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EFFETS DE LA FERTILISATION LOCALISÉE SUR LA CROISSANCE ET LA NUTRITION DE PEUPLIERS HYBRIDES EN ABITIBI-TÉMISCAMINGUE

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RÉSUMÉ

Deux dispositifs ont été établis en 2003 en milieu agricole et forestier afin d'étudier l'effet de différentes combinaisons de fertilisants (N-P-K) ainsi qu'à différents types d'entretien mécanique de la végétation compétitive sur la croissance de trois clones de peupliers hybrides (*Populus spp.*; PEH). La capacité des méthodes DRIS (Diagnosis and Recommandation Integrated System) et du ratio N:P foliaire à prédire les besoins en fertilisants a également été évaluée sur les arbres non-fertilisés. De plus, douze PEH ont été déracinés délicatement à l'aide de truelles afin de caractériser le développement racinaire des PEH suite à la fertilisation phosphatée. Les résultats après deux saisons de croissance montrent que la fertilisation en P a été la plus bénéfique sur la croissance en volume des arbres, en l'augmentant en moyenne de 63 % par rapport aux arbres non-fertilisés. Une application modérée de N et de P a généralement procuré les meilleurs taux de croissance lors de la première année, mais l'effet de N n'était plus significatif lors de la deuxième année. Le diagnostic nutritionnel à l'aide des ratios N :P s'est avéré relativement fiable lorsque la croissance était fortement liée à la disponibilité relative de ces 2 éléments, comme pour la plantation établie sur ancienne friche agricole. Cependant, la méthode DRIS a mieux prédit les besoins nutritionnels des plants parce qu'elle permet l'intégration de plusieurs ratios d'éléments nutritifs susceptibles d'influencer la croissance des plants analysés. Les trois types d'entretien mécanique pratiqués lors des deux premières années n'ont pas engendrés de différences significatives dans la croissance des plants. L'analyse de l'allocation de la biomasse a révélé que la fertilisation en P ne modifie pas le rapport de la masse des racines sur la masse de la tige (ratio racines/tige), mais elle permet une augmentation de la masse totale des arbres de l'ordre de 68 % lorsque le drainage est modéré.

CHAPITRE 1 : INTRODUCTION GÉNÉRALE

La nécessité de diminuer la pression de la récolte de bois en forêt naturelle s'illustre bien au Québec par la volonté d'appliquer à plus grande échelle un type d'aménagement « écosystémique » de la forêt et d'augmenter la superficie des aires protégées. Ce nouveau virage forestier que vit actuellement le Québec, devra cependant mener à la fois à l'atteinte d'objectifs de protection des écosystèmes forestiers et à la production ligneuse en qualité et en quantité suffisante afin d'assurer la viabilité des usines de transformation de la province. Ainsi, le Québec doit se doter d'une politique de rendement accru sur une portion du territoire située à proximité des usines de transformation. Cette nouvelle politique permettrait d'approvisionner les usines de façon continue et rentable tout en diminuant la pression de coupe sur la majorité du territoire existant.

La ligniculture, c'est à dire la culture intensive d'arbres à croissance rapide sur courtes rotations, est une des approches de rendement accru pouvant augmenter le volume de bois disponible le plus rapidement pour une superficie donnée. Le peuplier hybride (*Populus spp.* ci-après PEH) est l'essence la plus productive en terme de volume sur courte rotation en Amérique du Nord. Cependant, les expériences passées ont montré que la croissance du PEH est directement liée à l'intensité de culture, la fertilité du site et les conditions climatiques présentes. Bien que la région de l'Abitibi-Témiscamingue se situe au cœur de l'industrie forestière du Québec, les pratiques sylvicoles n'ont pas encore été développées pour y pratiquer la ligniculture. La nature compacte des sols et les conditions climatiques rigoureuses qui prévalent dans cette région peuvent être source de difficultés face à leur installation rapide après la mise en terre.

Les dépôts d'argile lourde représentent plus de 70% du territoire agricole de l'Abitibi (Rompré et Carrier 1997) et sont, par conséquent, le type de dépôt le plus susceptible à être reboisé en PEH. La texture fine de ces dépôts peut cependant causer des conditions difficiles à l'établissement des plants si le sol n'est pas travaillé correctement. En effet, les dépôts limono-argileux créés par les lacs proglaciaires Barlow et Objiway (Veillette *et al.* 2000), ainsi que leur mauvaise structure résultant des activités agricoles passées, peuvent limiter l'enracinement des plants. De plus, même si les sols sont bien pourvus en éléments nutritifs, ces derniers risquent de ne pas être disponibles pour les plants, compte tenu de la capacité limitée du système racinaire à exploiter pleinement le sol (Kozlowski et Pallardy 1997; Leroy 1969). Les sols à texture fine peuvent également occasionner des problèmes de soulèvement des plants lors des gelées automnales s'il n'y a pas eu un enracinement suffisant lors de la première saison de croissance. Finalement, les sols à texture argileuse prennent plus de temps à se réchauffer au printemps (Camiré et Brazeau 1998), et il a été démontré que la température froide du sol avait pour effet de retarder la croissance du peuplier (Landhäusser *et al.* 2001).

Certains milieux forestiers mal régénérés de la forêt boréale peuvent également constituer une alternative pour la ligniculture. Cependant, les sites mal régénérés après coupe indiquent souvent de mauvaises conditions édaphiques pour la croissance des plants. Les sols forestiers pourraient s'avérer avantageux pour la croissance des PEH, car ils ont l'avantage de posséder une meilleure structure que les sols des friches agricoles, dû à la proportion plus forte de matière organique déposée chaque année sur le sol et à l'absence de pratiques agricoles (Havlin *et al.* 1999). Cependant, afin de préserver l'intégrité des écosystèmes, les stations forestières productives et bien régénérées ne devraient pas être converties en des plantations monospécifiques. Ainsi, le déploiement des sites de ligniculture sur le territoire public québécois devrait se faire uniquement sur des stations présentant une régénération en essences désirées (commerciales) insuffisantes, mais possédant tout de même un bon de potentiel de croissance pour le PEH.

La survie et la croissance des PEH lors des premières années après leur mise en terre dépendent de la facilité avec laquelle ils développent un bon système racinaire. Cette période d'installation consiste essentiellement en la mise en place d'un enracinement capable d'alimenter efficacement le plant en eau et en minéraux. Au cours de cette étape, la croissance en hauteur est réduite et la croissance en diamètre est faible (Soulères 1995 *dans* Sirois 2001). La durée de la phase d'installation varie selon le clone, le milieu et l'intensité de la culture.

1.1 La fertilisation

Il est reconnu que les variétés de peuplier hybride répondent bien à la fertilisation (Ménétrier et Vallée 1980; van den Driessche 1999a, b; Brown and van den Driessche 2002). Il a d'ailleurs été démontré en Europe que les PEH réagissaient très bien à la fertilisation dans les sols d'argile lourde, même si ces sols sont généralement riches en éléments nutritifs (Leroy 1969). Bien que la quantité ou la forme d'engrais ont des effets sur la croissance, la localisation et la disponibilité de l'élément voulu au moment le plus opportun est tout aussi important : Le phosphore (P), pour le démarrage de la plantation et ensuite l'azote (N) pour la croissance (Ménétrier et Vallée 1980). La croissance de la plupart des clones de PEH semble être directement reliée à la disponibilité de N et P dans le sol, tel que démontré par différents tests de fertilisation (Barnéoud *et al.* 1979; Blackmon 1976, 1977b; Garbaye 1980; Ménétrier et Vallée 1980; van den Driessche 1999). Il n'est pas recommandé de fertiliser en plein champ les trois premières années, car c'est généralement la végétation compétitive qui profite de l'apport de fertilisants (Staples *et al.* 1999). Cette méthode a pour effet d'augmenter le nombre d'entretiens requis afin de limiter la croissance des herbacées. La fertilisation par pied d'arbre, au moment de la plantation peut quant à elle améliorer l'établissement des plants en maximisant les taux de croissance dès la première année, sans pour autant stimuler la croissance de la végétation compétitive (van den Driessche 1999). Rappelons que si la faible croissance initiale des PEH ne permet pas à la canopée de se fermer rapidement, l'ensoleillement favorise les herbacées qui ralentissent alors davantage la croissance des plants (van Oosten 2001).

L'habileté des plantes à extraire des sources ponctuelles de fertilisants explique pourquoi les traitements localisés procurent une meilleure croissance que les applications faites à la surface du sol (Caldwell 1980). Des études sur la nutrition des plantes vasculaires ont montré qu'une proportion de seulement 10 % du système racinaire pouvait maintenir la croissance d'un plant grâce à un apport suffisant en minéraux (Burns 1980). Ainsi, un test de fertilisation localisée dans une plantation de PEH a été établi sur l'île de Vancouver afin de vérifier l'impact de la méthode d'application (localisée *vs* en plein). Cette étude a démontré que le prélèvement de N et P par kilogramme de nutriments ajoutés était environ 10 fois plus élevé en traitement localisé comparativement au traitement à la surface du sol (van den Driessche 1999).

1.2 Le contrôle de la végétation compétitive

Il est bien connu qu'un contrôle rigoureux des herbacées effectué entre les rangs de peupliers hybrides favorise la croissance de ces derniers (Schroeder *et al.* 2003; Thomas *et al.* 2000b; Barnéoud *et al.* 1982; Dickmann *et al.* 2001). Des études nord-américaines ont d'ailleurs déjà démontré que l'entretien rigoureux des plantations de PEH lors de la deuxième année de croissance produisait le même gain de croissance qu'une application d'azote de 224 Kg/ha (Baker and Blackmon 1978). Leroy (1969) a démontré que le seul fauchage de la flore herbacée fait disparaître la carence en K et améliore la nutrition azotée sur un site argileux compact. Cependant, d'autres études (Thomas *et al.* 2000a; Dickmann *et al.* 2001) montrent qu'il est préférable de pratiquer des techniques d'entretien qui éradiquent les racines des herbacées comme le hersage ou le binage du sol, car le fauchage tend à augmenter la densité des racines des herbacées, qui puiseront à nouveau les minéraux du sol et formeront une couche isolante gardant les sols froids.

Les pratiques courantes de suppression de la végétation compétitive dans les plantations de PEH au Québec se font généralement avec un hersage dans un sens uniquement. En effet, les plants sont généralement bien espacés entre les rangées, mais ne le sont pas au niveau de la rangée elle-même, ce qui complique le passage de la machinerie dans les deux sens. Une étude portant sur les modèles d'entretien a mis en évidence que la végétation laissée entre les plants de PEH lors de l'entretien des rangées, même si la végétation compétitive est complètement retirée entre les rangées, ralentit significativement la croissance des PEH (Thomas et al. 2000b). Ainsi, le binage du sol entre et autour des arbres, grâce à un équipement spécialisé (Weed Badger™) pourrait avoir des effets bénéfiques sur la croissance des PEH. Cet appareil, grâce à son bras articulé, permet d'éliminer la végétation ne pouvant être éliminée par les méthodes conventionnelles d'entretien mécanique (par ex. une herse tirée par un tracteur).

Finalement, mentionnons que les entretiens mécaniques sont plus dispendieux que les applications d'herbicides. Il est plus facile d'obtenir un meilleur contrôle des herbacées à long terme avec les produits chimiques, mais lorsque fait de la bonne façon et au moment opportun, les entretiens mécaniques peuvent donner de meilleurs résultats de croissance sur les PEH (van den Driessche 1999 b). Hansen *et al.* (1986) ont d'ailleurs démontré que l'accumulation des débris végétaux au sol, causée par les applications d'herbicides, offrait un abri hivernal aux rongeurs et augmentait ainsi la proportion d'arbres pouvant être rongée.

Il existe un climat continental frais et modérément humide en Abitibi-Témiscamingue. Les étés sont chauds et humides, mais la période sans gel est relativement courte, d'où l'importance de maximiser les interventions sylvicoles lors de cette période. Selon les normales climatiques entre 1971 et 2000 établies par Environnement Canada, on retrouve environ 1450 degrés jours de croissance (>5°C) en Abitibi-Témiscamingue. L'accumulation des précipitations sous forme de pluie totalise 680 mm par an.

Le chapitre 2 de ce mémoire traite des expériences réalisées sur la fertilisation en traitement localisé dans le sol appliquée au moment de la mise en terre des plants de PEH. Cette expérience visait à identifier quelle combinaison de N-P-K selon différentes doses stimulerait le plus fortement la croissance des PEH suite à leur mise en terre. Ensuite, nous avons évalué deux techniques de diagnostics foliaires (DRIS et ratio N:P) appliquées sur les arbres non-fertilisés afin de voir si ces techniques permettent de prédire efficacement les besoins en éléments nutritifs des plants. En plus des traitements de fertilisation, nous avons utilisé trois traitements d'entretien mécanique de la végétation compétitive afin de voir s'ils entraineraient des réponses différentes dans la croissance des plants. Les trois techniques d'entretien utilisées étaient (1) le passage simple de la herse, (2) le passage croisé de la herse et (3) l'utilisation du Weed Badger^{TM} combiné au passage simple de la herse. Toutes ces techniques d'entretien on été répétées deux fois par an pendant les deux premières années de croissance. Cependant, faute de différences significatives entre les techniques d'entretien, cet aspect de la recherche n'est pas abordé dans le chapitre 2, mais une brève description des observations faites lors des opérations est présentée dans la conclusion générale de ce mémoire.

Dans le troisième chapitre nous examinons l'effet de la fertilisation en P sur la biomasse souterraine et aérienne de PEH âgés de 2 ans qui ont été reboisés sur un sol à texture d'argile lourde et un autre à texture de loam sableux. Plus spécifiquement, le but de cette expérience était de vérifier si l'application de 50 g/arbre de P en traitement localisé modifiait le ratio de la masse des racines sur la masse de la tige des plants après deux saisons de croissance.

CHAPITRE 2 : GROWTH AND NUTRITION OF HYBRID POPLARS FERTILIZED AT PLANTING IN THE BOREAL FOREST OF WESTERN QUÉBEC

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2.1 Abstract

In order to maximize growth and diagnose nutritional requirements of hybrid poplars (*Populus spp.*) grown in the boreal forest zone of Western Quebec, the Diagnosis and Recommendation Integrated System (DRIS) was evaluated in conjunction with N:P ratios of trees growing in two young plantations. Three hybrid poplar clones (747210; *P. balsamifera x trichocarpa*, 915005; *P. balsamifera x maximowiczii,* and 915319; *P. maximowiczii x balsamifera*) were fertilized at planting with 18 combinations of nitrogen (N), phosphorus (P) and potassium (K). Fertilizers used were granules of ammonium nitrate (34.5-0-0) at 3 levels (0, 20 and 40 g/tree of N), triple-superphosphate (0-45-0) at 3 levels (0, 25 and 50 g/tree of P), and potassium sulfate (0-0-50) at 2 levels (0, 20 g/tree of K). After two growing seasons, P fertilization was the most effective in promoting growth and increased mean stem volume by 63% compared to unfertilized trees. The combination of a moderate level of N and P fertilizers generally resulted in highest yield during first year, but the effect of N was not persistent throughout the second year. Nutritional diagnosis with N:P ratios was relatively reliable when growth was strongly related to these two nutrients, as we found at the farmland site. The DRIS method generally predicted nutrient requirements adequately, but relative proportions of nutrients needed did not always match growth responses to fertilization.

2.2 Résumé

Afin de maximiser la croissance et de prédire les besoins nutritionnels du peuplier hybride (*Populus spp.)* planté dans la zone boréale de l'ouest du Québec, nous avons évalué la méthode DRIS (Diagnosis and Recommendation Integrated System) et comparé les ratios N:P de deux jeunes plantations. Trois clones de peupliers hybrides (747210; *P. balsamifera x trichocarpa*, 915005; *P. balsamifera x maximowiczii*, et 915319; *P. maximowiczii x balsamifera*) ont été fertilisés au moment de la plantation avec 18 combinaisons d'azote (N), de phosphore (P) et de potassium (K). Les fertilisants utilisés étaient le nitrate d'ammonium (34.5-0-0) selon 3 niveaux (0, 20 et 40 g/arbre de N), le triple-superphosphate (0-45-0) selon 3 niveaux (0, 25 et 50 g/arbre de P), et le sulfate de potassium (0-0-50) selon 2 niveaux (0 et 20 g /arbre de K). Au terme de l'étude de 2 ans, la fertilisation en P a été la plus bénéfique sur la croissance en volume des arbres, en l'augmentant en moyenne de 63 % par rapport aux arbres non-fertilisés. Une application modérée de N et de P a généralement procuré les meilleurs taux de croissance lors de la première année, mais l'effet de N n'était plus significatif lors de la deuxième année. Le diagnostic nutritionnel à l'aide des ratios N :P s'est avéré relativement fiable lorsque la croissance était fortement liée à la disponibilité relative de ces 2 éléments, comme pour la plantation établie sur ancienne friche agricole. La méthode DRIS a généralement bien prédit les besoins nutritionnels lors de la première année de croissance, mais la proportion relative des éléments prescrits par DRIS ne concordait pas toujours aux gains de croissance obtenus suite à la fertilisation.

2.3 Introduction

Hybrid poplar (*Populus spp.*) plantations are economically attractive to the forest industry because of their fast growing rates and high yield potential. The decrease of wood supplies in native forests due, in part, to competing land uses and to more sustainable management practices, will accentuate the need to manage more intensively some portions of the available land. However, many operationally-established hybrid poplar plantations do not meet expected volume productivity, often because of a lack of maintenance during the establishment phase. Growing poplars in plantations is challenging, and good establishment the first year is critical to long-term success (Stanturf et al. 2001).

One option to improve plantation establishment and early growth across a wide range of site conditions is fertilization at planting. Hybrid poplars have high nutrient requirements (Brown and van den Driessche 2002), and they have been shown to respond well to fertilization (Blackmon 1977; Ménétrier and Vallée 1980; Sheedy 1982; van den Driessche 1999a, b; Brown and van den Driessche 2002). Usually, fertilizers are added as broadcast applications just before canopy closure of plantations, because it corresponds to the nutrient peak demand of the trees (Hansen 1994). Placed fertilization at planting, however, requires lesser amounts of fertilizer per hectare than broadcast techniques, since the contact area between the fertilizer and the soil particles is reduced, which limits adsorption processes and increases fertilization efficiency (Baldock and Burgess 1995). Another advantage of fertilization at planting is that it accelerates the installation period of trees so they are likely to be more resistant in case of a sudden drought or others stressing events. Moreover, placed fertilization limits nutrient uptake by weeds compared to a broadcast application, and this is particularly important since weeds are known to severely reduce hybrid poplar growth (Thomas et al. 2001).

Nitrogen (N) is generally the most limiting nutrient in poplar plantations (Blackmon 1976, 1977; Garbaye 1980, Ménétrier and Vallée 1980, Barnéoud *et al.* 1982; van den Driessche 1999a). However, phosphorus (P) fertilization is reputed to promote growth when it is applied at earlier stages of growth (Chapin et al. 1983; Zwart and Baldock 1996; van den Driessche 2003; Liang and Chang 2004; Brown and van den Driessche 2005). Potassium (K), applied with P and N, may also reduce mortality rate by increasing resistance to diseases (Leroy 1969).

When fertilizing, it is crucial to seek optimal nutritional balance and avoid fertilizing in excess of one nutrient for maximum productivity (Ingestad 1974, 1986). Ratios of nutrient concentrations are thus often better indicators of nutrient deficiencies than are single nutrient concentrations (Jones 1981, Walworth and Sumner 1987). Additionally, ratios of elements are less affected by sampling procedures, and they remain more constant with plant ageing (Walworth and Sumner 1987).

The boreal region has a long daily photoperiod during summer but a short growing season. Intensive short rotation forestry in boreal regions thus commonly relies on the use of fertilizers to achieve high productivity (Weih 2004), but also to correct possible soil nutrient deficiencies. No previous study has dealt with fertilizer requirements of hybrid poplars planted in the boreal regions of eastern Canada. The first objective of this study was therefore to assess the potential of placed fertilization at planting to increase early growth of hybrid poplar in this region. Secondly, we wanted to determine if it was possible to match tree responses to fertilizers with two diagnosis methods using foliar nutrient concentration ratios: (1) N:P ratios (Koerselman and Meuleman 1996) and (2) the Diagnosis and Recommendation Integrated System (DRIS) (Beaufils 1973). The first method focuses on N and P, with the rationale that these two elements govern a large part of the growth and that plant species have critical N:P ratios indicating whether the plant is N or P limited (Koerselman and Meuleman 1996). The second method goes further in the analysis and takes into account all pairs of nutrients susceptible to affect plant growth. The DRIS method can thus be viewed as a modified regression technique that uses boundary line conditions of an incomplete set of independent variables to describe the dependant variable, yield (Walworth and Sumner 1987). The average ratio of foliar nutrient concentrations of a random selection of faster growing trees becomes the norm or the 'field standards', by which growth performance of the slower growing trees is judged (Leech and Kim 1981). In this study, preliminary field standards are proposed for three hybrid poplar clones and their use is evaluated on unfertilized trees of two plantations.

2.4 Materials and Methods

2.4.1 Study sites

Two hybrid poplar plantations were established in spring 2003 in the region of Abitibi-Témiscamingue, Québec, Canada. The first plantation was established on an abandoned farmland site near the locality of Amos (48° 35' N, 78° 05' W), which is part of the western balsam fir-paper birch (*Abies balsamea* - *Betula papyrifera*) bioclimatic domain (Grondin 1996). This site is part of the clay belt of Quebec and Ontario resulting from deposits left by the proglacial Lakes Barlow and Ojibway (Vincent and Hardy 1977). The soil texture is a heavy clay Gray Luvisol (Canada Soil Survey Committee 1987). The average number of degree-days above 5° C for the region range from 1215 to 1450 and has had a yearly rainfall between 610 to 680 mm for the last three decades (Environment Canada 2004). No agricultural activity had been done on this site for the last 25 years. The site was dominated by grasses and a few patches of alder (*Alnus incana* ssp. *rugosa*), willow (*Salix spp.)* and trembling aspen (*Populus tremuloides* Michx.). The second plantation was established on a previously forested site located near to the locality of Rollet (47° 92' N, 79° 18' W) and is part of western balsam fir – yellow birch (*Betula* *alleghaniensis*) bioclimatic domain (Grondin 1996). This site was previously dominated by a trembling aspen forest which was commercially harvested in 2000. Its soil type is classified as a Humo-Ferrique Podzol with a sandy-loam soil texture (Agriculture Canada Expert Committee on Soil Survey 1987).

The planting sites were ploughed to a depth of 30 cm in the fall of 2002, followed by disking in the spring of 2003 to level the soil and incorporate organic matter to mineral soil as well as to remove the remaining stumps and logs. The trees were planted in the first week of June at the farmland site and in the first week of July at the forest site. Dormant, bare-root hybrid poplar trees of approximately 1.5 m in height (table 2.1) were planted 30 cm deep at a 3 x 3 m spacing. Three locally-produced clones from the Quebec Ministry of Natural Resources were used: 747210 (*P. balsamifera x trichocarpa*), 915005 (*P. balsamifera x maximowiczii*) and 915319 (*P. maximowiczii x balsamifera*). The fertilizers were applied according to a 3N x 3P x 2K factorial design within each of the three hybrid poplar clones (split plot). The clones were randomized and replicated into 3 blocks. The treatment unit was two trees of one clone (n = 324 per site). Fertilizers used were granules of ammonium nitrate (34.5-0-0) at 3 levels (0, 20 and 40 g/tree; equivalent to 0, 22 and 44 Kg/Ha), triple-superphosphate (0-45-0) at 3 levels (0, 25 and 50 g/tree; equivalent to 0, 28 and 56 Kg/Ha), and potassium sulfate (0-0-50) at 2 levels (0 and 20 g/tree). The fertilizers were applied at planting by inserting the granules into a spade slit made at 15 cm from the trees to a depth of about 15 cm. Vegetation control was done twice a year (end of June and August) by cross-cultivating the plantations using a farm tractor.

Table 2.1: Mean basal diameter, stem height and stem dieback of each clone at planting and after each growing season. Values with the same letter in a line within each site are not significantly different at $p < 0.05$.

	Farmland Site			**Forest Site**		
Clone	747210	915005	915319	747210	915005	915319
At planting						
Basal diameter (mm)	9.59a	11.43b	9.62a	9.10a	11.44b	9.65ab
Height (cm)	133.54a	170.85c	152.48b	128.49a	168.43b	152.29ab
Stem dieback (cm)	9.51a	20.45b	85.26c	11.72a	12.13a	38.43a
After the first growing season						
Basal diameter (mm)	16.58b	16.81b	12.71a	14.25a	15.64a	13.17a
Height (cm)	143.83b	163.85c	92.16a	127.48a	163.98a	125.94a
After the second growing season						
Basal diameter (mm)	26.81b	27.91b	20.67a	25.08a	26.14a	22.63a
Height (cm)	175.13b	196.88b	141.44a	164.20a	190.34a	173.45a

Soils were sampled at 0-20 and 20-40 cm depth in each site before planting. Samples were air-dried, sieved with a 2-mm screen, and analyzed for particle size distribution using a pipette. The pH of each sample was determined from a 1:40 dilution after a 1h agitation (Conseil des Productions Végétales du Québec 1988). Available phosphorus (P) was determined using the Mehlich-III method (Mehlich 1985). Exchangeable potassium, calcium and magnesium (K, Ca and Mg) were extracted with $BaCl_2$-NH_4Cl (Amacher and al. 1990) and their contents were determined by inductively coupled plasma (ICP; Perkin Elmer plasma model 40). Soils analyses from both sites are presented in table 2.2. Basal diameter and height of trees were measured right after planting and at the end of the first and second growing seasons. Stem volumes (V) were estimated as:

[1] $$V = ba * h/3$$

where ba = basal area and h = height (Brown and van den Driessche *2005*). Bud formation was examined at the end of the first growing season, while observations on bud burst was done at the beginning of the second growing season and characterized according to the Quebec Ministry of Natural Resource method (Gagnon et al. 1991).

Table 2.2 : Mean soil characteristics for the farmland and forest sites.

	Site			
Variable	Farmland		Forest	
Depth (cm)	0-20	20-40	0-20	20-40
Texture	Heavy clay		Sandy loam	
pH ($CaCl_2$)	4.36	4.82	4.25	4.60
N (%)	0.14	0.02	0.12	0.03
C.O. (%)	2.38	0.53	2.45	0.75
S.B. (%)	83.97	96.57	39.58	47.50
CEC (cmol(+) kg^{-1})	6.69	9.79	2.60	0.74
K (mg kg^{-1})	133.64	114.66	70.82	24.04
Na (mg kg^{-1})	19.72	31.33	5.28	3.41
Ca (mg kg^{-1})	559.57	939.21	105.63	37.63
Mg (mg kg^{-1})	226.11	492.37	19.89	8.90
P (mg kg^{-1})	8.87	12.87	21.98	13.74
Al (mg kg^{-1})	1225.35	970.16	1955.02	1913.41

2.4.2 Foliar analysis

Foliar samples were collected in mid-august of each growing season. Overall 1620 leaves were collected on fully expanded leaves located in the upper part of trees as follow: 15 leaves (on 2 trees) x 18 fertilizer treatments x 3 clones x 2 repetitions. We grouped 2 repetitions together in order to decrease analyses costs. Leaves were then air-dried at constant weight, ground and digested in a solution of sulphuric acid (H_2SO_4), peroxide (H_2O_2) and selenium catalyser (Se) (Parkinson and Allen 1975). N was calibrated by flow injection analysis (FIA), while P, K, Ca and Mg were also digested in a solution of H_2SO_4-H_2O_2-Se and then determined by ICP analysis (Perkin Elmer plasma model 40). N and P foliar concentrations were used to calculate N:P ratios of each tree from the nine possible combinations between N and P fertilizers for the first and second growing seasons. Others fertilizer combinations were not included as K may affect uptake of N and P. Calculated N:P ratios of each clone were compared to some critical N:P ratios found in the literature (Koerselman and Meuleman 1996; Tessier and Raynal 2003; Güeswell 2004).

The field standards for N, P, K, Ca and Mg presented in this study consist of foliar nutrient concentrations and ratios of the 18 best growing trees (high yielding groups) of each clone independently of treatments. The cut-off limit between the fast and the slow growing groups was 75 % of maximal yield (Needham et al. 1990). The high yielding groups were equally composed from trees located at both sites in order to alleviate bias due to specific soil conditions on a site and to encompass a greater range of foliar nutrients data. One DRIS formula per clone (table 2.3) was necessary to give accurate diagnostic because clones showed different optimum nutrients ratios and different growth responses to fertilizers (Annex 4). Hence, three DRIS norms (table 2.4) are presented to evaluate their efficiency in detecting nutrient imbalances of first-year unfertilized trees. Of the three possible nutrients ratios (e.g. N/P, P/N or N*P) used to express growth performance, the one with the highest variance between the fast and the slow growing groups of trees was chosen because it also maximizes the chances to detect a nutritional imbalance. In our case, no product (multiplication) ratio resulted in the highest variance between the two groups.

Table 2.3: DRIS formulas determined by the variance of nutrient ratios between the fast and the slow growing groups of each hybrid poplar clone.

clone	DRIS formulas
747210	N index = [+ f (N/P) + f (N/K) – f (Ca/N) + f (N/Mg)] / 4
	P index = [- f (N/P) – f (K/P) + f (P/Ca) + f (P/Mg)] / 4
	K index = [- f (N/K) + f (K/P) + f (K/Ca) + f (K/Mg)] / 4
	Ca index = [+ f (Ca/N) – f (P/Ca) – f (K/Ca) + f (Ca/Mg)] / 4
	Mg index = [- f (N/Mg) – f (P/Mg) – f (K/Mg) – f (Ca/Mg)] / 4
915005	N index = [- f (P/N) - f (K/N) + f (N/Ca) + f (N/Mg)] / 4
	P index = [+ f (P/N) + f (P/K) + f (P/Ca) + f (P/Mg)] / 4
	K index = [+ f (K/N) - f (P/K) - f (Ca/K) - f (Mg/K)] / 4
	Ca index = [- f (N/Ca) – f (P/Ca) + f (Ca/K) - f (Mg/Ca)] / 4
	Mg index = [- f (N/Mg) – f (P/Mg) + f (Mg/K) + f (Mg/Ca)] / 4
915319	N index = [+ f (N/P) - f (K/N) + f (N/Ca) + f (N/Mg)] / 4
	P index = [- f (N/P) + f (P/K) - f (Ca/P) - f (Mg/P)] / 4
	K index = [+ f (K/N) - f (P/K) - f (Ca/K) + f (K/Mg)] / 4
	Ca index = [- f (N/Ca) + f (Ca/P) + f (Ca/K) + f (Ca/Mg)] / 4
	Mg index = [- f (N/Mg) + f (Mg/P) – f (K/Mg) – f (Ca/Mg)] / 4

Data was analyzed by an analysis of variance (ANOVA) using the general linear models and mixed procedures of SAS (SAS 8.3, SAS Institute Inc. 1999). Stem volume datasets were analyzed separately by clone to satisfy assumptions of homogeneity of variances. Growth measurements of clone 915319 were log transformed to homogenize the variance. There were some significant stem volumes differences at planting, so tree volume at planting was included as a covariate in the analysis. Least squares means were compared using Fisher's Protected LSD. A significance level of $p \leq 0.05$ was chosen.

Table 2.4: DRIS norms and coefficients of variation (CV) for each clone. The means represent average nutrients ratios of first year high-yielding trees located at both sites.

Clone 747210			**Clone 915005**			**Clone 915319**		
	Mean	CV (%)		Mean	CV (%)		Mean	CV (%)
N (%)	2.027	14.51	**N (%)**	1.811	17.14	**N (%)**	2.226	12.97
P (%)	0.127	12.85	**P (%)**	0.105	13.59	**P (%)**	0.136	17.94
K (%)	1.338	17.51	**K (%)**	1.349	13.78	**K (%)**	1.648	17.61
Ca (%)	0.386	21.83	**Ca (%)**	0.444	16.82	**Ca (%)**	0.545	22.32
Mg (%)	0.187	31.91	**Mg (%)**	0.171	26.67	**Mg (%)**	0.202	31.91
N/P	16.17	18.25	**P/N**	0.06	25.41	**N/P**	16.83	20.10
N/K	1.58	27.63	**K/N**	0.77	26.92	**K/N**	0.75	21.80
K/P	10.62	18.46	**P/K**	0.08	18.98	**P/K**	0.09	27.86
Ca/N	0.19	22.51	**N/Ca**	4.16	19.85	**N/Ca**	4.25	20.95
P/Ca	0.34	19.85	**P/Ca**	0.24	21.20	**Ca/P**	4.04	18.19
K/Ca	3.67	32.15	**Ca/K**	0.34	24.80	**Ca/K**	0.35	34.28
N/Mg	11.76	30.03	**N/Mg**	11.10	23.64	**N/Mg**	12.16	32.59
P/Mg	0.75	31.73	**P/Mg**	0.66	30.20	**Mg/P**	1.48	25.62
K/Mg	8.18	43.99	**Mg/K**	0.13	36.72	**K/Mg**	9.32	44.10
Ca/Mg	2.16	16.34	**Mg/Ca**	0.38	18.76	**Ca/Mg**	2.82	20.26

2.5 Results

2.5.1 Growth response to fertilizers

Clones

At planting, trees from clone 915005 had the greatest height and basal diameter (Table 2.1). Trees from all three clones showed some stem dieback shortly after planting, particularly those of clone 915319 which lost more than half their length at the farmland site and a quarter of their length at the forest site (Table 2.1). Over all fertilizer treatments, trees from clone 915005 were the tallest after the first growing season even though they had the least height growth during that season (Table 2.1). Over the two year period, trees from clone 747210 had the greatest basal diameter growth while those from clone 915319 had the greatest height growth (Table 2.1). None of the fertilizer treatments delayed fall bud formation on any of the three studied clones. Bud burst happened within one week around May 10th for all clones and did not vary among the fertilizer treatments. Mean survival of clones 747210 and 915005 after 2 years was 98 % at both sites. Mean survival was only 84% for clone 915319, mostly due to poor stock quality.

Clone 747210

At the farmland site, stem volume was increased by 48 % and 41 % in the N20 ($p < 0.001$) and P25 ($p < 0.001$) treatments, respectively, after the first year (Fig. 2.1 a,b). Trees in the N40 and P50 treatments were also significantly bigger than the control, but had similar stem volumes than the moderate fertilizer levels. After the second growing season, trees in the P25 or in the P50 treatment had 67% more stem volume than the unfertilized trees ($p < 0.001$; fig. 2.1d), while the effect of N fertilization was no longer significant ($p = 0.18$; fig. 2.1c). First year stem volume

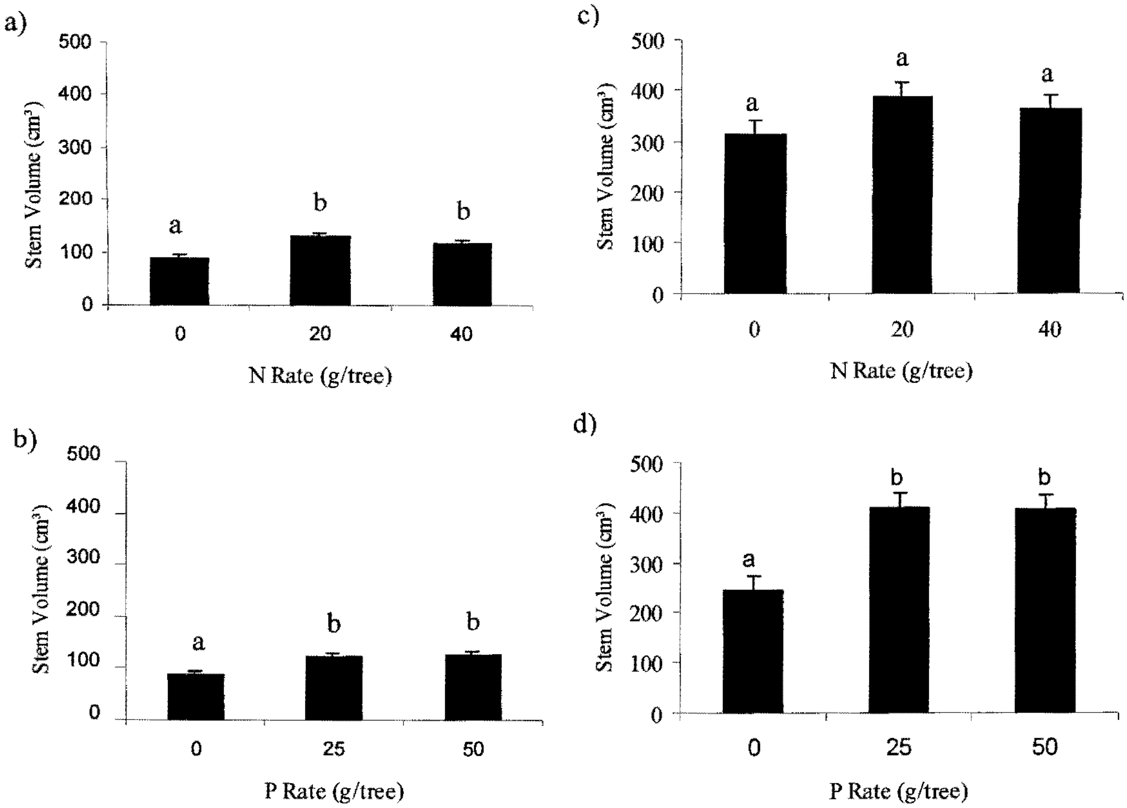

Figure 2.1: Mean stem volume of clone 747210 grown at the farmland site for each a) N and b) P fertilization level after the first growing season, and for each c) N and d) P fertilization level after the second growing season. Error bars are SEs. Bars with the same letters are not significantly different at $p < 0.05$.

also increased with N and P fertilization at the forest site, however this increase was smaller than at the farmland site with 30 % and 20 % greater stem volume in the N20 ($p = 0.001$) and P25 ($p = 0.04$) treatments, respectively (Fig. 2.2 a,b). Again, the effect of N on stem volume was no longer significant after the second growing season at the forest site ($p = 0.09$; fig. 2.2c) while trees in the P25 treatment had 41 % more stem volume ($p = 0.03$; fig. 2.2d). At both sites, the addition of more P (P50 treatment) or more N (N40 treatment) did not produce further increases in stem volume. Potassium did not have a significant effect on stem volume over the 2-year period, however it slightly increased first year stem height ($p = 0.02$; not shown).

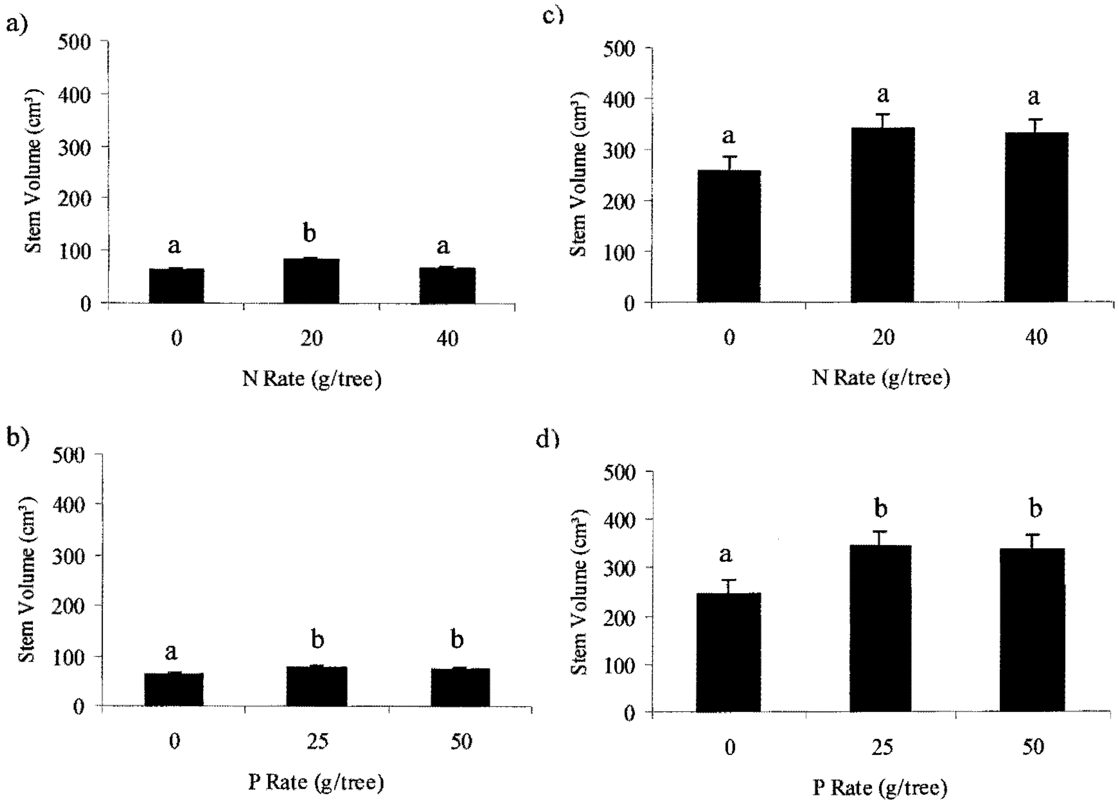

Figure 2.2: Mean stem volume of clone 747210 grown at the forest site for each a) N and b) P fertilization level after the first growing season, and for each c) N and d) P fertilization level after the second growing season. Error bars are SEs. Bars with the same letters are not significantly different at $p < 0.05$.

Clone 915005

First-year volume growth of this clone at the farmland site was promoted from the interaction between N and P ($p = 0.045$). The N20-P50 combination produced the greatest volume growth, with a 57 % increase above the control (Fig. 2.3). Fertilization with N or P separately did not significantly increase first year stem volume (Fig. 2.3). After the second growing season, trees in the P25 treatment reached 63 % greater stem volumes than the control ($p < 0.001$; fig. 2.4). Trees in the N treatments (N20 or N40) had similar stem volumes than unfertilized trees after two years ($p = 0.09$). Potassium did not significantly affect first or second-year stem volume at the farmland site. At the forest site, the P25 and P50 treatments produced a 28 % increase in stem volume after one growing season ($p < 0.001$; fig. 2.5a) and a 50 % increase after two growing seasons ($p = 0.01$; fig. 2.5b). N fertilization alone did not improve first year volume growth at the forest site ($p= 0.36$), but there was a significant interaction between N and K levels on second-year stem volume which increased by 46 % when K was added to the high N level.

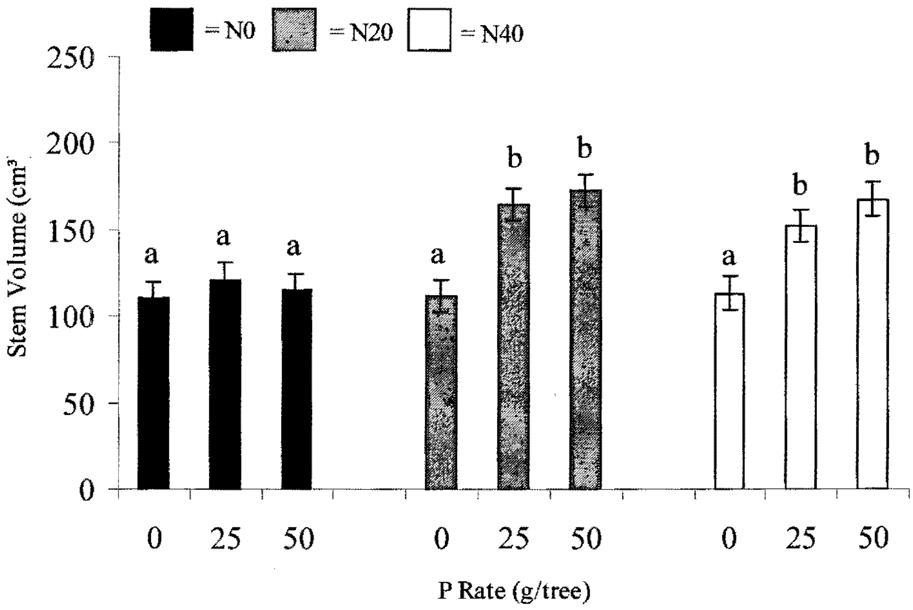

Figure 2.3: Mean stem volume of clone 915005 for each N and P fertilization level combinations after the first growing season, at the farmland site. Error bars are SEs. Bars with the same letters are not significantly different at $p < 0.05$.

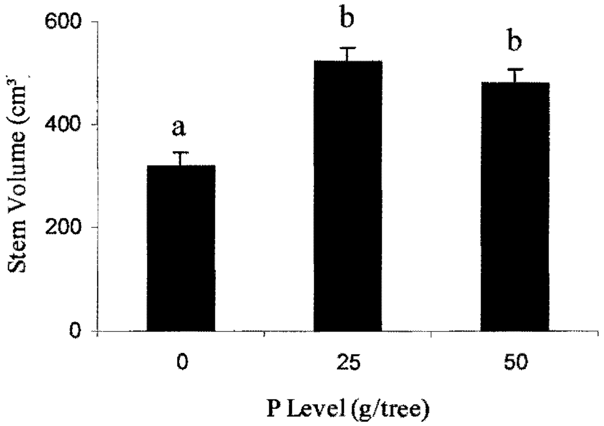

Figure 2.4: Mean stem volume response of clone 915005 to P fertilization at the farmland site after two growing seasons. Error bars are SEs. Bars with the same letters are not significantly different at $p < 0.05$.

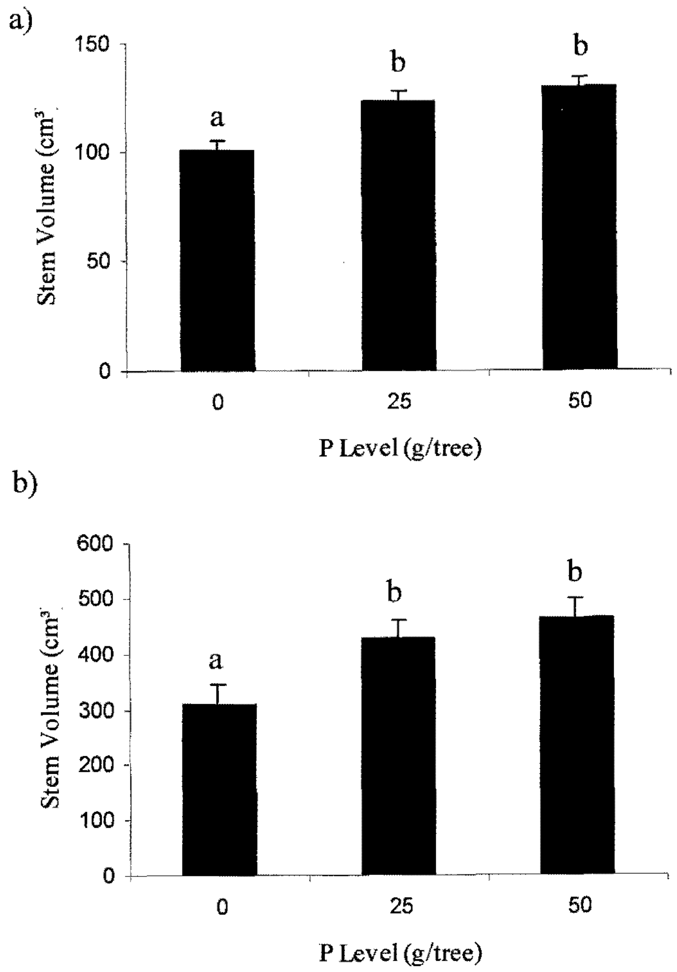

Figure 2.5: Mean stem volume response of clone 915005 to P fertilization at the forest site after a) the first and b) the second growing seasons. Error bars are SEs. Bars with the same letters are not significantly different at $p < 0.05$.

Clone 915319

Similarly to clone 747210, the N20 and P25 fertilization treatments increased first year stem volume by 41% ($p = 0.01$; fig. 2.6 a) and 51 % ($p = 0.001$; fig. 2.6 b), respectively, at the farmland site. The higher doses of N or P produced a similar volume increases than the moderate doses. After two growing seasons, only P fertilization still had a significant effect on stem volume, where a 95 % increase was reached in the P25 treatment above the control ($p = 0.01$; fig. 2.6 c,d). At the forest site, growth of trees was increased by the interaction between N and P during the first growing season ($p = 0.02$). Stem volume was increased by 66 % in the N20-P50 treatment, compared to the control, while trees that had received N or P separately had similar stem volumes than the unfertilized trees. After the second growing season, stem volume was 69 % greater for trees in the N20 treatment at the forest site compared to the control ($p = 0.02$; fig. 2.7a). The P25 and P50 treatments resulted in an average 59 % stem volume increase compared to the control after two years (fig. 2.7b). Potassium fertilization did not significantly affect stem volume of this clone after one or two growing seasons, on both sites.

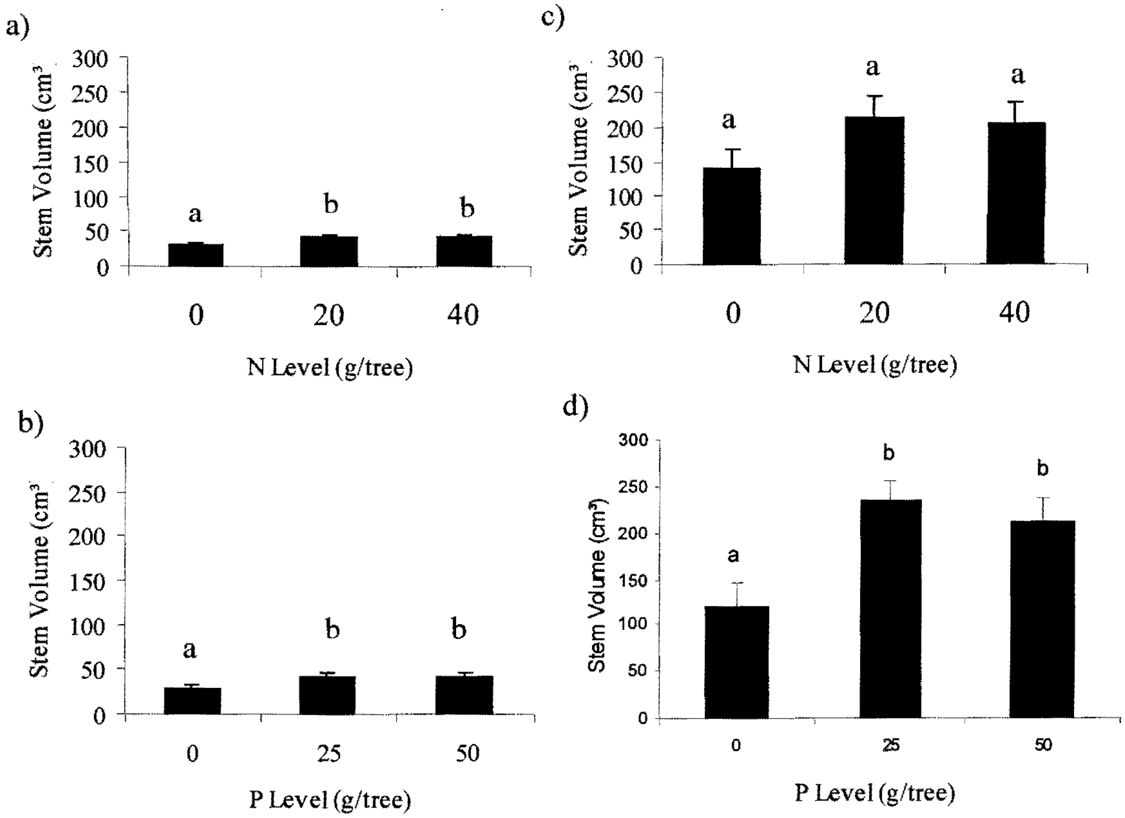

Figure 2.6: Mean stem volume of clone 915319 grown at the farmland site for each a) N and b) P fertilization level after the first growing season, and for each c) N and d) P fertilization level after the second growing season. Error bars are SEs. Bars with the same letters are not significantly different at $p < 0.05$.

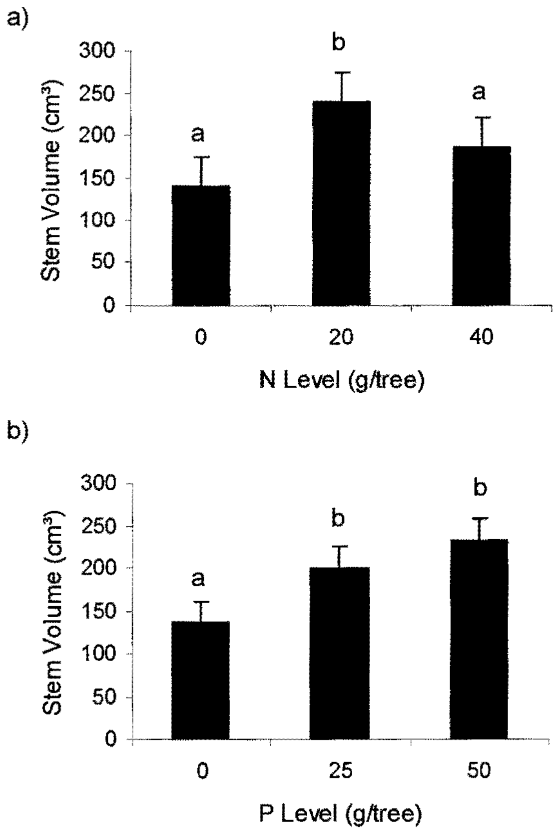

Figure 2.7: Mean stem volume of clone 915319 for each a) N and b) P fertilization levels, after two growing seasons at the forest site. Error bars are SEs. Bars with the same letters are not significantly different at $p < 0.05$.

2.5.2 N:P ratios

Mean first-year foliar N:P ratios of unfertilized trees planted at the farmland site were 18 and 17 for clones 747210 and 915005, respectively, while it was only 13 for clone 915319 (fig. 2.8 a,b,c). At the forest site, trees from clone 747210 had mean foliar N:P ratios of 13 during the first year (fig. 2.8 d), while clones 915005 and 915319 had N:P ratios of 17 and 16, respectively (fig. 2.8 e,f). Addition of N at planting resulted in increased N:P ratios, while P fertilization resulted in decreased ratios.

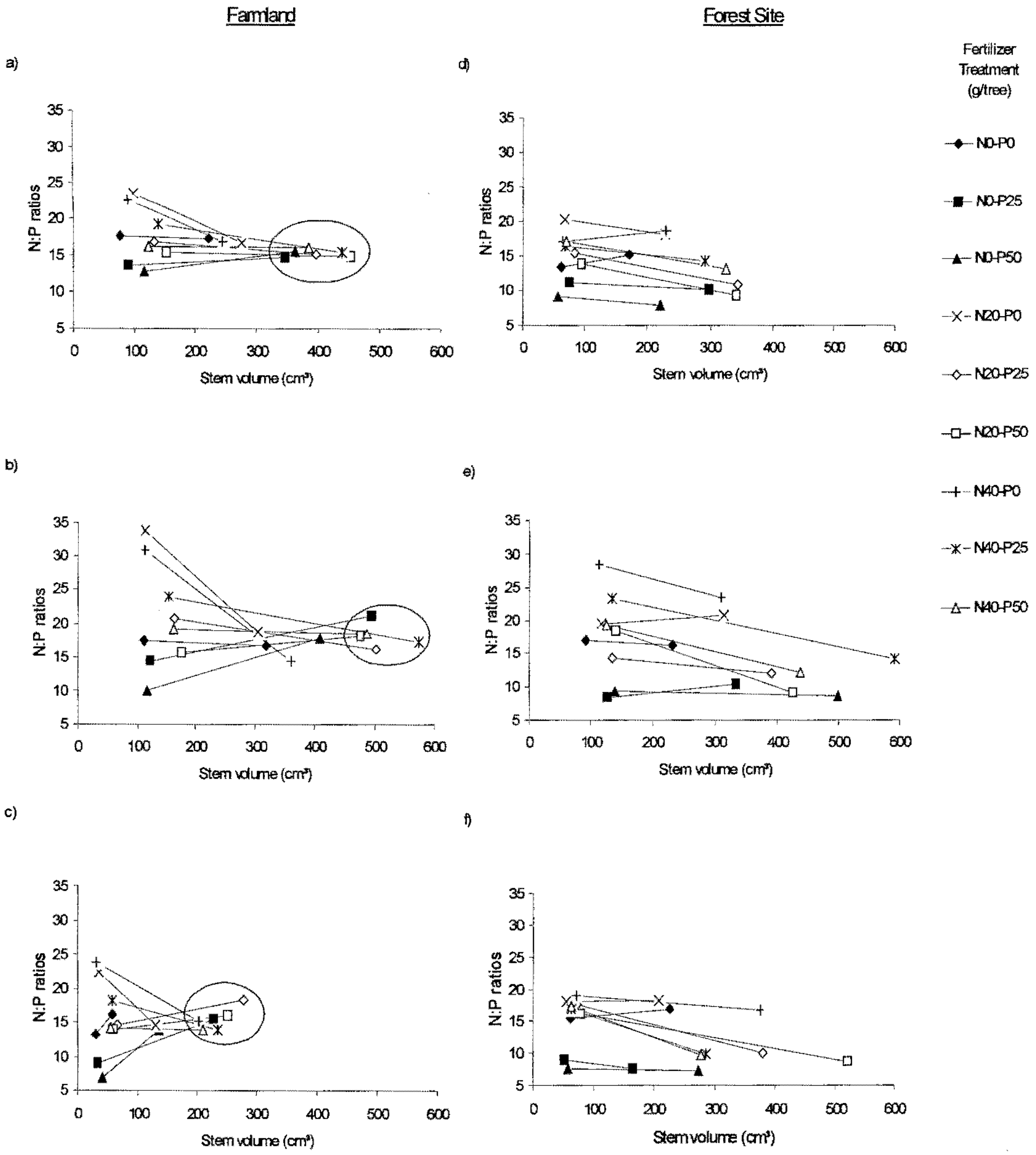

Figure 2.8: Relationship between foliar N:P ratios and first and second year stem volume for each N and P fertilization level combinations and for each clone: a) 747210 at the farmland site, d) 747210 at the forest site, b) 915005 at the farmland site and e) 915005 at the forest site c) 915319 at the farmland site and f) 915319 at the forest site. Each line represents the evolution in N:P ratios from the first year to the second year. Circles around symbols at the farmland site represent fertilization treatments not significantly different at $p < 0.05$.

The optimal ranges of N:P ratios, i.e. the N:P ratios at which the trees had the greatest volume growth over the study period, ranged from 15-16 for clone 747210, 16-21 for clone 915005 and 14-18 for clone 915319 at the farmland site after 2 growing seasons (Fig. 2.8 a,b,c). Ranges of optimal N:P ratios were greater at the forest site, ranging 8-18 for clone 747210, 9-14 for clone 915005 and 7-17 for clone 915319 (Fig. 2.8 d,e,f). Also, N:P ratios of trees grown at the forest site generally decreased between the first and the second growing seasons.

2.5.3 DRIS indices

DRIS indices obtained for trees planted at the farmland site showed that N was the most limiting nutrient for growth of clones 915005 and 915319, while P was most limiting for clone 747210 (Table 2.5). At this site, magnesium (Mg) was the nutrient with the highest positive imbalance for all clones (Table 2.5). A slight K deficiency in relation to others nutrients was also observed for each clone located on this site. At the forest site, the DRIS indices showed a deficiency in N for all clones and, to a lesser extent, P and Mg deficiencies (table 2.5). K and Ca were found to be in supra-optimal conditions for all clones grown at the forest site.

Table 2.5: DRIS indices of first year unfertilized hybrid poplar clones calculated from field standards.

	Farmland Site					Forest Site				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg
Clone 747210	- 5	- 13	- 3	+ 4	+ 17	- 19	- 4	+ 10	+ 15	- 2
Clone 915005	- 22	- 11	- 5	+ 14	+ 24	- 12	- 7	+ 14	+ 9	- 4
Clone 915319	- 30	- 1	- 1	+ 11	+ 21	- 17	- 12	+ 30	+ 4	- 5

2.6 Discussion

Placed fertilization at planting successfully increased early growth of all hybrid poplar clones used in this study. At the farmland site, the greatest stem volume growth responses after the first growing season were obtained with N or P fertilization separately for clones 915319 and 747210 or in combination, for clone 915005 (Figs. 2.1, 2.3 and 2.6). Unfertilized trees of clones 747210 and 915005 had similar N:P ratios of about 17 (Fig. 2.8 a,b). This corresponded to a N and P co-limitation, but more so P than N, as reflected by the growth response of these two clones to the fertilizers (Figs. 2.1 and 2.3). Unfertilized trees from clone 915319 had lower N:P ratios than the other clones (Fig 2.8c), suggesting that growth of this clone was more limited by N (Koerselman and Meuleman 1996; Tessier and Raynald 2003). However, its growth response to P fertilization was slightly greater than to N fertilization (Fig. 2.6). In this case, low N:P ratios did not exactly reflect a nutrient limitation but was rather a result of poor stock quality; trees from clone 915319 had significant stem dieback at planting (Table 2.1), which resulted in lost nutrients and stimulated height growth to restore root-to-shoot ratios. In fact, their N:P ratios increased to similar levels to the other clones during the second growing season, reflecting more accurately the nutrient requirements of this clone.

The unimodal graphical display of N:P foliar ratios at the farmland site (Fig. 2.8 a,b,c), indicates that maximal biomass production was obtained at critical or optimal N:P ratios (Güeswell 2004). The ranges of optimal N:P ratios varied among clones and sites, but there was a general trend showing that maximal growth was reached around a mean N:P ratio of 16.5 for all clones on both sites as defined by our DRIS norms (table 2.4). Based on our results, a N:P ratio between 13 and 18 would indicate a co-limitation by N and P, but a greater N deficiency within the lower part of this range and a greater P deficiency within the upper part of this range.

Critical concentrations of foliar nutrients are often used alone to diagnose the nutritional state of trees (Weetman and Wells 1990). In our study, these critical concentrations would not have been useful since all clones had foliar N and P concentrations far below the levels found in the literature for *Populus spp.* (Blackmon 1977; McLennan 1996; Camiré and Brazeau 1998; van den Driessche 1999). Hansen (1994) also reported that clones with *P. trichocarpa* or *P. maximowiczii* parentage may have low level of foliar N and still have adequate nutrition. However, critical concentrations used in conjunction with their ratio allow a better diagnosis accuracy, since trees with N and P concentrations below critical levels could have the same N:P ratio as trees with optimal concentrations. Moreover, foliar nutrient concentrations can also markedly change as trees age (Walworth and Sumner 1987), hence the benefit of using them along with their ratios.

Clones generally responded similarly to fertilizers at the forest site; however, the growth increases were smaller than at the farmland site. Even if differing soil conditions may have played a role (Table 2.2), it is probably also due to the fact that they were planted one month later in the season and thus had a shorter period of time to benefit from the fertilization. On this site, unfertilized trees of clone 747210 had lower N:P ratios than at the farmland site (Fig 2.8), suggesting a greater deficiency in N at the forest site. This diagnosis corresponded well to the DRIS indices that showed a greater negative imbalance for N (Table 2.5), and to the growth response of this clone to N fertilization (Fig. 2.2a).

First year growth of clone 915319, which had a N:P ratio of 16, increased with N and P fertilization, while growth of clone 915005, which had a ratio of 17, only responded to P fertilization (Fig. 2.5). These results agree with critical N:P ratios proposed by Koerselman and Meuleman (1996), as clone 915005 had N:P ratios > 16 corresponding to a P limitation, and clone 915319 had N:P ratios = 16 corresponding to a N and P co-limitation. However, second-year stem volume of clone 915005 also benefited from the interaction between N and K (Fig. 2.6), showing the importance of considering that nutrients other that N or P may be limiting. The greater ranges of optimal N:P ratios obtained at the forest site showed that the N:P ratio method alone would not have been useful to give an accurate diagnosis of N or P limitations. These greater ranges in critical N:P ratios suggest that elements other than N or P were limiting tree growth on this site. There may have been some Mg deficiencies, as suggested by the DRIS indices (Table 2.5). However, this seems unlikely because the high foliar Mg concentrations of trees planted at the farmland site accentuated the Mg deficiency diagnosed by the DRIS indices for trees located at the forest site, since high-yielding trees of both sites are included into our DRIS norms. When we used standards developed for poplar D38 (*Populus deltoïdes* Marsh.) in a greenhouse trial by Leech and Kim (1981) to diagnose the nutrition state of our clones, no Mg deficiencies were then detected. In order to alleviate this problem of diagnosis when site conditions differ, a greater spectrum of site conditions should be included into the DRIS calculations for a specific clone. The main limitation of the DRIS method with forest crops is often the lack of foliar nutrient concentration data for high-yielding populations from which to derive the field standards (Weetman and Wells 1990).

The general decrease in N:P ratios between the first and the second growing season at the forest site reflects an increase in P and a decrease in N uptake, perhaps because of the longer lasting effect of P fertilization or possibly because of the higher available soil P concentration on this site (table 2.2). Optimal or critical N:P ratios can vary widely for different types of ecosystems, with lower ratios for upland vegetation compared to wetland vegetation (Tessier and Raynald 2003). In their literature review on critical N:P ratios, Tessier and Raynal (2003) report critical N:P ratios around 11 for upland vegetation, and that higher ratios would indicate limitations in P only. Our growth results, however, clearly show that trees were limited by both N and P with N:P ratios around 16.5.

Soil available P was low at both sites (Table 2.2), in comparison with suggested minimum concentrations of 37 $mg \cdot kg^{-1}$ for optimal hybrid poplar growth (van den Driessche 2000). This is probably why P fertilization was so important in increasing growth of all clones. However, the moderate level of triple superphosphate (25 kg ha^{-1} of P) was in most cases sufficient to maximize tree growth. P applied at planting was still increasing growth during the second year, while N was probably leached or exhausted during the previous year (Hauck 1968).

2.7 Conclusion

Placed fertilization at planting was an effective management tool to improve early growth of hybrid poplar plantations established on heavy clay and sandy loam textured soils typical of the region. A moderate application of 25 g/tree of P fertilizer increased stem volume by an average of 63 % over the 2-year period. This study showed that it is possible to get a certain predictive accuracy with N:P ratios when N and P were mainly limiting, but should be used in conjunction with critical foliar nutrient concentration to maximize reliability. Because it considers more nutrient ratios, the DRIS method has better predictive accuracy, especially when nutrients other than N or P are limiting. The use of a larger spectrum of high-yielding trees of each hybrid poplar clone growing at different sites across the region will refine the DRIS field standards and result in better nutrition diagnoses and fertilization recommendations.

2.8 Acknowledgements

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2.9 References

Agriculture Canada Expert Committee on Soil Survey. 1987. *In*: The Canadian System of Soil Classification. 2nd edition. Publication 1646. Research Branch, Agriculture Canada, Ottawa, Ontario, 164 p.

Amacher, M.C., Henserson R.E., Breithaupt, M.D., Seale, C.L., and LaBauve, J.M. 1990. Unbuffered and buffered salt methods for exchangeable cations and effective cation-exchange capacity. Soil Sci. Soc. Am. J. **54**:1036-1042.

Baldock, J.A., and Burgess, D. 1995. Influence of fertilizer placement and form of nitrogen on the growth of hybrid poplar at a site in Eastern Ontario. *In*: Karau J. (Compiler) Proc. Can. Energy Plantation Workshop, Gananoque, ON, pp. 67-71.

Barnéoud, C., Bonduelle, P., and Dubois, J.M. 1982. Manuel de Populiculture. AFOCEL, Nangis, Paris, 319 p.

Beaufils, E.R. 1973. Diagnosis and Recommendation Integrated System (DRIS). University of Natal, South Africa. Soil Sci. Bull. No. 1, 132 p.

Blackmon, B.G. 1976. Response of *Aigeiros* poplars to soil amelioration. *In*: Proc. Symp. Eastern Cottonwood and Related Species. Greenville, MS. *Edited* by B.A. Thielges and S.B. Land Jr., pp. 344-358.

Blackmon, B.G. 1977. Effects of fertilizer nitrogen on tree growth, foliar nutrient and herbage in eastern cottonwood plantations. Soil Sci. Soc. Am. J. **41**:992-995.

Brown, K.R., and van den Driessche, R. 2002. Growth and nutrition of hybrid poplars over 3 years after fertilization at planting. Can. J. For. Res. **32**:226-232.

Brown, K.R. and van den Driessche, R. 2005. Effects of nitrogen and phosphorus fertilization on the growth and nutrition of hybrid poplars on Vancouver Island. New For. **29**:89-104.

Camiré, C., and Brazeau, M. 1998. Culture des genres *Populus* et *Larix* au Québec: sols, exigences nutritionnelles et productivité. Report presented to the Min. Res. Nat., Qc., 115 p.

Chapin, F.S., Tryon, P.R., and Van Cleve, K. 1983. Influence of phosphorus on growth and biomass distribution of Alaskan taiga tree seedlings. Can. J. for. Res. **13**:1092-1098.

Conseil des Productions Végétales du Québec. 1988. Méthodes d'analyse des sols, des fumiers et des tissus végétaux. Commission des sols, section méthodologie. Québec (Canada). AGDEX, 533 p.

Environment Canada. 2004. Canadian climate normals or averages 1971-2000. *Available at*: http://www.climate.weatheroffice.ec.gc.ca

Gagnon, H., Numainville, G., and Robert, D. 1991. Instructions pour la collecte informatisée des données dans les dispositifs. Service de l'amélioration des arbres, Ministère des Forêts, Québec, 26 p.

Garbaye, J. 1980. Nutrition minérale et production des peupliers « Robusta » et « I-214 » en populiculture traditionnelle dans le nord du bassin parisien. Ann. Sci. For. **37**:159-172.

Grondin, P. 1996. Écologie forestière. *In* : Manuel de foresterie. Presses de l'Université Laval, Québec, pp.135-279.

Güeswell, S. 2004. N:P ratios in terrestrial plants: variation and functional significance. Tansley review. New Phytol. **164**:243-266.

Hansen, E.A. 1994. A guide for determining when to fertilize hybrid poplar plantations. USDA For. Ser., North Central For. Exp. Sta.., Res. Pap. NC-319, 7 p.

Hauck, R.D. 1968. Forest Fertilization: theory and practice. Papers presented at the Symposium on Forest Fertilization. Gainesville, Florida, pp. 46-57.

Ingestad, T. 1974. Towards optimum fertilization. Ambio. **3**:49-54.

Ingestad, T. and Lund, A.B. 1986. Theory and techniques for steady state mineral nutrition and growth of plants. Scand. J. For. Res. **1**:439-453.

Jones, C.A. 1981. Proposed modifications of the diagnosis and recommendation integrated system (DRIS) for interpreting plant analyses. Commun. Soil Sci. Plant. Anal. **12**:785-794.

Koerselman, W., and Meuleman, A.F.M. 1996. The vegetation N:P ratio: a new tool to detect the nature of nutrient limitation. J. App. Ecol. **33**:1441-1450.

Leech, R.H., and Kim, Y.T. 1981. Foliar analysis and DRIS as a guide to fertilizer amendments in poplar plantations. For. Chron. **57**:17-21.

Leroy, P. 1969. Résultats précoces d'essais de fertilisation du peuplier sur sols à Gley dans la Meuse. Am. Sci. Forest. **26**:301-319.

Liang, H., and Chang, S.X. 2004. Response of trembling aspen and hybrid aspens to phosphorus and sulfur fertilization in a Gray Luvisol: growth and nutrient uptake. Can. J. For. Res. **34**:1391-1399.

McLennan, D.S. 1996. The nature of nutrient limitation in black cottonwood stands in south coastal British Columbia. *In* Ecology and Management of B.C. Hardwoods. Eds. Comeau, P.G., Harper, G.J., Blache, M.E., Boateng, J.O., and Thomas, K.D. B.C. Min. Forests, FRDA Rept. **225**:89-111.

Mehlich, A. 1985. Mehlich 3 soil extractant: a modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. **15**:1409-1416.

Ménétrier, J., and Vallée, G. 1980. Recherche et développement sur le peuplier. XVI. Résultats d'essai de quarante traitements de fertilisation d'une plantation de boutures. Min. Énergie et Ressources, Serv. Rech., Québec, Mémoire 57, 42 p.

Needham, T.D., Burger, J.A., and Oderwald, R.G. 1990. Relationship between diagnosis and recommendation integrated system (DRIS) optima and foliar nutrient critical levels. Soil Sci. Soc. Am. J. **54**:883-886.

Parkinson, J.A., and Allen, S.E. 1975. A wet oxidation procedure suitable for the determination of nitrogen and mineral nutrients in biological material. Commun. Soil Sci. Plant Anal. **6**:1-11.

Rompré, M. and Carrier, D. 1997. Étude pédologique des sols défrichés de l'Abitibi-Témiscamingue. Centre de recherche et d'expérimentation en sols. Min. Agri. Pêches et Aliment., Qc, 133 p.

SAS 8.3, SAS Institute Inc. 1999. Cary, NC.

Sheedy, G. 1982. Recherche et développement sur le peuplier XIX- Résultats de quinze traitements de fertilisation sur des plançons de deux clones de peuplier hybride. Service de la recherche, Min. Energie Ress., Mémoire no. 75, 35 p.

Stanturf, J.A., van Oosten, C., Netzer, D.A., Coleman, M.D., and Portwood, C.J. 2001. Ecology and silviculture of poplar plantions. *In* Poplar Culture in North

America. Part A, Chapter 5. *Edited by* D.I. Dickmann, J.G. Isebrands, J.E. Eckenwalder, and J. Richardson. NRC Research Press, National Research Council of Canada, Ottawa, ON. pp. 153-206.

Tessier, J.T., and Raynal D.Y. 2003. Use of nitrogen to phosphorus ratios in plant tissue as an indicator of nutrient limitation and nitrogen saturation. J. App. Ecol. **40**:523-534.

Thomas, K.D., Reid, W.J., and Comeau, P.G. 2001. Vegetation management using polyethylene mulch mats and glyphosate herbicide in a coastal British Columbia hybrid poplar plantation: four-year growth response. West. J. App. For. **16**:26-30.

van den Driessche, R. 1999a. First-year growth response of four *Populus trichocarpa x Populus deltoides* clones to fertilizer placement and level. Can. J. For. Res. **29**:554-562.

van den Driessche, R. 1999b. Nutrition of poplars with special reference to aspen. *Report presented to* Al.-Pac. For. Ind., 58 p.

van den Driessche, R. 2000. Phosphorus, copper and zinc supply levels influence growth and nutrition of a young *Populus trichocarpa* (Torr. & Gray) x *P. deltoides* (Bartr. Ex Marsh.) hybrid. New For. **19**:143-157.

van den Driessche, R., Rude, W., and Martens, L. 2003. Effect of fertilization and irrigation on growth of aspen (*Populus tremuloides* Michx.) seedlings over three seasons. For. Ecol. Manage. **186**:381-389.

Vincent, J.S., and Hardy, L. 1977. L'évolution et l'extinction des lacs glaciaires Barlow et Ojibway en territoire québécois. Géog. Phys. Quat. **31**:357-372.

Walworth, J.L., and Sumner, M.E. 1987. The Diagnosis and Recommandation Integrated System (DRIS). Adv. in Soil Sci. **6**:149-188.

Weetman, G.F., and Wells, C.G. 1990. Plant analysis as an aid in fertilizing forests. *In* Soil testing and plant analysis. Soil. Sci. Soc. Am., Madison, WI. SSSA Book Series: **3**:659-689.

Weih, M. 2004. Intensive short rotation forestry in boreal climates: present and future perspectives (review). Can. J. For. Res. **34**:1369-1378.

Zwart, P.D., Miller, M.H., and Baldock, J.A. 1996. Early response of hybrid poplar to phosphorus and potassium. *In* Proceedings of the Canadian Energy

Plantation Workshop, Gananoque, ON. J. Karau, *Eds*. Natural Resources Canada CFS, Ottawa, ON., pp. 81-83.

CHAPITRE 3 : BIOMASS ALLOCATION OF TWO-YEAR OLD HYBRID POPLARS FERTILIZED AT PLANTING WITH PHOSPHORUS

NOTE

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3.1 Abstract

Establishing plantations on heavy clay soils can be challenging because of their fine texture which impedes the movement of water, nutrient availability, soil aeration and root growth. The objective of this study was to examine if phosphorus (P) fertilization applied at planting can stimulate hybrid poplar trees to develop greater root-to-shoot ratios and increase growth rates in the first few years after planting. Two levels of triple-super-phosphate (0 and 50 g/tree of P) were applied at planting of a hybrid poplar clone (*Populus balsamifera x P. trichocarpa*) on a heavy clay and a sandy loam textured soils of the boreal region of Quebec. Twelve trees were excavated manually at the end of the second growing season. Trees growing at the heavy clay site had restricted root elongation but larger root diameters, so that root biomass was similar between the two sites. Root/shoot ratios were significantly lower at the heavy clay site indicating that trees grown on this site invested more biomass to stem and branches. P fertilization did not significantly change root/shoot ratios. However when drainage was taken into consideration, stem and branch biomass increased by 75 % after P application on microsites with moderate drainage. Tree height was also increased by 153 % after P fertilization on moderately drained microsites, but remained constant when trees were located on microsites with imperfect drainage, stressing the importance of considering drainage regime when selecting plantations sites with heavy clay soil texture.

Key words: Phosphorus, placed fertilization, heavy clay soil, biomass partitioning, boreal region.

3.2 Introduction

The installation of fast growing, high-yield plantations in Canada is becoming imperative to ensure wood supplies and vigour of the forest industry. Economic viability of fast growing plantations is directly related to rapid establishment of the trees after planting, since slow initial growth can lead to increased mortality, higher maintenance costs and a longer rotation period. Fast initial growth of hybrid poplars (*Populus spp.*) may depend on early root establishment (Rhodenbaugh and Pallardy 1993) because water and mineral nutrient acquisition depend on root activity. Cultural practices that enhance early and abundant rooting should thus also promote further growth of trees.

Heavy clay soils are often considered unfavourable for the establishment of hybrid poplar plantations, because fine textured soils have a high water holding capacity and thus may restrict equipment access during wet periods, making weed control difficult (Stanturf et al 2001). Moreover, root development and water and nutrient acquisition may be impeded by the poor aeration of this type of soil (Harrington 1987) and by its high mechanical impedance to root growth. This increases the likelihood of nutrient limitation to growth, especially for nutrients with low mobility such as P (Nadian 2002). It has also been reported that slow establishment and juvenile growth stagnation of planted trees observed on reclaimed agricultural fields of the region could be caused by a lack of mobility of P (Rompré and Carrier 1997). Finally, P availability in most of the abandoned farmland where hybrid poplars are likely to be planted in the province of Quebec is probably insufficient to meet the high demand for P by hybrid poplars at early stages of growth (Camiré and Brazeau 1998).

Phosphorus fertilization applied at planting is known to encourage root development (Marschner 1994; Stanturf and al. 2001). However, carbon allocated to root growth can also increase when the supply of nutrients is low (Chapin 1980; Grime 1993;

Ericsson 1995; Mollier and Pellerin 1999). Further investigation is needed to understand the effects of P fertilization on root/shoot ratios of hybrid poplars growing under field conditions. The overall objective of this study was to investigate the effect of P fertilization at planting on growth and dry matter allocation of field-planted hybrid poplars, and to compare these effects on a heavy clay soil and a sandy loam soil.

3.3 Methods

Two hybrid poplar plantations were established in spring 2003 in the region of Abitibi-Témiscamingue, Québec, Canada. The first plantation was established on an abandoned farmland site near the locality of Amos (48° 35' N, 78° 05' W), which is part of the western balsam fir-paper birch (*Abies balsamea - Betula papyrifera*) bioclimatic domain (Grondin 1996). This site is part of the clay belt of Quebec and Ontario resulting from deposits left by the proglacial Lakes Barlow and Ojibway (Vincent and Hardy 1977). Soil texture is a heavy clay Gray Luvisol (Agriculture Canada Expert Committee on Soil Survey 1987). The average number of degree-days above 5° C for the region range from 1215 to 1450 and has had a yearly rainfall between 610 to 680 mm for the last three decades (Environment Canada 2004). The site was previously dominated by grasses and a few patches of alder (*Alnus incana ssp. rugosa*), willow (*Salix spp.)* and trembling aspen (*Populus tremuloides* Michx.). The second plantation was established on a cutover site located near to the locality of Rollet (47° 92' N, 79° 18' W) and part of western balsam fir – yellow birch (*Betula alleghaniensis* Britt.) bioclimatic domain (Grondin 1996). This site was previously dominated by a trembling aspen forest which was commercially harvested in 2000. Its soil type is classified as a Humo-Ferrique Podzol with a sandy-loam soil texture (Agriculture Canada Expert Committee on Soil Survey 1987).

The planting sites were ploughed to a depth of 30 cm in the fall of 2002, followed by disking in the spring of 2003 to level the soil and incorporate organic matter to mineral soil as well as to remove the remaining stumps and logs. The trees were planted in the first week of June at the heavy clay site and in the first week of July at the sandy loam site. Dormant, bare-root hybrid poplar trees of approximately 1.5 m in height were planted at a 3 x 3 m spacing. Clone number 747210 (*P. balsamifera x trichocarpa*) from the Quebec Ministry of Natural Resources was used.

Phosphorus fertilizer used was granules of triple-superphosphate (0-45-0) applied at two levels (0 and 50 g of P / tree). The original plantation contained 324 trees, replicated 3 times at each of the sites. The fertilizer was applied at planting by inserting the granules into a spade slit made at 15 cm from the trees to a depth of about 15 cm. Vegetation control was done twice a year by cross-cultivating the plantations using a farm tractor. Three replicates of unfertilized trees and trees that had received 50 g of P were randomly chosen and excavated at each site at the end of September 2004. The soil moisture regime was validated using Brais and Camiré (1992) field keys.

The entire root system of trees was carefully hand-dug up to a root diameter of about 2 mm. The root systems were separated into coarse (> 5 mm) and fine (2-5 mm) root diameter. The roots, along with stems, branches were oven-dried at 80 °C to constant weight. Root lengths were recorded for the five longest lateral roots of each tree. Maximal depth of rooting was also recorded. Root/shoot ratios were calculated as the total root biomass divided by the biomass of the stem and branches. Specific root length (length / biomass) was only calculated for the five longest roots.

Soils were sampled at 0-20 and 20-40 cm depth in each site before planting. Samples were air-dried, sieved with a 2-mm screen, and analyzed for particle size distribution using a pipette. Cation content was extracted with Mehlich-III (Mehlich 1985) and exchangeable acidity was obtained by addition of $BaCl_2$-NH_4Cl (Amacher and al. 1990). Soils analysis variables of both sites are presented in table 3.1. Basal diameter and height of trees were measured right after planting and at the end of the first and second growing seasons.

A randomized split-plot design was used with three replicates at each site. Measurements were treated by analysis of variance (ANOVA) and site and fertilizer levels were the main plot factors. These two factors were considered fixed. Relationships among growth parameters were analyzed by correlation analyses.

Table 3.1: Means of soil analyses from the two sites.

	Site			
Variable	Farmland		Clearcut	
Depth (cm)	0-20	20-40	0-20	20-40
Texture	Heavy clay		Sandy loam	
pH (CaCl2)	4.36	4.82	4.25	4.60
N (%)	0.14	0.02	0.12	0.03
C.O. (%)	2.38	0.53	2.45	0.75
S.B. (%)	83.97	96.57	39.58	47.50
CEC (cmol(+) kg^{-1})	6.69	9.79	2.60	0.74
K (mg kg^{-1})	133.64	114.66	70.82	24.04
Na (mg kg^{-1})	19.72	31.33	5.28	3.41
Ca (mg kg^{-1})	559.57	939.21	105.63	37.63
Mg (mg kg^{-1})	226.11	492.37	19.89	8.90
P (mg kg^{-1})	8.87	12.87	21.98	13.74
Al (mg kg^{-1})	1225.35	970.16	1955.02	1913.41

3.4 Results and discussion

Phosphorus fertilization did not significantly change the root/shoot ratio (r/s) of trees after two growing seasons ($p = 0.13$). However, mean root/shoot ratio (r/s) found on the heavy clay soil ($r/s = 0.61$) was significantly lower ($p < 0.01$) than at the sandy loam site ($r/s = 0.92$; table 3.2). These r/s are high compared to other two-year old hybrid poplars growing in more southern areas: Scarascia-Mugnozza (1991) measured r/s ratios of 0.18 for two T x D (*Populus trichocarpa x Populus deltoides*) hybrid poplar clones. Although different excavation methods can easily lead to different results, the large differences in ratios is also probably due to lower above-ground productivity in our study due to less advantageous climatic conditions for tree growth in our region. P fertilization did not change root/shoot ratios because stem and branches biomass increased proportionally to total root biomass (Fig. 3.1). Zwart et al. (1996) also found that root/shoot ratios remained constant across different levels of P fertilization. Root/shoot ratios provide a limited evaluation of biomass allocation, because such ratios vary with plant size (Shipley and Meziane 2002). Since root/shoot ratios are subject to ontogenetic and environmental influences, such as light levels, soil fertility, water availability, etc. (Drew and Ledig 1980), a useful method for assessing treatment effects on biomass allocation during ontogeny is allometric analysis (Retzlaff et al. 2001). Recent information suggests that resource-induced shifts in allocation may largely be due to accelerated development; that is, that fertilization and irrigation simply result in larger, developmentally advanced trees with inherently different relative belowground growth than that observed in trees grown without amendments (Coleman et al. 2004; Coyle and Coleman 2005). However, it was not possible to do an allometric analysis of our data since we did only one destructive measure of roots biomass, but that kind of analysis require successive measurement during a determined period.

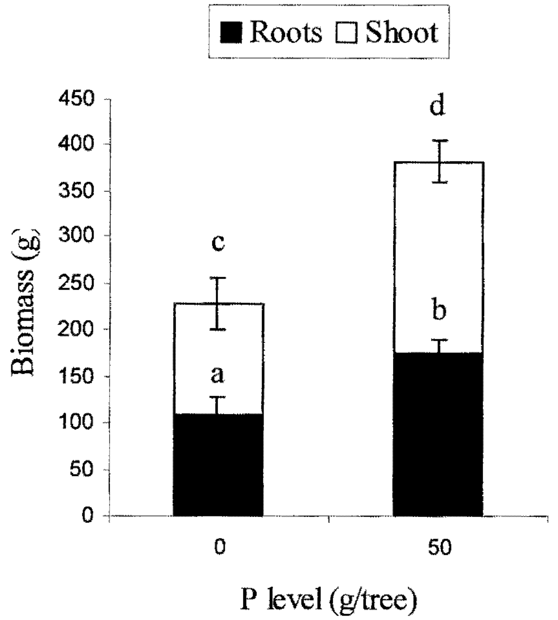

Figure 3.1: Effect of P fertilization on root and shoot biomass on clone 747210, two years after planting. Error bars are SEs. Bars with the same letters are not significantly different at $p < 0.05$.

Mean and maximum root length were about two-fold greater for trees growing on the sandy loam site compared to trees at the heavy clay site (Table 3.2). Total root biomass, however, was similar between the two sites ($p = 0.64$) indicating different root development strategies. Consequently, specific root length was also significantly lower at the heavy clay site ($p = 0.001$), which could suggest higher nutrient availability at this site (Fitter 1987). Soil analyses show that the heavy clay site indeed had a slightly higher fertility than the sandy loam site (table 3.1), but both sites seemed nevertheless nutrient-lacking when comparing CEC values and major exchangeable cations to values from various agricultural soils across the world (Bohn et al. 1985). Hence, it might be possible that the differences in root allocation observed between the sites were due to different soil fertility, but others factors such as soil bulk density may have affected root allocation (Shierlaw and Alston 1984).

We measured a high concentration of aluminium (Al) at the sandy loam site, which could have had a negative impact on root development (Oleksyn et al. 1996). However, such effects were not observed in this study. Mean depth of rooting of all trees were in the range of 10 to 20 cm, while maximum recorded depths of sinker roots were 45 cm and 60 cm at the heavy clay and sandy loam sites, respectively.

Table 3.2: Mean root characteristics for trees at the two sites. SE values are given in parentheses.

	Site	
Parameter	Heavy clay	Sandy loam
Mean root length (cm)	104.7 (13.48)	201.0 (15.36)
Maximum root length (cm)	135.5 (13.80)	261.0 (15.11)
Root/shoot ratio	0.61 (0.06)	0.92 (0.07)
Specific root length (cm/g)	0.72 (0.08)	1.55 (0.12)

We noticed during roots excavation that there were microsite differences in drainage. Although drainage was not originally assigned as a fixed factor in the ANOVA, the removal of variation due to drainage from the model allowed to narrow the effects of P fertilization on growth (table 3.3). Indeed, when variation due to drainage was removed, P fertilization increased total biomass of trees by 68 % ($p = 0.048$), basal diameter growth by 62 % ($p < 0.01$), thick root biomass by 102 % ($p = 0.01$), total root biomass by 61 % ($p = 0.02$) and stem and branches biomass by 75 % ($p = 0.04$). Moreover, the interaction between P fertilization and drainage class on height growth showed that fertilization only increased height growth when trees were located on microsites with moderate drainage ($p = 0.02$; figure 3.2). In this drainage class, height growth increased by 153 % with P fertilization, while it did not change for trees planted on microsites with imperfect drainage (figure 3.2). Trees on moderately drained microsites also had greater thin root biomass ($p < 0.001$) and mean root length ($p = 0.03$) compared to trees growing on imperfect drainage microsites (Table 3.3). Flooding is recognized to decrease uptake of nutrients (Harrington 1987). On sites with moderate drainage, however, P will persist and become slowly available for several years because of mineral fixation with iron, aluminium, and calcium, as well as immobilization in organic matter (Stanturf and al. 2001).

Table 3.3: Mean values of the measured parameters for each P fertilization level and drainage class. P fertilization was not significant at $p < 0.05$ for thin root biomass and mean root length only. SE values are given in parentheses.

	P fertilization		Drainage class	
Parameter	Control	50 g/tree	moderate	imperfect
Below-ground biomass (g)	109.0 (18.6)	175.3 (14.7)	194.6 (14.2)	89.7 (19.0)
Total biomass (g)	266.1 (61.0)	447.0 (48.2)	473.9 (46.6)	239.2 (62.2)
Thick root biomass (g)	48.0 (12.2)	97.1 (9.6)	100.9 (9.3)	44.2 (12.4)
Thin root biomass (g)	60.9 (7.3)	78.2 (5.8)	93.6 (5.6)	45.6 (7.4)
Stem and branches biomass (g)	118.4 (27.8)	207.3 (22.0)	209.7 (21.2)	116.0 (28.4)
Basal diameter growth (mm)	9.8 (1.2)	15.9 (0.9)	15.5 (0.9)	10.3 (1.2)
Mean root length (cm)	149.0 (16.5)	156.7 (14.3)	186.4 (22.7)	92.9 (30.4)

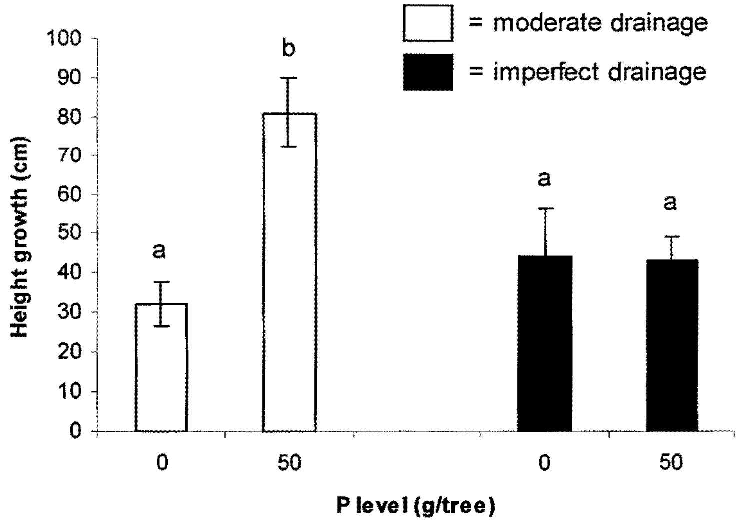

Figure 3.2: Effect of P fertilization on stem height growth of clone 747210 located on moderate and imperfect drainage classes, at both sites. Bars with the same letters are not significantly different at $p < 0.05$.

The improved growth of this hybrid poplar clone after P fertilization was probably also due to the low P-status at both sites. Liang and Chang (2004) reported on the lack of P-available forms for plant uptake in Luvisolic soils in Alberta. Chapin et al. (1983) also showed that balsam poplar (*Populus balsamifera* L.) was the most sensitive species to reduction in phosphate supply among five other boreal forest tree species.

Mechanical impedance to root growth is one of the most common factors determining root elongation and proliferation within a soil profile (Nadian 2002). It increases the likelihood of nutrient limitation to growth, especially for nutrients with low mobility such as P. It is generally assumed that the yield reduction from cultivation in compacted soil is a consequence of a lower rate of cell elongation and increased number of cells, thus enlarging plant root diameter (Benghough and

Mullins 1990; Liang et al. 1999). Although not measured, we assume that mechanical impedance was higher at the heavy clay site, where roots were effectively shorter and thicker (Table 3.2). However, we did not find a reduction in above-ground growth for trees grown in the heavy clay soil, which might be simply explained by their slightly longer period of growth. We also noticed that roots at the heavy clay site were mostly found along low impedance pathways, such as along the grass layer made by the ploughing operations and in cracks caused by periodical drying of the clay. A study with radiata pine (*Pinus radiata* D. Don) showed that the ability of roots to reach and proliferate in old root channels and desiccation cracks developed by shrinkage of clay soils plays a crucial role in maintaining a supply of water to trees (Nambiar and Sands 1992).

3.5 Conclusion

Results have shown that P fertilization did not change the root/shoot ratio of trees over two growing seasons in the field, because above- and below-ground productivity of trees increased proportionally. Sites with imperfect drainage regime should be avoided or drained before planting hybrid poplars as shown by lower productivity. P fertilization was not as effective to increase growth on microsites with imperfect drainage. However, P fertilizer applied to trees located on moderate drainage microsites improved overall growth.

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3.7 References

Agriculture Canada Expert Committee on Soil Survey. 1987. *In*: The Canadian System of Soil Classification. 2nd edition. Publication 1646. Research Branch, Agriculture Canada, Ottawa, Ontario, 164 p.

Amacher, M.C., R.E. Henserson, M.D. Breithaupt, C.L. Seale and J.M. LaBauve. 1990. Unbuffered and buffered salt methods for exchangeable cations and effective cation-exchange capacity. Soil Sci. Soc. Am. J. 54: 1036-1042.

Benghough, A.G. and C.E., Mullins. 1990. Mechanical resistance to root growth: a review of experimental techniques and root growth responses. J. Soil. Sci. 41:341-358.

Bohn, H.L., B.L., McNeal and G.A., O'Connor. 1985. Soil chemistry, 2nd edition. A Wiley-Interscience publication. John Wiley and Sons inc. USA, 341 p.

Brais, S. and C. Camiré. 1992. Keys to soil moisture regime evaluation for northwestern Quebec. Can. J. For. Res. 22:718-724.

Camiré, C. and M. Brazeau. 1998. Culture des genres *Populus* et *Larix* au Québec : sols, exigences nutritionnelles et productivité. Rapport présenté au Min. des Ressources Naturelles. Centre de recherche en biologie forestière. Université Laval. 132p.

Chapin, F.S. 1980. The mineral nutrition of wild plants. Annu. Rev. Ecol. Syst. 11: 233-260.

Chapin, F.S., P.R. Tryon and K. Van Cleve. 1983. Influence of phosphorus on growthand biomass distribution of Alaskan taiga tree seedlings. Can. J. for. Res. 13:1092-1098.

Coleman, M.D., A.L., Friend and C.C., Kern. 2004. Carbon allocation and nitrogen acquisition in a developing Populus deltoides plantation. Tree Physiol. 24:1347-1357.

Coyle, D.R. and M.D., Coleman. 2005. Forest production responses to irrigation and fertilization are not explained by shifts in allocation. For. Ecol. Manage. 208:137-152.

Drew, A.P. and F.T., Ledig. 1980. Episodic growth and relative shoot:root balance in loblolly pine seedlings. Ann. Bot. 45: 143-148.

Environment Canada. 2004. Canadian climate normals or averages 1971-2000. *Available at*: http://www.climate.weatheroffice.ec.gc.ca

Ericsson, T. 1995. Growth and shoot:root ratio of seedlings in relation to nutrient availability. Plant Soil. 168-169:205-214.

Fitter, A.H. 1987. An architectural approach to the comparative acology of plant-root systems. New Phytol. 106:61-77

Grime, J.P. 1993. Stress, competition, resource dynamics and vegetation processes. *In* Plant adaptation to environmental stress. *Edited by* L. Fowden, T. Mansfield, and J. Stoddart. Chapmann & Hall, London. pp 45-63.

Grondin, P. 1996. Écologie forestière. *In*: Manuel de foresterie. Presses de l'Université Laval, Québec, pp.135-279.

Harrington, C.A. 1987. Responses of red alder and black cottonwood seedlings to flooding. Physiol. Plant. 69:35-48.

Liang, J., J. Zhang, G.Y.S. Chan and M.H. Wong. 1999. Can differences in root responses to soil drying and compaction explain differences in performance of trees growing on landfill sites? Tree Physiol. 19: 619-624.

Liang, H. and S.X. Chang. 2004. Response of trembling and hybrid aspens to phosphorus and sulfur fertilization in a Gray Luvisol: growth and nutrient uptake. Can. J. For. Res. 34:1391-1399.

Marschner, H. 1994. Mineral nutrition of Higher Plants, 2nd ed. Academic Press. London.

Mehlich, A. 1985. Mehlich 3 soil extractant: a modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409-1416.

Meteorological Service of Canada. 2004. Retrieved February 14, 2005 from: http://www.weatheroffice.ec.gc.ca/

Mollier, A. and S. Pellerin. 1999. Maize root system growth and development as influenced by phosphorus deficiency. J. Exp. Bot. 50:487-497.

Nadian, H. 2002. Mechanical impedance to root growth and phosphorus uptake. World Congress of Soil Science. Symposium no.22. Paper no.1052.

Nambiar, E.K.S. and R. Sands. 1992. Effects of compaction and simulated root channels in the subsoil on root development, water uptake and growth of radiata pine. Tree Physiology 10:297-306.

Oleksyn, J., P. Karalewski, M.J. Giertych, A. Werner, M.G. Tjoelker and P.B. Reich. 1996. Altered root growth and plant chemistry of *Pinus sylvestris* seedlings subjected to aluminium in nutrient solution. Trees 10:135-144.

Retzlaff, W.A., J.A. Handest, D.M. O'Maley, S.E. McKeand and M.A. Topa. 2001. Whole-tree biomass and carbon allocation of juvenile trees of loblolly pine (*Pinus_taeda*): influence of genetics and fertilization. Can. J. For. Res. 31:960-970.

Rhodenbaugh, E.J. and S.G. Pallardy. 1993. Water stress, photosynthesis and early growth patterns of cuttings of three *Populus* clones. Tree physiol. 13:213-226.

Rompré, M. and D. Carrier. 1997. Étude pédologique des sols défrichés de l'Abitibi-Témiscamingue. Centre de recherche et d'expérimentation en sols. MAPAQ. 133p.

Scarascia-Mugnozza, G. 1991. Physiological and morphological determinants of yield in intensively cultured poplars (*Populus* spp.). Ph.D. dissertation, University of Washington, Seattle, WA. 189 p.

Shierlaw, J. and A.M. Alston. 1984. Effect of soil compaction on root growth and uptake of phosphorus. Plant Soil 77:15-22.

Shipley, B. and D. Meziane. 2002. The balanced-growth hypothesis and the allometry of leaf and root biomass allocation. Functional Ecology 16:326-331.

Stanturf, J.A., C. van Oosten, D.A. Netzer, M.D. Coleman and C.J. Portwood. 2001. Ecology and silviculture of poplar plantations. *In* Poplar Culture in North America. Part A, Chapter 5. *Edited by* D.I. Dickmann, J.G. Isebrands, J.E. Eckenwalder, and J. Richardson. NRC Research Press, National Research Council of Canada, Ottawa, ON K1A 0R6, Canada. pp. 153-206.

Vincent, J.S., and L., Hardy. 1977. L'évolution et l'extinction des lacs glaciaires Barlow et Ojibway en territoire québécois. Géog. Phys. Quat. 31:357-372.

Zwart, P.D., M.H. Miller and J.A. Baldock. 1996. Early response of hybrid poplar to phosphorus and potassium. *In* Proceedings of the Canadian Energy Plantation Workshop, Gananoque, ON. J. Karau, (ed). Natural Resources Canada CFS, Ottawa, ON.

CHAPITRE 4 : CONCLUSION GÉNÉRALE

Les objectifs de cette étude étaient (1) de vérifier le potentiel de la fertilisation en traitement localisé et au moment de la plantation à accélérer la croissance initiale et l'enracinement des PEH et (2) d'évaluer trois techniques d'entretien mécanique de la végétation compétitive.

Les résultats des tests de fertilisation ont démontré qu'il était possible d'accroître le volume des arbres de 41 % à 95 %, deux ans après leur mise en terre, avec une combinaison de fertilisants spécifique à chaque clone de PEH. L'application de 25 g de P a procuré le plus souvent les meilleurs gains de croissance après 2 ans, tandis que la combinaison de N et de P a généralement maximisé la croissance des arbres lors de la première année. Cependant, comme chaque clone a démontré des besoins spécifiques, il est difficile de généraliser quant à la combinaison idéale de fertilisants. De plus, nous avons plusieurs fois observé des interactions entre les différents fertilisants et les niveaux d'application sur la croissance, ce qui nous indique que la proportion relative des éléments nutritifs ajoutés lors de la fertilisation a un impact majeur si l'on désire maximiser la croissance des PEH. S'il fallait cependant recommander une formulation générale, nos résultats suggèrent qu'un engrais de type 1-3-1 en $N\text{-}P_2O_5\text{-}K_20$ serait à privilégier au moment de la plantation.

Les gains de croissance des PEH suite à la fertilisation étaient similaires entre les deux sites malgré leur texture contrastante (argile lourde *vs* loam sableux). Les arbres situés sur le site d'argile lourde ont cependant mieux répondu à la fertilisation. Ceci pourrait s'expliquer principalement par une période de croissance plus longue d'un mois dans le cas des arbres plantés sur le site d'argile lourde et par la meilleure capacité de rétention des nutriments de ce type de sol. La fertilité des deux stations sous-étude limite vraisemblablement la croissance des PEH, puisque ceux-ci ont tous bien répondus à la fertilisation. Cependant, l'utilisation de doses élevées de fertilisants appliqués au moment de la plantation n'est pas justifiée car elle n'a pas engendré une croissance supérieure par rapport aux doses plus faibles.

La comparaison des diagnostiques nutritionnels donnés par la méthode DRIS et celle du ratio N:P nous a permis de constater l'importance des rapports entre les éléments nutritifs afin d'assurer une nutrition optimale des arbres. Les résultats ont démontré que les prescriptions faites par DRIS s'avèrent plus précises lorsque les clones sont analysés séparément. L'utilisation de cette méthode a donné de bonnes indications sur les éléments nutritifs qui limitaient la croissance des PEH. Généralement, les indices calculés à partir des formules DRIS ont révélés que l'azote et le phosphore ont été les éléments nutritifs les plus limitatifs lors de la première saison de croissance, ce qui fut effectivement le cas. Cependant, la proportion de N par rapport au P dans les indices DRIS ne concordait pas toujours avec la réponse à ces 2 fertilisants. Le fait qu'un prélèvement accru en P puisse améliorer le prélèvement en N, et vice versa, pourrait expliquer cet écart. Ainsi, lorsque N et P ont des indices négatifs, il importe d'ajouter les 2 éléments en même temps tel que démontré par les interactions entre ces 2 éléments sur la croissance des arbres. Le type d'engrais, la méthode d'application utilisée ainsi que la réaction de l'engrais selon les conditions édaphiques peuvent également expliquer les différences entre les prescriptions faites par DRIS et les gains de croissance suite à la fertilisation. De plus, la valeur des indices DRIS peut être légèrement biaisée si les données (normes) contenues dans le groupe des arbres à croissance supérieure présentent tout de même une carence ou un excès en un élément (faible représentativité du groupe des arbres à croissance supérieure), faisant en sorte qu'un indice négatif n'est peut-être pas limitant pour la croissance. Néanmoins, les normes DRIS proposées dans cette étude pourront servir de base pour raffiner et prédire les besoins en fertilisants de ces clones de PEH.

En comparaison, le diagnostic nutritionnel à l'aide uniquement du ratio N:P peut identifier un déséquilibre entre ces 2 éléments si la croissance des arbres est fortement liée à la disponibilité de ceux-ci, comme pour les arbres situés au site agricole. Cependant, comme nous l'avons observé au site forestier, cette méthode ne permet pas d'identifier précisément une carence pour l'un ou l'autre de ces 2 éléments nutritifs compte tenu que les arbres les plus performants ont présentés des ratios N:P foliaires différents. Dans ce cas, il semble que d'autres facteurs limitaient encore plus la croissance des PEH que la disponibilité de N et de P. Ainsi, cette méthode semble avoir une portée assez limitée de par sa faible intégration de variables pouvant influencer la croissance des PEH.

L'étude des différentes techniques d'entretien mécanique des herbacées a démontré qu'il n'y avait pas de différences significatives entre celles-ci quant à leurs effets sur la croissance des PEH. La période d'étude fut peut-être trop courte afin d'observer des différences de croissance significatives, car à la fin de la deuxième saison de croissance, on observait, chez les PEH, une concentration foliaire en N plus forte avec le passage croisé de la herse et la combinaison herse + Weed Badger^{TM} comparativement au passage simple de la herse qui laissait plus de végétation vivante au sol. En plus de laisser une bande de végétation entre les plants, le passage simple de la herse avait tendance à ne pas éradiquer toutes les herbacées sur son passage. En effet, un seul passage de herse affectait peu le sol et les herbacées, tandis qu'un deuxième passage effectué perpendiculairement au premier éliminait la plupart des herbacées. Le hersage de la végétation a l'inconvénient de ne pas pouvoir éliminer la végétation près du tronc des arbres, ce qui limite son efficacité lors de la première saison de croissance compte tenu que le système racinaire des arbres est encore peu développé. Afin de ne pas blesser les arbres lors du hersage, nous recommandons de laisser une distance de 30 cm entre la herse et les plants. Ainsi, pour des plants alignés aux 3 mètres, il faut utiliser une herse de 2,40 m de largeur. L'utilisation du Weed Badger^{TM} nous a démontré que cette technique nécessite un bon niveau de dextérité de la part de l'opérateur afin de ne pas blesser les arbres. Par conséquent, l'opérateur doit circuler lentement ce qui en fait une technique environ deux fois moins productive qu'un passage de herse. D'autres études devront être réalisées afin de préciser les avantages liés à cette technique.

Compte tenu que la plupart des sites disponibles pour le reboisement en PEH ne rencontrent pas les exigences nutritionnelles de ces derniers, l'aménagiste devrait fortement envisager la fertilisation s'il espère maximiser la croissance des PEH. La fertilisation en traitement localisé dans le sol s'avère une option à la fois plus économique et plus écologique que la fertilisation en plein, c'est à dire appliquée sur toute la surface de plantation. En effet, la fertilisation localisée nécessite de très faibles quantités de fertilisants (environ 6 fois moins qu'une application en plein), elle n'encourage pas la croissance des herbacées, elle maximise l'efficacité de l'engrais en diminuant la surface de contact avec le sol, elle évite les pertes par volatilisation et diminue les pertes dues au lessivage. De plus, elle coûte environ 300 $/ha (0,13$/arbre pour l'achat et 0,15 $/arbre pour l'application), ce qui en fait une technique rentable si l'on considère son effet positif sur l'établissement des plants et sur la diminution du nombre d'entretiens mécaniques requis jusqu'à la fermeture du couvert compte tenu de la croissance accrue des arbres. Les bénéfices versus les coûts de la fertilisation localisée en fait une approche accessible et rentable dans un contexte d'aménagement intensif.

Il serait intéressant, par le biais d'autres études, d'évaluer les bénéfices à plus long terme de la fertilisation au moment de la plantation, de façon à déterminer si cette technique permet de raccourcir la période de temps jusqu'à la coupe. Dans le même ordre d'idées, il serait pertinent de bonifier les normes DRIS proposées à l'aide de nouvelles analyses foliaires provenant de PEH à croissance supérieure reboisés sur différents dépôts de surface de la région. Il serait également souhaitable d'établir des normes DRIS provenant de PEH cultivés en serre et soumis à un régime nutritif optimal. Ces expériences permettraient d'améliorer la fiabilité des prescriptions nutritionnelles faites pour les clones de PEH utilisés localement. Par la suite, les autres paramètres pouvant influencer la croissance des arbres comme la texture du sol, la pierrosité, la capacité de rétention en eau du sol, les données climatiques, etc. devraient être intégrés dans le système DRIS afin d'expliquer la plus grande proportion possible de la variance observée au niveau de la croissance des PEH.

RÉFÉRENCES

Baker, J.B., et B.G. Blackmon. 1978. Summer fallowing – a simple technique for improving old-field sites for cottonwood. U.S. For. Serv. Res. Pap. 142 p.

Barnéoud, C., P. Bonduelle et J.M. Dubois. 1982. Manuel de Populiculture. AFOCEL, Nangis, Paris. 319 p.

Blackmon, B.G. 1976. Response of Aigeiros poplars to soil amelioration. pp. 344-358. In: B.A. Thielges and S.B. Land Jr. *Eds.* Proc. Symp. Eastern Cottonwood and Related Species. Greenville, MS.

Blackmon, B.G. 1977b. Effects of fertilizer nitrogen on tree growth, foliar nitrogen and herbage in eastern cottonwood plantations. Soil Sci. Soc. Amer. J. 41:992-995

Burns, I.G. 1980. Influence of the spatial distribution of nitrate on the uptake of N by plants: A review and a model for rooting depth. J. Soil. Sci. **31**:155-173.

Camiré, C. et M. Brazeau. 1998. Sols forestiers - Notes de cours. Fac. for. géom., Univ. Laval, Québec.

Dickmann, D.I., Isebrands, J.G., Eckenwalder, J.E., Richardson, J. *(Editors).* 2001. Poplar culture in North America. NRC Research Press, Ottawa, Ontario, Canada. 397 p.

Environnement Canada. 2004. Archives climatiques nationales [en ligne]. Disponible à: http://www.climat.meteo.ec.gc.ca/climate_normals/results_f.html [mis à jour le 25février 2004]

Garbaye, J. 1980. Nutrition minérale et production des peupliers « Robusta » et « I-214 » en populiculture traditionnelle dans le nord du bassin parisien. Ann. Sci. For. 37:159-172.

Hauck, R.D. 1968. Forest Fertilisation: theory and practice. Tennessee Valley Authority. National Fertlizer Development Center. Alabama. pp.46-57.

Havlin, J.L., J.D. Beaton, S.L. Tisdale and W.L. Nelson. 1999. Soil Fertility and Fertilizers: An Introduction to Nutrient Management. Sixth edition. Prentice Hall, New Jersey. 499 p.

Hansen, E.A., D.A. Netzer and R.F. Woods. 1996. Tillage superior to no-till for establishing hybrid poplar plantations. Tree Plant. Notes 37: 6-10.

Heilman, P.E. 1992. Sustaining production: nutrient dynamics and soils. *In:* Ecophysiology of short rotation forest crops. Eds. Mitchell, C.P., Ford-Robertson, J.R., Hincley, T. and Sennerby-Forse, L. Elsevier, Amsterdam. pp.216-230.

Kovar, J.L., and S.A. Barber. 1989. Reasons for differences among soils in placement of phosporus for maximum predicted uptake. Soil. Sci. Soc. Am. J. 53:1733-1736.

Kozlowski, T.T. and S.G. Pallardy. 1997. Physiology of woody plants, second edition. Academic press, California. 411 p.

Landhäusser, S.M. and V.J. Lieffers. 1998. Growth of *Populus tremuloides* in association with *Calamagrostis canadensis*. Can. J. For. Res. 28:396-401.

Leroy, P. 1969. Résultats précoces d'essais de fertilisation du peuplier sur sols à Gley dans la Meuse. Am. Sci. forest. 26:301-319.

Ménétrier, J., et G. Vallée. 1980. Recherche et développement sur le peuplier. XVI. Résultats d'essai de quarante traitements de fertilisation d'une plantation de boutures. Min. Énergie et Ressources, Serv. Rech., Québec, Mémoire 57. 42 p.

Rikala, R. et T. Repo. 1997. The effect of late summer fertilization on the frost hardening of second-year Scots pine seedlings. New Forests 14:33-44.

Rompré, M. et D. Carrier. 1997. Étude pédologique des sols défrichés de l'abitibi-Témiscamingue. Centre de recherche et d'expérimentation en sols. MAPAQ. 133 p.

Schroeder, W.R., S. Silim, G. Inouye and L. Kalcits. 2003. Weed Management in Hybrid Poplar. Affiche présentée lors de la réunion annuelle du conseil du peuplier du Canada. Rouyn-Noranda, Québec.

Sheedy, G. 1982. XIX- Résultats de quinze traitements de fertilisation sur des plançons de deux clones de peuplier hybride. Mémoire no. 75. Service de la recherche. Ministère de l'énergie et des ressources. 35 p.

Sirois, G. 2001. Étude sur la culture d'essences à croissance rapide dans Charlevoix. Groupe de recherche et de développement de Charlevoix. 43 p.

Staples, T.E., K.C.J. Van Rees and C. van Kessel. 1999. Nitrogen competition using ^{15}N between early successional plants and planted white spruce seedlings. Can. J. For. Res. 29:1282-1289.

Tabi, M., L. Tardif, D. Carrier, G. Laflamme et M. Rompré. 1990. Inventaire des problèmes de dégradation des sols agricoles du Québec : Région 9, Abitibi-Témiscamingue. Gouvernement du Québec, Publication no. 910028. 81 p.

Thomas, K.D., P.G. Comeau et K.R. Brown (a). 2000. The Silviculture of Hybrid Poplar Plantations. B.C. Ministry of Forests, Research branch, Extension note 47, 7 p.

Thomas, K.D., W.J. Reid, and P.G. Comeau. 2001. Vegetation Management Using Polyethylene Mulch Mats and Glyphosate Herbicide in a Coastal British Columbia Hybrid Poplar Plantation: 4-yr Growth Response. West. J. Appl. For. 16(1): 26-30.

van Oosten, C. 2001. Hybrid poplar opportunities for Tembec. Rapport préparé pour Tembec, Ont., 18 p.

van den Driessche, R. (a) 1999. First-year growth response of four Populus trichocarpa x Populus deltoids clones to fertilizer placement and level. Can. J. For. Res. Canada. 29: 554-562.

van den Driessche, R. (b). 1999. Nutrition of poplars with special reference to aspen. Revue de littérature, Rapport remis à Alberta-Pacific For. Ind. Inc, 58 p.

Veillette J., Bergeron Y, Gaudreau L., Miron F.& Drainville G. 2000. Abitibi-Témiscamingue, de l'emprise des glaces à un foisonnement d'eau et de vie ; 1 000 ans d'histoire. Éditions multimondes, Minule. 159 p.

Annexe 1. Carte de localisation des dispositifs.

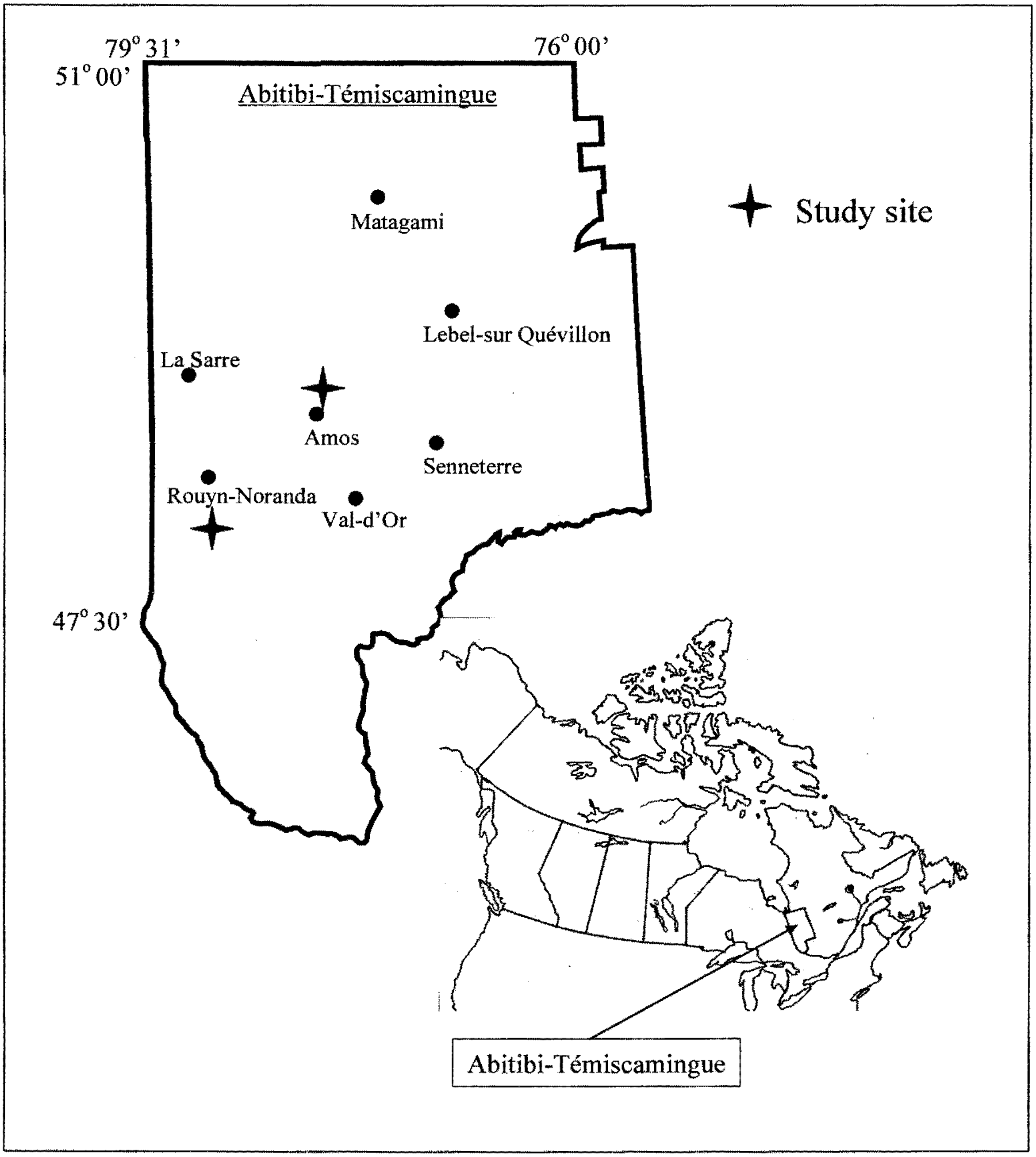
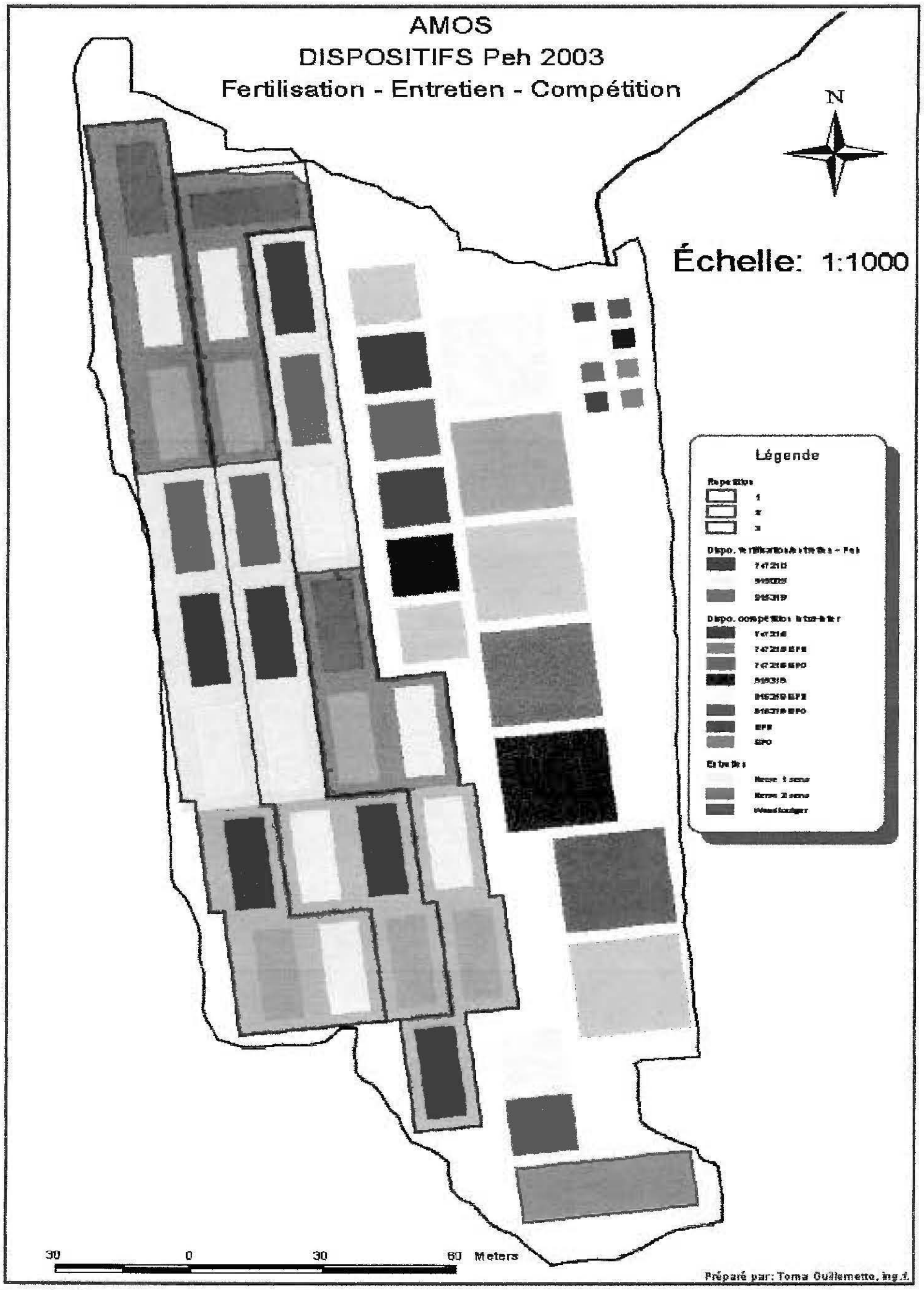
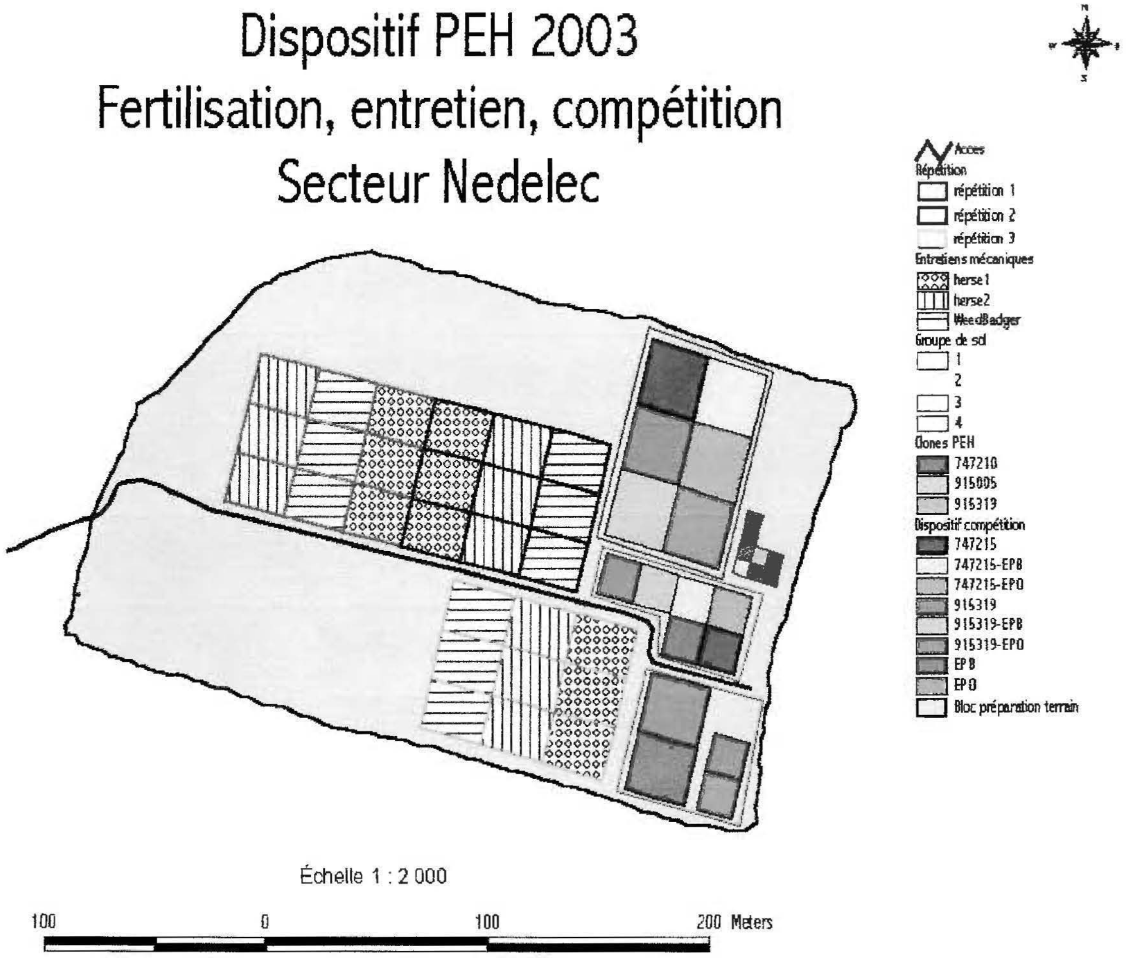


Figure 1. Location of fertilization trials in Abitibi-Témiscamingue (Québec, Canada)

Annexe 2. Schéma du dispositif en milieu agricole. La partie de droite du dispositif (les blocs sans trame de fond grise) ne fait pas partie de cette étude.



Annexe 3. Schéma du dispositif en milieu forestier. La partie de droite du dispositif (blocs avec couleur) ne fait pas partie de cette étude.



Annexe 4. Analyse de variance (ANOVA) pour le volume des tiges après la première et la seconde saison de croissance sur les deux sites d'étude.

		FARMLAND		FOREST SITE	
Source	DF[a]	*P* value for 1st year stem volume	*P* value for 2nd year stem volume	*P* value for 1st year stem volume	*P* value for 2nd year stem volume
		Clone 747210			
BLOCK	2	0.01	0.18	<.001	<.0001
N	2	0.00	0.18	<.001	0.09
P	2	0.00	<.001	0.04	0.03
K	1	0.24	0.41	0.97	0.62
N*P	4	0.50	0.86	0.09	0.77
N*K	2	0.36	0.82	0.55	0.75
P*K	2	0.29	0.12	0.22	0.55
N*P*K	4	0.42	0.95	.095	0.79
Volume covariate[b]	1	<.001	0.32	<.0001	0.25
		Clone 915005			
BLOCK	2	0.54	0.24	0.12	<.0001
N	2	<.001	0.16	0.36	0.09
P	2	<.0001	<.0001	<.001	0.01
K	1	0.68	0.94	0.73	0.97
N*P	4	0.05	0.77	0.30	0.12
N*K	2	0.67	0.73	0.25	0.01
P*K	2	0.71	0.84	0.57	0.70
N*P*K	4	0.62	0.60	0.11	0.59
Volume covariate[b]	1	<.0001	<.0001	<.0001	0.01
		Clone 915319			
Block	2	0.24	0.48	0.70	<.001
N	2	0.01	0.16	<.001	0.02
P	2	<.001	0.01	0.01	0.02
K	1	0.25	0.65	0.14	0.33
N*P	4	0.38	0.59	0.02	0.44
N*K	2	0.20	0.42	0.97	0.50
P*K	2	0.24	0.75	0.50	0.18
N*P*K	4	0.49	0.58	0.76	0.89
Volume covariate[b]	1	0.66	0.92	<.0001	<.0001

[a] Degree of Freedom

[b] The covariate is stem volume at planting

Annexe 5. Volume des tiges des trois clones de PEH localisés aux deux sites d'étude, un an et deux ans suite aux dix-huit traitements de fertilisation.

			FARMLAND / HEAVY CLAY SOIL				FOREST SITE / SANDY LOAM SOIL			
Treatment (g/tree)			1st year		2nd year		1st year		2nd year	
N	P	K	Stem volume	Std	Stem volume	Std	Stem volume	Std	Stem volume	Std
			Clone 747210							
0	0	0	69,07	17,57	240,27	69,64	54,55	9,08	181,63	67,79
0	0	20	78,79	17,54	219,44	69,50	61,95	9,09	182,32	67,86
0	25	0	89,87	17,43	317,01	69,10	70,26	9,37	340,71	69,95
0	25	20	82,72	17,69	406,56	70,09	76,87	9,08	311,22	67,80
0	50	0	93,52	17,65	331,95	69,96	64,57	9,10	259,14	67,98
0	50	20	110,73	17,82	367,46	70,61	53,14	9,12	281,54	68,13
20	0	0	103,51	17,53	302,58	69,47	64,46	9,23	263,16	68,94
20	0	20	88,41	17,45	229,28	69,15	65,33	9,15	266,64	68,30
20	25	0	123,39	17,92	341,10	71,03	77,65	9,25	380,61	69,09
20	25	20	157,60	17,43	519,96	69,06	96,94	9,12	394,15	68,07
20	50	0	121,72	17,43	448,53	69,07	98,08	9,08	372,16	67,81
20	50	20	182,85	19,06	488,78	75,54	93,30	9,08	368,78	67,83
40	0	0	97,88	17,42	287,17	69,04	67,91	9,31	323,14	69,50
40	0	20	78,00	17,49	199,66	69,32	65,16	9,18	259,41	68,57
40	25	0	126,74	17,47	414,97	69,24	67,42	9,25	404,83	69,03
40	25	20	144,60	17,97	471,52	71,21	65,72	9,19	247,94	68,64
40	50	0	130,69	17,42	383,07	69,05	78,03	9,22	341,53	68,88
40	50	20	121,30	17,53	410,99	69,47	63,26	9,14	410,53	68,27
			Clone 915005							
0	0	0	113,34	13,26	295,93	71,13	78,42	11,84	214,40	95,25
0	0	20	107,51	13,28	330,81	71,20	97,32	10,82	304,93	87,02
0	25	0	116,69	13,28	487,22	71,23	133,26	10,66	430,45	85,76
0	25	20	126,00	13,40	460,08	71,84	104,58	10,66	219,66	85,75
0	50	0	121,41	13,27	458,97	71,15	145,25	11,19	499,43	90,05
0	50	20	109,15	13,29	337,25	71,27	124,36	10,77	514,73	86,61
20	0	0	112,53	13,24	307,91	71,01	110,88	10,78	403,09	86,73
20	0	20	110,65	13,33	313,66	71,46	107,78	10,77	264,52	86,61
20	25	0	159,16	13,70	541,51	73,48	128,87	11,08	428,66	89,10
20	25	20	170,31	13,29	534,67	71,27	120,88	10,68	300,02	85,93
20	50	0	170,85	13,27	490,18	71,18	136,17	11,43	506,30	91,95
20	50	20	174,76	13,67	569,32	73,29	132,14	10,65	316,32	85,65
40	0	0	124,37	13,27	357,02	71,14	112,79	10,65	256,08	85,65
40	0	20	102,30	13,40	316,41	71,84	100,86	10,66	411,33	85,72
40	25	0	162,09	13,34	581,80	71,51	122,63	10,69	492,66	85,99
40	25	20	141,44	13,37	530,29	71,70	130,82	10,66	685,34	85,73
40	50	0	160,27	13,31	462,31	71,38	104,96	10,73	371,71	86,32
40	50	20	174,79	13,35	565,83	71,60	138,62	10,73	574,04	86,31
			Clone 915319							
0	0	0	27,76	10,36	71,65	69,17	34,60	6,07	75,04	97,40
0	0	20	25,59	12,54	49,53	83,42	30,88	5,59	101,43	89,74
0	25	0	32,12	10,13	242,05	67,32	38,33	5,99	144,72	96,07
0	25	20	30,31	10,14	170,70	67,35	30,39	5,82	150,94	93,37
0	50	0	37,91	10,13	165,64	67,34	31,98	5,65	170,26	90,67
0	50	20	34,32	10,26	137,35	68,44	31,90	5,60	203,55	89,76
20	0	0	26,73	10,16	118,69	67,65	37,01	5,61	171,13	89,91
20	0	20	41,08	12,76	129,16	85,03	34,82	6,26	135,33	100,35
20	25	0	56,23	12,56	183,52	83,52	46,36	5,70	161,84	91,49
20	25	20	62,84	10,38	303,64	68,94	36,98	5,59	181,35	89,70
20	50	0	50,71	10,18	235,00	67,60	65,38	5,95	451,57	95,51
20	50	20	67,51	10,48	313,81	70,09	60,61	5,64	402,79	90,49
40	0	0	23,10	10,16	111,08	83,89	39,19	6,13	153,40	98,32
40	0	20	35,13	10,24	253,97	68,02	27,99	5,59	82,05	89,68
40	25	0	67,07	10,23	309,11	67,92	43,09	6,22	156,12	99,77
40	25	20	49,54	10,31	201,62	68,80	34,68	5,63	174,78	90,38
40	50	0	35,73	10,24	171,28	68,00	39,13	6,08	120,86	97,49
40	50	20	60,81	10,16	187,19	67,60	46,50	5,65	266,23	90,66