
Coarse texture	Grondin *et al.* (1999, 2000)	69-75	25-31	0
	This study	67	-	33
Till	Grondin *et al.* (1999, 2000)	20-32	50-54	14-30
	This study	48	-	52
Fine texture	Grondin *et al.* (1999, 2000)	14-20	14-44	36-72
	This study	19	-	81

Cation pool sizes

Surface deposit is included in the best model (Table 2.7), and has a relatively strong ability to discriminate productivity classes. Other studies have shown the importance of surface deposit on productivity (Edwald, 2005; Hamel *et al.*, 2004; Pinno *et al.*, 2009). Surface deposits influence soil depth, stoniness and soil texture, which are three important variables of nutrient pool sizes or soil volume accessible to tree roots (equation 1). Different studies have shown the influence of those variables on productivity. In boreal forests, where trees have extended lateral root systems, it is believed that nutrient uptake takes place in the first 30 centimetres of the soil profile (Finér *et al.*, 1998), and that deeper soil is more critical for water uptake during water stress periods (Bélanger *et al.*, 1995). However, because of the importance of water in base cation uptake, reduced water absorption can negatively affect tree calcium nutrition (Palomäki, 1994). Consequently, the observed relationship between depth and productivity (i.e. Sánchez-Rodríguez *et al.*, 2002; Schmidt and Carmean, 1988) may be due to water shortage and nutrient uptake. Similarly, the influence of stoniness on productivity (Schmidt and Carmean, 1988) can be attributed to water and/or nutrient deficiencies. Finally, soil texture plays an important role in water holding capacity and nutrient availability (Fisher and Binkley, 2000). For example, magnesium deficiency in sugar maple trees was associated with coarse texture fluvioglacial deposits (Bernier and Brazeau, 1988). Thus, surface deposits can influence nutrition by determining soil depth, stoniness and texture, which can in turn explain the lower productivity observed on rock outcrop, shallow deposits and coarse texture deposits in this study.

However, cation pool sizes (soil thickness, stoniness, % of silt and % of clay in the B horizon) estimated by an association of surface deposit / drainage / ecological region of Quebec's ecological inventory plots show a weak ability to discriminate between high productivity and low productivity class. This could be due to a jump in scale, as pool sizes are obtained by an average of thickness, texture and stoniness by surface deposit / drainage class at the ecological regional scale, while surface deposit is determined directly on site. Also, even if a model with many variables can explain more clearly the dynamics of an ecosystem, it might be less effective than a simpler model in predicting its behaviors. Indeed, in this study, surface deposit gives a better estimation of stand productivity and has the advantage of being simpler.

Cation pool quality

Position on the slope and drainage can affect soil base cation concentrations and both variables are found in the most probable model (model 10).

Many studies observed that drainage is a critical factor of site productivity in the boreal forest (Wang and Klinka, 1996; Ung *et al.*, 2001; Bélanger *et al.*, 1995; Page, 1976). A higher water table on imperfectly drained sites can prevent deep root growth and consequently limit the access of trees to nutrients (Lieffem, 1987). Also, imperfectly drained soils can experience lower temperature and, as a result, lower decomposition rate and nutrient availability (Van Cleve *et al.*, 1981; Fisher and Binkley, 2000). In this study, a lower odd of being in the high productivity class was observed for imperfectly and well drained sites compared to moderately drained sites. Well drained sites can experience more nutrient leaching than moderately drained sites and can also be subjected to water shortage (Fisher and Binkley, 2000). Moderately drained sites have no constraint on root growth or organic matter decomposition and are not subject to important nutrient leaching (Bélanger *et al.*, 1995, Wang and Klinka, 1996). This is in accordance with the present study best model parameters (Table 2.7). Except for Ung *et al.* (2001), the studies cited above were conducted on a restrained area and their observations are valid on small or medium scale models. Present study results have the particularity of being obtained on a large area with a wide climatic gradient.

Seepage is the movement of water near the soil surface, which can carry nutrients, fine texture particles and organic matter from one site to another. Many studies have noted the importance of that phenomenon on stand productivity (Bélanger *et al.*, 1995; Meades and Robert, 1992). Position on slope can be an indicator of seepage, with stands on top of slope loosing nutrients to stands down slope. A lower odd of being in the high productivity class was observed in this study for stand on top of slopes. Other factors than seepage could explain the lower productivity observed on top of slopes and well drained sites. For instance, surface deposit could be an important driver of the lower productivity observed on top of slopes since shallow deposits are more frequent there. However, when surface deposit is controlled, we can still see a significant effect of position on the slope on productivity (Table 2.9). This suggests that position on the slope have an influence on its own on productivity. This study also shows that position on the slope can be used on a large scale and adds information to a solely climatic model.

Different reasons could explain the absence of correlation between productivity and the mean sediment base cation concentrations by geologic unit. The 82 000 sediment samples distribution was not uniform throughout the province and depended upon site mining potential. Few sample points were situated in Quebec's boreal forest and many stands visited in this study were more than 100 kilometres away from the nearest sediment sample point. For this reason, interpolation of the data, a technique widely used for attributing geochemistry data to different stands (*e.g.* Lahdenperä *et al.*, 2001), is actually not possible for Quebec's boreal forest. To bypass this problem, sample points were used to assign base cation concentrations to geological units. However, the geological units were not delimited only as a function of their geochemical properties, but also by the history of their formation. Consequently, those geological units may not be an adequate proxy of soil geochemistry, and may be the reason for the weak r square observed between productivity and base cation concentrations estimated with that technique.

Management recommendations

Based on our results, different recommendations can be drawn. Position on the slope, drainage and surface deposit can be used to identify quickly a number of sites vulnerable to biomass harvesting. Before establishing guidelines and best practices, it is useful to compare the results of this study with what is done elsewhere.

Shallow soils and rock outcrop seem to be a common concern in many jurisdictions, like France (Cacot *et al.*, 2006), Scandinavia (Raulund-Rasmussen *et al.*, 2008), European Union (European Environmental Agency, 2006), Wisconsin (Wiconsin Department of Natural resources, 2008), which classified those sites as highly vulnerable to biomass extraction. This was already mentioned in an expert opinion survey (Kershaw *et al.*, 1996), where experts ranked nutrient depletion as one of the most important threat for shallow soil. Coarse texture soils and excessive drainage are often found together, and are also classified as highly vulnerable in many jurisdictions like Finland (Aijälä *et al.*, 2005) and Wisconsin (Wiconsin Department of Natural resources, 2008). Also, some jurisdictions, like Finland and the European Union, consider as highly vulnerable stands on organic soils or bogs. Those soils are characterized by a water table near the soil surface that impedes root growth and nutrient cycling and could be associated with bad drainage. In that sense, drainage is more general as it includes both bogs and waterlogged mineral soils. Finally, position on slope or seepage is not a factor present in soil vulnerability guidelines. However, the importance of seepage has been identified as an important factor in the estimation of boreal forest sustainable biomass production (Bhatti *et al.*, 1998). This study also suggests the importance of position on slope in stand productivity.

The relationship between productivity and soil vulnerability is not systematic, as some stand growth may be limited by other factors than nutrition. However, variables linked to productivity in this study could also show lower nutrient availability, as demonstrated above. Therefore, this study suggests that vulnerable stands can be identified by surface deposit, drainage and position on slope. Those variables can be easily identified by forest maps and Quebec's ecological framework (Saucier *et al.*, 1998).

Other factors could be analyzed in the future in order to improve the precision of guidelines. While our approach allows identification of poor sites based on physical characteristics, it does not provide a method to identify sites that are limited by poor parent rock chemistry. For instance, tills, which are unsorted glacial sediment deposits, constitute the main surface deposit in Quebec's boreal forest (Robitaille and Saucier, 1998). In this study, the proportion of sites on tills harboring stands in the high or low productivity group is almost the same. However, because of the importance of this deposit in Quebec's boreal forest, it would be important to refine this analysis in order to improve the model for tills. For example, a better knowledge of soil nutrient concentrations could be very useful for those medium texture deposits.

Furthermore, following Liebig's law, forest stand productivity should be correlated with base cation pools when those pools are a limiting factor (Sverdrup and Rosen, 1998). However, some stands may not show deficiencies and still be vulnerable in the long-term to WTH. In that case, the link between soil and productivity would not be apparent and those sites not be identified as vulnerable in this study. It would be important to refine our model in order to include forest sites that are negatively affected by intensive forest management, although manifestations on forest production will only be apparent in the long term.

2.6 Conclusion

Quebec's government wants to increase intensive sylviculture practices on its territory (MRNF, 2008). Simultaneously, the government set ambitious objectives for biomass harvesting (MRNF, 2009). Those major changes in forest practices will increase nutrient uptake from forests soils. Some stands will probably be immediately affected by this augmentation of nutrient exportation.

This study suggests that biomass harvesting and intensive forestry practices should be avoided on stands with excessive or imperfect drainage; situated on top of slopes; and on rock outcrop, shallow or coarse deposits. Those stands could already be submitted to a limited nutrient supply and access, and any decrease in soil fertility could be followed by a productivity decrease. Biomass harvesting on those stands is probably unsustainable.

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CONCLUSION

La durabilité de la récolte de la biomasse forestière

La récolte des résidus forestiers, en augmentant l'exportation des nutriments en dehors de l'écosystème, augmente la pression sur les sols forestiers. Il est essentiel, dans une perspective de développement durable, de s'assurer que cette récolte ne se fasse pas au détriment de la fertilité des sols à long terme. Le but de cette recherche était double :

(1) Premièrement, en explorant les mécanismes régissant la nutrition des arbres et leur croissance, cette étude visait à analyser la possibilité d'utiliser la nutrition foliaire comme indicateur de suivi de la fertilité des sols. Cet indicateur de suivi pourrait ensuite être utilisé pour suivre l'évolution de la fertilité des sols et étudier l'impact de différents types d'aménagement forestier sur les réservoirs nutritifs des sols, et ainsi, assurer la durabilité de l'aménagement.

(2) Deuxièmement, en utilisant des variables pédologiques cartographiables, cette étude visait à identifier de manière opérationnelle des sites vulnérables à l'aménagement forestier intensif, comme la récolte de la biomasse forestière. Ainsi, pour assurer un maintien de la fertilité des sols de ces sites vulnérables identifiés, ce type de récolte pourrait être exclu.

Suivi de la fertilité des sols

Pour développer un indicateur de suivi des sols basé sur la nutrition foliaire, le lien entre des variables pédologiques (CEC, $pH_{(eau)}$, cations basiques HNO_3, % de limon, % d'argile, surface spécifique et présence/absence d'un dépôt meuble de moins de 50cm) et les cations basiques (Ca, Mg et K) contenus dans les aiguilles de l'épinette blanche, l'épinette noire, le pin gris et le sapin baumier a été analysé. Chacune de ces espèces s'est avérée à avoir un profil nutritionnel distinct et le lien qui les unissait au sol variait d'une essence à l'autre. La nutrition du sapin baumier, l'épinette blanche et le pin gris répondait davantage que l'épinette noire aux variations des variables pédologiques analysées.

La capacité d'échange cationique (CEC) et le pH du sol ont démontré de plus fortes et consistantes corrélations avec la nutrition foliaire que les variables physiques du sol (texture, surface spécifique et profondeur du sol). Différentes méthodes d'analyse de la nutrition foliaire ont été comparées. Entre la concentration en nutriments des aiguilles, le contenu en nutriments dans 100 aiguilles et les ratios multivariés des concentrations (CND), la dernière méthode semble plus fortement liée à la fertilité des sols.

L'âge du peuplement, la densité et les variables climatiques ont des effets variés sur la nutrition foliaire, mais souvent faibles et limités, suggérant la possibilité d'utiliser la nutrition foliaire comme indicateur sur de larges gradients environnementaux. Des normes CND établies avec la méthode « boundary-line » indiquent que la nutrition d'une importante proportion de peuplement est déjà déficiente en calcium et potassium. Conséquemment, le suivi des réservoirs en cations basiques des sols devraient devenir un enjeu d'aménagement forestier important.

Identification des sites vulnérables

Pour identifier les sites vulnérables à la récolte de la biomasse, la productivité de plus de 400 sites, déterminée par l'indice de qualité de station (IQS), la surface terrière et la végétation indicatrice de sous-bois, a été comparée à des variables climatiques et édaphiques. Les concentrations en cations basiques du sol, estimées à l'aide de 80 000 échantillons de sédiments de lacs et rivières provenant de la prospection minière, sont faiblement corrélées à la productivité dans les modèles testés par cette étude. La position sur la pente, le drainage, le dépôt de surface, les degrés-jours et les précipitations utiles formaient le modèle le plus probable selon les « Akaike's Information Criterion » (AIC). Un peuplement sur un dépôt argileux a respectivement 6,1, 7,7 et 21,5 moins de chance qu'un peuplement sur un site à texture grossière, dépôt mince ou sur un affleurement rocheux d'être dans une classe de bonne productivité. Les sites en haut de pente, à drainage imparfait ou bon ont aussi été identifiés comme étant moins productifs. Ces différences de productivité peuvent probablement s'expliquer en partie par les faibles réservoirs nutritifs dans le sol ou un accès limité des racines à ces réservoirs. Ces résultats suggèrent que des sites vulnérables à la récolte de la biomasse forestière pourraient être facilement identifiés à l'aide de variables cartographiées comme le dépôt de surface, la position sur la pente et le drainage.

Recommandations

La relation entre la nutrition et la productivité suggère qu'une proportion non-négligeable de peuplement de la forêt boréale est carencée en Ca ou K. Ces déficiences en cations basiques, que les pluies acides ou l'aménagement forestier intensif pourraient accentuer, démontrent l'importance de surveiller l'évolution des réservoirs en cations basiques des sols.

Les indices foliaires, étant faiblement corrélés à la densité, à l'âge du peuplement ou aux variables climatiques, pourraient être utilisés sur un large gradient environnemental et à l'échelle de la forêt boréale. La relation entre le sol et la nutrition foliaire dépend de l'essence échantillonnée, de l'élément étudié et de la méthode d'analyse foliaire utilisée. Les essences pionnière et à croissance relativement rapide, comme l'épinette blanche, le sapin baumier et le pin gris, sont plus sensibles aux variations de fertilité du sol que les espèces plus conservatrices, comme l'épinette noire. Le lien entre le sol et le calcium était généralement plus fort que celui avec le Mg ou K. Finalement, les ratios multivariés (CND) étaient plus fortement corrélés avec les variables pédologiques que les concentrations ou contenus foliaires. Ces informations pourraient être utilisées pour mettre sur pied un programme de suivi de la fertilité des sols.

Cette étude suggère aussi que la récolte de résidus forestiers et la sylviculture intensive devraient être évitées sur certains sites vulnérables et sujets à une diminution de la fertilité de leur sol. Certains de ces sites peuvent être identifiés facilement grâce à des cartes écoforestières. La croissance des peuplements sur des affleurements rocheux, des sols minces ou des dépôts grossiers sont limités ou seront potentiellement limités par leur capacité d'accéder à des nutriments. Les sites en haut de pente et avec un drainage excessif ou imparfait sont aussi probablement plus vulnérables. La récolte de la biomasse pourrait y être insoutenable à long-terme.

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APPENDICE A

Relationships between soil characteristics and CND ratios. Model used are presented in Table 1.2 of chapter 1.

Relationships between soil characteristics and Ca CND ratio.

	ID	AIC	Δ_i	w_i	r^2		ID	AIC	Δ_i	w_i	r^2
Balsam fir	1	-256.28	7.93	0.00	0.17	Black spruce	1	-406.60	7.27	0.01	0.09
	2	-260.28	3.93	0.04	0.17		2	-406.95	6.93	0.01	0.06
	3	-262.27	1.94	0.10	0.17		3	-405.66	8.22	0.00	0.03
	4	-262.22	1.99	0.10	0.17		4	-408.82	5.05	0.02	0.05
	5	**-264.21**	**0.00**	**0.26**	**0.17**		5	-407.23	6.65	0.01	0.03
	6	-262.04	2.17	0.09	0.14		**6**	-405.37	8.51	0.00	0.01
	7	-263.91	0.30	0.22	0.14		7	-407.02	6.85	0.01	0.01
	8	-256.63	7.58	0.01	0.09		8	-412.08	1.80	0.10	0.08
	9	-258.52	5.69	0.01	0.09		9	-411.80	2.07	0.09	0.06
	10	-258.61	5.60	0.02	0.09		**10**	**-413.87**	**0.00**	**0.25**	**0.08**
	11	-260.50	3.71	0.04	0.09		11	-413.59	0.29	0.22	0.06
	12	-258.31	5.90	0.01	0.06		12	-408.43	5.45	0.02	0.00
	13	-260.19	4.03	0.03	0.06		13	-410.06	3.82	0.04	0.02
	14	-256.48	7.74	0.01	0.06		14	-410.25	3.63	0.04	0.05
	15	-258.37	5.84	0.01	0.06		15	-412.13	1.74	0.11	0.03
	16	-258.42	5.80	0.01	0.06		16	-408.45	5.42	0.02	0.00
	17	-260.31	3.90	0.04	0.06		17	-410.35	3.52	0.04	0.02
	18	-256.60	7.62	0.01	0.01		18	-408.24	5.64	0.02	0.00
Jack Pnie	1	-158.49	5.26	0.02	0.20	White spruce	1	-56.44	2.17	0.15	0.59
	2	-160.11	3.64	0.04	0.16		2				
	3	-158.07	5.68	0.01	0.09		3				
	4	-160.82	2.92	0.06	0.14		**4**	**-58.61**	**0.00**	**0.43**	**0.55**
	5	-158.70	5.05	0.02	0.07		5	-54.38	4.23	0.05	0.37
	6	-159.95	3.79	0.04	0.10		6				
	7	-160.49	3.26	0.05	0.07		7	-56.19	2.42	0.13	0.36
	8	-159.76	3.99	0.03	0.13		8				
	9	-160.06	3.69	0.04	0.10		9				
	10	-161.28	2.47	0.07	0.12		10	-56.26	2.35	0.13	0.43
	11	-161.76	1.99	0.09	0.09		11	-51.63	6.98	0.01	0.19
	12	-162.04	1.70	0.11	0.10		12				
	13	**-163.75**	**0.00**	**0.25**	**0.09**		13	-53.56	5.04	0.03	0.19
	14	-160.02	3.73	0.04	0.10		14				
	15	-160.89	2.85	0.06	0.08		15	-54.72	3.89	0.06	0.31
	16	-157.79	5.96	0.01	0.02		16				
	17	-158.69	5.06	0.02	0.00		17	-49.71	8.89	0.01	0.00
	18	-159.68	4.07	0.03	0.02		18				

Model ID refers to Table 1.2, AIC is the Akaike's Information Criterion, Δ_i is the delta AIC, w_i is the Akaike weight, and r^2 is the r square from multiple linear regressions. All sampled white spruce where on surface deposits deeper than 50 centimetres, and so, models that included soil depth were not tested with this specie.

Relationships between soil characteristics and Mg CND ratio.

Species	ID	AIC	Δ_i	w_i	r^2	Species	ID	AIC	Δ_i	w_i	r^2
Balsam fir	1	-230.57	8.92	0.00	0.05	Black spruce	1	-501.05	4.62	0.03	0.13
	2	-234.26	5.23	0.01	0.05		2	-501.70	3.98	0.04	0.10
	3	-236.02	3.47	0.03	0.05		3	-503.68	2.00	0.11	0.10
	4	-235.29	4.20	0.02	0.04		4	-499.03	6.65	0.01	0.07
	5	-237.05	2.44	0.05	0.03		5	-501.02	4.66	0.03	0.07
	6	-237.32	2.17	0.05	0.04		**6**	**-505.68**	**0.00**	**0.29**	**0.10**
	7	-238.21	1.28	0.08	0.02		7	-503.00	2.68	0.08	0.07
	8	-234.18	5.31	0.01	0.02		8	-501.97	3.71	0.05	0.09
	9	-236.03	3.46	0.03	0.02		9	-503.56	2.12	0.10	0.09
	10	-235.25	4.24	0.02	0.01		10	-499.36	6.32	0.01	0.06
	11	-237.10	2.39	0.05	0.00		11	-500.93	4.75	0.03	0.05
	12	-238.01	1.48	0.08	0.02		12	-499.22	6.46	0.01	0.04
	13	-239.09	0.40	0.13	0.00		13	-496.55	9.13	0.00	0.00
	14	-235.98	3.51	0.03	0.02		14	-501.93	3.75	0.05	0.08
	15	-237.13	2.36	0.05	0.00		15	-498.43	7.24	0.01	0.03
	16	-237.84	1.65	0.07	0.02		16	-503.69	1.99	0.11	0.07
	17	-238.99	0.50	0.13	0.00		17	-500.21	5.46	0.02	0.03
	18	**-239.49**	**0.00**	**0.16**	**0.01**		18	-500.95	4.73	0.03	0.04
Jack Pnie	1	-211.52	9.09	0.00	0.08	White spruce	1	-60.38	3.06	0.07	0.39
	2	-215.30	5.31	0.01	0.08		2				
	3	-216.81	3.80	0.03	0.07		3				
	4	-215.63	4.99	0.02	0.05		**4**	**-63.44**	**0.00**	**0.32**	**0.36**
	5	-217.13	3.48	0.04	0.04		5	-59.83	3.60	0.05	0.14
	6	-218.57	2.04	0.07	0.07		6				
	7	-218.88	1.74	0.08	0.04		7	-61.58	1.86	0.13	0.13
	8	-215.76	4.85	0.02	0.05		8				
	9	-216.82	3.79	0.03	0.04		9				
	10	-216.18	4.43	0.02	0.02		10	-59.98	3.46	0.06	0.15
	11	-217.26	3.36	0.04	0.01		11	-59.19	4.25	0.04	0.02
	12	-218.80	1.81	0.08	0.04		12				
	13	-219.23	1.38	0.10	0.01		13	-61.02	2.41	0.10	0.01
	14	-217.63	2.98	0.05	0.05		14				
	15	-217.92	2.69	0.05	0.02		15	-61.95	1.49	0.15	0.15
	16	-218.63	1.98	0.07	0.03		16				
	17	-218.92	1.70	0.09	0.00		17	-60.88	2.56	0.09	0.00
	18	**-220.61**	**0.00**	**0.20**	**0.03**		18				

Model ID refers to Table 1.2, AIC is the Akaike's Information Criterion, Δ_i is the delta AIC, w_i is the Akaike weight, and r^2 is the r square from multiple linear regressions.

Relationships between soil characteristics and K CND ratio.

	ID	AIC	Δ_i	w_i	r^2		ID	AIC	Δ_i	w_i	r^2
	1	-277.07	6.72	0.00	0.10		1	-447.91	5.87	0.01	0.07
	2	-280.83	2.96	0.03	0.10		2	-451.46	2.32	0.06	0.07
	3	-282.83	0.96	0.08	0.10		3	-450.90	2.88	0.04	0.05
	4	-281.80	1.99	0.05	0.09		4	-452.72	1.06	0.11	0.06
	5	**-283.79**	**0.00**	**0.12**	**0.09**		5	-452.23	1.55	0.08	0.04
	6	-282.68	1.11	0.07	0.07		6	-452.25	1.53	0.08	0.04
	7	-283.55	0.24	0.11	0.06		**7**	**-453.78**	**0.00**	**0.18**	**0.04**
Balsam fir	8	-279.36	4.43	0.01	0.05	Black spruce	8	-448.71	5.07	0.01	0.03
	9	-281.02	2.77	0.03	0.05		9	-448.36	5.42	0.01	0.01
	10	-280.09	3.70	0.02	0.03		10	-450.65	3.13	0.04	0.03
	11	-281.76	2.03	0.04	0.03		11	-450.27	3.51	0.03	0.01
	12	-281.37	2.42	0.04	0.02		12	-450.34	3.44	0.03	0.01
	13	-282.14	1.65	0.05	0.01		13	-452.25	1.53	0.08	0.01
	14	-280.82	2.97	0.03	0.04		14	-449.87	3.90	0.03	0.02
	15	-281.80	1.99	0.05	0.03		15	-451.69	2.09	0.06	0.02
	16	-282.52	1.27	0.07	0.04		16	-449.79	3.99	0.02	0.01
	17	-283.50	0.29	0.11	0.03		17	-451.61	2.17	0.06	0.00
	18	-283.29	0.50	0.10	0.02		18	-451.37	2.41	0.05	0.00
	1	-234.94	6.83	0.01	0.27		1	-52.00	7.78	0.01	0.36
	2	-237.71	4.06	0.05	0.25		2				
	3	-239.36	2.41	0.10	0.24		3				
	4	-239.27	2.50	0.10	0.24		4	-55.96	3.82	0.08	0.36
	5	-240.94	0.84	0.23	0.24		5	-51.76	8.02	0.01	0.11
	6	-240.29	1.48	0.16	0.23		6				
	7	**-241.77**	**0.00**	**0.34**	**0.22**		7	-52.50	7.28	0.01	0.05
Jack Pnie	8	-225.86	15.9	0.00	0.03	White spruce	8				
	9	-227.55	14.2	0.00	0.02		9				
	10	-227.66	14.1	0.00	0.02		10	-57.82	1.95	0.21	0.35
	11	-229.36	12.4	0.00	0.02		11	-54.15	5.62	0.03	0.02
	12	-229.01	12.8	0.00	0.01		12				
	13	-230.82	11.0	0.00	0.01		13	-54.18	5.60	0.03	0.03
	14	-227.21	14.6	0.00	0.01		14				
	15	-229.00	12.8	0.00	0.01		**15**	**-59.77**	**0.00**	**0.57**	**0.27**
	16	-228.99	12.8	0.00	0.01		16				
	17	-230.79	11.1	0.00	0.01		17	-53.66	6.12	0.03	0.00
	18	-230.52	11.3	0.00	0.00		18				

Model ID refers to Table 1.2, AIC is the Akaike's Information Criterion, Δ_i is the delta AIC, w_i is the Akaike weight, and r^2 is the r square from multiple linear regressions.