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GROWTH OF TREE SPECIES AND HYDROLOGY IN MANAGED FORESTED PEATLANDS, QUEBEC

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Résumé

Le bilan hydrique des tourbières forestières est régi par une combinaison complexe de processus hydrologiques. Relativement stable en milieu naturel, ce bilan est facilement bouleversé par les activités d'aménagement forestier qui affectent le couvert végétal. Cette thèse de doctorat avait pour objectif d'étudier certaines interrelations existant entre la productivité forestière, la compétition pour les ressources et l'hydrologie des tourbières forestières du Québec.

Le premier chapitre visait à déterminer s'il était pertinent d'utiliser le drainage forestier afin de transformer des pessières noires improductives en sites productifs. Les résultats ont démontré que même si ce traitement avait significativement augmenté la croissance de certains arbres, seul le drainage intensif utilisant des fossés rapprochés permettrait la conversion de tels peuplements. Les quatre autres chapitres visaient à évaluer l'influence de la végétation sur le contrôle des processus hydrologiques et indirectement sur la croissance forestière. La nappe phréatique a été mesurée dans une tourbière forestière pré-mature afin d'évaluer son comportement à la suite du drainage et à la récolte (Chapitre 2). Des mesures comparables ont été effectuées afin de mesurer la remontée de la nappe phréatique causée par l'éclaircie précommerciale sur des sites humides drainées et fortement régénérés (Chapitre 3). Ces deux études ont démontré l'influence significative de la végétation forestière sur le contrôle de la nappe phréatique en milieux forestiers humides. Puisque cette végétation possède une influence évidente sur la nappe phréatique, la croissance d'une tige devrait être favorisée par la présence immédiate de voisins. Le rôle du drainage biologique (Chapitre 4) ainsi que l'effet de la présence de compétition (Chapitre 5) sur la croissance ont été évalués pour des sites drainés. Il a été démontré que le pouvoir de contrôle de la nappe phréatique que possède la végétation est favorable à la croissance forestière, mais uniquement dans certaines situations particulières. Il semble donc pertinent de recommander des pratiques sylvicoles qui préservent une proportion considérable de la végétation sur les tourbières forestières.

Abstract

The water budget of forested peatland sites is regulated by a complex combination of hydrological processes. Relatively stable in natural environments, this budget is exposed to major changes by forest management activities affecting the tree canopy. This Ph.D. thesis aimed to study the specific interrelations existing between growth and yield of tree species, above-ground competition, and hydrology of Quebec forested peatlands.

The first chapter aimed to determine the pertinence of using drainage to transform unproductive black spruce stands into productive ones. Results showed that even if tree growth was significantly increased by drainage, only intensive drainage using narrow ditch spacing would enable stand productivity improvement. The four other chapters intended to evaluate the influence of the vegetation on the regulation of hydrological processes and, indirectly, tree growth. The water table has been monitored on a pre-mature forested peatland site to evaluate its behaviour following drainage and harvesting (Chapter 2). Comparable water table monitoring has been done in densely regenerated post-harvest and drained peatland sites to measure the watering-up after precommercial thinning (Chapter 3). Both studies demonstrated the valuable water table regulation capacities of the treed vegetation in forested peatlands. Since this vegetation has an evident influence on soil growing conditions, tree growth should be affected by the presence of neighbours. The role of biological drainage (Chapter 4) and the presence of competition (Chapter 5) on growth have been evaluated for drained sites. The water table regulation power of the vegetation stratum was found to be favourable to tree growth, but only in specific situations. Management practices that preserve notable amount of vegetation on forested peatland stands seem to be the most pertinent guideline that should be considered in these fragile ecosystems.

Avant-Propos

Mon intérêt pour l'aménagement des milieux forestiers humides est né tout simplement. En tant que jeune étudiant motivé et prêt à tout pour acquérir de l'expérience, j'ai accepté en 1998 un emploi d'été nécessitant l'utilisation d'une bonne paire de bottes imperméables et d'une quantité importante de crème anti-moustique. J'ai donc passé mon été entre Matagami et Lebel-sur-Quévillon à rubaner des fossés de drainage dans des sites ayant été ravagés par des récoltes abusives, il y a plus de 20 ans, et aujourd'hui fortement paludifiés. Mon esprit critique s'est alors fortement manifesté en me faisant douter de la pertinence de mon travail. C'est alors que, pour la toute première fois dans ma vie, j'allais vérifier scientifiquement des hypothèses que j'avais moi-même formulées.

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Hannu Hökkä was the third mentor who gave me his full trust. When we first met, I was just a beginner but you discovered in me the germ of a competent researcher. You gave me an extraordinary opportunity to make it bloom. The Finnish journey Geneviève and I lived in 2001 was remarkable and we owe it to you. Paljon kiitoksia.

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Il serait difficile de dresser une liste exhaustive de tous les gens qui ont participé de près ou de loin à mes travaux de recherche au cours de mes études graduées tant ils sont nombreux. J'ai énormément apprécié votre aide et je vous en suis très reconnaissant. Affronter les hordes d'insectes piqueurs de toutes sortes, les longues heures de travail acharné sous des conditions climatiques souvent défavorables, les trous de « bouettes » mangeurs de bottes, ainsi que les milliers de kilomètres d'asphalte, de gravier, de boue et d'autres sentiers à peine carrossables n'auraient assurément pas été aussi agréables sans votre présence. Merci!

À mes parents, je voudrais une fois de plus exprimer ma gratitude pour leur support inconditionnel.

Geneviève, mon amour, ton dévouement pour moi et pour notre petite famille n'est pas passé inaperçu. Je suis un homme heureux. Je t'aime.

« J'te donnerais tout c'que j'ai mais c'pas sérieux parce qu'au fond,
tout c'que j'ai, c'est toi. »

Richard Desjardins; *Jenny ,* album *Kanasuta*

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General introduction

Being remarkable carbon and water reservoirs, peatlands have crucial ecological functions in our global environment. Recently, scientists from eastern Canada have been putting together their efforts to publish the most exhaustive book on peatland ecology of Quebec-Labrador (Payette and Rochefort 2001). The state of knowledge in peatland ecology, hydrology, geology, geography, forestry, agriculture and land management, among others, have been documented and synthesised meticulously. A complete chapter concerned peatland forestry and concluded with these comments:

> *Canadian boreal forested peatlands are important source of wood fibres for forest industries, therefore providing a substantial economical function. While the society claims for forest practices respectful of the vital functions of ecosystems, foresters recognise that peatland forestry should encompass practices adapted to their specific particularities. The lack of knowledge concerning the effects of perturbations on peatland hydrologic processes is considerably limiting our ability to evaluate the resilience capacities of these ecosystems.*
>
> *Prévost, Plamondon and Roy 2001*

Not long ago, great expectations were put on the beneficial effects of peatland management practices in Canada (Jeglum 1991). Many research projects were ongoing at that time but a rapid decline of interest occurred shortly after, leaving many unverified hypothesis. One of the reasons explaining this situation was the difficulty to observe significant changes in peatland black spruce growth on a short-term basis (Payandeh 1982, Sundstrom 1992, Sundstrom and Jeglum 1992, Prévost *et al.* 1999, Roy *et al.* 1999). Since the access to financial support for long-term experiments is very difficult (Hillman 1987, McLaren and Jeglum 1998), numerous research sites have ceased to be maintained. Moreover, the few scientific evaluations of drainage over periods exceeding 10 years showed deceiving results compared to what was first expected (Payandeh and Papadopol 1994, MacLaren and Jeglum 1998, Prévost *et al.* 2005). The resulting absence of forested peatlands management recommendations have left foresters with more unanswered questions than guidelines to follow. Since timber management activities are still broadly occuring on such forest sites, the conception of adapted management scenarios are still pertinent today, especially for the regenerating phase of the stands. The need of further investigation in forested peatland management is consequently a pertinent issue even though a manifest decline of interest has affected research on this subject in Canada since the mid-1990.

This doctoral thesis aimed at studying specific interrelations between growth and yield of tree species, above-ground competition, and hydrology of Quebec forested peatlands. The effect of drainage on the growth and yield of an unproductive peatland stand was evaluated in chapter 1. The impact of the canopy removal on the water table level of forested peatland sites have been evaluated in a previously drained mature stand (Chapter 2) and in a post-harvest and drained stand that was densely regenerated (Chapter 3). Then, the evaluation of the beneficial influence of neighbouring trees on each other's development was done by assessing the effect of neighbouring occupancy (Chapter 4) and above-ground competition (Chapter 5) on tree growth.

The large majority of the silvicultural practices adapted to forested peatlands in Quebec have been explicitly inspired by the noteworthy expertise earned in Fenno-Scandinavia through the last century (Paavilainen and Päivänen 1995). For example, the profitable growth reaction of Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.), and pubescent birch (*Betula pubescens* Ehrh.) to drainage in pre-mature or unproductive forested peatland stands (Seppälä 1969, Laine and Starr 1979, Hånell 1988) has motivated the use of this treatment throughout Canada. In North American boreal peatlands, drainage resulted in significant growth increases for black spruce (*Picea mariana* (Mill.) B.S.P.) and eastern larch (*Larix laricina* (Du Roi) K. Koch) (Dang and Lieffers 1989, McLaren and Jeglum 1998, Macdonald and Yin 1999). However, despite the response to drainage, black spruce still showed relatively small growth rates. Therefore, the long-term site productivity change provided by this treatment needed to be estimated before encouraging its extensive use. A few researchers attempted to estimate it (Stanek 1977, Payandeh 1973), but they published rather ambiguous results. In absence of clear recommendations, drainage of unproductive or pre-mature forests is still executed in

Quebec peatland sites. Hence, the first chapter evaluated the long term productivity of the oldest experimentally drained unproductive peatland stands of eastern Canada. The 18-year post-drainage stump diameter increment of black spruce was assessed in relation to ditch proximity and initial tree size. The change in site index that followed drainage operation was also monitored as a function of ditch proximity and was estimated over an 80-year period after drainage. While individual black spruce growth was expected to be significantly increased by drainage, substantial stand productivity gains did not seemed to be achievable on drained unproductive stand, even with optimistic assumptions.

Timber harvesting activities on undrained forested peatlands are known to create problems of water table rise (Dubé *et al.* 1995, Roy *et al.* 1997). The drastic reduction of the evapotranspiration is known as the principal cause of this watering-up (Dubé *et al.* 1995). Since tree establishment and growth are negatively affected by high water table levels (Lieffers and Rothwell 1986; Lieffers and MacDonald 1990; Landhäusser *et al.* 2003), corrective treatments will be needed to regenerate adequately those sites. Post-harvest drainage partly compensates for the watering-up and its effect varies with the distance from the ditch (Roy *et al.* 2000). Observations of watering-up have been made after clearcutting in forested peatlands previously drained in Finland (Heikurainen and Päivänen 1970, Päivänen 1980) but never beforein Canada. Up to now, neither the influence of distance to the ditch nor ditch spacing on the water table rise had been evaluated in such conditions. Therefore, the objective of the second chapter was to quantify the effect of harvesting on the water table level at five different distances from a ditch for three different ditch spacings in an old stagnant black spruce stand drained 10 years before clearcutting. The canopy removal, causing an important reduction of the evapotranspiration, was expected to drastically affect the site hydrological balance. Close to the ditch, the dominating influence of subsurface runoff over other hydrological processes was suspected to maintain the water table to the pre-harvest level. Farther away from the ditch, the water table was expected to rise.

The hydrological balance of mature forested peatland stands is strongly regulated by the evapotranspiration processes into which the treed vegetation plays an important role (Heikurainen 1967, Heikurainen and Päivänen 1970, Paavilainen and Päivänen 1995, Ahti and Päivänen 1997). Since recently harvested peatland stands are favourably regenerated after post-harvest drainage (Jutras *et al.* 2002, Prévost *et al.* 2005), stand density may be such that a release from competition may be required in the near future. As the vegetation re-establishes itself on harvested sites, evapotranspiration processes are gradually taking back their water table regulating role (Marcotte 2005). Precommercial thinning is actually the most important stand density treatment applied in Quebec's regenerated stands and guidelines bounding its application have never been evaluated for the specific situation of forested peatland sites. Since a large part of the hydrological balance of such sites is expected to be supplied by evapotranspiration, it was hypothesised that water-table level should increase after precommercial thinning. Thereafter, unfavourable growing conditions would be re-initiated. The third chapter evaluated the water table rise after precommercial thinning on post-harvest drained forested peatlands in relation to soil type, distance to the ditch, year of observation and other factors influencing the evapotranspiration processes. These were: basal area removal, residual basal area, water table depth, and observation day. The importance of the evapotranspiration as regulator of water table depth in regenerated stands was expected to be demonstrated in this chapter.

The re-establishment of dense and well growing vegetation after drainage is influencing the water table depth and it should consequently enhance the root-zone growing conditions. The beneficial effect of above-ground competition on tree growth have rarely been the direct object of scientific papers, but the existence of a biological drainage phenomenon in forested peatlands has been stated by different authors (Paavilainen and Päivänen 1995, Penner *et al.* 1995, Ahti and Päivänen 1997). Never studied in Canadian peatlands before, the effect of biological drainage on tree growth in post-harvest drained forested peatland stands has been the main objective of the fourth chapter. A retrospective annual diameter increment analysis was used to describe the influence of increasing tree neighbourhood occupancy on the growth of selected trees. Both the beneficial and detrimental effects of neighbourhood occupancy on tree growth were expected to be observed on the study site.

In order to extend such conclusions to a broader variety of forested peatland types, the fifth chapter intended to evaluate the positive and negative interferences of different levels of above-ground competition on black spruce growth in post-harvest drained forested peatland site types. The study areas used in Jutras *et al.* (2002), from which site specific growth reactions to drainage have been found, were re-analysed in combination to another experimental network of regeneration plots evaluating the establishment dynamics of black spruce's competitive tree species after drainage.

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CHAPTER 1

Draining an unproductive black spruce peatland stand: 18-year post-treatment tree growth assessment and future stand productivity estimation

Jutras, S.[1], Bégin, J.[1], Plamondon, A.P.[1], and Hökkä, H.[2] *To be submitted to Forestry Chronicle*. **Draining an unproductive black spruce peatland stand: 18-year post-treatment tree growth assessment and future stand productivity estimation.** [1]Faculty of Forestry and Geomatics, Université Laval, Ste-Foy, Québec, G1K 7P4, CANADA. [2]Finnish Forest Research Institute, Rovaniemi Research Station, P.O. Box 16, FIN 96301 Rovaniemi, FINLAND. *This chapter is the result of the candidate's labour. Jean Bégin, André Plamondon and Hannu Hökkä have been giving suggestions on the design and the preparation of this chapter.*

Abstract

In eastern Canadian boreal forest, drainage of unproductive black spruce peatland stands is a marginally used silvicultural treatment. The rare scientific literature concerning its influence on tree growth is moreover relatively enthusiast about the possibility to reach stand productivity. This study aimed to address this issue by assessing the individual tree growth and by estimating the future stand productivity on this type of drained site. Results showed larger mean annual post-drainage stump diameter increment with increasing ditch proximity but they also showed the minor effect of the treatment at distances greater than 15 m from the ditch. Small trees reacted more efficiently to the treatment than the larger ones. Estimated future stand productivity was also influenced by the ditch proximity. The unintended presence of excavating mounds on only one side of the ditch greatly influenced tree growth and site productivity. Considering the obtained results, intensive drainage operations, utilizing narrow ditch spacing, would be necessary in order to transform unproductive sites into productive ones. Using the estimated productivity rates, drained stands should yield, at maturity, relatively low merchantable volume.

Résumé

Le drainage de peuplements forestiers improductifs tels que les pessières noires sur sol organique est un traitement sylvicole marginal en forêt boréale de l'est du Canada. La littérature scientifique à ce sujet est rare et relativement enthousiaste à propos de la possibilité d'en obtenir éventuellement des peuplements productifs. Cette étude visait à clarifier cette possibilité en mesurant la croissance de tiges individuelles d'épinette noire et en estimant la productivité future d'un peuplement improductif drainé. Les résultats ont démontré des accroissements annuels moyens post-drainage en diamètre à la souche augmentant avec la proximité du fossé. Toutefois, ce traitement a peu d'effet à des distances supérieures à 15 m. Les petits arbres ont mieux réagi au traitement que les arbres plus gros. La productivité future a aussi été influencée par la proximité des fossés. La présence non planifiée de butons d'excavation sur un seul coté des fossés s'est avérée déterminante pour la croissance forestière et la productivité du site. En considérant les résultats obtenus, l'emploi de réseaux de drainage intensifs utilisant des espacements étroits entre les fossés semblerait nécessaire afin de rendre productif un peuplement improductif. En utilisant les taux de productivité estimés, les sites drainés devraient produire, à maturité, un volume marchant relativement bas.

Introduction

The periodically revived threat of stock rupture has brought Canadian foresters to think about different ways to avoid this undesirable eventuality. Managing slow-growing and unproductive boreal black spruce (*Picea mariana* (Mill.) B.S.P) peatland stands by draining them to achieve greater stand merchantability has been suggested by numerous authors in Alberta (Wang *et al.* 1985; Hillman 1987, 1991a, 1991b; Dang and Lieffers 1989; Hillman and Takyi 1998), in Ontario (Stanek 1968, 1977; Payandeh 1973a, 1973b, 1975, 1982, 1989; Rosen 1989; Jeglum 1991a, 1991b), in Québec (Stanek 1970; Nadeau and Parent 1982; Zarnovican 1989) and in Newfoundland (Heikurainen 1968; Pollett 1969; Päivänen and Wells 1978).

In Quebec, unproductive boreal peatland stands, by definition, support < 30 m³/ha of merchantable timber at 120 years (Saucier 1994). These stands have a site index of 3 m or less at 50 years (Payandeh 1978, 1990). They correspond to various ecological stand types, from treeless to sparsely wooded peatlands such as treed ombrotrophic bogs and extreme poor treed fens (e.g., Jeglum 1991c). According to the 3rd National Forest Inventory, unproductive peatland stands cover about 4 Mha, which represents 6.7 % of Quebec's total land cover under forest management. On these boreal sites, black spruce is the most abundant commercial tree species. Tamarack (*Larix laricina* (Du Roi) K. Koch), balsam fir (*Abies balsamea* (L.) Mill.) and eastern white-cedar (*Thuja occidentalis* L.) also are occasionally found in small numbers. The high water-table level and poor nutrient availability that characterise such sites severely limit tree growth (Payandeh 1973a; Leiffers and Rothwell 1986; Leiffers and Macdonald 1990).

Forest drainage is a silvicultural treatment that removes excess soil water through a network of inter-connected ditches, thereby lowering the water-table level of peatland sites (Heikurainen 1964; Paavilainen and Päivänen 1995; Lieffers and Rothwell 1987; Hillman 1992; Roy *et al.* 2000). Consequently, soil aeration will be improved, peat decomposition accelerated and nutrient availability increased (Lieffers and Rothwell 1987; Lieffers 1988; Prévost *et al.* 1997, 1999; Roy *et al.* 2000). Slow-growing black spruce subsequently can show enhanced annual diameter and height increments (Payandeh 1973a; Jutras *et al.* 2002; Prévost *et al.* 2005). The most favourable reactions to this treatment have been reported for small trees (Macdonald and Yin 1999) and for trees located in close proximity to ditches (McLaren and Jeglum 1998), while old and narrow-crowned trees are not likely to show response to drainage (Stanek 1968). Black spruce often has shown delayed growth reactions to improved soil conditions, with significant growth increments appearing only in the sixth year after drainage (McLaren and Jeglum 1998; Dang and Lieffers 1989). Consequently, most studies evaluating 5-year post-treatment black spruce growth have revealed no significant reaction to drainage (Payandeh 1982; Sundstrom 1992; Sundstrom and Jeglum 1992; Prévost *et al.* 1999).

In Canada, many papers have been published concerning the positive effects of forest drainage on tree growth in mid-rotation or pre-mature stagnant peatland stands. Some of the most enthusiast ones are however leaving readers perplex concerning the validity of their silvicultural recommendations (Stanek 1968; Nadeau and Parent 1982; Wang *et al.* 1985; Bolghari 1986; Zarnovican and Laberge 1994). Data selection often was questionable and the statistical analysis inappropriate, if not absent. Few well-designed, reproducible experiments have studied drainage of pre-mature stagnant peatland stands in the Canadian boreal forest (Payandeh 1973a; Stanek 1977; Dang and Lieffers 1989; McLaren and Jeglum 1998; Macdonald and Yin 1999; Prévost *et al.* 2005). When drainage is applied at mid-rotation on a relatively fertile, densely stocked, productive peatland stand, reasonable increases in stand yield can be expected (Payandeh 1973a; McLaren and Jeglum 1998; Macdonald and Yin 1999). However, no concrete management recommendations have originated from these studies. Also, very little is known about the potential transformation of unproductive peatland sites into productive ones, since only Stanek (1977) estimated the growth reaction of black spruce after drainage in such stands.

The effects of forest drainage on the quality of runoff water have been documented in Canada (Berry and Jeglum 1991a; Prévost *et al.* 1999). Even if on-site and downstream water quality is rarely degraded beyond acceptable limits when appropriate methods are used, environmental changes inevitably follow the drainage of peatland ecosystems. Ecological cautiousness and low anticipated financial returns have made drainage of unproductive and over-mature black spruce peatland stands a marginal treatment in eastern Canadian forests. With the currently renewed threat of stock depletion and the growing interest in intensive management (Coulombe *et al.* 2004), drainage may regain popularity in eastern Canada boreal regions where forested peatland stands cover wide areas. However, the extent of growth and productivity improvement due to this treatment is still undetermined. In the Canadian boreal forest, the oldest scientifically designed drainage experiments were established in the early 1980's (Hillman 1987; Paavilainen and Päivänen 1995). Determining stand productivity of drained unproductive peatland at maturity consequently requires monitoring periods exceeding the 20-year span of most study sites. In order to compensate for the lack of long-term information, Stanek (1977) used Plonski's (1974) yield tables while attempting to estimate the future yield of drained sites by monitoring alterations to the site index following drainage. Payandeh (1978) later demonstrated that the data used to create these yield tables grossly overestimated the true site index for short and old peatland black spruce stands, and suggested new height growth and site index formulae.

Using one of the oldest experimentally drained unproductive peatland stands of eastern Canada, we assessed the 18-year post-drainage stump diameter increment of black spruces in relation to ditch proximity and initial size. In this strongly uneven-sized slow growing stand, we hypothesised that black spruce diameter increment would be significantly greater for trees located in the first few meters from the ditch, and mainly for small-sized trees. The change in site index that followed drainage operations was monitored as a function of ditch proximity and was predicted over the 80-year period following drainage. We verified the hypothesis that, even with optimistic assumptions, stand productivity would not be achieved on this drained unproductive black spruce peatland stand.

Material and methods

The study area (49°28.7’N, 74°38.3’W) is located 60 km south of the town of Chapais, Quebec, Canada. In 1984, a 15 ha unproductive uneven-sized black spruce stand was drained for experimental purposes. This study site was part of a larger research project of the Ministry of Energy and Resources (Bolghari and Veilleux 1987), and was abandoned in 1993. Most information concerning the drained unproductive site and the network of permanent plots covering it was lost. However, the ditch network was still intact and the ecological descriptions of the sites were still available. Therefore, new experimental plots specifically designed to test the hypotheses were established in 2002.

The site was described as a *Chamaedaphne*-dominated peatland stand or OG14, using the Ontario Forest Ecosystem Classification for the Clay Belt, site Region 3e (Jones *et al.* 1983). Using the Quebec Forest Ecosystem Classification (Bergeron *et al.* 1998), the site was described as a *Picea mariana-Sphagnum* ombrotrophic peatland stand or RE39/LEG CAL SPS. The tree layer consisted exclusively of black spruce. The shrub layer was characterized by the presence of abundant *Chamaedaphne calyculata* (L.) D. Don. and *Rhododendron groenlandicum* (Oeder) Kron & Judd , as well as *Kalmia polifolia* Wang., *Kalmia angustifolia* L. and *Andromeda glaucophylla* Link. The moss layer was dominated largely by *Sphagnum flexuosum* Dozy & Molk., *S. fuscum* (Schimp.) Klinggr. and *S. magellanicum* Brid.; *Pleurozium schreberi* (Brid.) Mitt. was present in smaller proportions. The soil consisted of a deep organic layer (> 0.9 m) composed of weakly decomposed sphagnum moss. The thirty-year mean annual precipitation, temperature and degree-days above 5ºC, which were obtained from the “Chapais 2” meteorological station (49º46'N, 74º51'W), are 961.3 mm, 0.0ºC and 1235 degree-days, respectively (Environment Canada 2004).

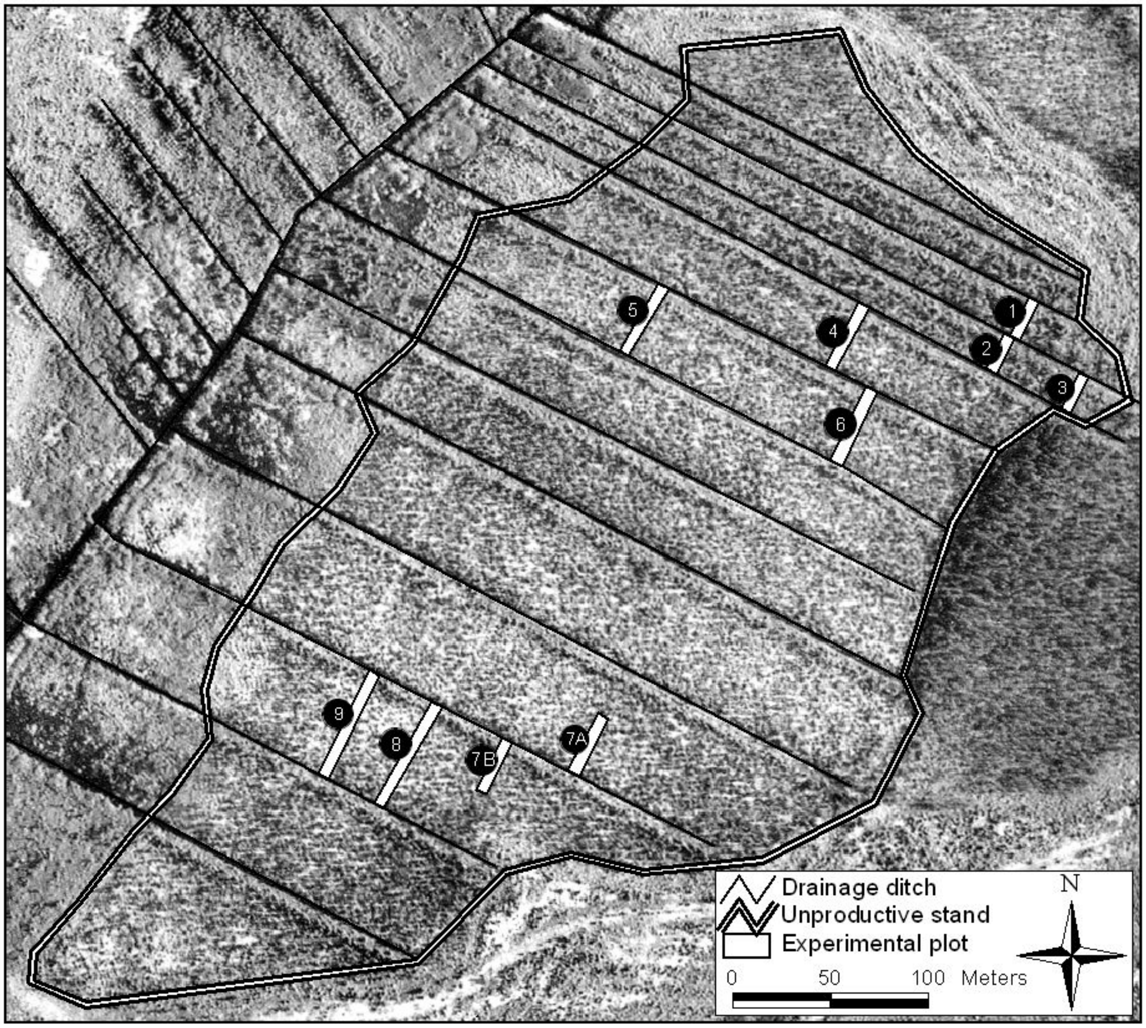

Figure 1. Map of the drained unproductive black spruce peatland stand, showing the numbered experimental plot locations. *Aerial photography #Q98509-149, June 1998. © Gouvernement du Québec*

Drainage had been executed using an excavator equipped with a "V"-shaped bucket. Overall, 12 secondary ditches, 0.9 m deep by 2 m wide and totalling 4 km in length, represented three different ditch spacings (20, 40 and 60 m) (Fig. 1). All excavated material was arranged in mounds of varying dimensions (1-3 m radius, 0.5-1.5 m high), and located at random along the south-western side of ditches. Three rectangular shaped plots, 6 m wide and ditch-to-ditch length, were established in 2002 for each ditch spacing (Fig. 1). All plots were positioned randomly to avoid superimposition of the previous experiment material with the new ones. All trees > 1.3 m in height in 2002 were located geographically in each plot using graduated tapes. For each tree, the distance to the center of the closest ditch (DIST) was measured at the nearest 5 cm. A categorical value described which ditch was used as reference (i.e., the closest ditch) by relating its slope position (DITCH: UP or DOWN). All trees were felled and a wood disk was collected at stump height (H = 0.3 m). The 5-year pre-drainage diameter increment (1979-1984) and the 18-year post-drainage diameter increment (1984-2002) were determined from rings in 1979, 1984, and 2002, which were measured on two perpendicular radii of the air-dried and sanded wood discs. Dendrochronological measurements were executed with a scanner and the WinDendro™ system (Regent Technology Inc., Sainte-Foy, QC, Canada) or a micro-metric table. The diameter distribution of the 967 black spruce that were measured in 1984 confirmed the uneven-size structure of the stand.

For each felled tree, total height was measured at the nearest cm. The height at the time of drainage was estimated by counting down annual whorls on the stem. Since the exhaustive assessment of annual whorl scars was rather imprecise, especially for slow growing trees, a second disc was collected under the estimated 1984 whorl for all trees. After being air-dried and sanded, these discs were used to confirm or adjust the 1984 height estimates. Mean stem characteristics of the treated plots are summarised in Table 1.

Table 1: Black spruce diameters at stump height (DSH), stem heights (H) and ages at stand drainage (1984) and 18 years after drainage (2002), together with mean pre- and post-drainage annual diameter increments.

		1984			2002			Mean annual stump diameter increment (mm/y)	
Plot	Spacing (m)	DSH (cm)	H (m)	Age (y)	DSH (cm)	H (m)	Age (y)	1979-1984	1984-2002
1	20	1.5	1.58	45	3.9	3.31	54	0.38	1.37
2	20	1.4	1.34	42	3.3	2.70	54	0.39	1.11
3	20	1.7	2.57	37	4.6	3.74	49	0.55	1.64
4	40	2.9	2.32	58	4.6	3.68	74	0.41	0.93
5	40	2.7	2.27	58	4.4	3.48	73	0.41	0.93
6	40	2.7	2.32	48	4.1	3.35	63	0.44	0.77
7	60	2.8	2.29	48	3.9	3.25	65	0.45	0.63
8	60	2.6	2.00	45	3.8	3.07	62	0.49	0.70
9	60	2.7	2.15	50	3.8	3.01	66	0.40	0.62
All		2.5	2.13	49	4.0	3.23	63	0.43	0.85

Diameter growth assessment

Individual tree mean annual stump diameter increment for the 18-year post-drainage period (ADI84-02) was expressed as a function of the diameter at drainage (D84) by means of analysis of covariance (ANCOVA). Logarithmic transformation of ADI84-02 and D84 were used to satisfy assumptions of normality and homogeneity of variance and to obtain a linear relationship between the two variables. The distance to the closest ditch (DIST), susceptible to express a non linear relationship with the response variable, was tested in the model with various transformations such as DIST, DIST^2, $\text{DIST}^{0.5}$, DIST^{-1} and ln(DIST). The reference ditch (DITCH: UP or DOWN) was used independently and in interaction with diameter and distance variables in the model. Growth variation between ditch spacings and plots were considered as random variables in the model. The MIXED procedure of SAS 9.1 (SAS Institute Inc., 2003) was used to perform the statistical analysis. All fixed and random parameters of the model were estimated simultaneously using the restricted maximum likelihood method. A level of significance of 5 % was used throughout this study. Selection of each explanatory variable or interaction was based on its significant influence on the response variable and its influence on the -2·log-likelihood value of the entire model. Minimising AIC (Akaike's Information Criterion) was an additional step used in selecting the final model.

Stand productivity estimation

By enhancing soil growing conditions, forest drainage should positively affect site productivity of forested peatlands. Site index, i.e., tree height at a given age, is commonly used to estimate site productivity. It is measured on a sub-sample of dominant or codominant stems selected within a plot, and normally necessitates the measurement of their height and age. When using changes in site index to evaluate the effect of a treatment on productivity, it is assumed that the status of the selected stems forming the dominant and codominant layers remained the same throughout time (Payandeh 1978; Hökkä and Ojansuu 2004). Since drainage is known to reduce size inequity of uneven-sized black spruce peatland stands (Macdonald and Yin 1998), the previous assumption might not be appropriate for the study area. It is preferable that site index should incorporate changing hierarchical height structure of these stands instead of being considered stable in time. This can be achieved by selecting the most dominant stems during each period of measurement and not restricting stem selection to the ones selected during the previous measurement. This site index estimation method was considered adequate to compensate for the low degree of reaction to drainage of large stems forming the dominant layer compared to that of smaller stems.

Future stand productivity was estimated for an 80-year period after drainage. This estimate required the calculation of individual tree heights for time periods beyond the 18-year period of observation. In order to determine the height growth of each tree with reasonable confidence, Payandeh's (1978) black spruce peatland height growth curve was used (Eq. 1).

$$[1] \qquad H = b_1 \cdot SI^{b_2}\left(1 - e^{-b_3 \cdot A}\right)^{b_4 \cdot SI^{b_5}}$$

Where H is the measured height at a given age; SI is the site index, i.e., the total tree height at 50 year; A is tree age measured at stump height (30 cm); b_1, b_2, b_3, b_4, and b_5 are parameters corresponding to 16.2149, 0.1496, 0.01326, 4.6602, and 0.5787 respectively;

Future tree height growth was assumed to be reasonably related to the observed 18-year post-drainage tree height growth increment. This assumption meant that the 18-year selected period of observation was representative of new site productivity and that the effect of drainage which occurred during this period would remain constant through time. Even if this statement is a working hypothesis, it appears the most appropriate for the following reasons. First, post-drainage height growth should provide a reasonable estimate of site productivity since it includes the growth reaction delay and the maximum growth effect of the treatment, which was occurred between 13 to 19 years after drainage (Dang and Lieffers 1989). Second, this 18-year average growth response is likely to be maintained for up to 40 years following treatment since ditches normally show reduced water flow capacities after 30 to 40 years. Flow reduction is due to ditch deterioration caused by peat subsidence, wall collapse and erosion (Paavilainen and Päivänen 1995). Hence, the expected height growth projected for the 80-year period after drainage is rather optimistic.

Since it was technically impossible to isolate SI from equation 1 (Payandeh 1978), an iterative method was used to estimate 18-year post-drainage site productivity. Equation 1 was modified (Eq. 2) to enable height prediction in 2002 from tree height in 1984 and for numerous values of site index (0.1 to 15 m, in 0.1 m increments). The site index value corresponding to the smallest absolute difference between predicted and observed height in 2002 was selected as the exact post-drainage site index. Individual tree heights were later estimated with equation 2 using the post-drainage calculated SI (1984-2002) for time periods corresponding to 30, 40, 50, 60, 70, and 80 years after drainage.

[2] $$H_{1984+x} = b_1 \cdot SI^{b_2}\left(1-\left(\left(\left(-\left(\frac{H_{1984}}{b_1 \cdot SI^{b_2}}\right)^{\left(\frac{1}{b_4 \cdot SI^{b_5}}\right)}+1\right)\cdot e^{-b_3 \cdot x}\right)\right)^{b_4 \cdot SI^{b_5}}\right)$$

Where H_{1984+x} is the predicted height x years after drainage; H_{1984} is the height at the moment of drainage; SI is the site index; b_1, b_2, b_3, b_4, and b_5, are parameters appearing in eq. 1;

Past, present and future site productivity of the stand was estimated with respect to the distance classes and the reference ditch. The mean height and age of the three tallest stems located in each sub-plot (6 m wide by 10 m large) was calculated for 0, 18, 30, 40, 50, 60, 70, and 80 years after drainage. The site index (SI) was calculated with the help of Payandeh's (1978) site index formula (Eq. 3).

[3] $$SI = 0.01835 \cdot H^{-0.18861}(1-e^{-0.00009 \cdot A})^{-0.81174 \cdot H^{0.1831}}$$

Where SI, H, and A as defined in eq. 1;

Results

The statistical analysis demonstrated the significant influence of initial stem dimension, the distance to the ditch, and the reference ditch used on black spruce growth (Table 2). The mean stem characteristics showed small variations between plots (Table 1), which were accounted for in the model by the plot random effect. This random effect almost showed a significant effect ($p = 0.0882$).

Table 2: Analysis of covariance (ANCOVA) of the 18-year post-drainage mean annual stump diameter increment (ln(ADI84-02)).

Source of variation	df	*F* value	*p* value
Fixed variables			
ln(D84)	1	45.94	<0.0001
DITCH	1	24.09	<0.0001
ln(D84) × DITCH	1	16.40	<0.0001
DIST	1	41.66	<0.0001
$DIST^{0.5}$	1	54.31	<0.0001
$DIST^{-1}$	1	19.93	<0.0001
DIST × DITCH	1	12.59	0.0004
$DIST^{0.5}$ × DITCH	1	16.92	<0.0001
$DIST^{-1}$ × DITCH	1	19.70	<0.0001
Random effects			
Spacing	2		0.2332
Plots	8		0.0882
Residual error	914		
Corrected total	931		

The diameter at drainage (ln(D84)) and the ln(D84) × DITCH interaction significantly influenced the mean post-drainage annual stump diameter increment (ln(ADI84-02)) (Table 2). Small trees exhibited larger diameter increments than did large trees (Fig. 2). Trees with distances associated with the UP-slope ditch showed fewer differences in growth between small and large stems than those that were measured towards the DOWN-slope ditch. Trees exceeding 0.5 cm of stump diameter showed greater annual stump diameter increments when located on the UP-slope position compared to the DOWN-slope position.

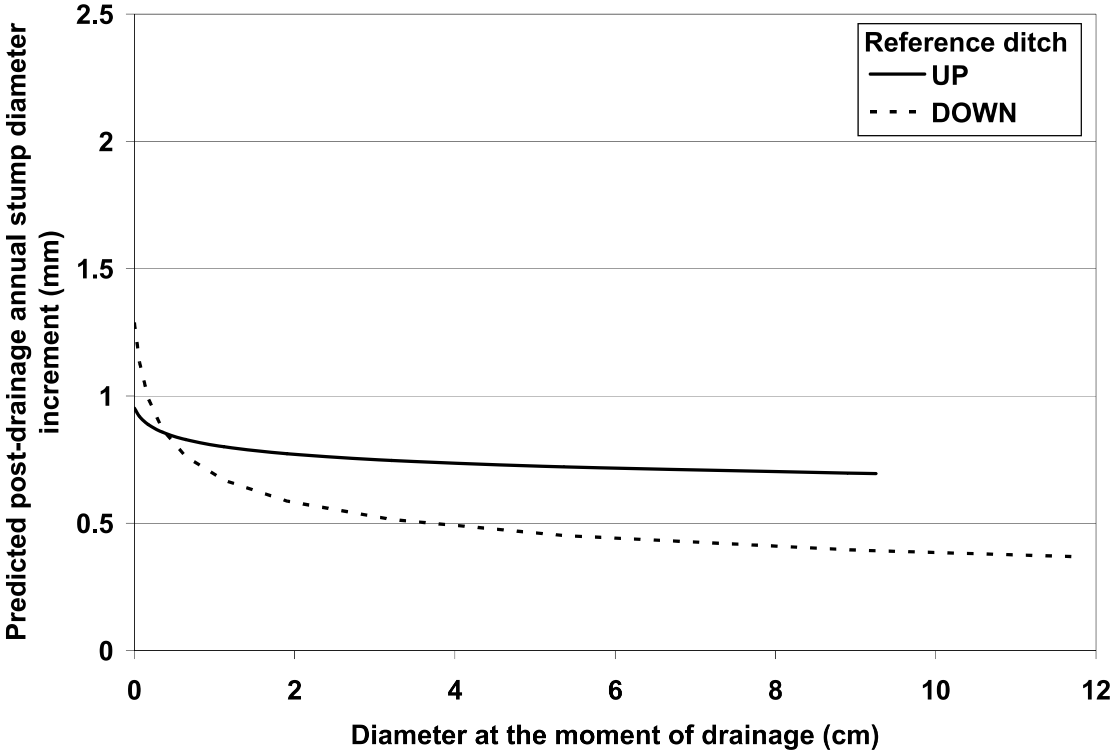

Figure 2. Initial black spruce dimensions as a tree growth factor on a drained unproductive peatland stand. Values were estimated for a fixed distance to the center of the ditch (mean distance = 11.68 m).

DIST, $DIST^{0.5}$, $DIST^{-1}$ and their respective interactions with DITCH were all found to have significant influence on the dependent variable (Table 2). The difference in growth reaction with respect to DITCH was evident within the first 15 m from the ditch (Fig. 3). The highest diameter increments were observed for trees located around 2.5 m from the UP-slope ditch. Trees found on the DOWN-slope side reacted to drainage only within the first few meters from the ditch (Fig. 3). Trees that were located farther than 15 m from a ditch showed comparable diameter growth for both DITCH classes.

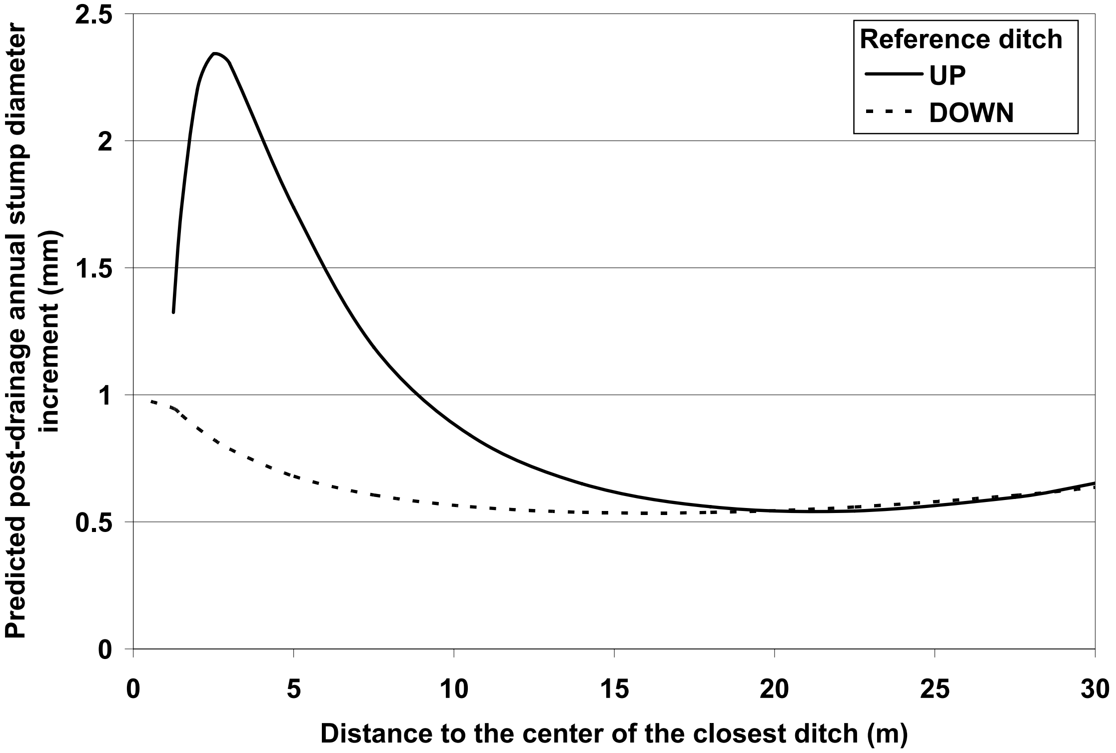

Figure 3. Effects of ditch proximity on black spruce growth in a drained unproductive peatland stand. Values were estimated for a fixed diameter at drainage (Mean diameter = 2.48 cm).

Calculated values of SI were plotted as a function of the distance from the closest ditch, the reference ditch and time since drainage (Fig. 4). Values observed in 1984 had a maximum of 3.1 m but averaged 2.5 m. Site index values generally rose with time. The highest SI value was obtained 60 years after drainage from 0 to 10 m from the center of the UP-slope ditch.

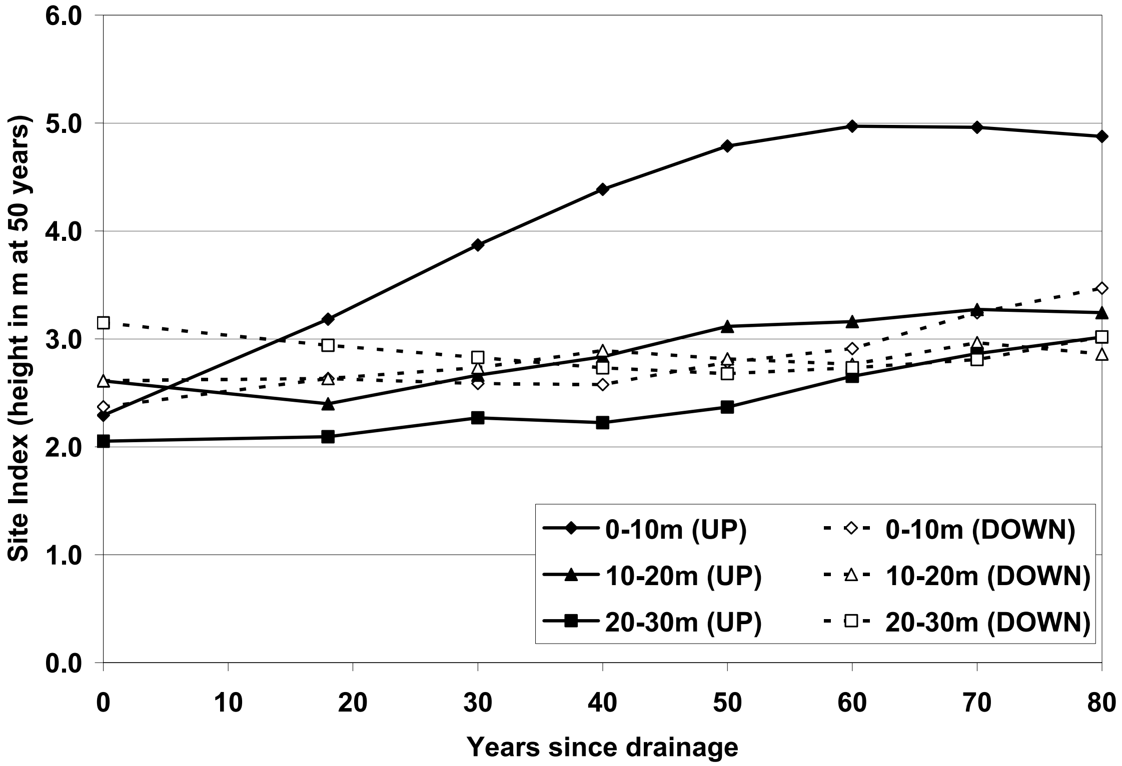

Figure 4. Site productivity estimation for a drained unproductive black spruce peatland stand over an 80-year post-drainage period. Classes of distance to the center of the closest ditch (0-10 m, 10-20 m, 20-30 m) and the reference ditch (UP or DOWN) were used to classify the observations. Actual SI values were measured at year 0 and 18, while they were predicted for year 30 and beyond.

Discussion

Diameter growth assessment

When interpreting the results concerning the post-drainage mean annual stump diameter increment, it seemed obvious that the reference ditch have played a very important role. This factor revealed significant differences in tree growth reaction following drainage. It appears, however, that this factor was not taken into consideration in the original experimental design since the presence of excavated soil mounds were systematically found on the same side of the ditches. The improperly replicated mound locations made it impossible to exactly determine the effect of DITCH influence on tree growth. It could have been the consequence of varying soil conditions that were triggered by differing shapes of the water-table along each side of the drained strip. For example, the commonly observed arch-shaped form of the water-table height between two ditches (Berry and Jeglum 1991b; Hillman 1992; Prévost *et al.* 1997) can be slightly tilted, showing lower water-table levels on the high side of the drained strip compared to the low side (Braekke 1983). Therefore, on our gently sloped study area (> 0.5 % slope), only small differences between water-table levels on opposite sides of the drained strip would have prevailed. Consequently, the possible differences in water-table shape along each side of the drained strip might have only resulted in minor differences in tree growth.

The most probable explanation for the observed tree growth difference with respect to the reference ditch was the systematic presence of excavation mounds located between 2 and 6 m from the center of the uppermost ditch. These mounds, made of dark and well decomposed peat, could have enhanced local soil conditions by leaching nutrients into the soil. On the DOWN-slope ditch side, soil conditions were likely enhanced only by lowering of the water-table caused by drainage, since excavated material was never laid on this side of the ditch. Tree growth and site productivity differences observed between UP and DOWN-slope positions of the reference ditch were consequently largely attributed to the presence of excavating mounds on the UP-slope ditch side.

The observed higher diameter growth of small trees compared to that of larger ones (Fig. 2) was consistent with some observations from other drainage experiments (Dang and Lieffers 1989; Macdonald and Yin 1999). Small trees, which were normally represented by young stems with vigorous green crowns, logically had superior abilities to take advantage of new soil conditions induced by drainage compared to large trees. Larger trees often were represented by old and stagnant stems showing narrow tufted living crowns. However, the small growth difference observed between small and large stems located close to the UP-slope ditch revealed that, in these sections of the drained site, drainage might have more equitably affected the growth of all stems. In the absence of excavation mounds, i.e., DOWN-slope, large stems generally showed annual stump diameter increments lower than 0.5 mm/y, a result comparable to pre-drainage growth increments (Table 1).

The arch-shaped form of the water-table between two ditches is the principal cause of gradually enhanced soil growing conditions with increasing ditch proximity (Roy *et al.* 2000). Most studies that assess lowering of water-table levels following drainage in organic soils have demonstrated that the significant effect of this treatment was limited to the first 10 to 15 m from the ditch (Belleau *et al.* 1992; Prévost *et al.* 1997; Jutras and Plamondon 2005). The mean annual stump diameter increments measured in our study reacted accordingly to the known spatially limited effect of drainage. Tree growth was high from 0 to 15 m from the ditch and it varied as a function of the ditch proximity. However, 15 to 30 m from the ditch, measured diameter increments showed low and constant values regardless of the distance to the ditch or the reference ditch used. These observations confirmed the absence of drainage effects farther than 15 m from the ditch.

Drainage enhanced growth within the first 15 m from the ditch, but important variations were observed with respect to the ditch used as reference. On the DOWN-slope ditch side, the highest diameter increments were found within the first 5 m from the ditch, showing evidence of the spatially restricted amelioration of the soil growing conditions caused by water-table drawdown in weakly decomposed organic soils. On the opposite side of the plot (DITCH = UP), higher diameter increments were observed since trees were simultaneously influenced by the effect of drainage and the presence of decomposing organic mounds. The rapidly rising diameter growth between 1.5 and 2.5 m from the UP-slope ditch could mainly be explained by modelling shortcomings. In presence of only the DIST and $\mathrm{DIST}^{0.5}$ factors in the model, tree growth would rise exponentially with increasing ditch proximity. The DIST^{-1} factor was mainly responsible for limiting the exponential shape of the curve, but diameter growth was underestimated for very low values of distance to the ditch. Biased growth estimation by the model could also have been caused by the poor representation of very low distance to the ditch values within the data set. Observations found in this specific area (DIST < 2.5 m, DITCH = UP) represented only 4% of the whole data set. From 2.5 to 15 m, the mean annual stump diameter increment gradually decreased, following the pattern of average water table level across the strip which has been observed in several studies (Berry and Jeglum 1991b; Hillman 1992; Prévost *et al.* 1997).

The results that we obtained confirmed our first hypothesis, since black spruce diameter increment was significantly greater for small-sized compared to large-sized trees and for trees located in the first few meters from the ditch compared to ones located farther away. Moreover, the influence of excavation mounds on tree growth was pronounced, since post-drainage mean annual stump diameter increments showed very important differences with respect to the presence or absence of such mounds.

Stand productivity estimation

Periodic calculations of SI that were executed for 1984 confirmed the unproductive state of the treated site at drainage. The highest SI estimate of 3.1 m corresponds to a merchantable volume at 120 years of 30.9 m^3/ha, a value which barely meets Quebec productivity criteria (Saucier 1994). After drainage, site productivity was considerably enhanced for the 0-10 m UP-slope class, where the highest individual post-drainage tree growth was observed. The determination of future SI values was strongly influenced by the very rapid growth of small trees, which quickly out-grew stems that were dominant in 1984. Estimated future SI for the 0-10 m UP-slope distance class showed a gradual increase in site productivity that reached a maximum value of 5.0 m, which corresponds to an expected merchantable volume at 120 years of 125 m^3/ha (Payandeh 1990). This calculated yield does not consider the physical presence of open ditches where trees will never grow. Considering the average width of a ditch, a one meter large strip of land should be subtracted, thereby reducing the merchantable yield of the 0-10 m classes by 10%. Moreover, if a realistic maintenance scenario is planned, ditches will need to be cleaned after a few decades to sustain their water flow capacities. The necessary passage of the excavation machinery required for ditch maintenance will destroy vegetation encountered within the first 2 meters on each side of the ditch, reducing the productive area of the 0-10 m classes by a further 10%. In such situations, it would be reasonable to expect a maximum merchantable volume at 120 years of 100 m^3/ha in the 0-10 m UP-slope class and of 42.7 m^3/ha in the 0-10 m DOWN-slope class. In all other distance classes (10-20 m and 20-30 m), SI barely surpassed the productivity criteria, even 80 years after the treatment. The restricted influence of drainage on the individual growth of trees located farther than 10 m from the center of the ditch was responsible for this unchanged site productivity.

We rejected our second hypothesis since we believed at first that, with optimistic assumptions, site productivity would never be reached on a drained unproductive black spruce peatland stand. The contrary behaviour was observed, but only within the first 10 m from the center of the ditch. This spatially limited reaction could possibly generate a productive stand, but precise prediction of future yields remains an optimistic estimate which needs to be considered with caution.

Conclusion

Individual tree growth and site productivity were favourably enhanced by drainage on the unproductive black spruce peatland site under study. However, the influence of drainage was limited such that only narrow ditch spacing would enable the transformation of entire sites into productive stands. Before supporting the use of intensive drainage in unproductive black spruce peatland sites, it would be appropriate to evaluate its economic profitability and environmental impacts. In the absence of appropriate information concerning these subjects, we would urge caution and suggest that such treatments should not be undertaken.

Acknowledgements

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CHAPTER 2

Water-table rise after harvesting in a treed fen previously drained for forestry

Jutras, S., and Plamondon, A.P. 2005. **Water-table rise after harvesting in a treed fen previously drained for forestry**. Suo. 56(3): 95-100. Forest Biology Research Centre, Université Laval, Sainte-Foy, QC, G1K 7P4, Canada. *This chapter is the result of the candidate's labour. André Plamondon has been giving suggestions on the design and the preparation of this chapter.*

Abstract

Water-table measurements were obtained in a treed fen that was drained in 1987 and harvested for timber in 1997. The water-table level was quantified at five different distances from the ditch for three ditch spacings. Water-table levels were compared between post-drainage and post-removal of the canopy. The phenomenon of watering-up after clear-cutting did not occur where a drawdown of at least 10 cm was caused by the drainage. This lowering was observed across the 20 m ditch spacing and within the first 6 m from the ditch, in the 40 and the 60 m spacings. The water-table fluctuations were also reduced after harvesting.

Résumé

La profondeur de la nappe phréatique a été mesurée pendant plusieurs saisons de croissances dans une tourbière forestière ayant été drainée en 1987 et récoltée en 1997. Le niveau de la nappe phréatique a été quantifié à cinq différentes distances du fossé, pour trois différents espacements et pour deux différentes périodes (post-drainage et post-récolte). La remontée de la nappe après la récolte n'est pas survenue aux endroits où un rabattement d'au moins 10 cm avait été préalablement causé par le drainage. Un tel rabattement a été observé partout pour l'espacement de 20 m et uniquement à moins de 6 m des fossés pour les espacements de 40 et 60 m. Les fluctuations annuelles de la nappe ont aussi été réduites après la récolte.

Introduction

Water-table rise, also called watering-up, has been observed on undrained forested peatlands in Canada after timber harvesting (Dubé et al. 1995, Roy et al. 1997, Roy et al. 2000b). Observations of watering-up have also been made after harvesting in forested peatlands previously drained in Finland (Heikurainen & Päivänen 1970, Päivänen 1980). Drainage on recently harvested sites is known to reduce watering-up (Prévost et al. 2001), to avoid further paludification, to improve rooting zone conditions (Roy et al. 2000a), and to improve seedling growth (Jutras et al. 2002). Vompersky & Sirin (1997) and Braekke (1983) found that the water-table depth in a drained peatland was largely dependent on the distance from the ditch and drainage intensity. However, these two factors have not been studied when drainage occurred several years before harvesting.

The objective of this study was to quantify the effect of harvesting on the water table level at five different distances from a ditch (3, 6, 10, 20 and 30 m) for three different ditch spacings (20, 40 and 60 m width) in an old stagnant black spruce (*Picea mariana* (Mill.) B.S.P.) stand drained 10 years before clearcutting.

Material and methods

The study was carried out on property owned by Stadacona Paper Inc, located 50 km southwest of Quebec City, Quebec Canada, (46º27'N, 71º23'W). Based on data collected at the St-Flavien meteorological station located 10 km from the study site (46º29'N, 71º34'W), the thirty-year mean annual precipitation is 1125 mm (Environment Canada 2004). For this same period, the mean annual temperature is 3.9ºC and the mean annual degree-days above 5ºC is 1674. Potential evapo-transpiration is 550 mm based on Thornthwaite's method (Wilson 1971)

This project evaluated two sites, a treated one and a control. They were located 270 m apart in a stand dominated by black spruce. Other tree species that were present included larch

(*Larix laricina* (Du Roi) K. Koch), balsam fir (*Abies balsamea* (Mill.)) and red maple (*Acer rubrum* L.). *Nemopanthus mucronatus* (L.) Trel., *Kalmia angustifolia* L. and *Ledum groenlandicum* Retz. dominated the shrub layer. On both sites the degree of humification of the *Sphagnum* peat layer increased with depth, ranging from a Von Post 7 at 10 cm to a Von Post 10 at 60 cm. On the drained site, this humified peat lay over a 20 cm layer of slightly less decomposed *Carex* spp. The underlying fine textured mineral soil of both sites was originating from the post-glacial Champlain Sea. Table 1 presents stand and peat characteristics of both sites.

Table 1: Site characteristics before drainage.

	Mean peat characteristics		Mean stand characteristics		
Treatment	Thickness (m)	pH	Age (year)	Diameter (cm)	Height (m)
Control	0.45	3.5	48	11,1	11.2
Drained	1.00	3.3	94	11,0	11.7

The control site was left undrained and unharvested during the study. The treated site was drained in April 1987 by digging five parallel parabolically-shaped ditches, 1 m deep, at 20, 40, 40 and 60 m spacing, respectively (Figure 1). The water was discharged through a roadside ditch. The drained site was harvested ten years later (January 1997) on frozen ground thereby protecting the regeneration and the soil. The trees were felled with chain saw and transported with a grapple skidder. The estimated harvested merchantable volume was approximately 60 m^3/ha.

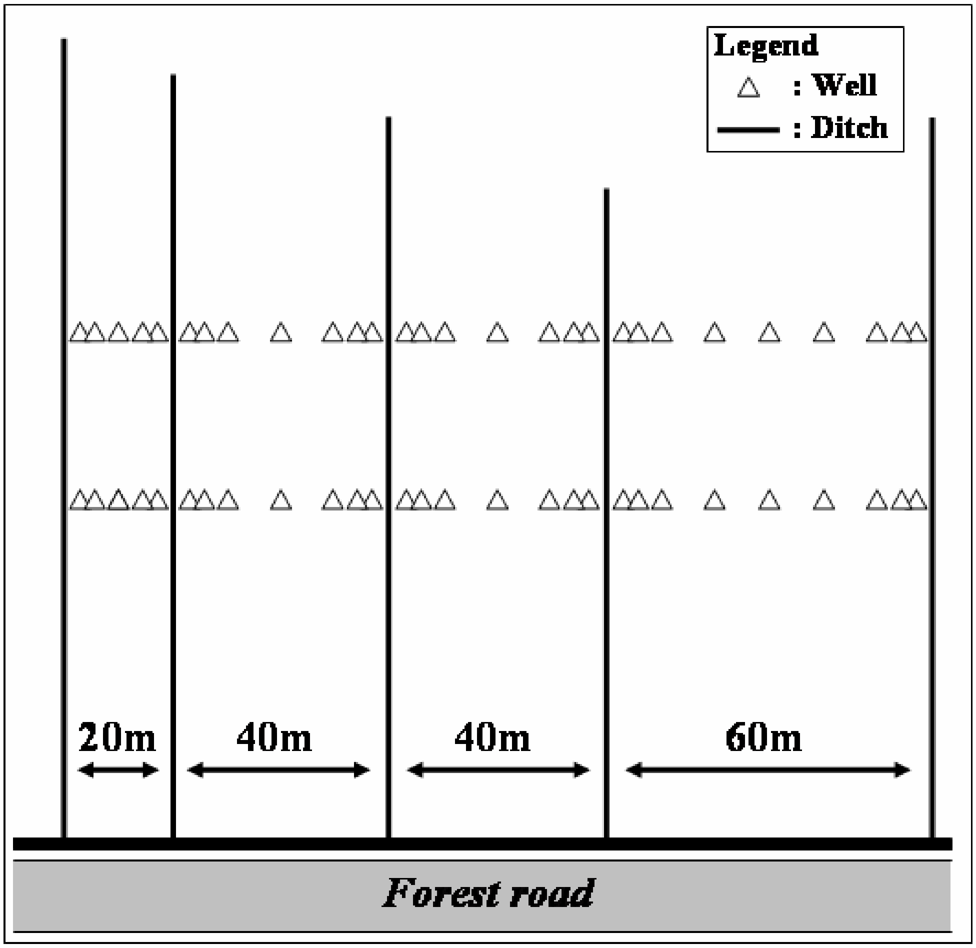

Figure 1: Drainage and sampling design on treated site.

Water-table depth was measured in individual wells that were constructed from plastic tubes (20 mm inner-diameter) perforated at the base with 5 mm diameter holes and inserted 1 to 1.5 m into the soil. Two rows of wells were located 20 m apart and parallel to the roadside ditch. Tubes within each row were located at 3, 6, 10, 20 and 30 m from each ditch, where spacing permitted (Figure 1). The wells were visibly identified on site and mapped in order to replace them in case of damage during harvesting. The depth of the water-table level was measured using a home-made electrical buzzer probe that signalled contact with water. Prior to any treatment, water-table depth was measured from September 15 to November 1 in 1986 on both sites. Following the drainage, measurements were made during the growing season, normally from the beginning of May to the end of October. This was done twice weekly from 1987 to 1989 and once weekly until 2000 except in 1991, 1992 and 1995 when no measurements were taken. In 1999 measurements were done bi-weekly. The elevation of the well above the peat was measured every year so that the water table depth was referenced to the peat surface.

Pre-drainage water-table depths were used by Belleau et al. (1992) to produce a calibration curve for this same study area. It was used to take into account the differences in water-table fluctuations and tree stand characteristics naturally occurring between the control and the treated sites. However, the curve had to be adjusted for deeper water-table levels because it was relatively high during the calibration of 1986. At the center of the 60 m spacing, the water-table drawdown caused by drainage was negligible. Therefore, the 1987 to 1989 summer data from this location was used to establish a new calibration curve (Figure 2). This curve was later used to predict the water-table depth for the treated site if no treatment was applied (PWTno) using the water-table depth of the control site. The possible bias caused by this calculation would give a slight underestimation of the drainage effects. However, it had no effect on the comparison of water-table depths before and after harvesting.

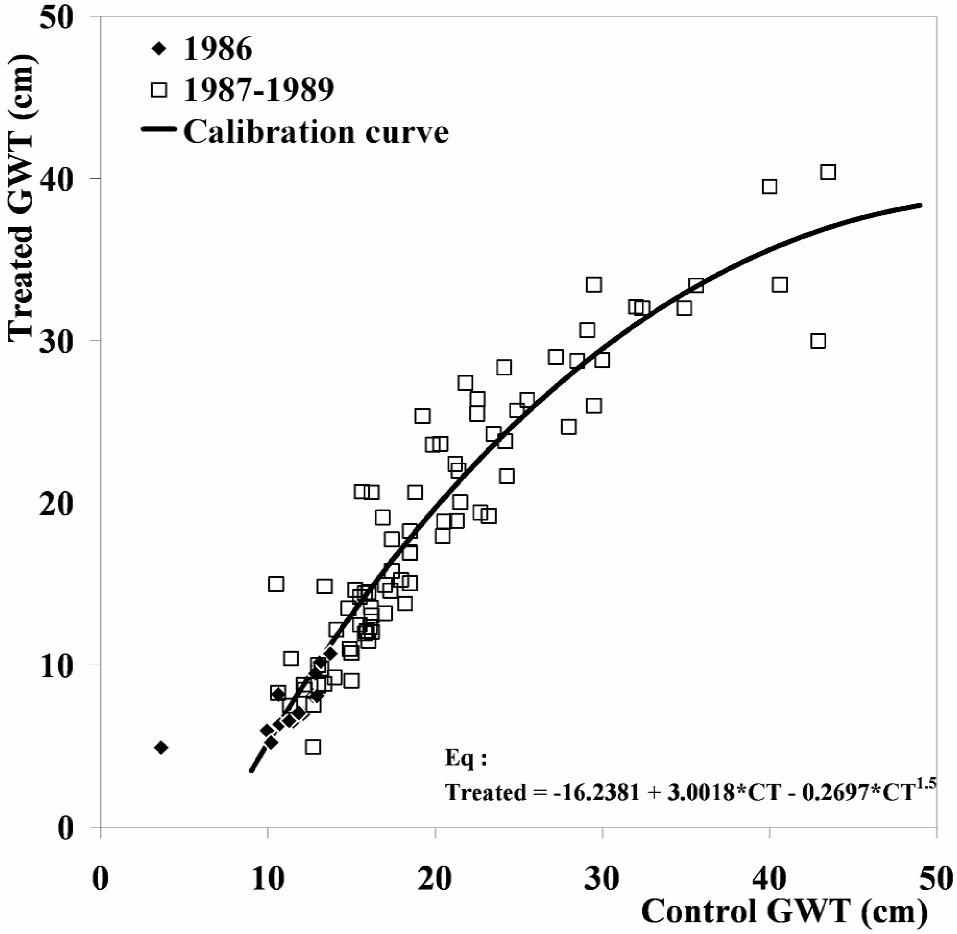

Figure 2: Calibration curve of the water-table depth for the treated site without drainage effect and the water-table of the control site. Treated water-table from 1986 was collected before drainage. From 1987 to 1989, it was collected after drainage in the 60 m spacing, from the well located at 30 m from the closest ditch.

Correlation of repeated observations of the same wells was evaluated in a random parameter regression model analysing the water-table level following drainage and clearcutting. This statistical design was similar to Hökkä et al. (2000). Fixed variables included the following: predicted water-table depth if no treatment was applied (covariable), distance to the closest ditch (3, 6, 10, 20 and 30 m), spacing between ditches (20, 40, 60 m), and period of observation (drained: 1987-1996 and harvested: 1997-2000). Random variables were: direction to the closest ditch, row number, well number, year within a period and date of measure. The complete model was tested so that all possible interactions between the four fixed variables were included. Statistical analyses were done with the MIXED procedure of the SAS/STAT software, Version 8.2 of the SAS System for Windows. Copyright © 1999 SAS Institute Inc., Cary, NC, USA.

Results and discussion

The model tested showed a significant difference (p = 0.0012) for the highest interaction which included all of the four fixed variables. This interaction has been illustrated separately for each of the three spacings (Figure 3).

The first period of observation (1987-1996) was used to evaluate the water-table fluctuations following drainage. The water-table at 3 m from the ditch was lower for each of the spacings. The lowering of the water-table at 6, 10 and 20 m from the ditch decreased as the spacings between ditches increased (Figure 3). The high degree of decomposition of the peat below 10 cm reduced the hydraulic conductivity (Plamondon & Belleau 1991) and consequently the water table lowering away from the ditch.

The second period of observation (1997-2000) was used to indicate watering-up following timber harvest. To do this, we compared the predicted water-table of this second period to the calibration curve. Watering-up was not observed within the 20 m spacing (Figure 3). For the 40 and the 60 m spacings, no watering-up was observed at 3 m from the ditch while at 6 m from the ditch, the water-table was close to the calibration curve. At 10, 20 and 30 m from the ditch, watering-up was observed mostly during dry episodes (low predicted water-table if no treatment was applied) and it was more important for the 60 m spacing than the 40 m spacing. These results were similar to Heikurainen & Päivänen (1970) and Päivänen (1980) who observed significant watering-up after the clearcutting of drained peatlands, for ditch spacings of 50 m and 70 m.

Fluctuations of the water-table were more important for the first period of observation than for the second period of observation (Figure 3). Reduced water-table fluctuations were also observed after the harvesting of drained stands in Finland (Heikurainen & Päivänen 1970, Päivänen 1980).

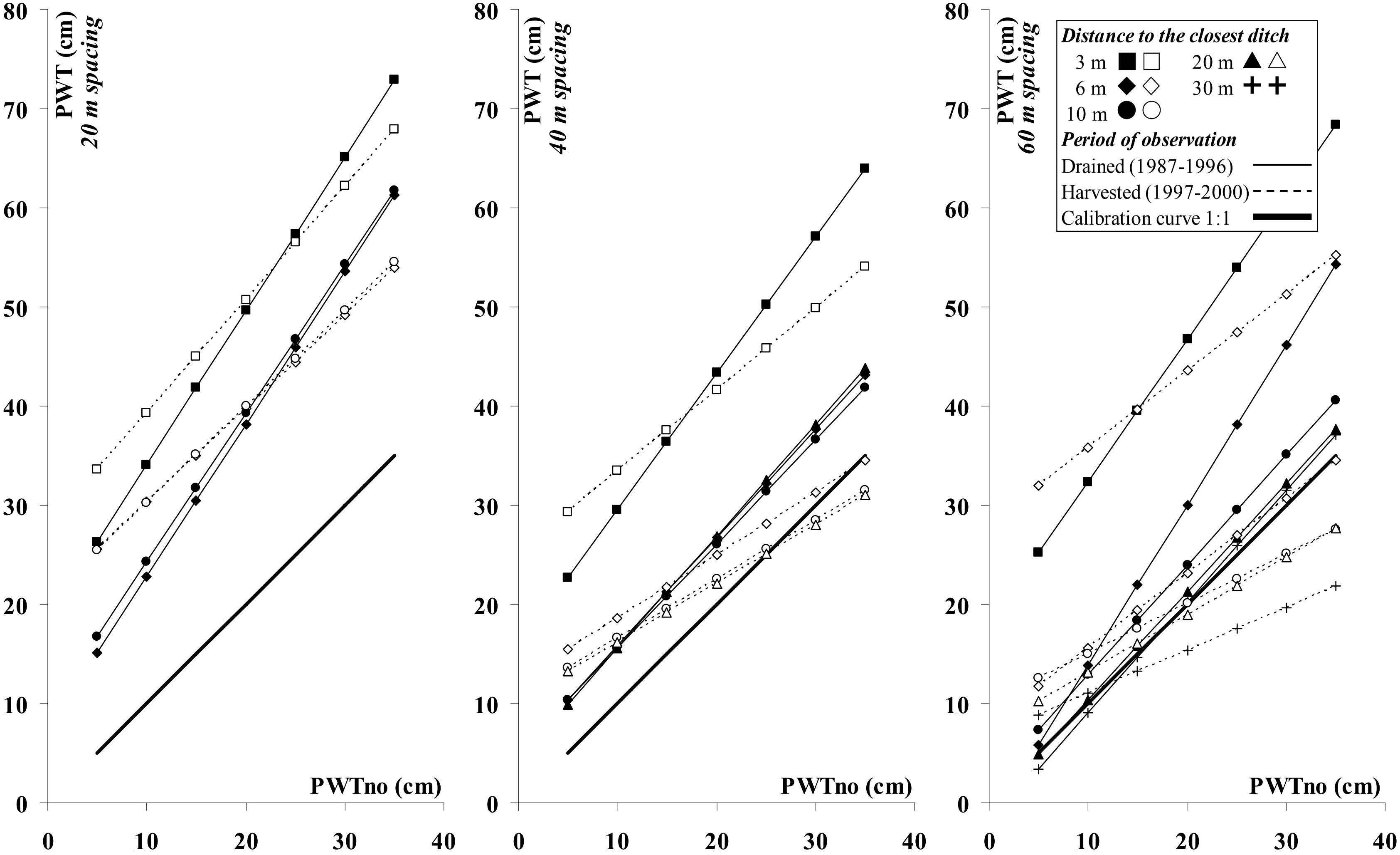

Figure 3: Predicted water-table depth (PWT) following drainage and timber harvesting of a forested peatland site in function of ditch spacing, distance to the closest ditch, period of observation and predicted water-table depth if no treatment was applied (PWTno).

When drainage was able to lower the water-table depth by more than 10 cm, watering-up did not occur and the variability of the water table fluctuation was reduced. Watering-up was evident in locations where drainage was inefficient. The most problematic drainage patterns were found at distances larger than 6 m from the ditch in the 40 and 60 m spacings. To enhance regeneration and growth conditions, drawdown by drainage should ideally be over 10 cm to compensate the subsequent watering-up due to harvesting. The significant water-table drawdown caused by drainage and the reduced water-table fluctuation caused by harvesting within the 20 m ditch spacing would create the most favourable tree growth conditions on the study site.

Every measurement location within the 20 m spacing offered a constantly lower water-table than the situation where no treatment was applied, even after clearcutting. Prescribing a drainage network that lowers the water-table by at least 10 cm throughout the whole spacing should be the best way to reduce the impact of the watering-up after harvesting. Furthermore, this prescription needs to be adapted to individual peatland soil and stand characteristics. The origin, the nature and the state of decomposition of the organic mater, as well as the amount of biomass removed from the site are important factors that might have an effect on the magnitude of the watering-up after harvesting.

Conclusion

This study quantified the water table level at 5 different distances from a ditch for three different ditch spacings in an old stagnant black spruce stand growing on highly decomposed Sphagnum peat that was drained 10 years before clearcutting. The amount that the water-table rose following clearcutting was different depending on the distance from the drainage ditch and the space between ditches. Watering-up occurred when drainage was unable to lower the water-table depth by more than 10 cm. When drainage was able to lower the water-table depth by 10 cm and more, watering-up did not occur and the variability of the water table fluctuation was reduced.

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CHAPTER 3

Water table changes following precommercial thinning on post-harvest drained wetlands

Jutras, S.[1], Plamondon, A.P.[1], Hökkä, H.[2], and Bégin, J.[1] *To be submitted to Silva Fennica.* **Water table changes following precommercial thinning on post-harvest drained wetlands.** [1]Faculty of Forestry and Geomatics, Université Laval, Ste-Foy, Québec, G1K 7P4, CANADA. [2]Finnish Forest Research Institute, Rovaniemi Research Station, P.O. Box 16, FIN 96301 Rovaniemi, FINLAND. *This chapter is the result of the candidate's labour. André Plamondon, Hannu Hökkä and Jean Bégin have been giving suggestions on the design and the preparation of this chapter.*

Abstract

Precommercial thinning is a silvicultural treatment commonly used to reduce the number of stems in densely regenerated stands. When applied to organic or mineral wetland sites, this treatment drastically eliminates a great portion of the canopy, which is responsible for maintaining evapotranspiration processes. The water table is susceptible, therefore, to rise in those sites where evapotranspiration is a significant regulator of the hydrological balance. The objective of this study was to investigate and quantify water table rise after precommercial thinning on post-harvest, drained forested wetlands, and to relate this rise to factors influencing evapotranspiration processes. The water table rose after precommercial thinning regardless of soil type, the distance to the drainage ditch, or the year of observation. In the second year after thinning on mineral soils, canopy openings were invaded by abundant and vigorous ground vegetation. Water table rise was significantly lower at that time than for the preceding year, indicating rapid hydrological recovery on mineral soil sites. The water table rise was related to the basal area removed, indicating the importance of woody vegetation in regulating water table depth in forested wetlands. Seasonal patterns in water table depth further illustrated the role of vegetation in the hydrological balance of such sites. Light to moderate thinning practices, therefore, appeared to be the most appropriate recommendation to avoid watering-up in young forested wetland stands.

Résumé

L’éclaircie précommerciale est un traitement sylvicole fréquemment utilisé afin de réduire le nombre de tiges des peuplements densément régénérés. Lorsque appliqué sur des sites humides, ce traitement élimine de façon drastique une grande portion de la canopée qui est responsable du maintient des processus d’évapotranspiration. La nappe phréatique est alors sujette à une remontée sur ces sites où l’évapotranspiration est un important régulateur du bilan hydrologique. L’objectif de cette étude était d’investiguer et de quantifier la remontée de la nappe phréatique après l’éclaircie précommerciale sur des milieux humides forestiers récoltés et drainés en fonction des facteurs influençant les processus d’évapotranspiration. La nappe phréatique a remonté après l’éclaircie précommerciale peu importe le type de sol, la distance du fossé et l’année d’observation. La deuxième année après l’éclaircie sur les sols minéraux, les ouvertures du couvert ont été envahies par une végétation basse abondante et vigoureuse. La remontée de la nappe phréatique était significativement plus basse à ce moment que pour l’année précédente, indiquant un rétablissement hydrologique rapide sur sol minéral. La nappe phréatique a présenté des remontées de plus en plus grandes lorsque le prélèvement de la surface terrière augmentait, indiquant l’importance de la végétation arborescente dans la régulation de la nappe phréatique des milieux humides forestiers. La variation saisonnière de la nappe phréatique indiquait aussi l’importance de la végétation dans le bilan hydrologique de tels sites. L’utilisation de pratiques d’éclaircies plus délicates apparaît donc comme la recommandation la plus appropriée afin de prévenir la remontée de la nappe phréatique sur les milieux humides forestiers.

Introduction

Evapotranspiration is a dominant process regulating the hydrological balance of natural forested wetlands (Paavilainen and Päivänen 1995; Ahti and Päivänen 1997). Elimination of the tree canopy drastically reduces interception and transpiration, which equally contribute to summer evapotranspiration (Dubé and Plamondon 1995). Hence, timber harvesting usually results in a significant rise of the water table after total (Heikurainen 1967; Berry and Jeglum 1991; Dubé et al. 1995; Roy et al. 1997) or partial canopy removal (Heikurainen and Päivänen 1970; Päivänen 1980, 1982; Pothier et al. 2003). Wet mineral soil sites have been found to exhibit greater watering-up after harvesting than organic ones, which is attributable to the smaller water storage capacities of fine-textured mineral soils compared to the organic materials (Dubé et al. 1995; Roy et al. 2000a).

Seedling survival and growth are negatively affected by high water table levels (Lieffers and Rothwell 1986; Lieffers and MacDonald 1990; Landhäusser et al. 2003), thereby creating regeneration problems in recently harvested wetlands. Evapotranspiration on ombrogenous forested wetlands, which is driven mainly by the canopy trees, is responsible, in part, for creating favourable soil growing conditions. Concomitantly, woody vegetation mainly owes its vigour to the prevailing favourable soil growing conditions. This reciprocal relationship between tree growth and soil growing conditions is jeopardised by canopy removal. Consequently, vegetation growth, evapotranspiration, and water table recovery are usually impaired for several years following harvesting (Roy et al. 2000a, 2000b; Xu et al. 2002; Jutras and Plamondon 2005; Marcotte 2005).

Vegetation and water table recovery can be enhanced by corrective treatments such as soil drainage through ditching (LeBarron and Neetzel 1942; Heikurainen 1964; Hillman 1991, 1992; Roy et al. 2000b; Jutras et al. 2002, 2004; Marcotte 2005). The degree to which the water table level drops can vary with ditch spacing, proximity to the ditch, and soil characteristics (Heikurainen 1964; Toth and Gillard 1988; Prévost et al. 1997; Roy et al. 2000b; Jutras and Plamondon 2005; Marcotte 2005). Following canopy removal, drainage can only maintain the water table level below its mature forest value within short distances from the ditch, typically 10 to 15 m (Jutras and Plamondon 2005; Marcotte 2005). In the absence of drainage, water table recovery to pre-harvest depths was found to be faster on organic soil sites than on mineral ones (Roy et al. 2000a; Marcotte 2005). During seven years of post-drainage observations, hydrological recovery was slower away from the ditch than close to it (Marcotte 2005).

Regardless of whether harvested wetlands are drained or left undrained, both desirable and undesirable species will eventually form a dense canopy cover (LeBarron and Neetzel 1942; Hillman 1991; Roy et al. 2000c; Jutras et al. 2002, 2004; Marcotte 2005). In a standard management scenario, treatments such as precommercial thinning (PCT) could be used to decrease inter-tree competition (OIFQ 1996). This type of treatment drastically reduces the vegetation coverage, therefore decreasing site evapotranspiration. Consequently, PCT is likely to induce a second watering-up, further delaying the growth of released trees. To our knowledge, no study has ever scrutinized this issue. The objective of this study was to investigate and quantify water table rise following PCT on post-harvest drained forested wetlands in relation to factors, which influence evapotranspiration processes. These factors include: soil type, distance to the ditch, year of observation, basal area removal, residual basal area, water table depth, and observation day.

Material and methods

The study was conducted in a forest stand owned and managed by Stadacona Paper Inc., and located 50 km southwest of Quebec City, Quebec, Canada (46º27'N, 71º23'W). Meteorological data for the study were obtained from the Saint-Flavien station, which was located 10 km from the site (46º29'N, 71º34'W). Annual precipitation was 1125 mm (thirty-year running average, Environment Canada 2004). For this same period, mean annual temperature was 3.9ºC, with 1674 mean annual degree-days above 5ºC. Potential evapotranspiration was estimated at 550 mm, using Thornthwaite's method (Wilson 1971).

The experimental area originally consisted of eight forested wetland sites located within an 8 km² area (Dubé et al. 1993). Five of these were characterized by organic soils (organic layer thickness >40 cm), while the other three were wet mineral sites (organic layer thickness <40 cm) according to the Canadian system of soil classification (Anon. 1987). The stands were harvested while the soils were frozen (November 1991 to January 1992), using chain saws and rubber-tired skidders in a tree-length harvesting system with protection of advance growth. The resulting cut-blocks were 80 m wide (east-west) by 120 m long (north-south). Ditches were dug in December 1994 on the eastern edge of each cutover area with an excavator equipped with a U-shaped bucket. Twelve years after harvesting, cutover sites were densely regenerated (*mean* ± *SD*: 23 000 ± 7 000 stems/ha; 6.1 ± 2.8 m^3/ha) to a point where inter-tree competition was threatening the growth and survival of the most desirable commercial tree species.

To remain consistent with the objectives of the study, two of the eight sites had to be rejected: the first had insufficient stocking with desirable commercial tree species to justify the application of PCT (<4000 saplings/ha; MRNFP 2003), while the second showed inadequate variation in soil and vegetation characteristics within the cutover area (Table 1). Thirty-six water wells, made of 4 cm diameter and 1.2 m long ABS perforated pipes, were installed in each selected site. They were positioned in six rows perpendicular to the ditch, at 3, 7, 10, 20, 40 and 60 m from the ditch centre (Fig. 1). Wells located at 40 and 60 m from the ditch were considered to be unaffected by drainage, according to the statistical analysis executed over a 7-years post-drainage period by Marcotte (2005). The rows were located every 15 m along the north-south direction of the cut-blocks and were grouped two by two in order to form three pairs of neighbouring rows (Fig. 1). Distance between the water table and the top of the tube were measured weekly to the nearest cm during the 2003, 2004 and 2005 growing seasons, from mid-May to the end of October, with the help of an electrical buzzer probe. The distance from the top of the tube to the soil level was measured once a year and it was used to calculate the water table depth below the soil surface. The post-treatment years 2004 and 2005 were alternately slightly wetter and dryer than the year 2003, which was used for calibration purposes (Fig. 2).

Table 1: Description of the six selected sites

	Mineral		Organic			
	D	H	A	B	C	I
Ecological type	RS36	RE36	RE39	RS38	RS39	RE39
Organic layer thickness (cm)	20	20	50	110	>130	>130
Dominant commercial tree species	Balsam fir	Tamarack	Tamarack	Balsam fir	Balsam fir	Tamarack
Principal competitor	White birch	Speckled alder	Red maple	Red maple	White birch	Red maple
Dominating moss species	Sphagnum	Sphagnum	Sphagnum	Sphagnum	Sphagnum	Sphagnum
Pre-thinning stand density (m^2/ha)	7.0	10.4	3.5	5.0	5.4	5.4
Post-thinning stand density (m^2/ha)	0.4	2.5	1.8	1.3	1.1	1.5

Note: The letters A – I are site identification codes corresponding to previous publications concerning the same site (Dubé et al. 1995; Roy et al. 2000a, 2000b, 2000c; Marcotte 2005). Ecological types were determined with the help of the Forest Ecological Classification Guide for the region 2b - Saint Lawrence lowlands (MRN 2000). Codes identification keys are: RS--, balsam fir - black spruce stands; RE--, black spruce - sphagnum stands; --3-, hydric drainage; ---6, fine textured subhydric deposit; ---8, minerotrophic mineral or organic deposit; ---9, ombrotrophic organic deposit.

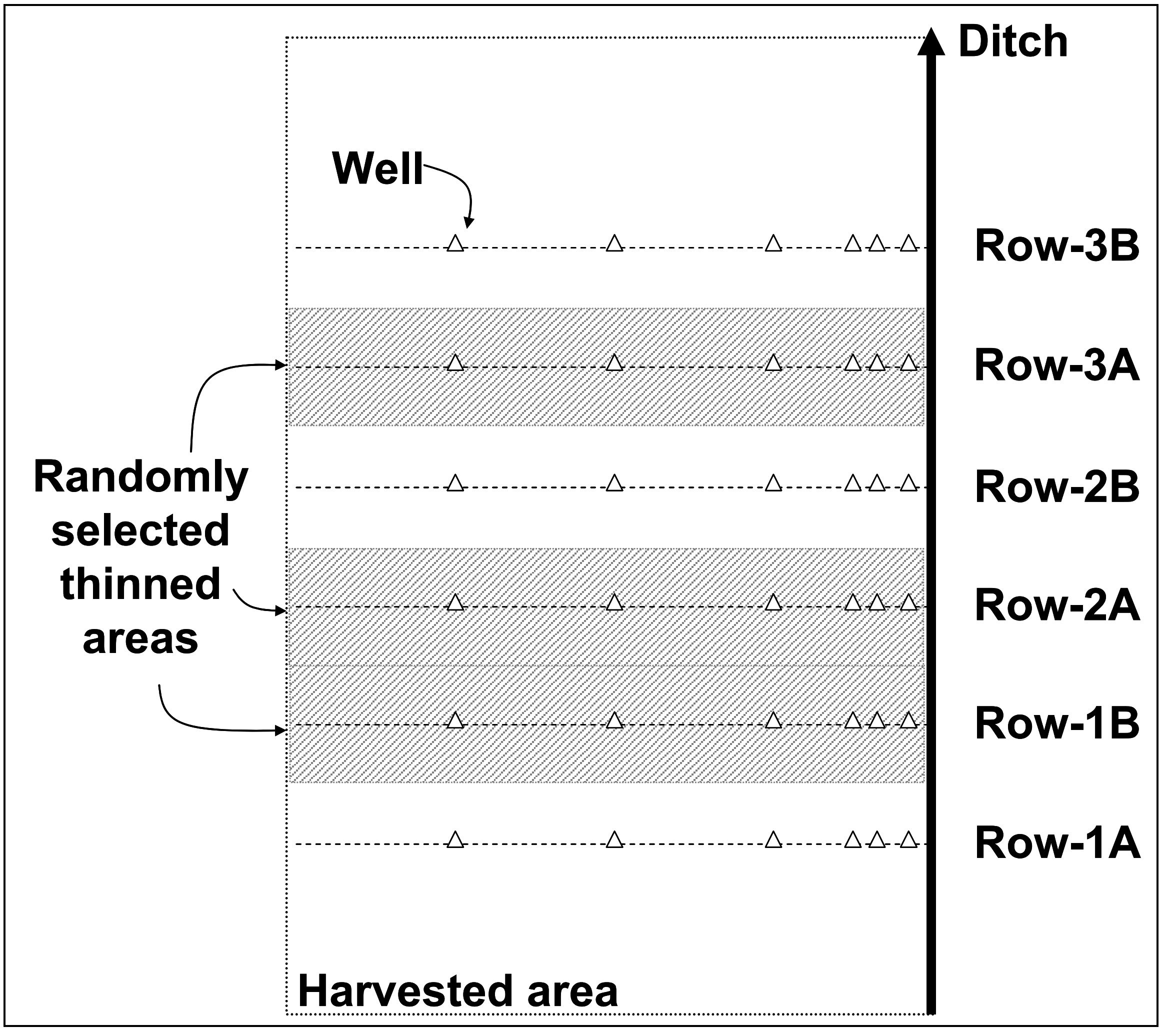

Figure 1: Details of the experimental design of a hypothetical study site.

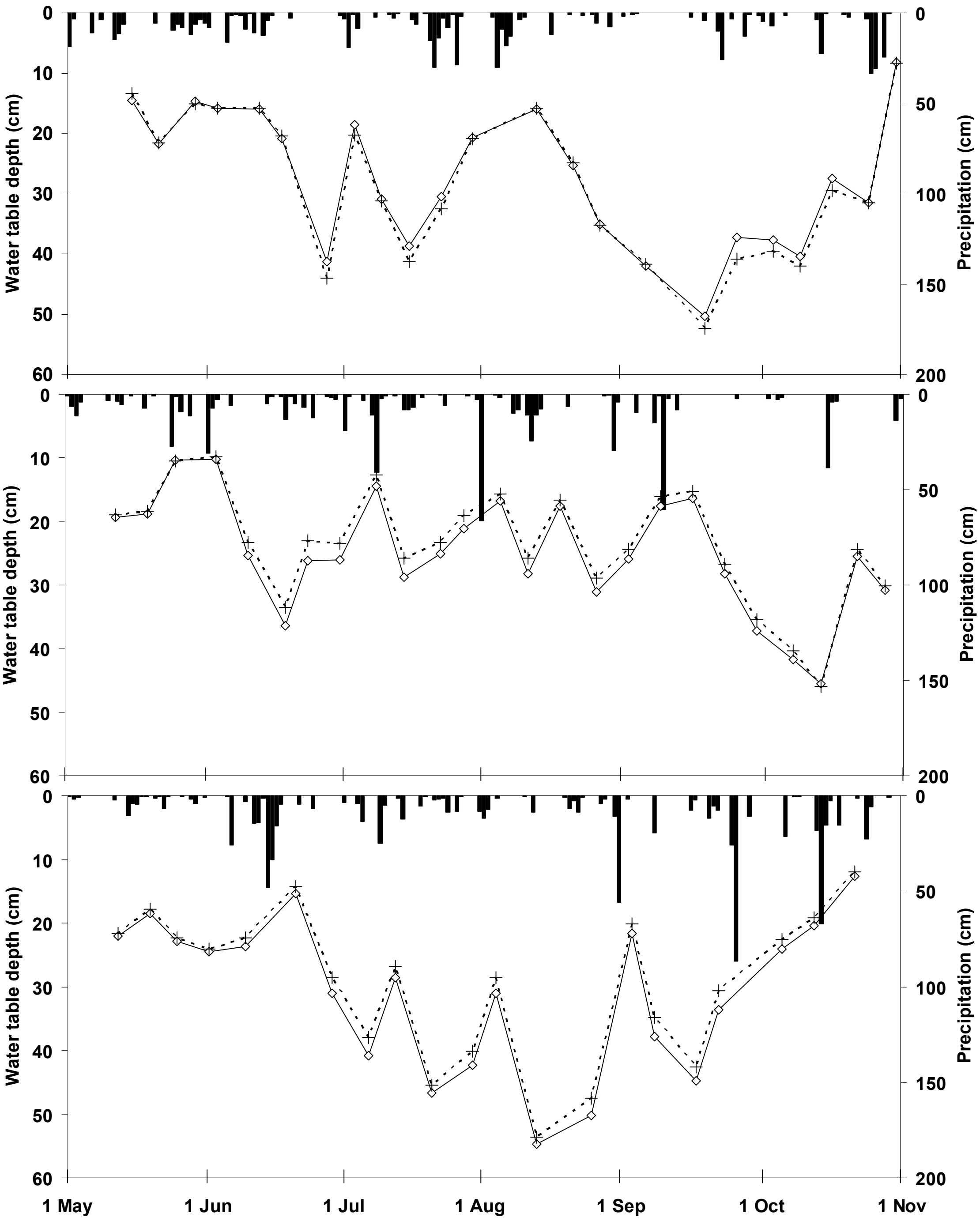

Figure 2: Daily precipitation and mean water table depth to the soil level for the control wells (diamonds, thin line) and the thinned wells (+, hatched line), before (2003) and after (2004-2005) precommercial thinning (all sites included).

At the end of the 2003 growing season (3 – 23 November), a specialized silvicultural firm carried out the PCT on the study area. The treatment was executed around one randomly selected row of water wells for each pair of rows. Hence, a treated or an untreated (control) rectangle, 15 m wide by 80 m long, was centered on each row of wells (Fig. 1). The target thinning density was 2 500 stems/ha, releasing, in order of preference, black spruce (*Picea mariana* (Mill.) B.S.P), balsam fir (*Abies balsamea* (L.) Mill.), eastern larch (*Larix laricina* (Du Roi) K. Koch), eastern white-cedar (*Thuja occidentalis* L.), white birch (*Betula papyrifera* Marsh.), and finally red maple (*Acer rubrum* L.). The measured mean stem density (±SD) after precommercial thinning was 2300 stems/ha (± 300).

Circular plots (1.13 m radius; 4 m^2) were used to monitor, in July, the vegetation surrounding each well before (2003) and after (2004) PCT treatment. Supplementary plots were located between wells, at 15, 25, 30, 35, 45, 50, 55, 65, and 70 m from the ditch, to characterize the vegetation throughout the whole experimental area. All trees >1.3 m in height were counted for each diameter class (2-cm) to calculate stand basal area (G; m^2/ha^{-1}). Besides the aforementioned tree species, speckled alder (*Alnus incana* ssp. *Rugosa* (Du Roi) J. Clausen) and mountain-holly (*Nemopanthus mucronatus* (L.) Trel.), two non-commercial thicket-forming tree species, were also monitored. In 2005, vegetation density, i.e.: basal area of trees >1.3 m, was not sampled since no important change occurred compared to the 2004 monitoring.

Water table calibration

All measured water table depths were plotted against time and distance to the ditch to enable detection and elimination of outliers from the dataset. At site H, 16 wells were installed at insufficient depth because of the physical restriction brought about by a cemented mineral soil layer present at –50 cm. Consequently, missing values represented nearly half of the 2003 water table depth measurements for these wells. So, for the site H, a complete pair of rows (12 wells) had to be excluded and two other pairs of wells were lost (40 and 60 m).

The water table rise (WTR) caused by PCT was evaluated with the help of a calibration method using pair of wells. Water table depths that were collected in 2003 prior to PCT were used to determine the relationship between the well in the area to be thinned (thinned well) and the well in the area left unthinned (control well), which were located at a same distance from the ditch for each pair of rows. The stepwise variable selection method of PROC REG (Version 9.1, SAS Institute Inc. 2003) was used to obtain 100 regressions (108 pairs of wells – 8 rejected pairs) expressing the thinned well's water table depth as a function of the control well's water table depth (Fig. 3). Transformations of the control water table depth (squared, square root or natural logarithm) were used to obtain the best-fit line. This calibration method compensated for possible differences in soil structure or water table depth which occurred between each pair of wells. The regressions were later used to calculate, from the control well data measured in 2004 and 2005, the predicted water table depth that would have been observed for the corresponding treated well in the absence of PCT. WTR was calculated for post-treatment observations, i.e., 2004 and 2005 data, for each well found on the thinned rows as the difference between the observed water table depth and the predicted water table depth. The regressions were used only for water table depth values found within the range of observations obtained during the calibration period.

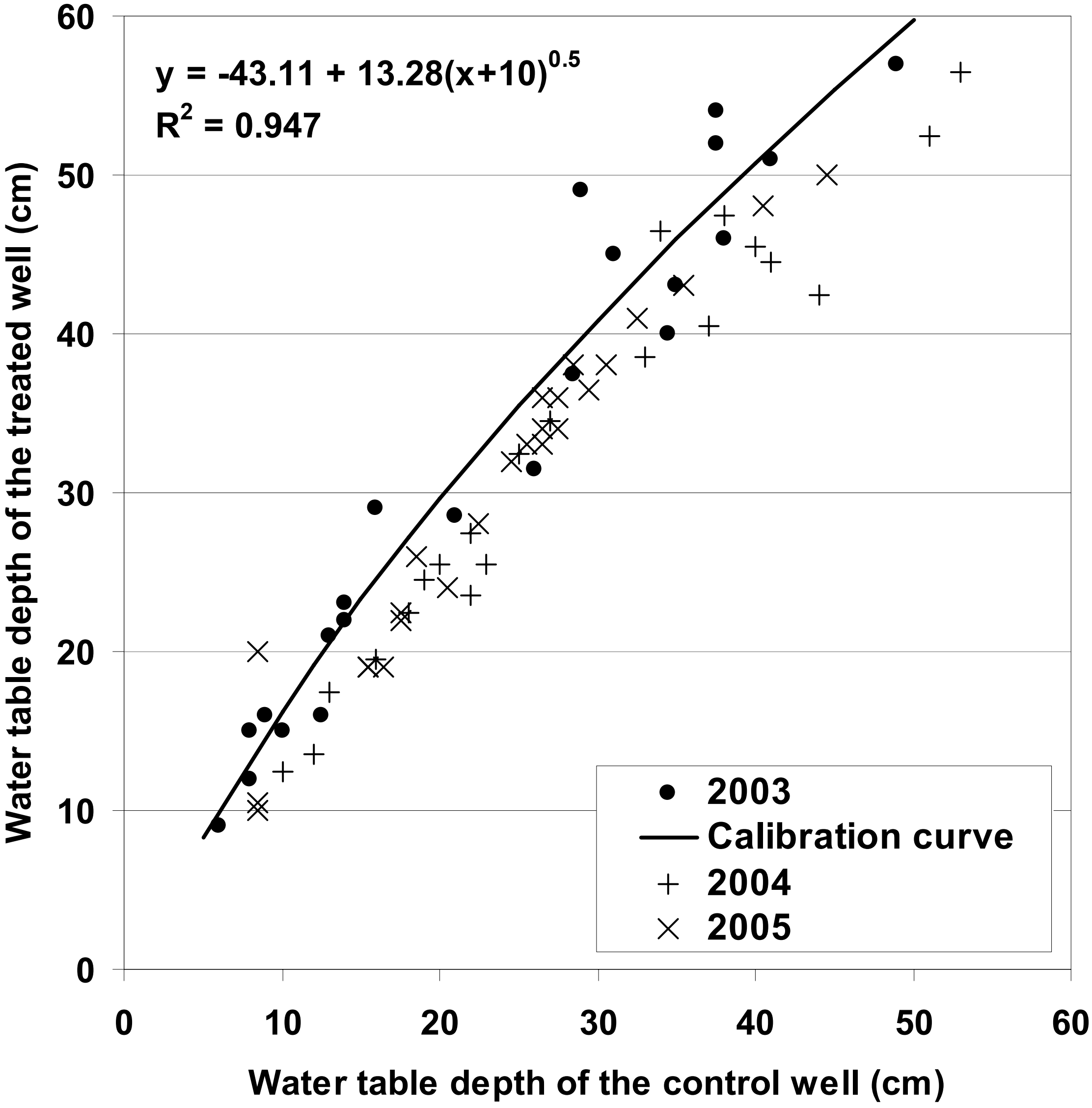

Figure 3: Example of the regression between treated and control wells for the calibration period (2003) and the post-treatment values for 2004 and 2005 (Site I, Row 3, DIST = 20 m).

Statistical analysis

An analysis of covariance (ANCOVA), which incorporated a split-split-plot arrangement of factors, was used to assess variation in WTR as a function of: soil type (TYPE: organic vs. mineral) as the main plot, distance to the ditch (DIST: 3, 7, 10, 20, 40, 60 m) as the subplots, and year of measurement (YEAR; 2004 vs. 2005), as the sub-subplots. Additional covariates were used to account for the basal area removal (ΔG, m^2/ha), the residual basal area (G, m^2/ha), the predicted water table depth (WT, cm) and the observation day (DAY, Julian day). Covariates were introduced in the model as continuous variables and different transformations were tested (squared, square root, natural logarithm). Covariates offering the best fit with the dependent variable and showing no trends in the residual plots were selected. Three random variables were used to serve as error terms for the fixed effects of the split split-plot design of the experiment: SITE(TYPE), DIST × SITE(TYPE), and DIST × YEAR × SITE(TYPE). An additional random variable was introduced in the model to account for variation between the three rows of wells in each site (ROW(SITE(TYPE))). A contrast was used to compare the WTR for the drained area (DIST = 3, 7, 10, and 20 m) with the undrained area (DIST = 40 and 60 m). The analysis was executed in PROC MIXED of SAS.

Depending on each individual well's pre-treatment stand density and PCT intensity, a broad range of basal area removal (ΔG, $m^2 \cdot ha^{-1}$) was encountered after application of the treatment. ΔG was calculated for each thinned well as the difference between the basal area that would have been found in absence of PCT in 2004 (G_{2004P}) and the residual basal area measured in 2004 after PCT (G, $m^2 \cdot ha^{-1}$). All vegetation plots located in the control rows (no-thinning) were used to produce an equation (Eq. 1) that estimated the basal area in absence of PCT in 2004 (G_{2004P}) from the basal area measured in 2003 (G_{2003}). This equation was later used to estimate the G_{2004P} for each thinned well.

[1] $$G_{2004P} = e^{0.2875 + 0.9145 \cdot \ln(G_{2003} + 1)} - 1$$

where G_{2004P} is the basal area in absence of PCT in 2004 and G_{2003} is the measured basal area in 2003.

Basal area measurements are strongly correlated to the abundance of above-ground tree biomass, which is directly influencing evapotranspiration processes. Therefore, ΔG and G were considered as adequate estimators of the evapotranspiration changes caused by PCT, evaluating the evapotranspiration depletion and its actual level, respectively.

Water table depth is a simple and objective indicator of the broad precipitation regime prevailing in an area and also is correlated to the potential evapotranspiration in wetlands (Verry 1997). Therefore, soil water availability (lack or excess) was described by the covariate WT, which was used to explain WTR fluctuations following PCT. The DAY covariate was mainly used to describe the expected influence of tree phenology on evapotranspiration. Both the presence of leaves and the seasonal tree growth activity were accounted for by this covariate.

Results

The statistical analysis showed no significant differences for a majority of the split-split-plot factors (Table 2). Only YEAR and YEAR × TYPE revealed significant differences in the WTR following PCT (Table 2). The WTR was smaller in 2005 than in 2004, especially for mineral soils (Fig. 4).

Table 2: Analysis of covariance of the water table rise (WTR) after precommercial thinning (PCT).

Variables	df	*F* value	*p* value
TYPE	1	0.06	0.8160
Main plot error: SITE(TYPE)	4		
DIST	5	1.17	0.3592
DIST × TYPE	5	1.46	0.2476
Contrast (drained vs undrained)	1	2.87	0.1057
Sub-plot error: DIST × SITE(TYPE)	20		
YEAR	1	9.65	0.0048
YEAR × TYPE	1	5.60	0.0264
YEAR × DIST	5	0.56	0.7262
YEAR × DIST × TYPE	5	0.56	0.7286
Sub-sub-plot error: YEAR × SITE(TYPE) + DIST ×YEAR × SITE(TYPE)	24		
ln(ΔG + 1)	1	23.17	<0.0001
ln(G + 1)	1	1.30	0.2543
ln(WT + 10)	1	426.86	<0.0001
DAY	1	6.93	0.0085
$\mathrm{DAY}^{0.5}$	1	5.97	0.0146
Additional random effect: ROW(SITE(TYPE))	15		
Residual error	3905		

Note: TYPE, site type; SITE, site identification; DIST, distance class to the closest ditch; YEAR, year of measurement; ΔG, basal area removal; G, residual basal area; WT, predicted water table depth; DAY, observation day; ROW, row of wells.

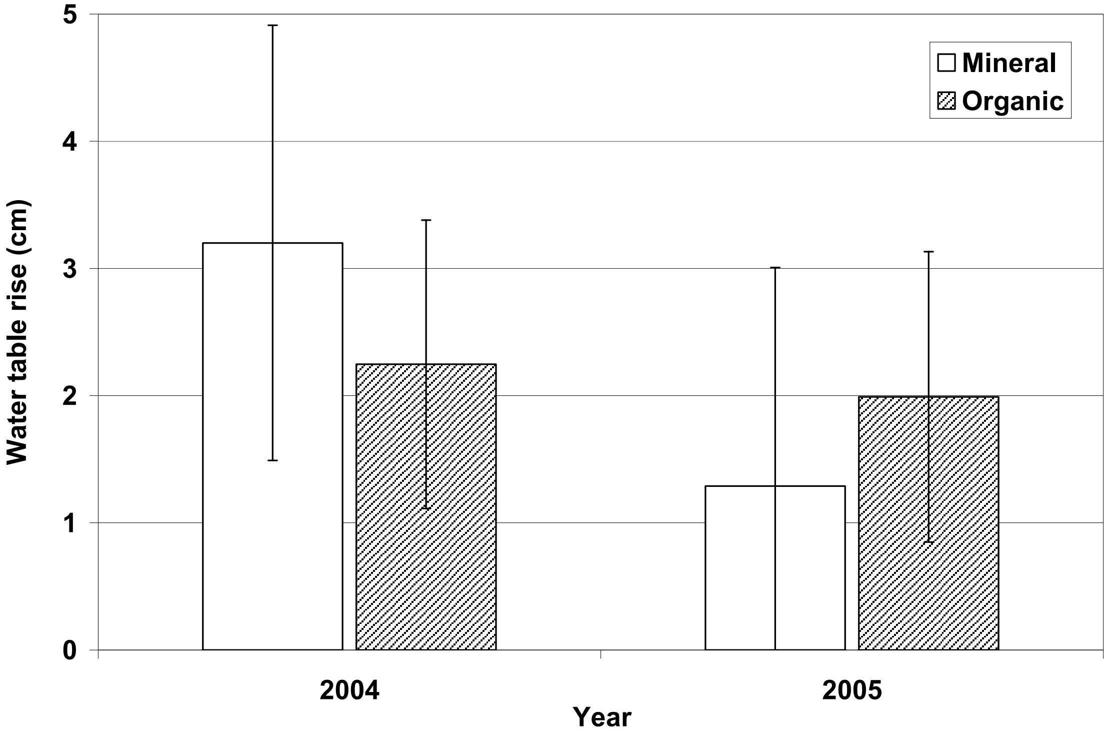

Figure 4: Least square means and error bars (± 2SE) of the water table rise (WTR) in function of the year of measurement and the soil type.

With the exception of ln(G+1), all covariates showed significant influence on the WTR (Table 2). As the basal area removal value (ln(ΔG+1)) increased, WTR showed larger values (Fig. 5). Basal area retained after PCT, expressed by G, had no effect on WTR (Table 2). WTR significantly increased with increasing WT (Fig. 6). WTR showed a quadratic relationship with respect to the observation day (Fig. 7). Lower values of WTR were observed in spring and autumn, while higher WTR were found during summertime.

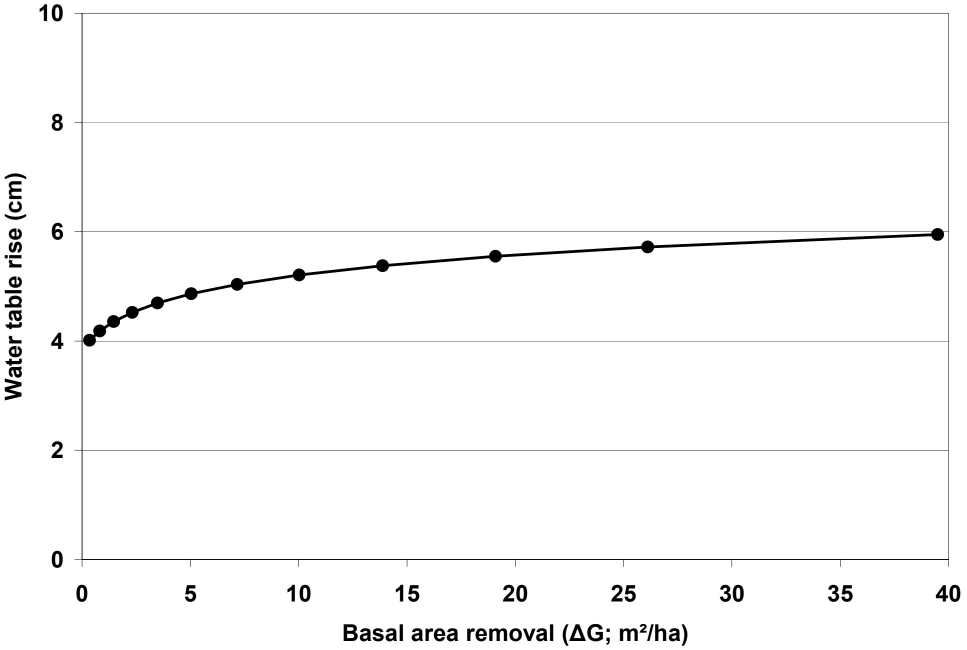

Figure 5: Predicted mean values of the water table rise (WTR) as a function of the basal area removal (TYPE = Mineral, DIST = 7 m, YEAR = 2004 and general mean values for the other covariates).

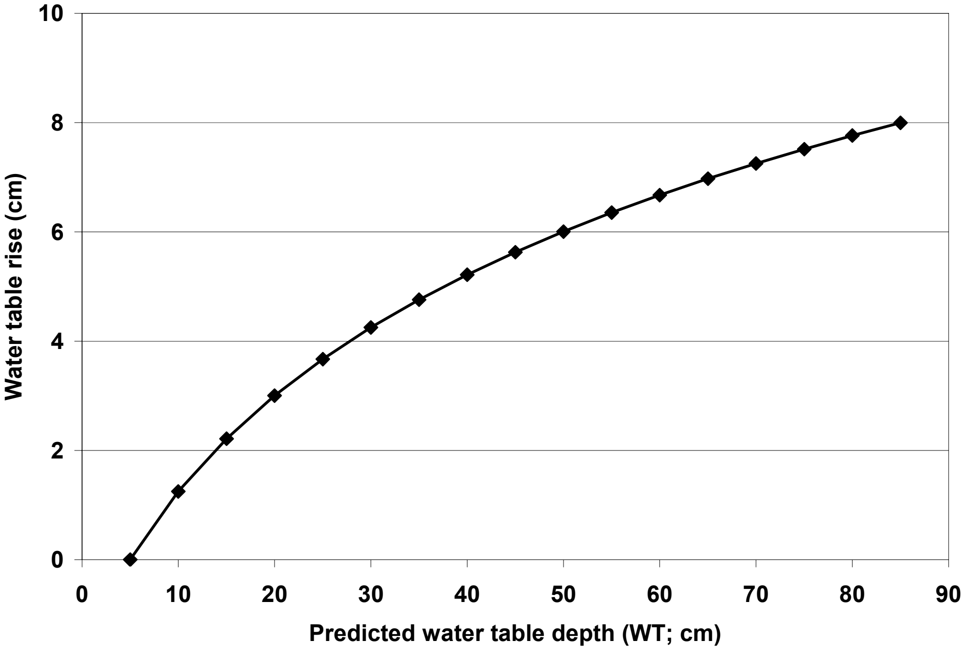

Figure 6: Predicted mean values of the water table rise (WTR) as a function of the predicted water table depth (TYPE = Mineral, DIST = 7 m, YEAR = 2004 and general mean values for the other covariates).

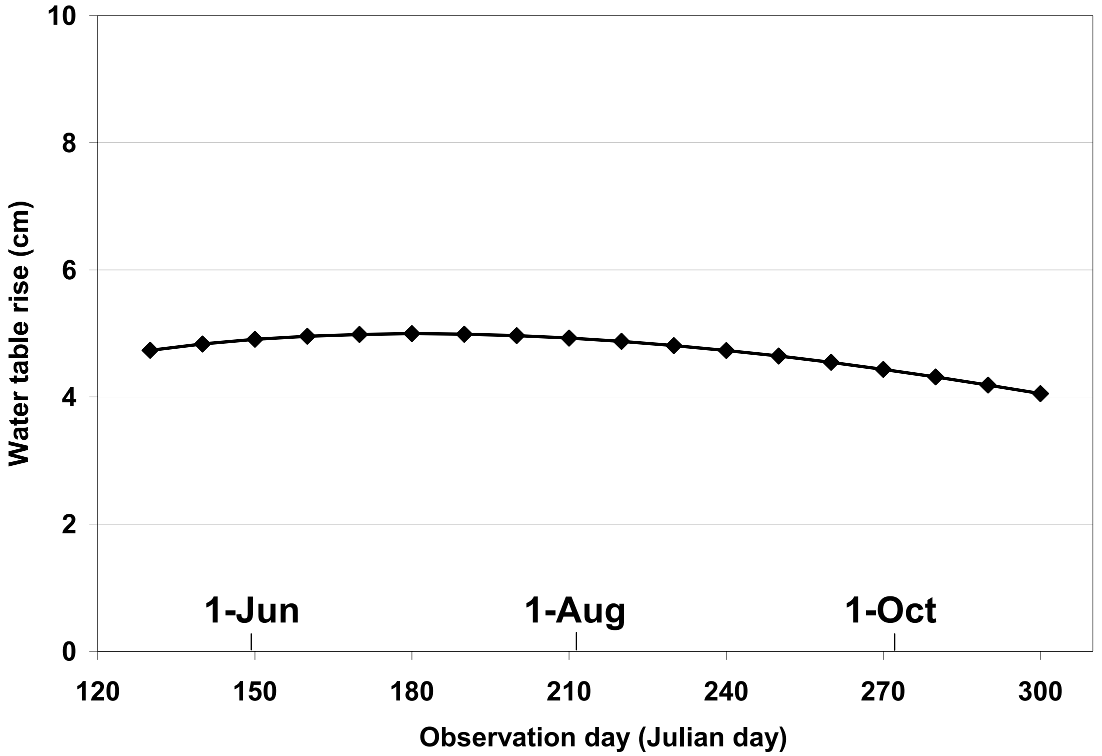

Figure 7: Predicted mean values of the water table rise (WTR) as a function of the observation day (TYPE = Mineral, DIST = 7 m, YEAR = 2004 and general mean values for the other covariates).

Discussion

The water table depths of the treated and control sites, before and after precommercial thinning, broadly followed the same patterns in response to precipitation (Fig. 2). Before thinning, water table depths tended to be deeper for wells located in the thinned treatments compared to wells in the control treatments, especially when the top of the water table was deeper than 30 cm. These water table depth differences were fortuitous since the treatments were randomly distributed among each pair of rows in each site. This indicates that water table depths between a pair of wells may be non-linearly related. Soil layers thickness, vertical structure and porosity can differ markedly between two wells located only a few meters away. Hence, the calibration before treatment for each individual well in relation to an adjacent control well was considered necessary to obtain precise and unbiased evaluation of the water table rise due to PCT. Calibration methods based on graphical analysis of water table depth between treated and control plots have been frequently used to assess the water table changes following a treatment (Heikurainen 1967; Heikurainen and Päivänen 1970; Päivänen 1980; Belleau et al. 1992; Dubé et al. 1995; Marcotte 2005). However, the use of regressions to compare treated and control water table depths is considered a more robust method than graphical analysis (Pothier et al. 2003; Jutras and Plamondon 2005).

The statistical analysis simultaneously addressed several categorical and continuous variables influencing the fixed effects. The data structure was correctly accounted for using the mixed model approach. No apparent problems of multicollinearity appeared between explanatory variables, and the final model was very stable regardless of modifications made to its structure. No trend could be found in the residuals when they were plotted against explanatory variables or predicted values.

The investigations carried out since 1991 on the study sites indicated important differences between mineral and organic soils with respect to the water table level changes over time (Dubé et al. 1995; Roy et al. 2000a,b; Marcotte 2005). The differences observed in watering-up after harvest were explained by the lower water retention capacity of fine textured mineral soils compare to organic soils. Therefore, for a same quantity of water in excess, watering-up will be more important on mineral sites than on organic ones. Marcotte (2005) demonstrated that, after clearcutting the mature stands, water table depth recovery was faster on organic sites than on mineral sites. The vegetation involved in the water table depth regulation was judged to be more efficient in decreasing the water table on organic sites. In the present study, contrary behaviour was observed after PCT.

The YEAR × TYPE interaction showed the similar effect of PCT on WTR in 2004 for both site types (Fig. 4). The significantly lower WTR in 2005 compared to 2004 for mineral soil sites suggested a faster hydrological recovery in this site type. This reaction was consistent with field observations (data not shown) indicating a gradual invasion of thinned areas by vigorous ground vegetation (mean height = 0.5 - 1 m), especially visible on mineral soil sites by the end of the 2005 growing season. PCT created noticeable openings in the canopy and therefore increased light availability at the ground surface. Pioneer broadleaved species, such as red maple, white birch, speckled alder and red raspberry (*Rubus idaeus* L.), which were especially frequent on mineral soils, rapidly proliferated through stump sprouting and seedling establishment. Although this ground vegetation is suspected of having an important role in interception (Prévost and Plamondon 1987; Xu et al. 2002), it was not monitored by the stand density measurement method that we used, but gradually reduced WTR caused by PCT on mineral sites. Since the stand composition and development largely differed at the times of harvesting, drainage and thinning, it seems difficult to explain intelligibly the results obtained in this study with those of Marcotte's (2005) study.

Forest drainage may strongly influence the hydrological balance of wetlands by changing an evapotranspiration-dominated process to a runoff-dominated one (Ahti and Päivänen 1997). Therefore, the impact of PCT, which was directly affecting evapotranspiration, was expected to have a smaller effect on WTR in drained areas than in undrained ones. In a nearby stand that had been drained 10 years prior to harvesting, clearcutting caused no watering-up in the first 6 m from the ditch, while the water table rose significantly at ditch spacings exceeding 40 m (Jutras and Plamondon 2005). In the present study, WTR was expected to be negligible < 20 m from the ditch, but high at 40 and 60 m. Results have shown that neither DIST class nor the contrast testing the effect of drainage revealed a difference in WTR (Table 2). The observed WTR, however, illustrated a slight trend showing smaller values close to the ditch than farther from it. The lower water table and the more important peat subsidence in proximity to the ditch (Prévost et al. 1997, Roy et al. 2000b) could partly explain the WTR occurring within the first few meters from the ditch. The various combinations of distance to the ditch, vegetation density and effective hydrological recovery were probably too numerous on the study area to clearly ascertain the individual effects of both drainage and PCT on the water table depth. Nevertheless, a significant watering-up occurred after PCT regardless of distance to the ditch.

The increase of WTR with increasing ΔG reinforces the assumption that the evapotranspiration provided by the vegetation on regenerating forested wetlands is playing an important role as a water table depth regulator. Small basal area removals corresponded to low WTR, while substantial canopy removal was related to considerably higher WTR. However, the lack of statistically significant influence of G on the WTR might have been caused by a large variance of the estimated local basal area around each well due to the plot size used. When the study areas were established, plots of small dimensions (4 m^2) were chosen over larger plots since the vegetation was characterized by the presence of abundant and evenly distributed small-sized saplings. Small plots are exponentially less time-consuming than larger ones while they provided reasonably precise estimate of the local basal area. This permitted us to distribute many plots to uniformly characterize the whole studied areas. The use of these small plots after PCT may locally under- or overestimated the basal area due to non-harvested veteran stem outside or within the plots. However, the small-sized plots used gave unbiased values of ΔG and G, but, in certain situations, they might be less accurate than values obtained with larger plots. Though, the greatest disadvantage of the small-sized plots was related to the determination of G.

The very important influence of WT on the WTR (Table 2) confirmed the importance of the vegetation in the water table depth regulation of wetland sites. After PCT, the WTR was greater during dry episodes than during wet ones. Under dry conditions, the water table depth is expected to be mainly influenced by transpiration and runoff, while water table depth under wet conditions is mostly regulated by precipitation, interception and runoff. PCT only affected interception and transpiration since precipitation was the same regardless the treatment. The variation of runoff within each site, which is strongly affected by drainage, was accounted for by the DIST factor. The minor WTR observed when WT was near the surface (high precipitation or spring snowmelt recharge) is mainly attributed to the reduced interception after thinning. The largest WTR was obtained during dry episodes, since the reduced transpiration provided by the residual vegetation could not affect the hydrological balance of the site as much as complete vegetation coverage could.

Transpiration and interception were largely related to tree phenology, explaining the seasonal pattern of WTR observed during each annual sampling period. Water depth monitoring started each year before bud break and ended a few weeks after broadleaf litterfall. The full development of leaves and growth activity was reached by the end of May to early June. WTR was maximal from this period until about the end of August. At that time, tree growth activities and evapotranspiration are significantly reduced (Bernier et al. 1999). From mid-September to mid-October, leaves were gradually senescing and falling from deciduous trees, while decreasing interception, which explained the lower WTR in thinned area.

Evapotranspiration by the woody vegetation was found to be a very important part of the hydrological balance of densely regenerated wetlands. However, this study did not evaluate the impact of WTR on the productivity of forested wetland sites. After harvesting, watering-up averaged 10 cm on mineral sites and 4 cm on organic sites (Marcotte 2005). The mean value of WTR following PCT from early June to the end of August was 2.6 ± 4.9 cm (*mean* ± *SD*). This WTR represents a 10.2 % change of the water table depth during the most critical growth period for trees. It is actually difficult to predict if a value of this magnitude could significantly affect tree growth. Tree growth would have to be followed for another 5 to 10 years to assess the impact of WTR on site productivity. Otherwise, lighter precommercial thinning intensities should efficiently limit WTR on densely regenerated wetland sites. Mechanical release of a smaller number of desired commercial stems, would simultaneously lower inter-tree competition and preserve a favourable hydrological balance of the site. However, further yield investigations are necessary to assess the profitability of such treatments over standard intensity precommercial thinning.

Conclusion

Precommercial thinning, by drastically reducing stand density, caused a significant (2.6 cm) rise in the water table on a wide range of densely regenerated wetland sites in the Saint-Lawrence lowlands. Water table rise was found to be similar for mineral and organic sites in the first year after treatment, but a marked hydrological recovery was observed during the second year on mineral sites. The abundant ground vegetation, which was established after the canopy was opened up, likely contributed to a higher interception rate, causing the water table depth to reach its pre-treatment level. The reduced evapotranspiration rate caused by canopy loss was considered the most important factor causing the water table to rise. Low basal area removal showed a smaller degree of water table rise than did more intense treatments, suggesting the application of light to moderate precommercial thinning practices on forested wetlands.

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CHAPTER 4

Beneficial influence of plant neighbours on tree growth in drained forested peatlands – A case study

Jutras, S.[1], Hökkä, H.[2], Bégin, J.[1], Plamondon, A.P.[1] S*ubmitted to the Canadian Journal of Forest Research.* **Beneficial influence of plant neighbours on tree growth in drained forested peatlands – A case study.** [1]Faculty of Forestry and Geomatics, Université Laval, Ste-Foy, Québec, G1K 7P4, CANADA. [2]Finnish Forest Research Institute, Rovaniemi Research Station, P.O. Box 16, FIN 96301 Rovaniemi, FINLAND. *This chapter is the result of the candidate's labour. Hannu Hökkä, Jean Bégin and André Plamondon have been giving suggestions on the design and the preparation of this chapter.*

Abstract

In boreal forest, drainage can be successfully used to lower the water-table level of post-harvest forested peatland stands suffering from watering-up. The later vegetation revival and growth is suspected to gradually create a water-table drawdown described in this study as biological drainage. Its effect on the annual stump diameter increment of planted eastern larch (*Larix laricina* (Du Roi) K. Koch.) and naturally regenerated black spruce (*Picea mariana* (Mill.) B.S.P.) was studied on a post-harvested and drained forested peatland located in eastern part of the Canadian boreal forest. A factor describing the neighbourhood occupancy of every subject tree was used to illustrate biological drainage in a retrospective growth analysis. Results showed the dual effect of the neighbourhood occupancy factor: competing situations close to the ditch and growth-favouring situations farther from it. In the latter case, the studied trees demonstrated better growth with moderately increasing neighbourhood occupancy. This was interpreted as evidence of the beneficial effect of biological drainage on tree growth. The presence of speckled alder (*Alnus incana* ssp. *rugosa* (Du Roi) J. Clausen) in the neighbourhood of selected trees corresponded to improved growth for both studied species.

Résumé

En forêt boréale, le drainage permet de rabattre efficacement la nappe phréatique des tourbières forestières récemment récoltées affectés par une nappe haute. La croissance subséquente de la végétation forestière sur ces sites est susceptible de créer un rabattement de la nappe phréatique, appelé ici drainage biologique. Son effet sur l'accroissement annuel en diamètre à la souche de plants de mélèze laricin (*Larix laricina* (Du Roi) K. Koch.) et de semis naturels d'épinette noire (*Picea mariana* (Mill.) B.S.P.) a été étudié sur une tourbière forestière récoltée et drainée. Un facteur décrivant l'occupation du voisinage des arbres étudiés a été utilisé afin de décrire le drainage biologique dans une analyse de croissance rétrospective. Les résultats ont démontré les deux effets opposés de l'occupation du voisinage sur l'accroissement en diamètre : des situations de compétition à proximité des fossés et des situations favorables à la croissance forestière plus loin. Dans ce dernier cas, les arbres étudiés ont démontrés une meilleure croissance avec une augmentation modérée de l'occupation du voisinage. Ceci a été interprété comme une démonstration de l'effet bénéfique du drainage biologique sur la croissance forestière. La présence d'aulne rugueux (*Alnus incana* ssp. *rugosa* (Du Roi) J. Clausen) dans le voisinage des arbres étudiés correspondait à une croissance accrue des deux essences étudiées.

Introduction

Boreal forested peatland sites are susceptible to watering-up after canopy removal (Heikurainen and Päivänen 1970; Dubé et al. 1995; Roy et al. 1997). This rise of the water-table level is principally caused by the abrupt change of evapotranspiration resulting from the removal of the higher vegetation cover. The reduction of the interception and transpiration were each responsible for about 50% the watering-up (Dubé and Plamondon 1995).

High water-table level results in anoxic conditions within the rooting zone (Ponnamperuma 1972; Campbell 1980), diminished soil volume available for rooting, nutrient uptake (Lieffers and Rothwell 1987; Koslowski 1997) and cold soil temperature (Lieffers 1988). The growth of North-American boreal tree species such as black spruce (*Picea mariana* (Mill.) B.S.P.), eastern larch (*Larix laricina* (Du Roi) K. Koch.) and white spruce (*Picea glauca (*Moench) Voss) is impaired by high water-table level (Lieffers and Rothwell 1986; Lieffers and MacDonald 1990; Landhäusser et al. 2003a).

Successful regeneration of water-logged sites is therefore closely linked to the water budget. Forest drainage can be used to promptly lower the water-table level of recently harvested forested peatlands (Roy et al. 2000a). The gradual re-establishment of the evapotranspiration, proportional to the vegetation revival, is also expected to play a major role in the future water budget of such sites (Paavilainen and Päivänen 1995). Biological drainage is the most common term used to describe the vegetation induced water-table drawdown observed on forested peatlands (Heikurainen and Päivänen 1970; Paavilainen and Päivänen 1995; Ahti and Päivänen 1997; Sun et al. 2001; Lauhanen and Ahti 2002; Ahti et al. 2004). The terms hydrological recovery (Roy et al. 2000b; Pothier at al. 2003; Xu et al. 2002) and hydrological nurse (Landhäusser et al. 2003a, 2003b) have also been used alternatively. Biological drainage has been studied in arid environments (Zhao et al. 2004) and in agroforestry systems (Livesley et al. 2004), however, neither its possible impact on water-table level, ecohydrological processes nor tree growth has ever been directly studied in regenerating forested peatlands (Jutras et al. 2002, 2004). With a better understanding of the reciprocal interaction between plant neighbours in water-logged sites, specific silvicultural guidelines concerning the education of such forest stands could be developed.

Biological drainage is assumed to induce a notable water-table drawdown (Heikurainen 1963; Heikurainen and Päivänen 1970; Aust et al. 1997; Roy et al. 2000b; Sun et al. 2001; Xu et al. 2002) which could consequently increase tree growth (Penner et al. 1995; Hökkä and Groot 1999). The best approach to the study of biological drainage would be based on simultaneous analysis of vegetation coverage, tree growth, and water-table spatial variability at tree-scale. Such intensive monitoring, executed through many growing seasons, would however be extremely laborious. Alternatively, the evaluation of past annual tree diameter increments of regenerating trees as a function of their plant neighbour abundance and their soil water conditions could enable the evaluation of the influence of biological drainage on tree growth. This approach would necessitate a study site where forest drainage has been implemented years ago, and where the tree stand is currently characterized by notable size-differences among trees, resulting from differences in local stem density around tree and soil water conditions. Such an area was available from a former innovative research project concerning the effect of drainage on post-harvested peatlands suffering from water-table rise caused by the vegetation removal and the impeding of evapotranspiration (Bolghari and Veilleux 1987).

Eastern larch was planted on sections of the experimental area to monitor the performance of this species in drained peatland soils. Sixteen years later, tree growth varied considerably with respect to proximity of the ditch. Consequently, the site appeared appropriate to attempt an evaluation of plant neighbour influence on tree growth through different soil water conditions, which were provided by the presence of drainage ditches. The aim of this study was to demonstrate the effect of biological drainage on tree growth in post-harvest drained forested peatlands. The quantification of its influence was expected to be possible by the study of individual tree growth in varying situations in terms of local competition and site water conditions. A retrospective annual diameter increment analysis was used to describe the influence of increasing tree neighbourhood occupancy on the growth of selected trees.

Material and methods

Study site and experimental design

The study area (49°28.5’N, 74°38.3’W) is located 60 km south of the town of Chapais, Quebec, Canada. The thirty-year mean annual precipitation, temperature and degree-days above 5ºC based on weather data collected at the “Chapais 2” meteorological station (49º46'N, 74º51'W), are 961.3 mm, 0.0ºC and 1235, respectively (Environment Canada 2004). The 120-year old black spruce-dominated stand was harvested using the whole tree method in 1981. Suspected to show severe regeneration problems because of its obvious poor soil drainage (Bolghari and Veilleux 1987), the site was experimentally drained in 1983. This experimental area is, to our knowledge, the oldest post-harvest drainage experiment in Canadian boreal forest. An excavator equipped with a “V”-shaped bucket dug 1 m deep by 2 m wide ditches with a mean spacing of 30 m (± 2 m). The effective water-table drawdown could not be estimated since no water-table level measurement took place before drainage. However, two wells located outside the experimental area (less than 200 m away) were used to measure weekly the water-table level during the four growing seasons that followed drainage. The 4-year mean annual water-table depth at mid-distance of 30 m-spaced drained strips was 41 cm. Conversely, a depth of 24 cm was observed for a well situated in comparable soil conditions but within a 70 m wide drained strip.

The soil characteristics and the vegetation type were uniform throughout the study area. The soil was characterized by a 30 cm thick, weakly decomposed (VonPost = 4) peat layer overlying a silty-clay textured mineral soil. The site corresponded to a OG 8 of the Ontario Forest Ecosystem Classification (Jones et al. 1983) and to a RE26/KAA LEG of the Quebec Forest Ecological Classification (Bergeron et al. 1998). At the time of drainage, the tree layer was dominated by advanced black spruce regeneration, speckled alder (*Alnus* *incana* ssp. *rugosa* (Du Roi) J. Clausen) was also present. The shrub layer was characterized by an abundant presence of *Rhododendron groenlandicum* (Oeder) Kron & Judd (syn. *Ledum groenlandicum* Oeder) associated with *Kalmia angustifolia* L. and *Vaccinium angustifolium* Ait.. The moss layer was dominated by *Sphagnum flexuosum* Dozy & Molk. and *Sphagnum magellanicum* Brid., *Pleurozium shreberi* (Bird.) Mitt. was present in smaller proportions. The study site is referred to as peatland in this paper even though it is considered a mineral soil site (organic layer < 40 cm) in the Canadian System of Soil Classification (Canada Soil Survey Committee 1978). The abundance of typical ombrotrophic peatland species, the obvious paludification processes responsible for the soil formation and the *Sphagnum* spp. dominated moss layer are the principal reasons why the term peatland was used.

In 1985, bare-root eastern larches were planted manually with approximately 2 m spacing in areas where black spruce regeneration was insufficient. There has not been any fertilization or vegetation control performed in the following years. In 2002, tree growth and neighbourhood occupancy was evaluated within 11 plots varying in size from 64.5 to 110.4 m². The plots were fitted to enclose at least three strips of planted larches (4.3 to 6.9 m in width) and to cover the distance from the ditch edge to the midpoint between ditches (14.2 to 16 m in length). All trees > 1 cm diameter over bark at breast height (DBH; h = 1.3 m) located within the plots were mapped and felled. The distance to the center of the closest ditch was measured with a graduated tape at the nearest 5 cm for each tree. In total, 168 planted eastern larches and 72 naturally regenerated black spruces were analysed. DBH and diameter over bark at stump height (DBH; h = 0.3 m) were measured on all felled trees. Discs, collected at stump height, were air-dried and sanded. Their annual ring increments (4 radiuses) were measured using a scanner and Windendro® software (Regent Technology Inc., Sainte-Foy, QC). Principal attributes of the studied plots and trees appear in table 1.

Table 1: Attributes of the plots and the eastern larch and black spruce trees.

		Larch			Spruce		
Variables[a]	Period[b]	min	mean	max	min	mean	max
$\Delta D_{0.3}$ (mm)	1	0.3	2.0	5.3	0.3	1.4	4.0
	15	0.7	6.3	14.3	1.1	4.2	9.4
	1-15	0.3	5.0	16.4	0.2	2.7	9.4
$D_{0.3}$ (mm)	1	0.4	1.4	5.2	0.9	7.1	19.3
	15	14.4	63.7	142.4	12.2	36.4	92.0
	1-15	0.4	29.8	142.4	0.5	19.4	92.0
$G_{<3m}$ (m^2/ha)	1	0	0.01	0.2	0	0.1	0.3
	15	0.8	9.4	26.4	0.1	5.3	15.9
	1-15	0	3.1	26.4	0	1.8	15.9
G (m^2/ha)	1	0	0.02	0.2	0	0.02	0.2
	15	4.1	6.6	9.8	4.1	6.6	9.8
	1-15	0	2.0	9.8	0	2.0	9.8
DIST (m)	1-15	1.2	6.9	15.7	2.9	9.2	15.2
ALDER	1-15	0	0.46	1	0	0.16	1
TIME (y)		1		15	1		15
Plots			11			11	
Trees			168			72	
Observations			2293			966	
Obs./ tree		8	13.6	15	7	13.4	15
Trees / plot		3	15.3	27	2	6.5	22

[a] *$\Delta D_{0.3}$, annual stump diameter increment; $D_{0.3}$, stump diameter; $G_{<3m}$, total basal area of neighbours located within 3 m from the studied tree; G, plot total basal area; DIST, distance of the tree to the closest ditch; ALDER, presence or absence of speckled alder within 3 m from the studied tree; TIME, years since plantation.*

[b] *Attributes for the first, the last and the whole period of observation (TIME = 1, TIME = 15 and TIME = 1 to 15)*

Model building

The analysis was based on construction and interpretation of individual-tree growth models for eastern larch and black spruce. Variability in tree growth models can be explained by differences in tree size and age. In forested peatlands, individual tree growth has been commonly expressed as a function of tree's status and vigour (Miina 1994; Hökkä and Groot 1999). Some of the models residual variability can be accounted for by temporal change in the basal area of neighbours, which may be related to the differences in soil saturation. If significant, these effects could then be interpreted as indicators of biological drainage.

In this study, the growth models' response variable was the annual stump diameter increment under bark ($\Delta D_{0.3}$) of planted larches and of naturally regenerated black spruces. The assumptions of normality and homogeneity of the variance were satisfied by adding a constant ($c = 2$) and making a logarithmic transformation for the response variable.

$\Delta D_{0.3}$ was expressed here as a function of the initial stump diameter under bark ($D_{0.3}$). Combination of both the first power of $D_{0.3}$ and logarithmic transformation of $D_{0.3}$ resulted in a linear relationship. As larches were planted in the same year and naturally regenerated black spruces were small at that time, age was replaced in the analysis by the number of years since the larch plantation occurred (TIME). The plot stump basal area (G) was used as a plot-level stand density indicator in the model. Since the site index was assumed to be uniform among plots, it was consequently omitted from the model.

Tree growth is affected by ditch closeness in drained forested peatlands (Miina 1994; McLaren and Jeglum 1998; Jutras et al. 2002). Following ditching, the maximum water-table lowering occurs near the ditch while the minimum occurs at the midpoint between them, describing a parabolic shape (Braekke 1983; Berry and Jeglum 1991; Hillman 1992; Prévost et al. 1997). The nutrient content of peat soil water and the soil aeration are higher in proximity to ditches (Prévost et al. 1999), resulting in enhanced tree growth at shorter distances from the ditch edge (Heikurainen 1964; Seppälä 1972; McLaren and Jeglum 1998; Jutras et al. 2002). The different water conditions across the drainage strips were utilized in this study to demonstrate biological drainage, which was assumed to be more important where soil water is in excess than where soil water is not limiting growth. Since the form of the relationship between ditch closeness and tree growth was unknown, the use of categorical variables was preferred to a continuous one. Ditch distances, ranging from 1 to 16 m, were reclassified into two unequally sized classes; $DIST_{NEAR}$ and $DIST_{FAR,}$ based on their influence on growth as detected in the analysis. Each class represents the distance from the closest ditch; 1 to 6 m, and 6 to 16 m, respectively. Since the average diameter growth rate was highest close to the ditch and lowest far from the ditch, interactions between distance class and initial diameter were included in the model.

The neighbourhood occupancy of subject trees was determined by the concept of the "zone of influence" defined by Opie (1968) as "the total area over which the tree may at present obtain or compete for site factors". The use of a fixed-radius plot, a distance-independent index, was preferred to diameter-dependent radius plot and to distance-dependent competition indices because the latter ones only marginally improve estimates of individual tree growth in growth models (Opie 1968; Biging and Dobertin 1992, 1995; Woodall et al. 2003). Miina (1994) assumed that a 3 m radius adequately expressed the area that Scots pine (*Pinus sylvestris* L.) saplings growing on drained peatlands need for access to below-ground resources. Neighbourhood occupancy values were calculated here for fixed radiuses of 1, 2, 3, 4, 5 and 6 m. A correlation analysis revealed no major additional contribution of the competitors beyond a 3 m radius.

The tree neighbourhood occupancy factor ($G_{<3m}$) was calculated as the sum of the stump basal area of all trees located within three meters of the subject tree. It has been computed for each year of the 15-year period of observation. $G_{<3m}$ for trees located close to the plot borders was estimated by positioning and measuring the DBH of 990 trees located outside the plots, within a 6 m distance from its border. Fifteen regression equations were built from the trees measured within the plots using the DBH and the distance from the ditch to reclusively estimate each annual $D_{0.3}$. These regressions were later applied to the trees outside the plot to calculate their development.

Known to be a good estimator of competition (Woodall et al. 2003), neighbourhood occupancy normally shows a negative effect on growth as it increases (Biging and Dobbertin 1992; Miina 1994; Woodall et al. 2003) in areas where the below-ground resources are the principal factor limiting growth. In this study, the neighbourhood occupancy factor is expected to be strongly correlated to the evapotranspiration rate of the area that it is describing. Consequently, in areas where excess water in the soil is the limiting growth factor, the neighbourhood occupancy factor is assumed to be an indicator of the potential for biological drainage. Optimum tree growth conditions are therefore expected to appear when the opposing effects of neighbourhood occupancy counter-balance each other. Various transformation of $G_{<3m}$, such as second power, square root, natural logarithm and inverse value, were tested.

$G_{<3m}$ showed constantly increasing value through time. At TIME = 1, trees were inevitably subjected to low neighbourhood occupancy due to the small size of trees, while at TIME = 15, neighbourhood occupancy could vary from low to high values, depending on the number and size of neighbours found within the fixed-radius plot. The beneficial effect of biological drainage might consequently be present only after neighbourhood occupancy attained specific levels, which needed time to occur after clearcutting. In addition, this interaction is probably different for different intensity of soil water excess, i.e., among the DIST classes. The triple interaction $\ln(G_{<3m})\times\text{DIST}\times\text{TIME}$ term in the model was used to test whether neighbourhood occupancy had different effects on growth at different soil water conditions in these data.

Another growth factor introduced in the model was the presence of speckled alder, a shrub with no commercial value. This thicket forming species was the only other treed vegetation, apart from eastern larch and black spruce, to be found on the site. Known to be a vigorous competitor for light in regenerating coniferous stands (Jobidon 1995), speckled alder might also play a role in the biological drainage phenomenon. A dummy variable expressing the presence or absence of this species within a 3 m radius from the subject tree (ALDER) was used in the model. This value was determined for observations completed in 2002 and thus has remained unchanged over time.

Data structure and model estimation

The data, like in many other tree growth model studies (Miina 1994; Hökkä & Groot 1999; Hökkä & Ojansuu 2004), were hierarchically structured. Three levels were specified: annual diameter increment observations repeated within each tree, numerous trees within plots, and several plots in the whole data. Furthermore, a non-hierarchical random interaction was detected between annual diameter increment observations and the plots. To account for this structure, and obtain unbiased parameter estimates for variables at each level, the mixed linear model with both fixed and random effects was applied. The following denotations were used: u_j, the plot-level random effect of the plot j; u_{jk}, the random interaction effect between the plot j and time k; u_{ij}, the tree-level random effect for the tree i in plot j; ρ_{ijk-1}, the autoregressive (first order) correlation coefficient of growth of tree i in plot j between time k and k-1; and e_{ijk}, the random error.

$$\begin{aligned} &\ln(\Delta D_{0.3\,ijk}+2)=b_0+b_1D_{0.3\,ij}+b_2(\ln(D_{0.3\,ij})\times DIST_{\mathrm{NEAR}\,ij})+b_3(\ln(D_{0.3\,ij})\times DIST_{\mathrm{FAR}\,ij}) \\ [1]\quad &+b_4TIME_{ijk}+b_5G_{<3\mathrm{m}\,ij}+b_6(\ln(G_{<3\mathrm{m}\,ij})\times DIST_{\mathrm{NEAR}\,ij}\times TIME_{ijk}) \\ &+b_7(\ln(G_{<3\mathrm{m}\,ij})\times DIST_{\mathrm{FAR}\,ij}\times TIME_{ijk})+b_8ALDER_{ij}+u_j+u_{jk}+u_{ij}+\rho_{ijk-1}+e_{ijk} \end{aligned}$$

The MIXED procedure of the SAS/STAT software (SAS System for Windows, Version 8.2) was used for the estimation. All fixed and random parameters (variances and covariances of the random effects) of the final model were estimated simultaneously using the restricted maximum likelihood method (Eq. 1). Random parameters were assumed to follow independent multivariate normal distributions with zero means and constant variances at each level. Calculated values of the denominators degrees of freedom were obtained by the Satterthwaite method (SAS Institute Inc. 1999). The first-order autoregressive structure was assumed for the correlation of the successive annual increments within each tree. Each explanatory variable or interaction was selected based on its influence on the response variable and on the -2·log-likelihood value of the entire model. A 5 % level of significance was used throughout this study for the model building and for contrasts executed on specific categorical variables. Minimum value of the AIC (Akaike's Information Criterion) of specific model was used as the criteria in selecting the final model to be presented.

Prior to transformation of the predicted values to the original growth scale, the following correction term was added to the predictions (see Flewelling and Pienaar 1981): $0.5\sigma^2 = 0.5(\sigma^2_{j} + \sigma^2_{jk} + \sigma^2_{ij} + \sigma^2_{ijk})$; where σ^2_{j} is the plot-level variance, σ^2_{jk} is the variance of plot × time interaction, σ^2_{ij} is the tree-level variance and σ^2_{ijk} is the variance of annual growth observations.

Results

Annual diameter increment of larch and spruce was positively influenced by a higher value of the initial diameter with different coefficients for both distance classes (Table 2). Contrasts indicated that trees located within the NEAR distance class obtained a significantly higher estimate for $\ln(D_{0.3})$ than those in the FAR class for both species ($p < 0.0001$). The increasing number of years since plantation (TIME) corresponded to a smaller annual diameter increment of larch, while this factor was non-significant for spruce (Table 2). The plot stump basal area (G) had non-significant influence on the annual diameter increment of either species. Overall, larch had higher annual diameter increment than spruce for comparable situations (Fig. 1 and 2).

Table 2: Estimates, standard errors (SE) and *p* value of the fixed parameters and the variance components of the annual stump diameter increment models.

	Larch			Spruce		
Parameter[a]	Estimate	SE	*p* value	Estimate	SE	*p* value
Intercept	1.4207	0.0398	<0.0001	1.2557	0.0678	<0.0001
$D_{0.3}$	0.0039	0.0006	<0.0001	0.0063	0.0013	<0.0001
$\ln(D_{0.3})\times DIST_{NEAR}$	0.2615	0.0109	<0.0001	0.1732	0.0206	<0.0001
$\ln(D_{0.3})\times DIST_{FAR}$	0.2196	0.0126	<0.0001	0.0958	0.0174	<0.0001
TIME	-0.0280	0.0052	<0.0001	0.0092	0.0048	0.0549
$G_{<3m}$	-0.0137	0.0055	0.0130	-0.0368	0.0118	0.0021
$\ln(G_{<3m})\times DIST_{NEAR}\times TIME$	-0.0036	0.0025	0.1570	0.0007	0.0038	0.8582
$\ln(G_{<3m})\times DIST_{FAR}\times TIME$	0.0039	0.0019	0.0359	0.0060	0.0022	0.0066
ALDER	0.0772	0.0189	<0.0001	0.1392	0.0550	0.0141
σ^2_j	0.0033	0.0022	0.0636	0.0118	0.0063	0.0297
σ^2_{jk}	0.0123	0.0017	<0.0001	0.0055	0.0009	<0.0001
σ^2_{ij}	0.0006	0.0017	0.3685	0.0058	0.0031	0.0328
$\rho_{k,k-1}$	0.6410	0.0245	<0.0001	0.6952	0.0392	<0.0001
σ^2_{ijk}	0.0296	0.0020	<0.0001	0.0208	0.0026	<0.0001

[a] *NEAR, distance class for trees situated from 1 to 6 m from the closest ditch; FAR, from 6 to 16 m from the closest ditch;* σ^2_j*, plot-level variance;* σ^2_{jk}*, variance of plot × time interaction;* σ^2_{ij}*, tree-level variance;* $\rho_{k,k-1}$*, autoregressive (first order) correlation coefficient;* σ^2_{ijk}*, variance of growth observations within a tree; see table 1 for other parameter descriptions.*

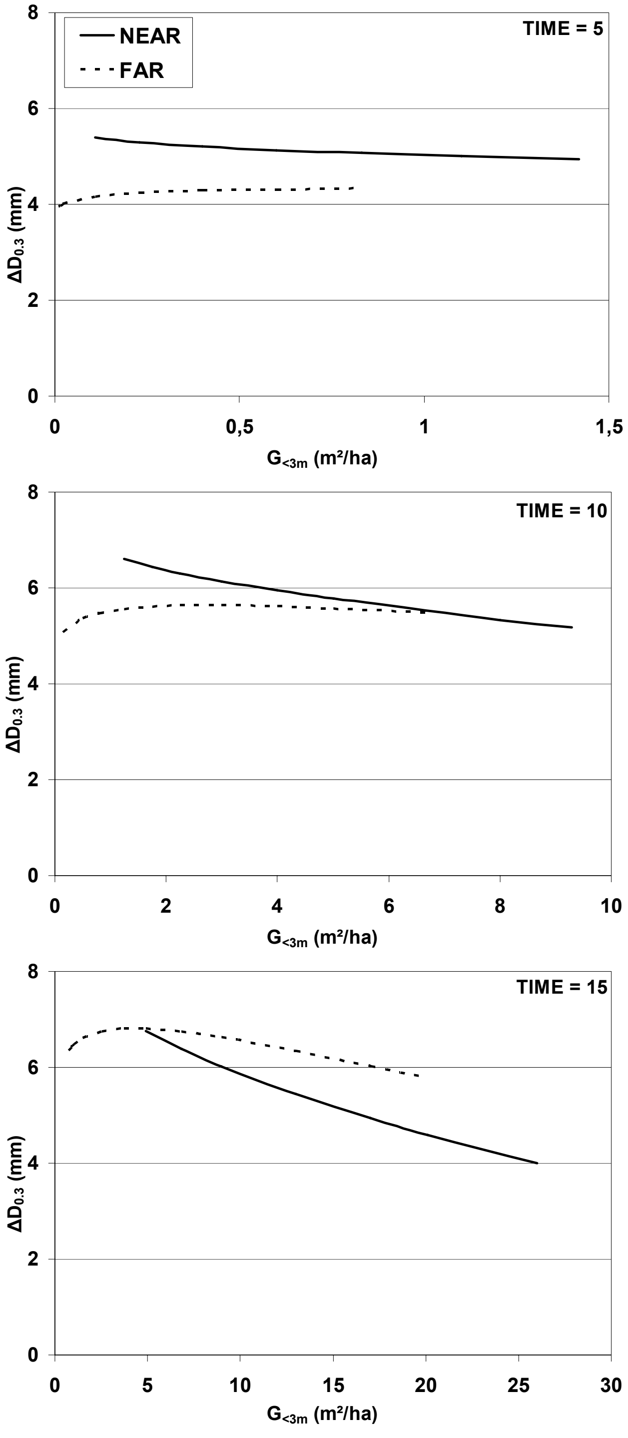

Figure 1: Annual stump diameter increment ($\Delta D_{0.3}$) for eastern larch, 5, 10 and 15 years after plantation (TIME) as a function of distance to the closest ditch (NEAR: 1 to 6 m; FAR: 6 to 16 m) and neighbourhood occupancy ($G_{<3m}$). Mean values at each predicted TIME period were used for the other explanatory variables.

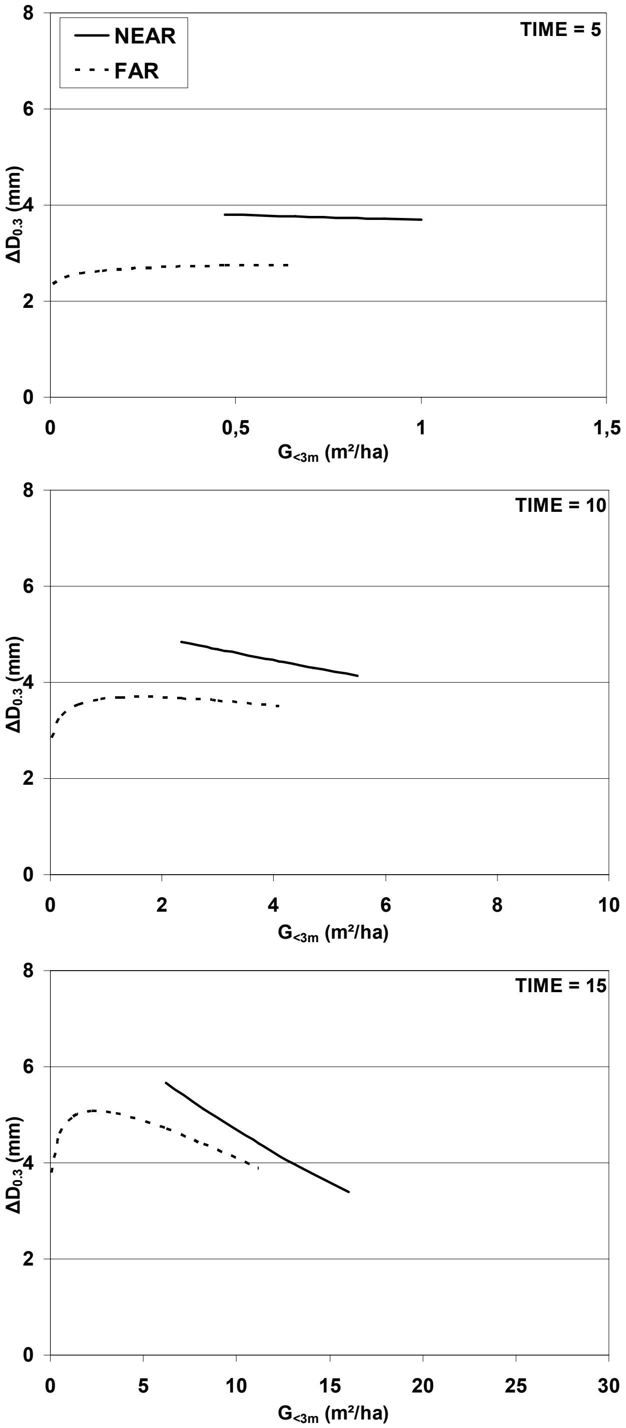

Figure 2: Annual stump diameter increment ($\Delta D_{0.3}$) for black spruce, 5, 10 and 15 years after plantation (TIME) as a function of distance to the closest ditch (NEAR: 1 to 6 m; FAR: 6 to 16 m) and neighbourhood occupancy ($G_{<3m}$). Mean values at each predicted TIME period were used for the other explanatory variables.

The factors characterising the influence of biological drainage on the response variable i.e., the $\ln(G_{<3m})\times DIST\times TIME$ interaction, showed for both species a significant effect on diameter increment for the FAR distance class (Table 2). The predicted annual diameter increment presented a rising trend as $G_{<3m}$ increased up to values of 4.3 and 2.4 m²/ha at TIME=15 for larch and spruce, respectively (Fig. 1 and 2). The trend then inversed and larger values of site occupancy resulted in smaller annual diameter increments. For the NEAR distance class, the $\ln(G_{<3m})\times DIST\times TIME$ interaction was non-significant. The diameter increment of trees located in the NEAR distance class was influenced by the $G_{<3m}$ as a single effect: as neighbourhood occupancy increased the $\Delta D_{0.3}$ decreased (Fig. 1 and 2). The presence of speckled alder in the neighbourhood of the studied trees was associated with a larger annual diameter increment (Table 2, Fig. 3).

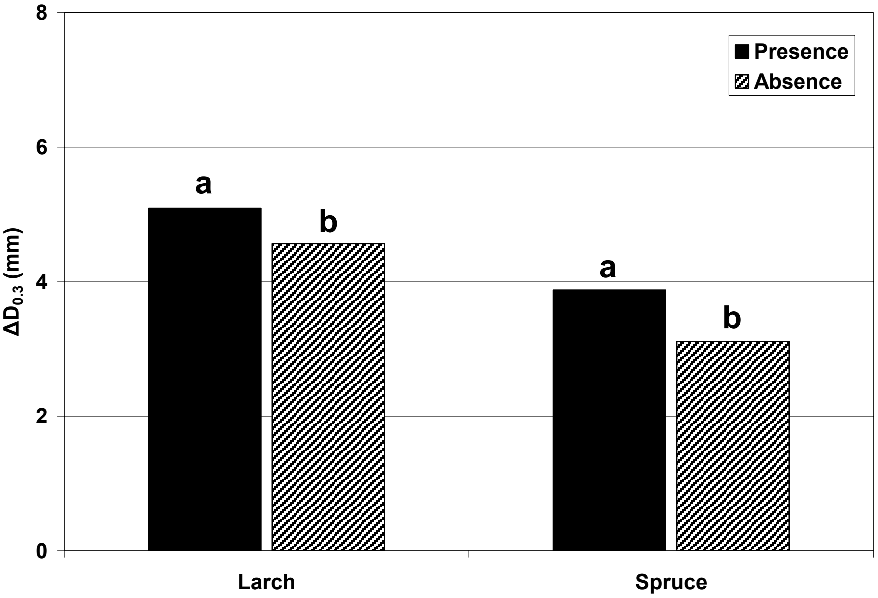

Figure 3: Mean annual stump diameter increment ($\Delta D_{0.3}$) of eastern larch and black spruce in function of the presence or absence of speckled alder in a 3 m radius from the subject tree. Different letters indicates significant differences between classes of the same species.

For larch, the random variation among trees (σ^2_{ij}) was non-significant and among plots (σ^2_j) was slightly beyond the 5% risk level (Table 2). All random parameters were significant for spruce. The autocorrelation coefficients were relatively high for both species

(0.6410 and 0.6952). Significant random interaction (σ^2_{jk}) indicated that temporal growth dynamics were different among plots.

Discussion

In regenerating stands, forest drainage favours tree size inequality, even after only few years of growth because of the unequal soil water conditions between the parallel drainage ditches. This study site was no exception since the annual diameter increment of both larch and spruce was higher for trees located near the drainage ditch ($DIST_{NEAR}$: 1 to 6 m) than trees located farther from it ($DIST_{FAR}$: 6 to 16 m). These circumstances were created by the improved soil water conditions close to a ditch rather than far from it (Roy et al. 2000a).

However, it was hypothesized that a gradual increase in evapotranspiration resulting from a vegetation revival would improve growth conditions. This phenomenon was assumed to be proportional to the tree neighbourhood occupancy. As notable tree mortality was not observed during the 15-year growth period, the value of this growth factor was continuously increasing with time. Neighbourhood occupancy or similar competition variables generally show negative impacts on tree growth, even in the very first years of seedling growth (Varmola 1989). Therefore, they have been used in previous studies to express the effect of competition for limited below-ground resources on tree growth (Miina 1994; Woodall et al. 2003). In the present study, the positive effects (biological drainage) of the neighbourhood occupancy appeared to overcome the negative effects (competition) in some circumstances. This interpretation of the opposing effects of the neighbourhood occupancy factor on growth has been previously proposed by Penner et al. (1995).

Larches and black spruces located close to the ditch ($DIST_{NEAR}$) constantly showed a decreasing diameter increment with increasing $G_{<3m}$ (Fig. 1 and 2). This observation was interpreted as the detrimental effect of competition for limited resources on individual-tree diameter growth. Biological drainage is expected to lower the water table level as neighbourhood occupancy increases, but within this specific area, the excess of soil water might not have been the principal limiting growth factor. Consequently, biological drainage did not notably improve tree growth for this distance class since the negative effect of competition prevailed.

Within the FAR distance class, moderate values of neighbourhood occupancy clearly had a beneficial influence on growth of both species (Fig. 1 and 2). This behaviour was interpreted as evidence of the effect of biological drainage on tree growth. In this case study, the effective water table drawdown caused by the biological drainage phenomenon could not be quantified. However, tree growth observations were consistent with the assumption that biological drainage progressively lowers the water-table level in specific areas at a rate proportional to the neighbourhood occupancy. In the FAR distance class, the growth limiting situation due to excess water was gradually modified into more favourable growth conditions, because average growth increased with time (Fig. 1 and 2). It appears that optimum conditions were reached where equilibrium was obtained between biological drainage and competition. Beyond this point, the negative effects of competition prevail over the beneficial effects of biological drainage.

It should be noted that for most of the 15-year period of observation, the average growing conditions in proximity to ditches resulted in better than average tree growth despite higher neighbourhood occupancy (Fig. 1 and 2). For larch trees, the beneficial influence of biological drainage in the FAR distance class at TIME=15 resulted in superior growth rates compared to the NEAR distance class for similar values of $G_{<3m}$. In this case, it is expected that the differences in tree size between NEAR and FAR distance classes will be diminished. For spruce, tree growth rates were almost equal between distance classes at time 15 (Fig. 2). Tree size inequity is likely to stabilise, but size differences already expressed between trees may persist.

The demonstrated beneficial effect of biological drainage on tree growth in a post-harvested and drained forested peatland emphasizes the importance of a rapid and successful re-establishment of a vigorous vegetation stratum. Regeneration management on recently harvested forested peatlands should therefore focus on the main growth limiting factors. Where the excess of soil water is not limiting growth, such as within the first few metres from the ditch, vegetation management should be adapted to the prevailing above- and below-ground competition. Since the most favourable growing conditions are found in this area, full stocking should be achieved by plantation of adapted species. Where the principal growth limitation is the excess of soil water, vegetation management should be adapted to the beneficial influence of biological drainage. Larches and spruces located farther than 6 m from the ditch on this specific study area showed their best growth performances with neighbourhood occupancy of 2 to 8 m^2/ha and 2 to 5 m^2/ha, respectively. Such neighbourhood occupancy values, expressed in m^2/ha, are not commonly used in day-to-day forest management practices. Therefore, these values are representing stem densities of 6 000 and 4 000 coniferous stems/ha ($D_{0.3}$ = 4 cm) for larch and spruce dominated stands, respectively. These site-specific values should therefore be carefully considered when determining density objectives for the application of pre-commercial thinning on young sapling peatland stands. Variations should be considered among peatland stands since the influence of biological drainage could have different effects with respect to stand composition, tree age and size, and soil characteristics such as thickness of the organic layer, degree of decomposition of peat, and mean water-table level.

The presence of speckled alder was another complementary variable included in the models that showed a significant influence on tree growth. On recently harvested sites, this bushy species can rapidly create a dense canopy, 3 to 4 m high, under which light availability is extremely limited, impairing growth and survival of small coniferous trees (Vincent 1964; Fortin et al. 1983; Jobidon 1995). In this particular study, the speckled alder canopy, where present, was already overgrown by both larches and spruces. The presence of alder was therefore seen as a favourable tree growth factor since its negative light competition effect was not restricting the growth of conifers (Fig. 3). Speckled alder is known to ameliorate the nutrient status of the soil by nitrogen fixation (Fortin et al. 1983; Jobidon 1995), and thus improve tree growth. It could also have been playing a role in the evapotranspiration budget of these regenerating peatland sites. However, the information gathered in this study is not sufficient to precisely differentiate which of these two phenomena was the exact cause of the beneficial effect of speckled alder. This species should therefore only be controlled when the light availability of commercial trees is jeopardized.

The use of a retrospective diameter increment analysis was deemed an appropriate approach to show the effect of biological drainage on tree growth. The unique data used in this study provided a wide range of competition situations and soil water conditions that were reflected in the growth dynamics of individual trees. To some extent, the results obtained were conditional to the choices made during model building, such as the selection of the variables and their transformations. These adjustments were intentionally made to enable the verification of the biological drainage hypothesis. The final models demonstrated logical behaviour and optimal fit with the data in terms of statistical measures. Moreover, the diameter increment models showed similar reactions of tree growth to the same explanatory variables used in other drained peatland growth models (Miina 1994; Hökkä et al. 1997; Hökkä & Groot 1999). Prior to our study, Penner et al. (1995) were the first to show that neighbouring trees can have a beneficial effect on tree growth in mature forested peatland stands. They also stressed the importance of separating the positive and negative effects of competition in forested peatlands growth models. The differentiation of the varying effect of the neighbourhood occupancy with distance to the ditch has been a key issue in this study to demonstrate of the existence of biological drainage in a regenerating drained peatland stand.

In an adapted post-harvest management scenario, drainage could be used to re-establish the favourable vegetation water-table interaction that prevailed prior to harvesting of forested peatland stands. Hypothetically, a successfully regenerated site should eventually benefit from biological drainage up to a point where the water-table level will be mainly regulated by the vegetation, therefore decreasing the utility of ditches. In such a case, ditch maintenance, an operation that destroys all the treed vegetation in the first few meters on the sides of the ditches, would be unnecessary.

In the province of Quebec, Canada, forest drainage is at the moment mainly restricted to post-harvested stands (Prévost et al. 2001). The state of knowledge concerning this treatment in north-American boreal forests is restricted to a short period of time. Our study site consisted of a small section of the oldest and largest Canadian post-harvested drainage experimental area located in boreal forest. It was established using the latest equipment and methods (Päivänen and Wells 1978) that have not changed since. Consequently, the data collected is representative of operational methods actually used in forested peatland stands. Furthermore, the ecological characteristics of the study site were representative of post-harvested eastern boreal peatlands that respond adequately to drainage (Jutras et al. 2002). However, this case-study is among the first successful attempts describing the beneficial growth effect of biological drainage on a forested peatland site. Important aspects concerning the complex mechanisms affecting the relationship between vegetation, soil and water are still unknown and further investigation is needed.

Conclusion

This study revealed a complex growth pattern of post-harvested drained peatland stands that was not previously reported in other forested peatlands growth model. The opposing effects of the neighbourhood occupancy factor on growth were essential to describe the situation observed in the present study. The favourable effect of neighbourhood occupancy, biological drainage, was demonstrated for specific situations where the excess of soil water is limiting growth. Near the ditch, the water-table might not have been the main limiting growth factor. This explains why the effect of biological drainage on growth could not be demonstrated there while evidence of competition was observed. This study highlights the need for a rapid and successful re-establishment of a vigorous vegetation stratum in post-harvested peatland stands. Regeneration management objectives should therefore consider the main limiting growth factors as guidelines for silvicultural treatment applications.

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CHAPTER 5

Influence of intra- and inter-specific competition on black spruce growth in post-harvest drained forested peatlands

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Abstract

Neighbouring plants can have positive and negative interferences on each other. The detrimental effects of this relationship, such as competition for light and nutrients, are more documented than its beneficial effects. Both types of interference are susceptible to appear on sites where the main limiting growth factor is the excess of soil water. The importance of competitors in the immediate surrounding of black spruce seedling was evaluated in terms of light interception on a network of 42 operationally drained post-harvest peatlands. This information was later used as an explanatory variable in annual diameter and height increment models. However, reasonable doubts appeared concerning the independency of the presence of competitors in function of drainage. Therefore, an independent network of regeneration plots located in post-harvested and drained peatlands was used to evaluate the establishment dynamics of black spruce's competitive tree species after drainage. Results demonstrated that moderate intra-specific light interception had detrimental effects on black spruce diameter increments, while low to moderate inter-specific light interception had beneficial effects on diameter and height growth. The nitrogen-fixing abilities of speckled alder and the biological drainage caused by the vegetation-induced evapotranspiration could explain the enhanced growing conditions, which consists in an example of positive interference of plant neighbours on black spruce seedling growth.

Résumé

Les plantes voisines peuvent avoir des interférences positives et négatives sur leur croissance respective. Les effets nuisibles de ce voisinage, tel que la compétition pour la lumière et les nutriments, sont plus documentés que ses effets bénéfiques. Ces deux types d'interférences sont susceptibles d'être présents sur les sites où le principal facteur limitant la croissance est l'excès d'eau du sol. L'importance des compétiteurs dans le voisinage immédiat de semis naturels d'épinette noire a été évaluée en terme d'obstruction lumineuse sur un réseau de 42 tourbières forestières récemment récoltées et drainées. Cette information a ensuite été utilisée comme variable explicative dans des modèles d'accroissement annuel en diamètre et en hauteur. Toutefois, des doutes raisonnables apparaissaient à propos de l'indépendance de la présence de compétiteurs par rapport au drainage. Un réseau indépendant de parcelles de régénération localisé dans des tourbières forestières récoltées et drainées a alors été utilisé afin évaluer la dynamique d'établissement des espèces compétitrices de l'épinette noire à la suite du drainage. Les résultats ont démontré qu'une interception lumineuse intra-spécifique modérée était nuisible à l'accroissement en diamètre de l'épinette noire, tandis qu'une interception lumineuse inter-spécifique allant de légère à modérée était favorable à la croissance en diamètre et en hauteur. Les propriétés fixatrices d'azote de l'aulne rugueux ainsi que le drainage biologique causé par l'évapotranspiration provenant de la végétation expliqueraient l'amélioration des conditions de croissance, ce qui constituerait un exemple d'interférence positive du voisinage sur la croissance de l'épinette noire.

Introduction

Harvesting activities on undrained forested peatlands are known to create problems of water-table rise (Dubé et al. 1995; Roy et al. 1997; Verry 1997). By reducing the rainfall interception and transpiration (Dubé and Plamondon 1995), vegetation removal increases soil water accumulation. Excess soil water restricts the growth of planted, recently installed, or protected advance black spruce seedlings (Lieffers and Rothwell 1986, 1987; Lieffers and Macdonald 1990). Such growth stagnation may last for decades (Bolghari 1986). Depending on the magnitude of watering-up, corrective treatments might be needed to adequately regenerate post-harvest, waterlogged sites.

Forest drainage, when applied to recently harvested forested peatlands, can markedly lower the water-table level (Roy et al. 2000). Implementation of drainage increases the root-accessible soil volume, raises soil temperature and accelerates the decomposition of peat soils (Prévost et al. 1997), while improving root zone conditions (Roy et al. 2000). This situation enhances the growth of black spruce (*Picea mariana* (Mill.) B.S.P) (LeBarron and Neetzel 1942; McLaren and Jeglum 1998; Macdonald and Yin 1999; Jutras et al. 2002), but drainage is also expected to influence the growth of black spruce's principal competitors. Abundant intra- and inter-specific competition has been observed and reported in post-harvest drained forested peatlands (LeBarron and Neetzel 1942; Hillman 1991; Jutras et al. 2002), but its influence on black spruce growth has never been directly evaluated. In the forested peatlands of eastern boreal Canada, the principal tree species that compete with black spruce are speckled alder (*Alnus incana* ssp. *rugosa* (Du Roi) J. Clausen), pussy willow (*Salix discolor* Mühl.), trembling aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marsh.), eastern larch (*Larix laricina* (Du Roi) K. Koch) and balsam fir (*Abies balsamea* (L.) Mill.). Ericaceous shrubs, such as Labrador tea (*Rhododendron groenlandicum* (Oeder) Kron & Judd; syn. *Ledum groenlandicum* Oeder) and sheep laurel (*Kalmia angustifolia* L.) are also known to interfere with black spruce growth (Inderjit and Mallik 1996, 1997, 2002; Mallik 2003).

Plant neighbours can have positive and negative interferences on each other, depending on the species involved and the nature of the factors limiting growth. Positive interferences are rare and often masked by more important negative interferences (Radosevich and Osteryoung 1987). The few positive effects that are found in boreal forested peatland sites include the association with speckled alder of nitrogen-fixing symbionts in the genus *Frankia*, which is known to increase nitrogen availability in soils (Chatarpaul and Carlisle 1983; Fortin et al. 1985) and to favour growth of tree species, such as black spruce (Jobidon 1995). Likewise, the evapotranspiration of vigorous neighbouring vegetation may, in certain circumstances, diminish the adverse effects of excess soil water on tree growth. This later positive interference of plant neighbours on waterlogged sites is referred to as biological drainage (Paavilainen and Päivänen 1995; Penner et al. 1995; Jutras et al. 2004) or hydrological nurse (Landhausser et al. 2003). Negative interferences in boreal forested sites have been widely documented and they mostly refer to the limitation of light and nutrients.

On mesic sites, the growth of planted black spruce seedlings is affected by both intra-specific (Newton and Jolliffe 1998; Mailly et al. 2003) and inter-specific competition (Wagner and Radosevich 1991; Morris and MacDonald 1991; MacDonald and Weetman 1993; Jobidon 1994; Wang et al. 2000; Noland et al. 2001; Jobidon et al. 2003). In each situation, optimal growth was observed in the absence of competition. On one hand, intra-specific competition is known to be very intense because closely related individuals must exist in similar, if not identical, microenvironments (Radosevich and Osteryoung 1987). On the other hand, different species interacting together in inter-specific competitive situations are exerting influences on different parts of the environment, and may therefore more equitably share available resources. However, the simultaneous consideration of both types of competition in growth analysis is rare (Canham et al. 2004).

On the post-harvest and drained forested peatland sites that were studied by Jutras et al. (2002), it was obvious that the tallest black spruce stems were found in moderate, above-ground competitive situations. The importance of competition was therefore measured for every black spruce seedling under study so that it could be used as an explanatory variable in tree growth analysis. However, there was no way to determine precisely vegetational composition when drainage was initiated. Black spruce found in competitive situations could have exhibited higher growth rates because: a) they were located in especially fertile micro-environments, where the establishment of other species was favoured; or b) neighbours exerted a positive growth interference with them. Therefore, if drainage was responsible for initiating competition with respect to ditch proximity, competition could not be considered as an independent black spruce growth factor. Conversely, if establishment dynamics of competitive tree species were not affected by drainage, competition could be considered as an independent growth factor. Since there was no means of evaluating competitive behaviour following drainage on the study area, competition had been omitted from the analysis of black spruce growth by Jutras et al. (2002).

A 16-year-old experimental network of regeneration plots that had been established in post-harvested and drained peatlands was located in the same ecological region as that in Jutras et al. (2002). This area was used to evaluate the establishment dynamics of black spruce's competitive tree species after drainage. With the addition of this second study area, independence between the presence of competition and drainage could be assessed. It was then possible to evaluate simultaneously the beneficial and detrimental interferences of neighbours on black spruce seedling growth in the Jutras et al. (2002) dataset. The objective of the present study was to evaluate the positive and negative interferences of different levels of competition on black spruce growth in post-harvest drained forested peatlands.

Material and methods

Competition establishment dynamics study

The first part of this study describes establishment dynamics of the principal black spruce's competitive tree species on post-harvest, drained forested peatlands. Vegetational composition of the network of regeneration plots, established before drainage operations, was compared to their composition 16 years later. Three experimental sites that had been established in 1985 were used: Hazeur (49°29'N, 74°38'W), Bruneau (49°22'N, 77°09'W) and Dalet (49°14'N, 78°15'W). These sites were situated in the western black spruce-mosses bioclimatic sub-domain, as were the majority of the study sites of Jutras et al. (2002). Typical 30-year climate normals from the closest meteorological station (Chapais 2: 49°47'N, 74°51'W) were: 0.0 °C, mean annual air temperature; 1235 degree-days (over 5 °C); 961.3 mm, annual precipitation (Environment Canada 2004).

All of these experimental sites were dominated by black spruce before they were harvested (whole-tree) in 1981 (Hazeur) and in 1983 (Dalet, Bruneau). Severe regeneration problems were expected on these sites because of their poor natural soil drainage and the evidence of watering-up, which occurred as a consequence of harvesting (Bolghari and Veilleux 1987); consequently, they were drained experimentally in 1985. Ditch spacing varied from 30 to 60 m. The installation, marking and measurement of 200 circular regeneration plots (1.13 m radius = 4 m2) in each site took place in 1985, just prior to drainage. The plots were systematically installed at 50 m intervals using parallel (Hazeur and Dalet) or randomly oriented (Bruneau) transects, with random positioning of the first plot. These plots were measured again in 1986 after the completion of ditching operations to assess the possible destruction or modification of the vegetation and soils by the machinery. In 2002, regeneration plots that were still available and undisturbed were remeasured using the same inventory method. Overall, 85, 84 and 52 plots were remeasured for the Hazeur, Bruneau and Dalet sites, respectively. Plots were unavailable for inventory in 2002 due to flooding caused by beaver dams (195 plots), insufficient information that enabled the exact relocation of the plot in the field (156 plots), and plot destruction during ditching operations (28 plots).

The data collected in 1986 contained information about the soil and vegetation characteristics of the individual plots. In keeping with the objectives of the present study, only data related to black spruce's competitive tree species was considered. In every plot, the presence or absence of speckled alder, pussy willow, trembling aspen, white birch and black spruce had been recorded. However, alder and willow had been lumped into one category on the Dalet site. Since these two thicket-forming species have comparable sizes and shapes (max. height ≈ 6 m, Farrar 1995), they were grouped together for all sites. Trembling aspen and white birch also were grouped together, since their respective occurrences were relatively infrequent and their role as competitors was expected to be comparable on regenerating forested peatland sites. Eastern larch and balsam fir were observed within the plots, but their occurrence (4 % and 3 %, respectively) was too low to enable an adequate statistical analysis. Black spruce, considered as an intra-specific competitor, was also taken into account.

In 2002, the presence-absence of alder-willow, aspen-birch and black spruce categories was recorded in every accessible plot. The ecological description of each plot (Table 1) was done at the same time using the operational group (OG) classification key of the Ontario Forest Ecological Classification system (Jones et al. 1983). Ditches and remeasured plots were located on the landscape using a March II® GPS handset (CMTinc, Corvallis, OR). Differential correction was done later with PCGPS 3.7® software (CMTinc, Corvallis, OR), with reference data coming from two different bases (49°56'N, 74°22'W and 48°15'N, 79°02'W). Distance of each plot to the closest ditch was determined using ArcView GIS 3.2® (ESRI, Redlands, CA). Measured distances ranged from 1 to 30 m, with a mean value of 13 m.

Table 1: Ecological descriptions of the study sites (OG adapted from Jones et al. 1983)

Operational Group	n_1	n_2	Organic soil thickness (cm)	Principal species	
OG 5 *Feathermoss - fine soil*	39	0	5 to 20	Shrub: Herb: Moss:	*Ledum groenlandicum* *Cornus canadensis* *Pleurozium schreberi*
OG 8 *Feathermoss - sphagnum*	52	11	20 to 39	Shrubs: Mosses:	*Ledum groenlandicum* *Vaccinium angustifolium* *Pleurozium schreberi* *Sphagnum* spp.
OG 11 *Ledum*	46	21	> 40	Shrubs: Moss:	*Ledum groenlandicum* *Chamaedaphne calyculata* *Sphagnum* spp.
OG 12 *Alnus - herb poor*	18	6	> 40	Shrub: Mosses:	*Alnus rugosa* *Sphagnum* spp. *Pleurozium schreberi*
OG 14 *Chamaedaphne*	19	4	> 40	Shrubs: Moss:	*Chamaedaphne calyculata* *Ledum groenlandicum* *Andromeda glaucophylla* *Sphagnum* spp.
Undetermined OG *Alnus - Perturbed area*	46	0	5 to > 40	Shrub: Moss:	*Alnus rugosa* *Salix* spp. Bare peat or deciduous litter
Total	221	42			

Note: n_1 refers to the number of regeneration plots used in the competition establishment dynamics study; n_2 refers to the number of sites used for the black spruce growth study.

Black spruce growth study

The original goal of the Jutras et al. (2002) study was to determine the impact of drainage on the 9-year diameter and height increments of naturally regenerated black spruce in relation to ecological characteristics of the sites. The study was executed on a sub-sample of the oldest operationally drained, post-harvest peatlands located in northwest boreal Quebec. From 1987 to 1991, more than 420 drainage networks were established in the regions of Chibougamau and Abitibi. Based on Finnish techniques and equipment (Päivänen & Wells 1977), drainage networks were constructed with a main ditch collecting the water that was evacuated by several secondary ditches, which ran parallel to one another and which were separated by 30 m. Ninety drainage networks were visited during the 1999 and 2000 growing seasons. Evaluation of the study potential of each drainage network was carried out based on three criteria: the uniformity of the growth conditions throughout the drained area, the proximity of a similar undrained area that could be used as a control, and the uninterrupted flow capacity of the ditches since drainage. This last aspect was estimated by assuming a minimum ditch depth of 50 cm and an apparent capacity to evacuate water, characterized by the absence of beaver dams or any misconception of ditches, e.g.: inverse slope or disconnection to the network. Overall, 48 drainage networks were retained for monitoring black spruce growth.

Black spruce growth was evaluated retrospectively using a method modified after Dang and Lieffers (1989). Post-drainage tree growth was evaluated for paired drained and undrained sites, which were selected for their proximity, their similar ecological characteristics and their comparable pre-drainage growth rates. Undrained sites were located at least 100 m from any drainage ditches. Based on paired pre-drainage tree growth comparisons, 9 out of the 48 sites selected from Jutras et al. (2002) study were rejected. In 2004, establishment of new control sites, followed by pre-drainage growth comparisons, allowed 3 out of the 9 rejected sites to be included in the database. For the present study, 42 pairs of drained-undrained sites were used (Table 1).

On each drained site, growth was measured on the most dominant black spruce tree found in each of the 24 circular plots (4 m^2), which were situated along eight transects perpendicular to the ditch. Transects were located at 5 m distances from one another, four on either side of a ditch; three plots were located along the transects at 2.5, 7.5 and 12.5 m from the ditch edge. On every control site, 12 plots of the same size were located in a 5 m systematic grid within a 10 × 15 m area (see Jutras et al. 2002 for details).

Selected black spruce trees were felled at ground level to collect a wood disk, which was later air-dried and sanded. Annual ring increments were measured along four radii with the help of a digitizer and WinDendro™ software (Regent Instruments Inc., Ste.-Foy, Canada). Annual diameter increments were calculated as two times the mean value of the four measured ring widths. Annual black spruce height increments were measured by assessing the lengths separating each annual whorl scars. Mean (±SD) diameter and height of study trees were 20 ± 12 mm and 120 ± 74 cm, respectively.

Black spruce above-ground competition was assessed from the respective light interception percentage (5 % classes) at mid-crown height offered by the two most important competitive species. This measurement was done by the same evaluator for all selected trees, as a visual estimate. Several studies have stressed the utility and accuracy of predicting competition from rapid visual estimates over photosynthetically active radiation (PAR) measurements (Wagner and Radosevich 1991, 1998; Ter-Mikaelian et al. 1999; Wang et al. 2000). The visual estimates of light interception were considered appropriate for the proportion of full sunlight intercepted by the canopy of competitive tree species surrounding each black spruce targeted for study. The abundance of foliage blocking light transmittance was also considered to be proportional to the amount of biomass found in the area immediately surrounding the study trees. It was therefore assumed that these light interception measurements would correlate with local evapotranspiration provided by the vegetation.

For growth analysis, the type and intensity of light interception (LI) were described by a single categorical variable. Intra-specific, mixed or inter-specific types of competition were described as the proportion of light intercepted by black spruce (> 75 %, 74 to 25 % and <25 %, respectively). The intensity of light interception was separated into three classes for each type of competition: low (L, 5-30 % of total intercepted light), moderate (M, 35-60 %), and high (H, >60 %). A 0 % class was also added for trees free of light interception.

Of the selected black spruces subjected to mixed and inter-specific light interception, 44 % contained speckled alder. Among all competitive species found in the study area, it is the only one having documented nitrogen-fixing abilities (Fortin et al. 1985). A dummy variable (ALDER), which indicated the presence of alder among the species blocking light interception, was added to differentiate this competitor from the others.

Ericaceous shrubs that intercepted light above black spruce seedlings were rarely found. The presence of Labrador tea and sheep laurel appeared to be constant for all trees within each site and comparable for all sites described by the same OG. The measurement method was therefore considered inappropriate for this type of competition. The adverse effect of ericaceous shrubs on black spruce growth was consequently considered as a component of the OG factor.

Statistical analysis

The establishment dynamics of black spruce's competitive tree species was evaluated as a function of the distance to the ditch, using a logistic regression approach. The presence of alder-willow, aspen-birch and black spruce within each plot in 2002 was analysed in relation to their respective presences in 1986, their distance to the closest ditch (DIST: 0-5 m, 5-10 m, 10-15 m, 15-20 m and >20 m) and their operational group (OG). The presence in 1986 × DIST interaction was used in the analysis to consider the possibly drainage-dependent differences in post-drainage tree establishment. Variation occurring within the three different studied sites was taken into account, as a random block effect.

For the black spruce growth study, the last growing season's diameter (DI) and height (HI) increments were used as the dependent variables in a split-plot design. Operational group (OG) was used as the main plot effect while distance to the ditch (DIST: control, 0-5 m, 5-10 m and 10-15 m) was used as the sub-plot effect. Other explanatory variables used in the analysis were: initial dimension (D_0, H_0); light interception (LI: 0 %, L-intra, M-intra, H-intra, L-mixed, M-mixed, H-mixed, L-inter, M-inter and H-inter); presence of alder (ALDER: 0 and 1) and last measured growing season (YEAR: 1998, 1999 or 2000, as categorical values). Logarithmic transformations were used for continuous variables ($\ln(DI)$, $\ln(HI)$, $\ln(D_0)$, $\ln(H_0)$) to satisfy assumptions of normality and homogeneity of the variance. Numerous interactions, such as OG × DIST, LI × DIST, LI × ALDER, $\ln(D_0) \times$ OG and $\ln(H_0) \times$ OG were also tested in the models. Each explanatory variable or interaction was selected based on its significant influence on the response variable and its influence on the -2·log-likelihood statistic for the entire model. Random parameters were included to consider the variation between sites within the same operational group (SITE(OG); main plot error) and the variation between trees located in the same distance class for each site (DIST × SITE(OG); sub-plot error).

All statistical analyses were performed with the SAS/STAT Version 8.2 software (SAS Institute Inc., 1999). The GLIMMIXED macro was used for the competition establishment dynamics study. The MIXED procedure was used for the estimation of the parameters of the black spruce growth model. All fixed and random parameters of the models were estimated simultaneously using the restricted maximum likelihood method. The denominator degrees of freedom were estimated by the Satterthwaite approximation (SAS Institute Inc. 1999). A level of significance of 5 % was used throughout this study. When significant results were obtained for a categorical variable, a Tukey multiple comparison test was performed (Steel and Torrie 1980).

Results

Competition establishment dynamics

In 2002, alder-willow and black spruce were present in a majority of the regeneration plots (69 and 54 %, respectively), while aspen-birch were found only in 17 % of them (Table 2, 3 and 4). Tree establishment following drainage (absence in 1986 and presence in 2002) occurred for every species under study, even though most situations remained unchanged over the measurement period (Table 2, 3 and 4).

Table 2: Frequency tables of alder-willow in the permanent regeneration plots located in recently harvested and drained peatlands. Percentage appears in parenthesis.

		2002		
		Absence	Presence	Total
1986	Absence	63 (28)	64 (29)	127 (57)
	Presence	6 (3)	88 (40)	94 (43)
	Total	69 (31)	152 (69)	221 (100)

Table 3: Frequency tables of aspen-birch in the permanent regeneration plots located in recently harvested and drained peatlands. Percentage appears in parenthesis

		2002		
		Absence	Presence	Total
1986	Absence	166 (73)	19 (9)	185 (84)
	Presence	17 (8)	19 (9)	36 (16)
	Total	183 (83)	38 (17)	221 (100)

Table 4: Frequency tables of black spruce in the permanent regeneration plots located in recently harvested and drained peatlands. Percentage appears in parenthesis

		2002		
		Absence	Presence	Total
1986	Absence	72 (33)	27 (12)	99 (45)
	Presence	29 (13)	92 (42)	121 (55)
	Total	101 (46)	119 (54)	220 (100)

The presence of every competitive species in 2002 was highly dependent ($p < 0.0001$) on its presence in 1986 (Table 5). The presence of alder-willow in 2002 also was dependent on OG (Table 5). A multiple comparison Tukey test showed the significantly higher presence of alder-willow in 2002 in the Feathermoss - sphagnum (OG 8) and Alnus - perturbed area (undetermined OG) comparatively to the Chamaedaphne (OG 14) operational group ($p = 0.0130$ and 0.0053, respectively). High presence of alder-willow was also found in the Alnus – herb poor (OG 12) group, but it did not significantly differ from OG 14. DIST and the 1986 presence × DIST interaction were non-significant in all three models.

Table 5: Logistic regression summaries on the occurrence of the principal black spruce's competitive tree species in the permanent regeneration plots located in recently harvested and drained peatlands.

Presence in 2002	Explanatory variables	df	*p* values
Alder-willow	**Fixed effects**		
	Alder-willow presence in 1986	1	<0.0001
	DIST	4	0.9382
	Alder-willow presence in 1986 × DIST	4	0.8742
	OG	5	0.0069
	Random effect		
	Block	2	0.2019
Aspen-birch	**Fixed effects**		
	Aspen-birch presence in 1986	1	<0.0001
	DIST	4	0.8722
	Aspen-birch presence in 1986 × DIST	4	0.4916
	OG	5	0.0633
	Random effect		
	Block	2	0.1944
Black spruce	**Fixed effects**		
	Black spruce presence in 1986	1	<0.0001
	DIST	4	0.1828
	Black spruce presence in 1986 × DIST	4	0.3114
	OG	5	0.2730
	Random effect		
	Block	2	0.2290

Note: DIST = Distance to the closest ditch (classes)

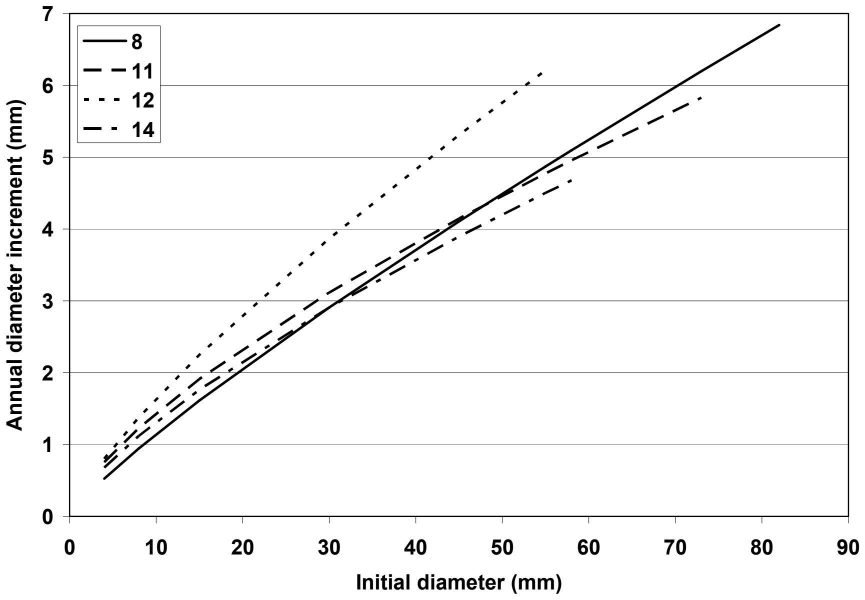
Black spruce growth

Annual diameter and height increments of black spruce seedlings were strongly influenced by their initial dimensions, but this relationship significantly varied with the OG, as the significant ln(D0) × OG and ln(H0) × OG interactions showed (Table 6, Fig. 1). Large trees showed greater increments than smaller trees for all OG. Trees in OG 12 had the greatest diameter increments of all OGs for comparable initial diameter (Fig. 1a). Smaller height increments were observed for trees in OG 14 having initial height greater than 100 cm compared to other OGs (Fig. 1b).

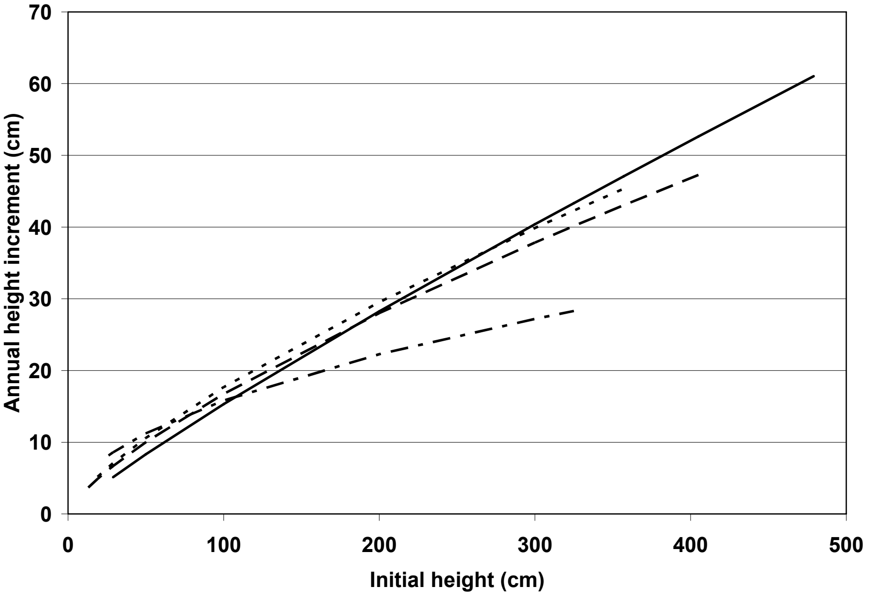
Table 6: Summary of the variance analysis on ln-transformed last annual diameter (ln(DI)) and height increment (ln(HI)) of black spruce seedlings located on drained peatland sites.

		ln(DI)		ln(HI)	
Explanatory variables	df	*F*	*p*	*F*	*p*
OG	3	5.49	0.0031	5.48	0.0031
Main plot error : Site(OG)	38				
DIST	3	16.10	<0.0001	12.19	<0.0001
Sub-plot error : DIST × Site(OG)	123				
$\ln(D_0)$ *or* $\ln(H_0)$	1	1010.50	<0.0001	423.14	<0.0001
$\ln(D_0) \times$ OG *or* $\ln(H_0) \times$ OG	3	4.37	0.0045	5.46	0.0010
LI	9	9.65	<0.0001	3.94	<0.0001
ALDER	1	5.82	0.0160	5.20	0.0227
Residual error	1327				
Corrected total	1508				

Note: OG = Operational Group, Site = Studied site, DIST = Distance from the closet ditch, D_0 *= Initial diameter,* H_0 *= Initial height, LI = Light interception class, ALDER = Presence of alder.*



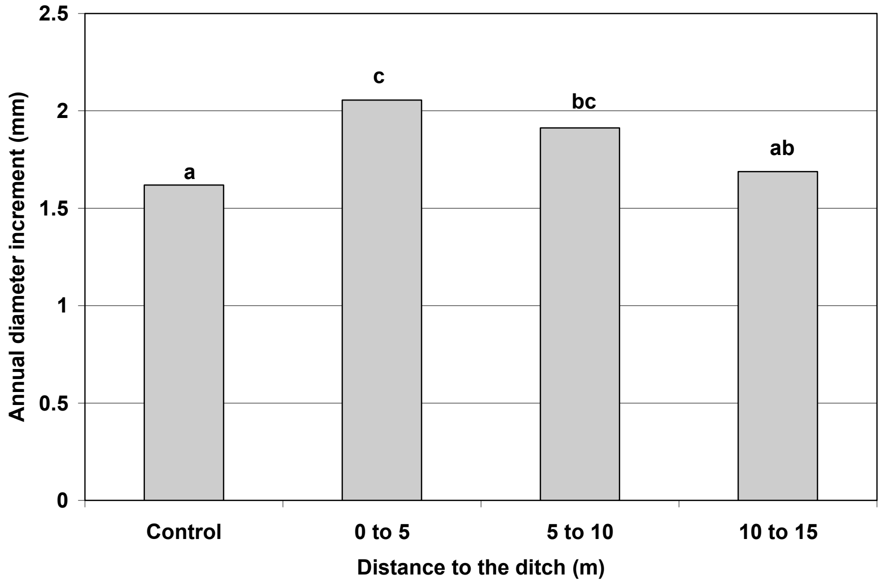
A)



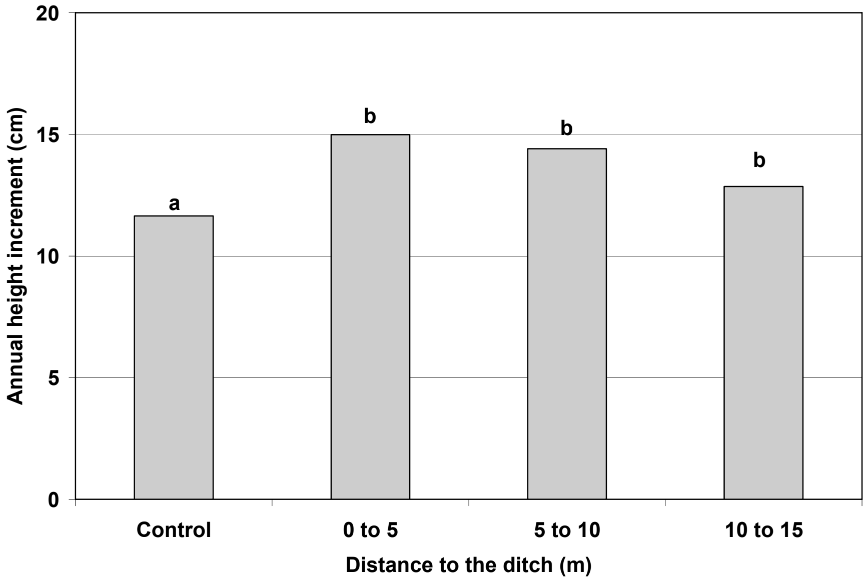
B)

Figure 1: Annual diameter (A) and height (B) increments of naturally regenerated black spruce seedlings in post-harvest drained, forested peatlands as a function of the initial dimensions and the operational group (OG). Other variables have been fixed at specific values: DIST = 5 to 10 m, LI = M-Mixed, and ALDER = 0.

Drainage had a significant influence on the growth of black spruce. Diameter increment was significantly greater for the 0-5 and 5-10 m distance classes when compared to the control (Table 6, Fig. 2a). All drainage-distance classes showed significantly greater height increments than the control distance class (Table 6, Fig. 2b). These effects of drainage were comparable for all OG and all LI classes since the OG × DIST and the LI × DIST interactions were non-significant for both diameter and height models.



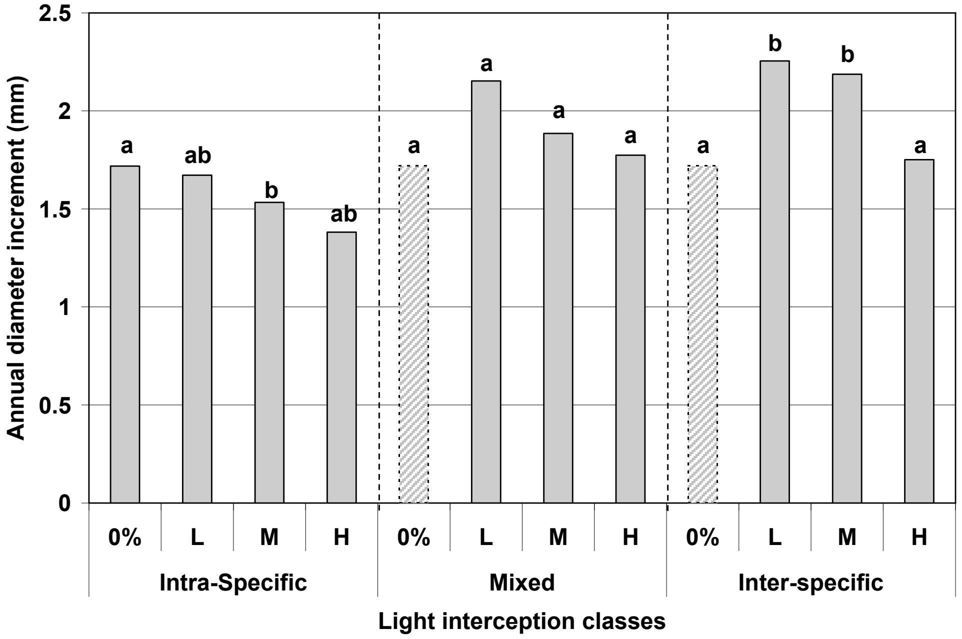
A)



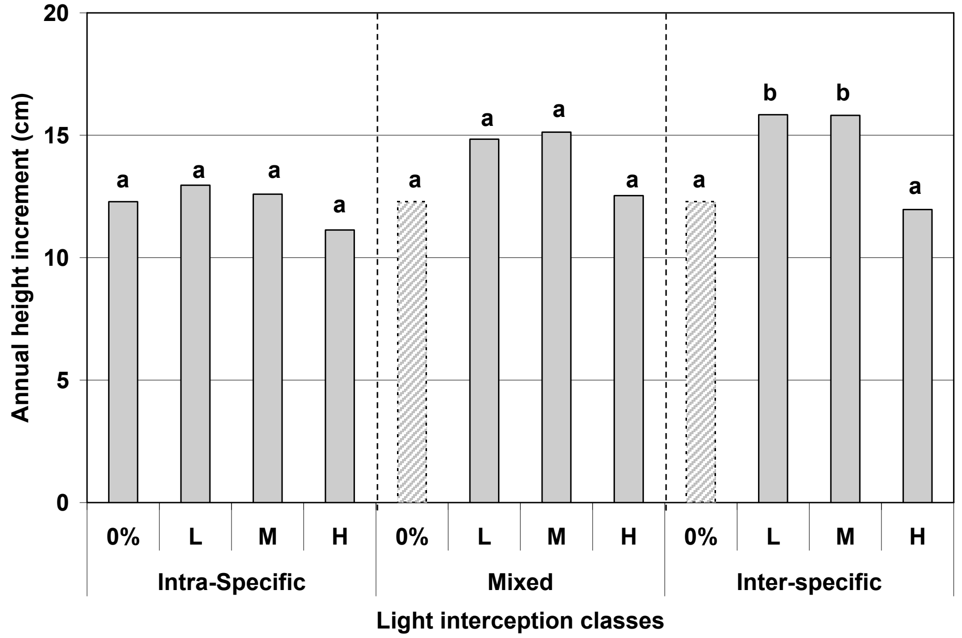
B)

Figure 2: Annual diameter (A) and height (B) increments of naturally regenerated black spruce seedlings in post-harvest drained forested peatlands in function of the distance to the ditch (DIST). Different letters indicate significant differences at the 5 % level.

Significant differences in annual diameter and height increments were found between the light interception classes (Table 6, Fig. 3). All three types of competition showed reduced mean annual diameter and height increments with increasing light interception intensity (Fig. 3a-b) but only inter-specific competition revealed significant growth differences between low and high levels. When compared to trees free of competition, described by the 0 % LI class, only moderate intra-specific LI had a significantly detrimental effect on diameter growth (Tukey adjusted p value = 0.0186, Fig. 3a). No annual height increment variations were observed between intra-specific LI classes and the 0 % class (Fig. 3b). Neither annual diameter nor height increments demonstrated differences between mixed LI classes and the 0 % class (Fig. 3a-b). Low and moderate inter-specific LI illustrated significantly higher annual diameter and height increments when compared to the 0 % class (Fig. 3a-b). Black spruce growth did not differ between high inter-specific LI situations and the absence of competition.



A)



B)

Figure 3: Annual diameter (A) and height (B) annual increments of naturally regenerated black spruce seedlings in post-harvest drained, forested peatlands as a function of light interception (LI). Different letters indicate significant differences at the 5 % level between LI classes of the same type. The 0 % LI class was repeated (hatched bars) for every type of LI to facilitate class comparisons. L = 5-30 % of total intercepted light; M = 35-60 % and H = >60 %.

The presence of alder among the species contributing to the light interception of the black spruce seedlings (ALDER) was significant in both models (Table 6). The parameter estimates were negative for both annual diameter and height increments (-0.1093 and -0.1341, respectively), meaning that black spruce growth was lower when speckled alder was present within inter-specific competitors than when it was absent. The LI × ALDER interaction was found to be non-significant, meaning that the effect of ALDER on black spruce growth was the same for all light interception classes. The year of the last growing season (YEAR) had no effect on the dependent variable. Therefore, the annual diameter and height increments were comparable for the 1998, 1999 and 2000 growing seasons.

Discussion

The three types of black spruce's competitive tree species that were examined over a 16-year period exhibited comparable behaviour concerning their establishment dynamics following drainage. Even if a majority of regeneration plots in 2002 contained the same species that were found in 1986, post-drainage tree establishment accounted for 29, 9 and 12 % of the alder-willow, aspen-birch and black spruce observations, respectively (Table 2, 3 and 4). The non-significant influence of the 1986 presence × DIST interaction specifically revealed that neither the pre-drainage presence of competitors nor their post-drainage establishment were dependent on the distance to the closest ditch. It can therefore be confirmed that in regenerating post-harvested and drained boreal forested peatlands, the presence of black spruce's competitors was not influenced by the proximity of the ditch. Since the presence of competition is considered to be independent from the drainage treatment itself, it can therefore be used as a black spruce growth factor in drained clearcut peatland sites.

Observations that were made concerning the influence of the ecological classification on the presence of black spruce's competitive tree species were consistent with expectation. Only the presence of alder-willow varied among OGs in the competition-establishment dynamics study, and it corresponded to the description of the vegetation dominating each

OG. Speckled alder was an indicator species for OG 12 and commonly can be found invading perturbed areas. The poorest group, OG 14, was characterised by the absence of alder. Trembling aspen, white birch and black spruce could not be used to differentiate OGs. They were found in all OGs with similar occurrences.

Results concerning the effect of drainage on black spruce growth were consistent with previous observations made by Jutras et al. (2002). The favourable effect of drainage on black spruce seedling diameter and height growth, expressed by the DIST factor, behaved as expected. When compared to undrained areas, diameter increment of drained black spruce seedlings increased within the first 10 m from the ditch. Height increment significantly increased over the whole 30 m spacing drained area. This effect was not significantly different among the OGs, suggesting a similar impact of drainage on the last annual growth increment of black spruce for all OGs. In the study by Jutras et al. (2002), differences among OGs with respect to the DIST classes were observed for the 9-year growth period following drainage. Significant growth increments after drainage were limited to the first DIST class on poor sites (e.g. OG 14), while drainage was having a broader influence on richer sites (e.g. OG 8 and 12). Tree response to the treatment might have differed among OGs, especially for the first few years after drainage. Possible OG-specific delays in response could have influenced the 9-year growth period following drainage. The non-significant effect of the OG × DIST interaction is therefore showing the similar effect of DIST classes among OGs on the last measured annual diameter and height increments.

The method used to account for the positive and the negative interferences between the selected black spruce and their immediate tree neighbours was derived from the measurement of shared above-ground resources. Light interception was assumed to be a reasonable estimator of standing biomass in the immediate neighbourhood of the trees being studied. We also assumed below-ground resource interferences to be proportional to the LI factor. The adverse effects of the different interferences between plant neighbours and black spruce growth were simultaneously considered in the growth models constructed.

Our results demonstrated that a moderate level of intra-specific LI was sufficient to reduce black spruce diameter growth. Annual height increment, on the other hand, did not respond to this type of competition. The presence of numerous trees of the same species in a resource-restricted site, such as forested peatlands, could have prompted intensive uptake of particular nutrients, which could have become rapidly limiting. The inevitable sharing of below-ground resources affected all neighbouring trees, compelling black spruce seedlings in moderate intra-specific competitive situations to sub-optimal diameter growth when compared to competition-free individuals.

In the simultaneous presence of both intra- and inter-specific competition, trees tended to react positively to the presence of low and moderate LI intensity. Mixed LI classes were less represented than other types of competition, which resulted in wide variation in annual diameter and height increments. This may explain why no significant differences were observed among mixed LI classes and the 0 % class.

The influence of inter-specific LI on black spruce growth showed a different pattern than other types of light interception. High inter-specific LI strongly suppressed black spruce growth when compared to the low and moderate intensity classes, but such intensive light interception showed similar annual diameter and height increments to the 0 % class. These results did not correspond to the observations made by Jobidon (1994), demonstrating that inter-specific levels of competition exceeding 60 % of light interception are harmful to black spruce growth. Accordingly, low and moderate inter-specific LI classes showed significantly higher diameter and height increments when compared to the 0 % class, which is contrary to the widely observed detrimental effect of inter-specific competition on black spruce growth in mesic sites (Wagner and Radosevich 1991; Wang et al. 2000; Noland et al. 2001; Jobidon et al. 2003). The situation that prevailed where inter-specific competition was found was subsequently considered as an evidence for positive interactions between other species neighbouring black spruce growing in post-harvest drained peatlands. The non-significant influence of the LI × DIST interaction on diameter and height increments suggested a similar influence of plant neighbours in the control and the drained areas.

The interaction observed between black spruce seedlings and their inter-specific competitors could have been attributed to two kinds of positive effects: soil enrichment and biological drainage. Speckled alder is known to increase the soil nitrogen content (Fortin et al. 1985), but its presence within a group of competing neighbours corresponded to reduced black spruce growth. Consequently, other inter-specific competitors were suspected to have an even more important positive interference on black spruce growth. Since these species are not known to play a role in soil enrichment, the existence of biological drainage as a regulator of evapotranspiration on waterlogged sites seemed a plausible explanation.

In waterlogged peatland sites, the principal factor limiting growth is the excess of soil water. Even if drainage is practiced in such areas, soil water may still be present in excess and therefore remain the limiting growth factor. In such cases, the presence of vigorous vegetation in the neighbourhood of selected trees favours the re-establishment of evapotranspiration to regulate soil water. The subsequent water-table drawdown is assumed to indirectly increase the nutrient availability by expanding the volume of unsaturated soil to a point where the main limiting growth factor becomes the restricted above- or below-ground resource availability. However, increased competition for light and nutrients caused by this vegetation revival and growth can become harmful to tree growth.

Isolated trees, i.e. 0 % LI class, which generally showed optimum growth potential in light or nutrient competitive situations (Wagner and Radosevich 1991; Wang et al. 2000; Noland et al. 2001; Jobidon et al. 2003), were found to be growing more slowly than trees having a few neighbours in their immediate surroundings. The growth of such isolated trees might have been limited by the excess of soil water resulting from lower evapotranspiration. As the occupancy of neighbouring trees increased, which limited the light reaching the study trees, diameter and height increments were diminished up to a point were no more differences were observed between trees which were isolated and those subject to strong inter-specific competition (LI: 0 % vs >60 %). Biological drainage might have reduced the growth-limiting influence of excess soil water. However, as soil growing conditions improved with increasing neighbour abundance, it appears that light interception became the most important factor limiting the growth of black spruce seedlings.

It is unclear why black spruce under low and moderate intra-specific competition did not show evidence of positive interference such as biological drainage. Selected trees consisted of the dominant black spruce tree within each 4 m² circular plot, which had a mean initial height H0 = 120 cm. Consequently, all intra-specific neighbours were smaller than the selected tree, while inter-specific neighbours could be of any size, i.e., smaller or larger than the selected black spruce. Intra-specific light interception was therefore provided by black spruce shorter than the selected trees. On the other hand, inter-specific LI could have been caused by fast-growing individuals overtopping the selected black spruce trees. Hence, the relationship between light interception and the evapotranspiration potential in each black spruce neighbourhood might have been dependent on the type of competition. For equal values of LI, intra-specific competition might have yielded smaller relative values of evapotranspiration than inter-specific competition. This explanation could partly explain why low and moderate intra-specific LI were not showing evidence of biological drainage. The stronger negative interference of intra-specific competition on resource pre-emption, relative to that of to intra-specific competition could also be considered as an adequate justification. Further investigation would be needed in order to differentiate the exact influence of intra-specific competition on biological drainage and its resulting effect on black spruce growth.

When planning drainage operations in recently harvested peatlands, forest managers could predict with fair accuracy vegetational composition that will characterise the site in subsequent years by carefully monitoring the actual vegetation. For example, if speckled alder is found at the moment of drainage in a clearcut peatland, there is a high probability that regenerating black spruce seedlings would be later subjected to a strong competitive situation created by this fast growing pioneer species. On the contrary, if the site is almost exclusively covered with black spruce, mainly intra-specific competition could be expected during the coming years. The need for vegetation control could therefore be successfully planned in advance depending on the competition susceptibility of each treated sites.

In drained, clearcut peatlands, the fastest growing black spruces were found in situations of low and moderate inter-specific above-ground competition. This stresses the importance of favouring and tolerating moderately dense stands where inter-specific competition occurs. Full stocking should be achieved by plantation of adapted trees, especially in the first few meters from the ditch where the advanced regeneration was destroyed by harvesting and drainage operations. Precommercial thinning should be practiced only when high levels of light interception are reached (>60%), impairing the growth and survival of black spruce.

Conclusion

In post-harvest, drained forested peatlands, black spruce annual diameter and height increments were affected by both positive and negative interferences provided by neighbouring vegetation. Moderate intra-specific light interception had a detrimental effect on black spruce annual diameter increment, while annual height increment was not affected by this type of competition. Conversely, low to moderate inter-specific light interception had a beneficial effect on black spruce growth. The soil enhancement provided by the nitrogen-fixing capabilities of speckled alder and the biological drainage created by evapotranspiration were both assumed to represent the principal positive interferences of plant neighbours on dominant black spruce seedling growth.

The reduced evapotranspiration level of post-harvest forested peatlands seems to be gradually re-established by the presence of abundant and vigorous vegetation. Forest drainage enhances growth conditions for all the vegetation by lowering water table level and might consequently increase their influence on evapotranspiration. The over-abundance of competition can however limit black spruce growth.

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General conclusion

This thesis successfully demonstrated the existence of specific interrelations existing between growth and yield of tree species, above-ground competition, and hydrology of Quebec forested peatlands. Black spruce growth was significantly increased after forest drainage, but this beneficial effect was insufficient to recommend the application of drainage in unproductive forested peatland stands (Chapter 1). In mature or densely regenerated wetland sites, the water table level has been significantly affected by the depletion of the treed vegetation stratum (Chapter 2 and 3). The importance of this vegetation in the evapotranspiration processes ruling the hydrological balance of such sites has been reaffirmed. It has also been demonstrated that neighbouring trees do have a beneficial influence on each other's growth in specific vegetational situations (Chapter 4 and 5).

A fairly exhaustive evaluation of the Canadian scientific literature concerning the effect of pre- and post-harvest drainage on tree growth inexorably lead me to believe that low-productivity black spruce peatland stands should not be considered as good candidates for intensive management. Taken independently thus, the articles published before the mid 1990's on this subject were rather enthusiastic concerning the future of drainage. Chapter 1 therefore aimed to settle this confusing situation by accurately estimateing the long term site productivity of a drained unproductive black spruce peatland site. As expected, the individual tree growth was favourably enhanced by drainage, corroborating results obtained in similar studies. However, only small sized trees and trees located within the first few meters from the ditch demonstrated significant results. However, the overall productivity of the drained site was very small. The change from an unproductive status to a productive one occurred only within the first 10 m from the ditch. Only narrow ditch spacing would enable such stand conversion but this solution seems, at a first sight, of little interest. The high cost of intensive drainage operations would necessitate a very high yield to present, at maturity, a profitable situation. Even with the optimistic estimation methods used, little harvestable volume is expected to be produced on such sites over a very long period. For these reasons, we would plead the principle of cautiousness and suggest that drainage of unproductive black spruce peatland stands should not be undertaken anymore. This experiment also shows the necessity to adapt foreign expertise into our particular climate and our distinctive ecosystems instead of simply transferring it. Adaptations are often needed and testing them remains the best way to accurately verify their effectiveness.

The objective of chapter 2 was also derived from an adaptation of the Fenno-Scandinavian expertise. It aimed to acquire more knowledge about the watering-up caused by harvesting on previously drained forested peatlands. The analysis put to evidence the important influence of the distance to the ditch on the water table level within drained strips before and after harvesting. At proximity of the ditches, the efficient water table regulation overcomes the effect of the reduced evapotranspiration. Further away, watering-up occurred after harvesting. Again, the evapotranspiration provided by the treed vegetation was a non-negligible regulator of the water table level. The canopy removal also reduced the variability of the water table fluctuations when compared to the pre-harvest period. This reaction was explained by the increased open-water and soil evaporation during wet episodes and the reduced interception and transpiration during dryer episodes. Once again, the importance of evapotranspiration as a major regulator of the hydrological balance of forested peatland stands was demonstrated. The prevailing soil growing conditions after harvesting in a drained site should favour the re-establishment and growth of trees where narrow ditch spacing was used. Otherwise, tree size inequality might prevail in the future stand due to the varying growth conditions with respect to ditch proximity.

In recently harvested sites, a few studies have emphasised the importance of hydrological recovery for successful site regeneration. As the vegetation revival is going on, both the favourable and detrimental effects of high stand density might appear in regenerating peatland sites. In chapter 3, the water table rise caused by precommercial thinning applied on densely regenerated peatland sites was evaluated. The stand density was strongly reduced by this silvicultural treatment and the water table rose significantly throughout the study area. At proximity of the drainage ditch, the measured water table rise may not considerably affect tree growth since the water table levels were low. However, farther away from the ditch, tree growth might suffer more from this watering-up due to the already high water table level. The vigorous ground vegetation that rapidly invaded mineral sites showed their rapid resilience capacities. Consequently, precommercial thinning might affect only a few years the soil growing conditions on mineral sites. The organic soils' situation might return to its previous state on a short-time base too, but this study could not validate such hypothesis. Since small basal area removal showed smaller water table rise than heavier removal, the application of lighter precommercial thinning practices on forested wetlands should show smaller watering-up than standard practices. The importance of evapotranspiration as regulator of the water table depth in forested peatland stands was once again demonstrated, but this time in regenerated stands.

Since evapotranspiration has an evident influence on soil growing conditions, tree growth should be affected by the presence of neighbours surrounding them. This hypothesis was evaluated in chapters 4 and 5. In chapter 4, the opposing effects of neighbourhood occupancy, namely competition for limited resources and biological drainage, were considered simultaneously when analysing tree growth in post-harvest drained peatland stands. While biological drainage favoured the growth of trees found in areas where soil water was in excess, competition for limited resources prevailed in effectively drained areas. The water table regulation power of the vegetation stratum therefore seems to be favourable to tree growth, mainly further away than 7 m from the ditch. The chapter 5 results are also confirming this issue since black spruce annual diameter and height increments were affected by both positive and negative interferences provided by neighbouring vegetation. Moderate intra-specific light interception had a detrimental effect on black spruce annual diameter increment, while annual height increment was not affected by this type of competition. Conversely, low to moderate inter-specific light interception had a beneficial effect on black spruce growth. The soil enhancement provided by the nitrogen-fixing capabilities of speckled alder and the biological drainage created by evapotranspiration were both assumed to represent the principal positive interferences of plant neighbours on dominant black spruce seedling growth. The results from these two last chapters emphasise the importance of a rapid and successful tree re-establishment in post-harvested peatland stands, but also that regeneration density should later be closely monitored and controlled to reach optimal site productivity.

Clearcutting is practically the only forest management activity applied in Quebec's forested peatland stands. The poor reaction of old peatland black spruces to drainage made unpopular most of the silvicultural treatments that could be adapted to such wet ecosystems. However, the acute regeneration problems on recently harvested peatland stands documented in the mid-1980s are still present today, even if very little is done to straighten the situation. In many occasions, post-harvest drainage is an appropriate treatment that can mitigate the detrimental effects of the canopy removal on water surplus. Moreover, the vegetation revival is increasing tree growth and vigour by re-establishing the evapotranspiration which is an essential regulator of the hydrological balance on peatland sites. Supporting management practices that preserve a notable amount of vegetation on forested peatland stands is the most pertinent guideline that should lead the decision making process in these fragile ecosystems.