UNIVERSITÉ DU QUÉBEC EN ABITIBI-TÉMISCAMINGUE

COMMENT LES RÉSIDUS DE COUPE AFFECTENT L'ÉTABLISSEMENT DE PLANTATIONS AU

QUÉBEC : UNE ÉVALUATION DU MICROCLIMAT, DE LA COMPÉTITION ET DE LA PERFORMANCE

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AMÉLIE TROTTIER-PICARD

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Ce mémoire contient une introduction (chapitre I), un développement sous forme d'articles (chapitres II et III) et une conclusion générale. Le deuxième chapitre porte sur l'effet des résidus de coupe sur les microsites de plantations et a été publié dans le périodique scientifique *Forest Ecology and Management*, avec Evelyne Thiffault, Annie DesRochers, David Paré, Nelson Thiffault et Christian Messier comme co-auteurs. Le troisième chapitre reprend une partie des résultats, mais porte spécifiquement sur l'effet des résidus de coupe sur la physiologie de peupliers hybrides à leur deuxième saison de croissance et sera soumis pour publication, les co-auteurs étant Annie DesRochers, Evelyne Thiffault, David Paré, Nelson Thiffault et Christian Messier. Dans les deux cas, j'ai contribué à la quasi-totalité des travaux de terrain, j'ai déterminé les mesures à effectuer, j'ai effectué le traitement statistique des données et j'ai rédigé les articles.

Je tiens à remercier ma directrice, Annie DesRochers, qui a su me guider tout au long de cette aventure, et ma co-directrice, Evelyne Thiffault, pour sa présence, son dévouement, son expertise et son soutien moral. Si Annie et Evelyne m'ont dirigée, les membres de mon comité de supervision ont été très présents tout au cours de mon cheminement : merci à David Paré, pour ses conseils si pertinents; merci à Nelson Thiffault, pour sa présence constante, pour son enthousiasme à prendre part au projet et à m'aider et pour ses judicieux conseils; et merci à Christian Messier, pour son accueil dans son laboratoire et pour sa présence plus discrète, mais sans faille et tellement appréciée.

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RÉSUMÉ

L'extraction des résidus de coupe forestière (branches et houppiers d'arbres récoltés) a été étudiée surtout pour ses effets sur les nutriments du sol, mais moins pour ses effets sur la végétation compétitive et la température et l'humidité du sol, surtout lors de la période d'établissement de la régénération et à l'égard de différents seuils de récolte. Cette étude visait, dans un premier temps, à déterminer l'effet de différentes charges de résidus de coupe sur la température et la teneur en eau du sol, la couverture de végétation compétitive et les nutriments (NH_4^+, NO_3^-, P et cations basiques mobiles) la deuxième année suivant la coupe. Dans un deuxième temps, l'étude visait à comprendre comment les résidus de coupe ont affecté la physiologie ($\delta^{13}C$ foliaire comme indicateur de l'utilisation d'eau, concentration foliaire en N et P et masse de dix feuilles) et la croissance initiale d'arbres plantés. On a supposé que les résidus de coupe auraient des effets contradictoires sur la physiologie des plants : d'un côté, les résidus de coupe diminueraient le couvert de végétation, accélérant la croissance; d'un autre côté, les résidus de coupe diminueraient la température du sol, ralentissant la croissance. Suite à la coupe et l'extraction des résidus sur quatre sites au Québec (Estrie, Bas-Saint-Laurent, Lac-Saint-Jean et Abitibi), trois espèces ont été plantées : peuplier hybride *Populus* spp., pin gris *Pinus banksiana* Lamb. ou épinette blanche *Picea glauca* (Moench) Voss selon le site, et épinette noire *Picea mariana* (Mill.) B.S.P. Sept traitements ont ensuite été répétés sur chaque site, à l'échelle de l'arbre (9 m²) : un témoin (sans résidus de coupe); trois niveaux d'application de résidus de coupe représentant un gradient croissant jusqu'à 80 kg de résidus par 9 m²; et trois traitements (géotextile, herbicide et une combinaison herbicide et résidus de coupe) créant des conditions contrastées d'environnement. Chaque combinaison Espèce plantée × Traitement a été répétée 7-16 fois sur chaque site, pour un total de 714 placettes de 9 m² aléatoirement distribuées. L'étude détaillée de la réponse physiologique a ensuite été limitée au peuplier hybride et à trois sites (excluant l'Abitibi). Les résidus de coupe ont diminué la température du sol à tous les sites; l'effet de la dose de résidus était quadratique : les résidus atténuaient les fluctuations quotidiennes de température du sol (différence entre maximum et minimum quotidiens). Les résidus de coupe ont linéairement diminué la couverture de végétation compétitive sur deux sites sur quatre, mais n'ont pas eu d'effet sur les nutriments et l'humidité du sol. Les variations de la température du sol et de la couverture de compétition par des plantes ligneuses ont majoritairement dicté la réponse physiologique des peupliers hybrides. Une diminution du couvert de végétation compétitive a mené à une augmentation de la masse de feuilles, de la concentration en N et du $\delta^{13}C$ foliaire. Les effets d'une diminution de la température du sol ont varié en fonction du site, avec une augmentation du ratio $^{13}C/^{12}C$ des feuilles au Lac-Saint-Jean, mais une diminution du même indicateur en Estrie. Toutefois, la magnitude des variations de la couverture de végétation compétitive et du microclimat induites par les résidus de coupe n'était pas suffisante pour affecter la croissance des arbres deux ans après leur mise en terre. Cela suggère que les résidus de coupe influencent de manière significative le microenvironnement des plants, mais n'ont pas un effet instantané sur la croissance de la régénération. Un effet à plus long terme, notamment un effet nutritionnel en réponse à différentes charges de résidus, est toutefois possible.

CHAPITRE I

INTRODUCTION GÉNÉRALE

1.1 Contexte

Les résidus de coupe forestière (branches et houppiers des arbres récoltés) peuvent servir pour la production de bioénergie, particulièrement le chauffage et la production d'électricité. Il s'agit d'une source d'énergie renouvelable qui peut contribuer à l'effort de réduction des gaz à effet de serre (Stupak et al. 2007), réduire les importations d'hydrocarbures et améliorer la sécurité énergétique des populations en diversifiant les sources d'énergie. Toutefois, la récolte des résidus de coupe forestière (avec leur contenu en éléments nutritifs), supplémentaire à la récolte d'arbres, pourrait diminuer la fertilité des sols à long terme (Sachs et Sollins 1986, Paré et al. 2002, Akselsson et al. 2007) et affecter la productivité de la régénération ligneuse à moyen terme (Proe et al. 1999).

De nombreuses recherches se sont attardées aux impacts de la collecte des résidus dans les dernières décennies (voir Hall et Richardson 2001, Powers et al. 2005, Scott et Dean 2006, Akselsson et al. 2007, Thiffault et al. 2011), menant à des recommandations sur la quantité de résidus pouvant être récoltée selon les caractéristiques des sites. La Suède, la Finlande, le Danemark et la Lituanie (voir Stupak et al. 2008), la Grande-Bretagne (United Kingdom Forestry Commission 2008) et le Nouveau-Brunswick (Government of New Brunswick 2008) ont notamment adopté des lignes directrices sur la récolte des résidus de coupe.

Dans la plupart des cas, les quantités de résidus pouvant être récoltés ont été basées sur des modèles ou des évaluations d'experts et n'ont pas été validées empiriquement (Samuelsson 2002, Government of New Brunswick 2008, Stupak et al. 2008). La presque totalité des études sur le terrain s'est attardée à l'effet de la présence/absence de résidus de coupe sur les stocks d'éléments nutritifs dans le sol et la nutrition de la régénération (Thiffault et al. 2011). L'effet de la présence de résidus de coupe, notamment au début de l'établissement de plantations, pourrait se manifester seulement à partir d'un certain seuil de récolte, ou encore avoir un effet linéaire sur les différents paramètres (par exemple, les

conditions microclimatiques et la végétation compétitive) pouvant affecter la croissance initiale d'arbres plantés.

1.2 État des connaissances

En créant une barrière physique, les résidus de coupe forestière diminuent la température du sol en été d'un à trois degrés Celsius (Zabowski et al. 2000, Proe et al. 2001) en empêchant le soleil de s'y rendre, mais l'augmentent en hiver d'un degré Celsius (Proe et al. 2001), protégeant les plants du gel dans certaines conditions. Les résidus permettraient donc de limiter les fluctuations de température quotidiennes et saisonnières. De plus, les résidus interceptent les précipitations, mais réduisent l'évaporation de l'eau du sol, pour un effet total des résidus sur l'humidité du sol soit légèrement positif d'environ 1 % (Roberts et al. 2005), soit neutre (Zabowski et al. 2000). Finalement, en créant des zones d'ombre et en diminuant la température du sol, les résidus de coupe limitent la couverture de végétation compétitive (Hendrickson 1988, Stevens et Hornung 1990, Fahey et al. 1991, Roberts et al. 2005), pour une diminution allant jusqu'à 30 % de la couverture de végétation compétitive en présence de résidus plutôt qu'en leur absence selon Stevens et Hornung (1990).

Les résidus de coupe contenant une quantité considérable d'éléments nutritifs ayant le potentiel d'être recyclés pour la régénération, leur récolte pourrait négativement affecter la fertilité des sols en retirant ces éléments nutritifs de l'écosystème (Vitousek et Matson 1985, Fahey et al. 1991). Notons toutefois que l'apport supplémentaire d'éléments nutritifs par les résidus est typiquement négligeable pour la régénération durant les deux années suivant la plantation, contrairement au microclimat et à la compétition (Proe et al. 1999, Belleau et al. 2006, Thiffault et al. 2011).

Au niveau de la physiologie des arbres, en augmentant l'humidité du sol, les résidus devraient diminuer le stress hydrique pour les espèces qui y sont plus sensibles, malgré les températures de sol moins élevées en journée qui pourraient nuire à l'absorption de l'eau. De plus, les résidus seraient une source de N et leur absence augmenterait le risque de carence, notamment durant la première décennie (Thiffault et al. 2011). Toutefois, aucun impact des résidus sur l'état nutritionnel de P des plants n'a été observé dans les cinq premières années d'établissement d'une plantation en forêt boréale et tempérée (Thiffault et al. 2011).

Pour les deux premières années de croissance, Proe et Dutch (1994) et Fleming et al. (1998) ont suggéré que l'effet des résidus de coupe sur la régénération passerait par des modifications aux conditions microclimatiques (température et humidité du sol) et à la couverture de compétition, alors qu'un effet nutritionnel se ferait sentir plus tard dans le développement du peuplement. L'absence de résidus pourrait favoriser la croissance en augmentant la température du sol et en prolongeant la saison de croissance, mais l'effet serait contrecarré par l'établissement plus dense de la végétation compétitive (Coll et al. 2007). Conséquemment, les résidus pourraient avoir un effet nul sur la croissance en hauteur et en diamètre des plants.

Le pin gris serait plus affecté par l'absence de résidus que l'épinette noire (Thiffault et al. 2006), tandis que le peuplier est plus sensible aux changements de température que les épinettes (Bonan et al. 1990, Thiffault et al. 2011). De plus, le retrait des résidus augmenterait le risque de gel, menant à une plus forte mortalité. L'épinette noire, très peu sensible aux changements de température du sol (Bonan et al. 1990, Landhäusser et al. 1996), pourrait être davantage influencée par l'abondance de la végétation compétitive et moins par la température du sol que le peuplier. Un effet positif des résidus pourrait apparaître après quelques années supplémentaires, notamment à travers un effet nutritionnel (Proe et Dutch 1994, Roberts et al. 2005, Egnell 2011, Thiffault et al. 2011).

1.3 But, objectifs et hypothèses

Le but de cette étude était d'évaluer l'effet des résidus de coupe sur l'établissement et le succès de plantation en conditions de forêt boréale et tempérée. Plus spécifiquement, l'étude visait à déterminer le lien entre (1) différentes charges de résidus de coupe, (2) le microclimat, la compétition et la fertilité du sol durant la deuxième année de croissance suivant la coupe, alors que la canopée est ouverte et que les semis sont encore exposés aux fortes variations de température à la surface du sol et (3) la croissance des arbres au cours de la deuxième et de la troisième année après leur plantation. J'ai prédit que (1) les résidus de coupe n'auraient aucun effet sur les nutriments du sol à l'échelle de temps étudiée; (2) les résidus diminueraient la température du sol, ralentissant la croissance, et la couverture de compétition, favorisant la croissance; et (3) la croissance des plants ne serait pas affectée par les résidus, compte tenu des effets sur la température du sol et la couverture de compétition.

1.4 Démarche méthodologique

Dans une approche expérimentale, quatre sites de coupe ont été sélectionnés sur un gradient de conditions de température, de précipitations et de fertilité des sols : Weedon (Estrie), Kamouraska (Bas-Saint-Laurent), Lac-Bouchette (Lac-Saint-Jean) et Duparquet (Abitibi) – voir Fig. 1.1. Chaque site a été récolté par arbre entier (les arbres sont abattus et transportés en bordure de route, où ils seront ébranchés et tronçonnés) en 2009 puis a subi une préparation de terrain par monticules (Weedon), avec la pelle en V (Kamouraska) ou la herse forestière (Lac-Bouchette), excepté la plantation à Duparquet qui n'a pas été préparée mécaniquement. Trois espèces ayant des exigences contrastées en eau, lumière et nutriments ont été mises en terre sur chaque site au printemps 2010 : le peuplier hybride (*Populus* spp.) à tous les sites, le pin gris *Pinus banksiana* Lamb. à Lac-Bouchette et Duparquet ou l'épinette blanche *Picea glauca* (Moench) Voss à Weedon et Kamouraska, et l'épinette noire *Picea mariana* (Mill.) B.S.P à tous les sites.
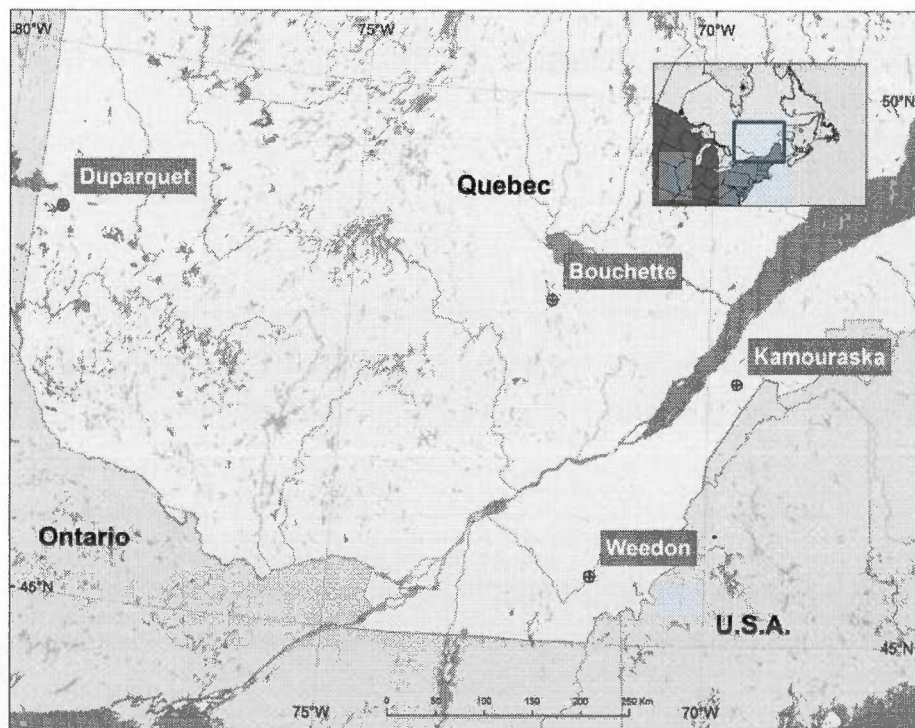
Figure 1.1 Localisation des plantations incluses dans le dispositif.
Carte réalisée par Jacques Morissette.

Sept traitements ont été utilisés pour les analyses, mais huit traitements ont été appliqués à l'échelle de l'arbre sur des parcelles de 9 m^2 réparties aléatoirement sur chaque site, peu après la plantation. Un dispositif à l'échelle de l'arbre permet un grand nombre de répétitions de différentes quantités de résidus de coupe sur un même site et la possibilité de manipuler les résidus de coupe pour tester leur effet quantitatif. Chaque combinaison Espèce plantée × Traitement a été répétée sept à seize fois par site et distribuée aléatoirement, pour un total de 714 parcelles de 9 m^2.

Quatre traitements visaient à tester l'effet quantitatif des résidus : un témoin; une demi-dose de résidus; une dose simple; et une dose double. La dose simple représentait la quantité moyenne de résidus produite par la coupe, l'ébranchage et l'écimage du peuplement, telle qu'estimée à partir de la composition en espèces et la surface terrière du peuplement avant coupe (Pothier et Savard 1998, Lambert et al. 2005), et calculée pour une surface de 9 m^2. Selon ces calculs, la dose simple à Duparquet était de 10 kg sur 9 m^2, pour une demi-dose de 5 kg et une dose double 20 kg; la dose simple à Weedon, Kamouraska et Lac-Bouchette était de 40 kg sur 9 m^2, pour une demi-dose de 20 kg et une dose double de 80 kg.

Quatre traitements visaient à détailler les mécanismes en œuvre dans l'effet des résidus et sont complémentaires aux quatre traitements cités précédemment : un paillis constitué de géotextile gris de Solmax-Texel perméable à l'eau; un contrôle de la végétation par phytocide sylvicole VisionMax^{TM} à 1,34% (Monsanto Canada); de la chaux dolomitique et de l'engrais avec une dose étalée sur trois ans et correspondant à l'apport nutritionnel de la dose simple de résidus; et une combinaison de la dose simple de résidus combinée au contrôle de la végétation. Le traitement de chaux dolomitique et d'engrais a été exclu à cause de valeurs anormalement élevées de δ^{13}C foliaire.

Le premier chapitre de ce mémoire quantifie l'effet de la dose de résidus de coupe sur la température, l'humidité et les nutriments du sol, de même que sur la couverture de végétation compétitive durant la deuxième saison de croissance, et sur la croissance des quatre espèces mises en terre (trois par site) jusqu'à la troisième saison de croissance. Ce premier chapitre s'est limité aux quatre traitements visant à tester l'effet des résidus : le témoin, la demi-dose de résidus, la dose simple et la dose double.

Le deuxième chapitre de ce mémoire s'attarde aux effets indirects des résidus de coupe sur la croissance de peupliers hybrides à travers des variables microclimatiques et pédologiques et à travers des variables physiologiques, au cours de la deuxième saison de croissance. Ce deuxième chapitre s'est limité au peuplier hybride sur trois des quatre sites, la plantation de Duparquet étant éliminée de cette analyse à cause de la forte mortalité des peupliers hybrides sur ce site.

CHAPITRE II

AMOUNTS OF LOGGING RESIDUES AFFECT PLANTING MICROSITES: A MANIPULATIVE STUDY
ACROSS NORTHERN FOREST ECOSYSTEMS

Amélie Trottier-Picard, Evelyne Thiffault, Annie DesRochers, David Paré, Nelson
Thiffault and Christian Messier[1]

Abstract

We quantified the effects of different loads of forest logging residues on the microenvironment (soil temperature, soil volumetric water content, competing vegetation cover, and available nutrients) of planted hybrid poplars one year after planting, and assessed the seedling growth of three species until the third growing season: hybrid poplars (*Populus* spp.), black spruce (*Picea mariana* (Mill.) BSP), and either jack pine (*Pinus banksiana* Lamb.) or white spruce (*Picea glauca* (Moench) Voss), depending upon the site. In four experimental plantations across Quebec (Canada), we used a factorial design of four residue loads that were applied at the tree-level over the three planted species. Logging residues linearly decreased competing vegetation cover on two of four sites and reduced fluctuations in soil temperature on all sites. Logging residues also decreased summer soil temperatures at all sites through a negative quadratic effect. On one site, the frequency of freeze-thaw cycles increased under logging residues, while logging residues increased soil water content on another site, for certain measurement events. Logging residues did not affect available nutrients. Seedlings showed no consistent growth response to logging residues for three years after planting, except for a beneficial effect of logging residues on hybrid poplar growth on one site. Because logging residues affected seedling microclimate and competing vegetation, their maintenance and on-site spatial arrangement on site could be used to manipulate the growing conditions for planted trees.

Résumé

Nous avons quantifié les effets de différentes charges de résidus de coupe forestière sur l'environnement immédiat (température du sol, teneur volumétrique en eau du sol, couvert de végétation compétitive et disponibilité des nutriments du sol) de peupliers hybrides un an après leur plantation et nous avons évalué la croissance subséquente de semis de trois espèces jusqu'à leur troisième saison de croissance : peuplier hybride (*Populus* sp.), épinette noire (*Picea mariana* (Mill.) BSP), et soit le pin gris (*Pinus banksiana* Lamb.) ou l'épinette blanche (*Picea glauca* (Moench) Voss), selon le site. Sur quatre plantations expérimentales à travers le Québec (Canada), nous avons utilisé un design factoriel de quatre charges de résidus de coupe qui ont été appliquées à l'échelle de l'arbre par trois espèces plantées. Les résidus de coupe ont diminué la couverture de végétation compétitive à deux sites sur quatre et ont amenuisé les fluctuations de température du sol à tous les sites. Les résidus de coupe ont également diminué les températures estivales à tous les sites par un effet quadratique. Sur un site, la fréquence des cycles de gel–dégel a augmenté sous les résidus de coupe, alors que les résidus de coupe ont augmenté la teneur en eau du sol à un autre site pour certains événements de mesure. Les semis n'ont pas montré de réponse constante aux résidus de coupe en termes de croissance, excepté un effet bénéfique des résidus sur les peupliers hybrides à un site. Considérant que les résidus de coupe ont affecté le microclimat et la végétation compétitive autour des plants, leur maintien et leur arrangement sur les sites de coupe pourraient être utilisés pour manipuler les conditions de croissance des arbres mis en terre.

2.1 Introduction

Over the past decade, interest has increased regarding the use of logging residues (tops and branches of harvested trees) as feedstocks for bioenergy production. Many studies have focused on comparisons of the ecological impacts of whole-tree (i.e., removal of stem, tops and branches) versus stem-only harvesting (Freedman et al. 1986, Hall and Richardson 2001, Powers et al. 2005, Lamers et al. 2013). Yet studies with more quantitative approaches (Harrington et al. 2013) are needed, because national guidelines are being established concerning the quantity of residues that can be sustainably harvested without adversely affecting soil productivity (Stupak et al. 2008), and because operational harvesting of the forest biomass leaves inconsistent and variable quantities of logging residues (Nurmi 2007). Thus, the question arises: How much logging residue should be retained while maintaining tree growth and soil fertility?

Modelling studies have shown that whole-tree harvesting consistently causes greater removal of nutrients from the forest than does stem-only harvesting (Weetman and Webber 1972, Freedman et al. 1986), increases risks of nutrient depletion (Sachs and Sollins 1986, Paré et al. 2002, Akselsson et al. 2007), and decreases stand productivity (Wei et al. 2000). However, Thiffault et al. (2011), in a review of 53 empirical field studies regarding the impacts of residue harvesting, found no consistent effect of logging residue removal on soil productivity. When effects on post-harvest growth of planted trees were detected, they were site-, species-, and time-dependent (Thiffault et al. 2011).

The growth of planted trees after forest harvesting is affected by nutrient supply, light and water availability, and soil temperature (Margolis and Brand 1990), all of which are affected by logging residues at different times of stand establishment (Proe et al. 1999, Harrington et al. 2013). Residue effects on soil nutrients are limited during the first few years following harvest, as nitrogen is mostly retained in the litter and residues during this period and slowly released (Titus and Malcolm 1999, Palviainen et al. 2004). In an evaluation of Norway spruce (*Picea abies* (L.) Karst) productivity 31 years after planting, Egnell (2011) found that removal of logging residues negatively affected tree growth. However, this

response occurred only 8 to 12 years post-planting, most likely due to a nutrient effect, thereby emphasising nutrient limitation later rather than earlier during stand establishment. Logging residues can increase light and water availability very rapidly after harvest through a reduction of competing vegetation, by reducing available microsites, or limiting light penetration (Stevens and Hornung 1990). Control of competing vegetation through the application of logging residues could diversify the tools that are available to foresters, considering that mechanical site preparation is partly aimed at controlling competing vegetation, that herbicides have been banned for use on Quebec forest lands (Thiffault and Roy 2011), and that European countries are experiencing a similar trend (Willoughby et al. 2009). Logging residues can also immediately affect soil water through their influence on two processes: 1) a shelter effect, which limits evaporation from the soil but intercepts precipitation; and 2) a decrease in vegetation cover, which reduces total plant uptake of water (Roberts et al. 2005). Finally, logging residues quickly limit seasonal fluctuations in soil temperatures, and decrease mean temperatures over summer (Zabowski et al. 2000, Roberts et al. 2005, Harrington et al. 2013) while increasing them over winter (Proe et al. 2001). Proe and Dutch (1994) and Fleming et al. (1998) have suggested that during the first few years following the harvest of logging residues, vegetation cover and microclimate are the main drivers affecting seedling growth, while a nutritional effect drives physiological responses of trees much later in the rotation, when the canopy cover has buffered microclimatic extremes and nutrient requirements of trees have increased.

The objectives of this study were to quantify the effects of increasing loads of logging residues on planting microsites one year after planting and on the subsequent growth of seedlings over the first three growing seasons. We compared tree-level effects of four loads of logging residues on microclimate, competition from weedy vegetation, and soil nutrients, across a range of sites in the commercial forest land base of Quebec (Canada), which covers both boreal and temperate deciduous forest biomes. We hypothesised that logging residues would decrease soil temperature, increase soil moisture, hamper the emergence of competing vegetation, and increase growth of planted trees, and that the effects would be proportional to residue load. Because of the short time-span of the study, we anticipated no effect of residues on soil nutrients.

2.2 Materials and methods

2.2.1 Study sites

Four sites were selected that represented a range of contrasting soil characteristics and bioclimatic conditions across Quebec (Table 2.1). In the Bouchette, Kamouraska and Weedon sites, mature stands were clear-cut by whole-tree harvesting before leaf fall in 2009, with logging residues (i.e., tree tops and branches of felled trees) being piled at the roadside and mechanical preparation being undertaken in autumn 2009. At Duparquet, the previous forest stand was clear-cut by stem-only harvesting in 2009; trees were felled, bucked and delimbed at the stump and residues were windrowed on the clear-cut site. Different site preparation techniques were used at each site prior to planting, and represented the operational techniques that were commonly used in these regions. Therefore, effects of mechanical preparation techniques are confounded with within-site effects, viz., harrowing at Bouchette, shearing using a V-blade at Kamouraska, mounding at Weedon, and no site preparation at Duparquet, where the forest floor was left intact on top of the mineral soil. Planting on all sites was carried out in spring 2010.

Soil pits were dug in two to six randomly selected locations per site to perform complete descriptions of their soil profiles. B-horizon samples were collected, air-dried, and sieved to pass a 2-mm mesh, after which soil texture was determined by hydrometer (Canadian Society of Soil Science 2008; Table 2.1). Soil pH was determined with distilled water (Pansu and Gautheyrou 2006, Table 2.1). Soil organic carbon, total nitrogen, and sulphur were determined with an elemental analyser by dry combustion at 1350 °C, followed by thermo-conductometric detection of N, and infrared detection of C and S (CNS-2000, LECO Corporation, St. Joseph, MI, USA). Fe- and Al-organic complexes were extracted with Na-pyrophosphate and analysed by inductively coupled plasma optical emission spectrometry (ICP-OES) (Optima 7300 DV, PerkinElmer, Waltham, MA, USA) to confirm the soil subgroups (Soil Classification Working Group 1998; Table 2.1).

Table 2.1 Characteristics of the studied experimental plantations in Quebec (Canada).

Site	Duparquet	Bouchette	Kamouraska	Weedon
Site preparation	None	Harrowing	Shearing	Mounding
Location	48°31'N, 79°9'W	48°7'N, 72°12'W	47°24N, 69°36'W	45°37'N, 71°31'W
Elevation (m)	330	460	475	230
Slope/Aspect	1-2 %	5% NE	7% SW	4% W
Area (ha)	6.2	4.5	3	1.8
Bioclimatic domain[a]	Balsam fir – White birch	Balsam fir – White birch	Balsam fir – Yellow birch	Sugar maple – Basswood
Mean annual temperature (°C)[b]	0.7 (-18 to 17)	1.5 (-17 to 17)	4.1 (-12 to 19)	4.1 (-12 to 18)
Mean annual precipitation (mm)[b]	890	1030	960	1140
Mean annual rain (mm)[b]	640	700	670	870
Soil subgroup[c]	Orthic Humo-Ferric Podzol	Orthic Humo-Ferric Podzol	Orthic Humo-Ferric Podzol	Fragic Humo-Ferric Podzol
Drainage	Good	Imperfect	Imperfect	Poor
Soil texture[c,d]	Sand	Sandy loam	Sandy clay loam	Loam
pH[d]	5.1	4.6	4.3	4.5
Dominant species harvested	Jack pine Pinus banksiana Lamb.	Paper or white birch Betula papyrifera Marshall	Trembling aspen Populus tremuloides Michx. and paper birch	Red maple Acer rubrum L.

[a] Saucier et al. (2009)
[b] Long-term average (1971 to 2000) from the nearest meteorological station (Environment Canada, 2012)
[c] According to the Canadian system of soil classification (Soil Classification Working Group, 1998)
[d] As averaged from samples of the B horizon

2.2.2 Experimental design

A factorial design of three planted species and four residue loads was replicated in each site. Hybrid poplars (*Populus* spp.) and black spruce (*Picea mariana* (Mill.) BSP) were planted on all sites. The third species that was planted was jack pine (*Pinus banksiana* Lamb.) at Duparquet and Bouchette, and white spruce (*Picea glauca* (Moench) Voss) at Weedon and Kamouraska. We chose these species to represent a gradient of ecophysiological requirements, where hybrid poplar grows quickly, is nutrient-demanding and shade-intolerant (Stettler et al. 1996), and black spruce tolerates shade and poor soil conditions; white spruce and jack pine are intermediate species with respect to their light and nutrient requirements (Nienstaedt and Zasada 1990, Rudolph and Laidly 1990, Viereck and Johnston 1990). All conifer species were one-year-old containerised seedlings. Hybrid poplar clones were selected based on availability and recommendations that were provided by provincial guidelines: dormant bare root stock of *Populus maximowiczii* A. Henry × *P. balsamifera* L. (clone 915319) at Duparquet and Bouchette; bare root stock of *P. canadensis* Moench [*deltoides* Bartram ex H. Marshall × *nigra* L.] × *P. maximowiczii* (clone 915508) at Weedon; and cuttings of *P. maximowiczii* × *P. balsamifera* (clone 915308) at Kamouraska. Plots were defined at the tree-scale, i.e., 9 m^2 around the planted trees, with a minimum buffer of 3 m between plots. Squared plots were used, except at Weedon, where the mounding site preparation technique forced us to use circular plots of the same area. Only one hybrid poplar was planted in each plot, while conifer plots had two trees, which allowed for destructive sampling in subsequent years.

Logging residue loads were defined based on previous stand characteristics. To estimate stand basal area prior to harvest, we used the production tables of Pothier and Savard (1998), given the species that were being harvested, the site index, and stand density. We computed an average mass of branches per hectare that was expected from these forest stands, using the above-ground biomass equations of Lambert et al. (2005). The corresponding load of residues for 9 m^2 was then estimated, with this mass being designated as a 'single load'. Based on these calculations, four residue loads were defined as: Control (no residues); Half load; Single load; and Double load. Consequently, the three residue treatment levels (on 9

m^2) were 20 kg, 40 kg and 80 kg, respectively, at Bouchette, Kamouraska and Weedon, while 5 kg, 10 kg and 20 kg were applied at Duparquet.

The four logging residue loads were applied immediately after tree planting in spring 2010. Residues were gathered from the roadside or windrow piles, in a mixture of species and branch diameters (1 to 9 cm diameter) that were representative of available residues at each site, weighed in the field, and manually carried to the plots. Logging residues from Bouchette, Kamouraska and Weedon originated mainly from deciduous species and were leafless overwintered materials. According to Lambert et al. (2005), foliage would have represented less than 20 % of total branch biomass. Logging residues from Duparquet were derived solely from jack pine and most needles, which represented around 40 % of total branch biomass (Lambert et al. 2005), were still on branches when the residue loads were applied. We put residue loads into each 9 m^2 plot, at the base of the planted trees. We chose an experimental design at the tree-level (Slesak et al. 2009), instead of a typical plot-level experiment comparing whole-tree harvesting (little to no residues) and stem-only harvesting (leaving residues behind) over larger areas. This design permitted a study where several residue loads would be compared based on a relatively large number of repetitions, rather than an "all or nothing" approach. In considering within-site variability of microenvironments, a tree-level experimental design should best capture the effects of different quantities of logging residues. Yet we recognise that the manipulation of logging residues used in this study was not representative of regular forest operations that are employed in the field, where logging residues would be left on-site during harvesting. In our study, tree tops and branches were removed, the soil was mechanically prepared on three out of four sites, and logging residues were put back.

Each residue load × species combination was replicated 8 times within each site as a completely randomised design, except at Weedon, where there were 16 replicates of each residue load for hybrid poplar and 7 replicates for black and white spruce. A total of 408 plots (9 m^2) were distributed over the four sites.

2.2.3 Micrometeorological measurements

We measured volumetric water content and soil temperature three times between June and August 2011, at least 24 h after the last rain event, and between 13:00 and 15:00 hours EDT. Measurements were taken in 8 hybrid poplar plots per residue load (32 plots per site), at the base of the planted tree and within the residue loading area (9 m^2). We measured soil temperature at 12 cm depth with a hand-held digital thermometer (DURAC 3818, H-B Instrument Company, Collegeville, PA), while soil volumetric water content was measured in the uppermost 12 cm by time-domain reflectometry (FieldScout TDR 300, Spectrum Technologies Inc., Plainfield, IL). Three spot measurements of soil moisture were made in each targeted plot and averaged.

Meteorological stations were set up between July 2010 and June 2011 for continuous recording of general meteorological site conditions and soil temperatures in each site. General data were recorded at the approximate centres of the sites, and included air temperature, precipitation, soil volumetric water content, and photosynthetic photon flux density. We excluded precipitation data on days when the air temperature was < 0 °C due to risks of errors being incurred by freezing of the rain gauge (TE525WS-L, Campbell Scientific, Logan, UT). On each site, two hybrid poplar plots were selected for each residue load, for a total of 32 plots. Soil temperature probes (107B, Campbell Scientific, Logan, UT) were installed at depths of 5 and 15 cm below the soil surface, or below the organic-mineral interface at Duparquet (no site preparation). Measurements were taken every 5 min and averaged over 30 min using data loggers (Campbell Scientific, Logan, UT).

2.2.4 Competing vegetation cover

From 8 July to 11 August 2011, we visually assessed the percent cover of competing vegetation, i.e., the proportion of the plot area that was covered by the vertical projection of aerial plant parts using 5% classes, within a 1 m^2 square plot that was centred on the planted trees. Species were aggregated and recorded according to the following functional groups: ericaceae; non-ericaceous woody plants; herbaceous plants, including ferns; gramineae; and mosses plus lichens (see Jobidon, 1995). The same observer evaluated all plots to obtain the greatest consistency between estimates (Ter-Mikaelian et al. 1999).

Competition was also estimated from measurements of photosynthetically active radiation (PAR) that were performed between 10:00 and 14:00 under clear skies. Due to meteorological constraints, data could only be obtained from one site (Weedon) on 14-15 July 2011, with 8 hybrid poplar, 3 black spruce, and 3 white spruce plots per residue load. Using a Sunfleck PAR Ceptometer (model SF80, Decagon Devices Inc., Pullman, WA), we made two orthogonal measurements at the base of the seedlings, avoiding any shade from the planted tree. For each seedling, these data were averaged and standardised with respect to a control measurement taken above canopy. The resulting ratio provided a percent of the light that was intercepted by the competing vegetation cover.

2.2.5 Soil nutrient availability

Soil nutrient availability was evaluated with mixed bed ion-exchange resins (Ionac NM-60, Lenntech, Delft, The Netherlands; H^+/OH^- Form, Type I, Bead) for four months in 2011, cumulating information from this whole period. The exchange resins were placed in nylon bags, charged with 1 M HCl, and rinsed with deionised water. Resins were installed over the first two weeks of June 2011 within the same plots where soil temperatures and moisture were measured, and < 50 cm from the planted seedlings. A slit was manually created at a depth of 10 cm in the mineral soil to insert the resin bag horizontally and the hole was refilled; care was taken not to disturb the overlaying soil. Resin bags were recovered in October 2011, rinsed with deionised water, and separated into two samples that were weighed. The first sample was extracted for 1 h in 75 mL of 2 M HCl, the extract was filtered and analysed for P and exchangeable base cations (summed) with ICP-OES (mg/kg of soil). We extracted the second sample for 30 min in 50 mL of 2 M KCl. Concentrations of NO_3^- and NH_4^+ (mg/kg of soil) in the KCl extracts were determined by flow-injection (QuickChem 8500, Lachat Instruments, Loveland, CO).

2.2.6 Growth and survival

Height and basal diameter of all trees were measured in the autumn of each year from 2010 to 2012. Annual survival was also noted, together with yearly damage caused by pathogens, insects or wildlife. For conifers, only the seedling that had been selected for measurement (as opposed to that selected for sampling) was considered in this analysis.

2.2.7 Statistical analyses

To determine if residue load had a linear, quadratic or non-linear pattern on any response variable, model selection was based on the Akaike information criterion (AIC) corrected for small sample sizes (AICc), using the *aictab* function of the *AICcmodavg* package of R (Mazerolle 2013). Some models did not meet the criterion of having at least 40 times more observations than the number of parameters to estimate, so AICc was used instead of AIC (Burnham and Anderson 2004). Since AICc converges to AIC for large sample size, AICc was used for all model selections, regardless of the sample size. Delta AICc (Δ AICc) was calculated relative to the model with the lowest AICc and the AIC weight represented the ratio of the Δ AICc relative to all models tested (Burnham and Anderson 2004). Only the best model was retained and interpreted for each selection. Sets of candidate models always included three models: 1) residue load as a numerical value (from 0 for Control to 2 for Double load) and its interactions with other factors to detect a linear pattern of residue load, 2) residue load centred, its square and the interactions between the square of the centred variable and other factors, to detect quadratic pattern of the residue load, and 3) residue load as a categorical factor to detect non-linear patterns in response to the residue load.

For microclimate data (afternoon soil temperature and volumetric water content measurements; continuous soil temperature records), linear mixed-models accounted for repeated measurements through time, using the *lme* function in the *nlme* package of R (Pinheiro et al. 2012). Residue load, site and their interaction were tested as fixed effects, and date was added to the model as a random effect. To better identify time-specific patterns of soil volumetric water content due to previous precipitation events, analysis was also separated by measurement event (three measurement events on each of the four sites, yielding 12 measurement events). For the continuous soil temperature records, we computed daily maximum and minimum values, and the range of values within a day, thereafter termed "fluctuation", and separated these by season to identify time-dependent patterns. Spring included the period from mid-April to mid-June 2011, and mid-March to mid-June 2012. The summer period was mid-June to mid-September of each year. Autumn was mid-September to end of November, while winter was December 2010 to mid-April 2011, and December 2011 to mid-March 2012. The period defined as winter depended upon the weather and covered the

time when soil temperatures remained below 5°C, the temperature at which black spruce root growth largely slows down (Tryon and Chapin 1983). For each response variable (daily maximum, minimum, and fluctuation), one analysis was run for each season; depth and the Residue load × Depth interaction were added as fixed effects. We did not use AICc model selection for continuous soil temperature records to avoid over-interpretation, given that there were only two plots per residue load on each site. Only linear models were tested to identify patterns. Of the microclimatic measurements, only soil volumetric water content required ln-transformation to meet model assumptions of homoskedasticity and normality, according to quantile-quantile plots and residual distributions.

For percent cover (total, and by functional group) of competing vegetation, residue load, planted species and their interaction were tested as fixed effects. Planted species was included to verify assumptions that seedlings would not influence their environment. We separated the analysis by site to avoid three-way interactions. For soil nutrient data from the resin bags (sum of exchangeable base cations, P, and available NO_3-N and NH_4-N), residue load, site and their interaction were tested as fixed effects. Resin-NO_3^- and resin-NH_4^+ was also summed to test the total N measured by resins. Analysis of height and basal diameter included residue load, species, year and their interactions as main fixed effects. Analysis was run by site to avoid complex four-way interactions. Tree was added as a random effect to account for repeated measurements. Since yearly growth is correlated with previous year growth and this correlation decreases through time, we incorporated a first-order autoregressive correlation structure into the *lme* function (Pinheiro et al. 2012). We included seedling height and diameter at planting as a fixed effect for height and basal diameter, except at the Bouchette site, where initial height was used in the analysis of basal diameter (initial diameter not available). Competition cover, soil data, and height required ln-transformation to meet linear model assumptions.

Seedling mortality and damage responses were analysed using a binomial distribution (dead vs alive, affected vs unaffected) with a logit link. Analyses were performed per site and species depending on the predominant form of damage that was incurred in the trees. Due to the low number of repetitions, only the model including residue load as a categorical factor was tested.

We assumed that, during the first years following plantation, the impact of residues on soil temperature, water content and nutrients, was not affected by the species of trees that had been planted, given that soil microclimate and nutrients were measured on only one tree species during the first year. This assumption would probably not be valid as vegetation further develops with time and as difference between species growth rates are becoming important. However, we believe that this assumption was reasonable during the first years of growth.

All statistical analyses were conducted in R version 2.15.0 (R Core Team 2012) using a significance level of $\alpha = 0.05$. When a response variable was independently tested several times with subsets, the significance level was adjusted using Bonferroni correction for multiple comparisons, for which the Type 1 error (false-positive results) for any of the experimental tests was limited to 0.05. Hence, for competing vegetation cover and for continuous soil temperature records, α significance level was divided by four and adjusted to 0.0125. For soil volumetric water content that was tested by date, α was divided by 12 and adjusted to 0.0042. When an interaction with residue load was significant, multiple comparisons of means (post hoc Tukey HSD tests) were computed using the *glht* function of the *multcomp* package (Hothorn et al. 2008), to identify in which case the residue load had an effect.

2.3 Results

2.3.1 Micrometeorological measurements

For afternoon soil temperatures, the selected model contained a quadratic effect of residue load (Table 2.2). Soil temperature significantly decreased with single residue load and remained stable when residue load increased (Fig. 2.1; estimate of centred [Residue load]^2 = 0.59, SE = 0.22, P = 0.008), which led to a total reduction of 1.6 °C under double load compared to control conditions. Despite the [Residue load]^2 × Site interaction not being significant (e.g., estimate of centred [Residue load]^2 × Site (Weedon) = -0.50, SE = 0.28, P = 0.07), the decrease in temperature that was due to residue load was closer to a linear relationship at Weedon and Duparquet (Fig. 2.1). According to the full analysis, Residue load as a categorical factor (selected model, Table 2.2) had no effect on volumetric water content.

The Residue load (category) × Site interaction was significant for Kamouraska, but subsequent multiple means comparisons revealed no significant differences. A more detailed analysis separating the dataset by measurement event showed no residue load effect on soil volumetric content for any date at Duparquet, Bouchette and Weedon. On 27 June and 20 July 2011, residue load increased soil moisture at Kamouraska compared to control conditions (Fig. 2.2). Selected models included Residue load as a categorical factor with a peak at the half load (half load estimate = 0.48, SE = 0.13, P = 0.001), and as a squared-centred variable (estimate = -0.48, SE = 0.14, P = 0.002), respectively. Soil volumetric water content was highly variable, except at Duparquet, where the soil moisture remained below 20% (Fig. 2.2).

Table 2.2 Models selected for each response variable according to the Akaike information criterion corrected for small samples (AICc). Interactions in models imply that all potential interactions and individual variables were also included in the model (e.g., Residue load × Site represents Residue load + Site + Residue load × Site). [Residue load] is a centred variable. ΔAICc is calculated relative to the model with the lowest AICc, the AICc weight represents the ratio of the ΔAICc relative to all models tested, K is the number of estimable parameters, and log-likelihood is the value of the maximised log-likelihood.

Response variable	Dataset	Random effect	Model	ΔAICc	AICc weight	K	Log-likelihood
Soil temperature (afternoon measurements)	All data	Date	[Residue load] + [Residue load]² × Site	0.00	0.98	11	-649.89
			Residue load × Site	7.73	0.02	10	-654.81
			Residue load (category) × Site	11.16	0.00	18	-647.95
Soil volumetric water content	All data	Date	Residue load (category) × Site	0.00	0.98	18	-110.75
			[Residue load] + [Residue load]² × Site	8.63	0.01	11	-122.59
			Residue load × Site	12.33	0.00	10	-125.49
Total cover of competing vegetation	Duparquet	None	Residue load × Species	0.00	0.66	7	-117.93
			[Residue load] + [Residue load]² × Species	1.38	0.33	8	-117.42
			Residue load (category) × Species	9.62	0.01	13	-115.11
	Bouchette	None	Residue load × Species	0.00	0.88	7	-96.14
			[Residue load] + [Residue load]² × Species	4.04	0.12	8	-96.97
			Residue load (category) × Species	9.18	0.01	13	-93.13
	Kamouraska	None	Residue load × Species	0.00	0.91	7	-103.68
			[Residue load] + [Residue load]² × Species	4.63	0.09	8	-104.80
			Residue load (category) × Species	14.25	0.00	13	-103.22
	Weedon	None	[Residue load] + [Residue load]² × Species	0.00	0.74	8	-157.72
			Residue load × Species	2.11	0.26	7	-159.92

Response	Data	Category	Model				
Resin-NO$_3^-$	All data	None	Residue load (category) × Species	9.44	0.01	13	-156.37
			Residue load × Site	0.00	0.98	9	-212.05
			[Residue load] + [Residue load]^2 × Site	8.62	0.01	10	-215.17
			Residue load (category) × Site	10.34	0.01	17	-207.08
Resin-NH$_4^+$	All data	None	Residue load × Site	0.00	0.58	9	-384.14
			[Residue load] + [Residue load]^2 × Site	0.61	0.42	10	-383.26
			Residue load (category) × Site	12.88	0.00	17	-380.47
Resin-P	All data	None	[Residue load] + [Residue load]^2 × Site	0.00	0.69	10	-179.81
			Residue load × Site	1.58	0.31	9	-181.80
			Residue load (category) × Site	16.58	0.00	17	-178.99
Sum of exchangeable cations	All data	None	[Residue load] + [Residue load]^2 × Site	0.00	0.95	10	-154.81
			Residue load × Site	5.72	0.05	9	-158.86
			Residue load (category) × Site	13.75	0.00	17	-152.73
Height	Duparquet	Tree	[Residue load]^2 × Site × Year + Initial height	0.00	0.61	17	140.03
			Residue load × Species × Year + Initial height	0.86	0.39	16	138.39
			Residue load (category) × Species × Year + Initial height	19.32	0.00	28	144.73
	Bouchette	Tree	Residue load × Species × Year + Initial height	0.00	1.00	22	0.26
			[Residue load] + [Residue load]^2 × Site × Year + Initial height	10.84	0.00	23	-3.97
			Residue load (category) × Species × Year + Initial height	30.90	0.00	40	7.64
	Kamouraska	Tree	Residue load × Species × Year + Initial height	0.00	1.00	22	122.60
			[Residue load] + [Residue load]^2 × Site × Year + Initial height	12.76	0.00	23	117.40
			Residue load (category) × Species × Year + Initial height	32.86	0.00	40	128.94
	Weedon	Tree	Residue load × Species × Year + Initial height	0.00	0.69	22	48.96
			[Residue load] + [Residue load]^2 × Site × Year + Initial height	1.58	0.31	23	49.31
			Residue load (category) × Species × Year + Initial height	35.90	0.00	40	52.69

Basal diameter						
Duparquet	Tree	[Residue load] + [Residue load]^2 × Site × Year + Initial diameter	0.00	0.79	17	-352.34
		Residue load × Species × Year + Initial diameter	2.60	0.21	16	-354.85
		Residue load (category) × Species × Year + Initial diameter	19.03	0.00	28	-347.50
Bouchette	Tree	Residue load × Species × Year + Initial height	0.00	0.98	22	-757.56
		[Residue load] + [Residue load]^2 × Site × Year + Initial height	7.36	0.02	23	-760.06
		Residue load (category) × Species × Year + Initial height	28.47	0.00	40	-748.97
Kamouraska	Tree	Residue load × Species × Year + Initial diameter	0.00	1.00	22	-670.06
		[Residue load] + [Residue load]^2 × Site × Year + Initial diameter	18.51	0.00	23	-678.13
		Residue load (category) × Species × Year + Initial diameter	37.70	0.00	40	-666.08
Weedon	Tree	Residue load × Species × Year + Initial diameter	0.00	0.74	22	-991.83
		[Residue load] + [Residue load]^2 × Site × Year + Initial diameter	2.08	0.26	23	-991.73
		Residue load (category) × Species × Year + Initial diameter	38.03	0.00	40	-989.17
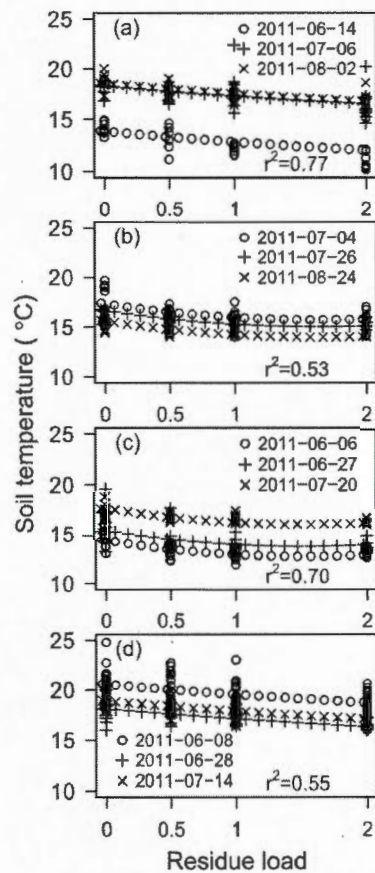
Figure 2.1 Afternoon measurements and predicted values of soil temperature as a function of residue load and date of measurement on four experimental plantations in Quebec (Canada): Duparquet (a), Bouchette (b), Kamouraska (c), and Weedon (d).

The selected model based on Akaike information criterion contains a quadratic effect, which is represented in the predicted values. Residue loads were centred for the statistical analysis but are presented on the original scale. See Table 2.1 for site descriptions.
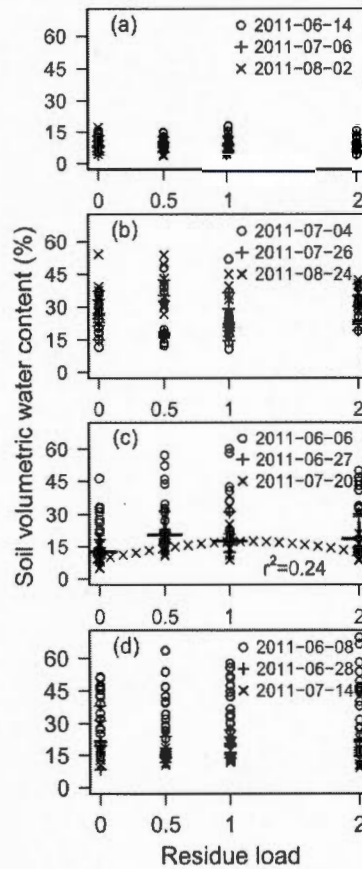
Figure 2.2 Afternoon measurements of soil volumetric water content as a function of residue load and date of measurement on four experimental plantations in Quebec (Canada): Duparquet (a), Bouchette (b), Kamouraska (c), and Weedon (d).

One model selection based on Akaike information criterion was run for each of the twelve measurement events and the significance level was adjusted using Bonferroni correction and set at $P <$ 0.00417. The models that were selected included a significant effect of residue load for two measurement events at Kamouraska: on 2011-06-27, the selected model included residue load as categorical factor and predicted values are presented with bold signs; on 2011-07-20, the selected model included a quadratic effect of residue load, which was centred in the statistical analysis, predicted values are presented as a curved line on the original scale, and the associated r2 is presented. See Table 2.1 for site descriptions.

Logging residues significantly decreased daily maximum soil temperatures year-round on all sites, but the effect was stronger over summer and spring than over autumn and winter (Table 2.3). The strongest effect of logging residues on maximum soil temperatures was

measured over the summer at Duparquet. The negative effect of logging residues on maximum soil temperatures was weaker at 15 cm compared to 5 cm depth, year-round. Compared to the effects of logging residues on maximum soil temperatures, effects on minimum soil temperatures were much weaker, leading to differences of less than 1 °C year-round due to residue load (Table 2.3).

Table 2.3 Daily maximum and minimum soil temperatures as influenced by site, residue load and depth between July 2010 and October 2012.
The estimates, standard errors and P-values are given for each factor, together with n and r^2 for each model. Considering analyses were conducted by season, significance level was adjusted using the Bonferroni correction and set at $P < 0.0125$. Values in bold are significantly different from zero. See Table 2.1 for site descriptions.

Factors	Maximum soil temperature (°C)			Minimum soil temperature (°C)		
	Estimate	SE	p-value	Estimate	SE	p-value
Spring ($n = 7,860$)						
$r^2 = 0.90$				$r^2 = 0.92$		
(Intercept)	8.97	0.46	**<0.001**	5.43	0.40	**<0.001**
Residue load	-1.17	0.07	**<0.001**	-0.35	0.05	**<0.001**
Site (Duparquet)	0.49	0.11	**<0.001**	0.24	0.08	**0.003**
Site (Kamouraska)	0.58	0.10	**<0.001**	-0.48	0.07	**<0.001**
Site (Weedon)	5.90	0.10	**<0.001**	2.93	0.07	**<0.001**
Depth (-15)	-2.10	0.07	**<0.001**	0.44	0.05	**<0.001**
Residue load × Site (Duparquet)	0.10	0.10	0.287	0.30	0.07	**<0.001**
Residue load × Site (Kamouraska)	0.01	0.09	0.956	0.19	0.06	**0.003**
Residue load × Site (Weedon)	-0.21	0.08	**0.012**	0.36	0.06	**<0.001**
Residue load × Depth (-15)	0.49	0.06	**<0.001**	-0.11	0.05	**0.012**
Summer ($n = 11,994$)						
$r^2 = 0.72$				$r^2 = 0.71$		
(Intercept)	18.41	0.13	**<0.001**	14.27	0.11	**<0.001**
Residue load	-1.26	0.05	**<0.001**	-0.27	0.04	**<0.001**
Site (Duparquet)	0.74	0.07	**<0.001**	0.36	0.05	**<0.001**
Site (Kamouraska)	1.23	0.07	**<0.001**	0.22	0.05	**<0.001**
Site (Weedon)	4.19	0.07	**<0.001**	2.33	0.05	**<0.001**
Depth (-15)	-2.08	0.05	**<0.001**	0.62	0.04	**<0.001**
Residue load × Site (Duparquet)	-0.13	0.06	0.039	0.13	0.05	**0.007**
Residue load × Site (Kamouraska)	-0.10	0.06	0.129	0.17	0.05	**<0.001**
Residue load × Site (Weedon)	0.56	0.06	**<0.001**	0.55	0.04	**<0.001**
Residue load × Depth (-15)	0.45	0.04	**<0.001**	-0.20	0.03	**<0.001**

Autumn (*n* = 8,300)

	$r^2 = 0.92$			$r^2 = 0.91$		
(Intercept)	7.17	0.30	**<0.001**	4.85	0.26	**<0.001**
Residue load	-0.40	0.05	**<0.001**	0.18	0.04	**<0.001**
Site (Duparquet)	0.41	0.08	**<0.001**	0.71	0.07	**<0.001**
Site (Kamouraska)	0.49	0.07	**<0.001**	-0.19	0.06	**0.003**
Site (Weedon)	2.21	0.07	**<0.001**	0.42	0.06	**<0.001**
Depth (-15)	-0.36	0.05	**<0.001**	1.18	0.04	**<0.001**
Residue load × Site (Duparquet)	0.07	0.06	0.267	-0.05	0.05	0.392
Residue load × Site (Kamouraska)	-0.13	0.06	0.041	0.01	0.06	0.906
Residue load × Site (Weedon)	-0.11	0.06	0.052	0.05	0.05	0.361
Residue load × Depth (-15)	0.30	0.04	**<0.001**	-0.11	0.04	**0.003**

Winter (*n* = 10,668)

	$r^2 = 0.45$			$r^2 = 0.51$		
(Intercept)	0.17	0.05	**<0.001**	0.06	0.05	0.217
Residue load	-0.12	0.03	**<0.001**	-0.12	0.03	**<0.001**
Site (Duparquet)	0.28	0.04	**<0.001**	0.35	0.04	**<0.001**
Site (Kamouraska)	-0.27	0.04	**<0.001**	-0.31	0.04	**<0.001**
Site (Weedon)	-0.63	0.03	**<0.001**	-0.99	0.04	**<0.001**
Depth (-15)	0.27	0.03	**<0.001**	0.41	0.03	**<0.001**
Residue load × Site (Duparquet)	0.08	0.04	0.024	0.09	0.04	0.024
Residue load × Site (Kamouraska)	-0.04	0.03	0.283	-0.05	0.03	0.138
Residue load × Site (Weedon)	-0.20	0.03	**<0.001**	-0.28	0.03	**<0.001**
Residue load × Depth (-15)	0.08	0.02	**<0.001**	0.07	0.02	**0.003**

The site or depth given within parentheses corresponds to the category being considered. The Bouchette site and depth [-5 cm] are the reference levels. "Estimate" columns are regression coefficients from which predicted values are computed according to the linear model. The Residue load is a numerical value and ranges from 0 (Control – no residue) to 2 (Double load). For example, in the model Spring, the maximum temperature at 5 cm (reference level) at Kamouraska under half load is represented by [(Intercept) + (0.5) (Residue load) + Site (Kamouraska) + (0.5) (Residue load × Site (Kamouraska))] and would therefore be: 8.97 + (0.5) (-1.17) + 0.58 + (0.5)(0.01) = 8.97 °C.

Logging residues significantly decreased daily fluctuations in soil temperatures, which were computed as the difference between the maximum and the minimum for each day, over the spring, summer and autumn on all sites (Fig. 2.3). Strongest effects of logging residues on daily temperature fluctuations were measured over summer (linear estimate for single load = -0.99, SE = 0.04, $P < 0.001$), especially at the Duparquet and Kamouraska sites (Residue load × Site (Kamouraska) estimate = -0.26, SE = 0.05, $P < 0.001$). The model predicted

temperature fluctuations to be 2.5 °C lower for the double residue load compared to the control. The decreasing residue effect on temperature fluctuations was buffered by depth, especially over summer (Residue load × Depth (15 cm) estimate = 0.65, SE = 0.04, $P <$ 0.001). Logging residues had no effect on temperature fluctuations over winter ($P = 0.991$).

All soil temperature parameters (daily maxima and minima, and fluctuations) depended on specific weather events over winter (Fig. 2.3). For most of the winter, logging residues had a very weak effect on soil temperatures (Table 2.3), but over the winter of 2010-11 (Fig. 2.3f), soil temperatures at Weedon dropped below zero under the logging residues but not in the control on two occasions that followed days of warm air temperatures, i.e., on 15 December 2010 and on 20 March 2011. This pattern was not repeated the following winter.
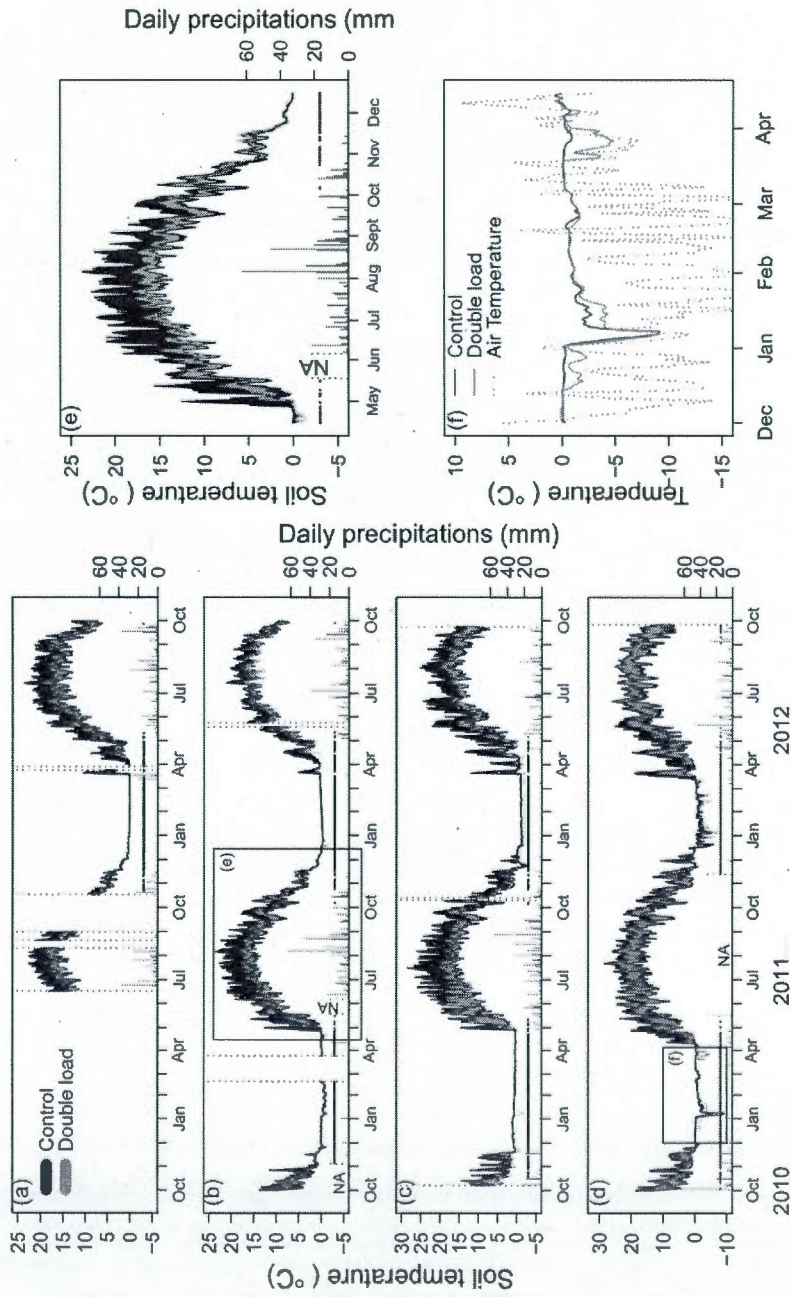
Figure 2.3 Daily profiles of soil temperature at 5 cm depth under control and double load conditions, and precipitation over two years on four experimental plantations in Quebec (Canada).

Panel (a) is Duparquet, (b) is Bouchette, (c) is Kamouraska, and (d) is Weedon. Panels (e) and (f) are more detailed close-ups from Bouchette and Weedon, respectively, of air temperature and minimum soil temperatures. Vertical dotted lines delimit periods of missing data due to technical difficulties; NA represents missing precipitation data. When minimum air temperature was < 0°C, precipitation was indicated by a solid black dot at 15 mm. See Table 2.1 for site descriptions.

2.3.2 Competing vegetation cover

Logging residues significantly decreased the percent cover of ericaceae and mosses and lichens at Duparquet, non-ericaceous woody plants at Bouchette and Kamouraska, and herbaceous plants at Bouchette only (Fig. 2.4). At Duparquet and Bouchette, the selected models for total vegetation cover (Table 2.2) included a significant negative (Table 2.4) linear effect of residue load (i.e., lower percentage cover with increasing residue load). At Kamouraska and Weedon, the selected models for total vegetation cover respectively included a linear effect and a quadratic effect of residue load (Table 2.2), but these effects were not significant (Table 2.4). At Bouchette only, the Residue load × Species interaction was significant, demonstrating that the planted species could have influenced the residue effect on competing vegetation cover. Lastly, a negative correlation ($r = -0.73$, $P < 0.001$) was observed between PAR and total percent vegetation cover at Weedon, the only site for which the light measurements were available (data not shown).
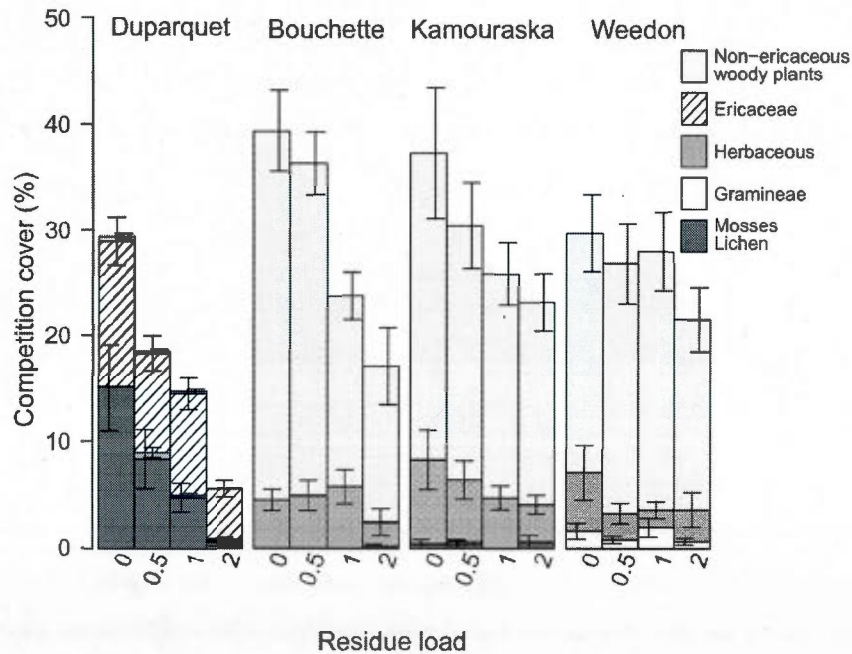
Figure 2.4 Average percent cover (± SE) of the main groups of competing vegetation as a function of residue load, as evaluated during the second growing season following planting in four experimental plantations in Quebec (Canada).

See Table 2.1 for site descriptions.

Table 2.4 Ln-transformed competition cover by site as influenced by residue load, species and their interactions during the second growing season after planting.

The estimates, standard errors (SE) and *P*-values are given for each factor, together with *n* and r^2 for each factor, together with *n* and r^2 for each model. The models presented for each site are the most parsimonious according to model selection using Akaike information criterion. [Residue load] is a centred variable. Values in bold are significantly different from zero. Considering 4 analyses were conducted (for each site), significance level was adjusted using the Bonferroni correction and set at $P < 0.0125$. See Table 2.1 for site descriptions.

Factors	Estimate	SE	*P*-value	Factors	Estimate	SE	*P*-value
	Duparquet *n* = 94; r^2 = 0.36				Bouchette *n* = 95; r^2 = 0.51		
(Intercept)	3.08	0.24	**<0.001**	(Intercept)	3.74	0.19	**<0.001**
Residue load	-1.09	0.21	**<0.001**	Residue load	-1.21	0.17	**<0.001**
Species (Black spruce)	-0.04	0.35	0.898	Species (Black spruce)	-0.08	0.27	0.768
Species (Jack pine)	0.17	0.35	0.621	Species (Jack pine)	0.12	0.27	0.656
Residue load × Species (Black spruce)	0.53	0.30	0.081	Residue load × Species (Black spruce)	0.84	0.23	**0.001**
Residue load × Species (Jack pine)	0.48	0.30	0.115	Residue load × Species (Jack pine)	0.64	0.23	**0.007**
	Kamouraska *n* = 96; r^2 = 0.10				Weedon *n* = 120; r^2 = 0.07		
(Intercept)	3.40	0.20	<0.001	(Intercept)	2.93	0.18	<0.001
Residue load	-0.39	0.18	0.029	[Residue load]²	0.06	0.25	0.820
Species (Black spruce)	0.18	0.29	0.540	[Residue load]	-0.20	0.13	0.129
Species (White spruce)	-0.32	0.29	0.264	Species (Black spruce)	0.61	0.31	0.052
Residue load × Species (Black spruce)	0.13	0.25	0.608	Species (White spruce)	0.10	0.31	0.759
Residue load × Species (White spruce)	0.42	0.25	0.097	[Residue load]² × Species (Black spruce)	-1.00	0.42	0.019
				[Residue load]² × Species (White spruce)	-0.10	0.42	0.810

The species given within parentheses corresponds to the category being considered, with hybrid poplar as the reference level. "Estimate" columns are regression coefficients from which predicted values are computed according to the linear model. The Residue load is numeric and ranges from 0 (Control – no residue) to 2 (Double load), whereas the [Residue load] is centred and is -0.875, -0.375, 0.125, or 1.125 for the four residue loads, respectively. For example, the predicted value for ln-transformed competition cover at Duparquet under control (Residue load = 0) and black spruce is represented by [(Intercept) + (0) (Residue load) + Species (Black spruce) + (0) (Residue load × Species (Black spruce))] and, therefore, would be: 3.08 + (0) (-1.09) + (-0.04) + (0)(0.53) = 3.04.

2.3.3 Soil nutrient availability

Selected models included a linear effect of residue load on resin-NH_4^+, resin-NO_3^-, and total resin-N, and a quadratic effect of residue load on resin-P and the sum of exchangeable base cations (Table 2.2). Logging residues had no significant effect on the availability of resin-NH_4^+ ($P = 0.735$), total resin-N (resin-NH_4^+ plus resin-NO_3^-, $P = 0.131$) and resin-P ($P = 0.798$), or on the sum of exchangeable base cations that had been extracted from the resins ($P = 0.483$) (Table 2.5). Effects of residue load on resin-NO_3^- availability were site-dependent. Residues had no significant effect (log-scale linear estimate for single load = 0.499, SE = 0.371, $P = 0.181$) at Bouchette, Kamouraska and Weedon, but the Residue load × Site interaction was significant at Duparquet (estimate = -1.066, SE = 0.504, $P = 0.037$). Subsequent means comparisons revealed no residue effects within this site.

Table 2.5 Mean (± SE) soil available nutrients from resin bags installed during the second growing season, in four experimental plantations in Quebec (Canada). See Table 2.1 for site descriptions.

Site	Residue load	NO_3^- (mg/kg)			NH_4^+ (mg/kg)			P (mg/kg)			Exchangeable base cations ($cmol^+$/kg)		
Duparquet	Control	3.04	±	0.71	4.41	±	2.11	5.28	±	1.98	1.48	±	0.15
	Half	0.93	±	0.34	1.25	±	0.48	4.03	±	1.34	1.09	±	0.24
	Single	1.34	±	0.69	1.06	±	0.28	5.95	±	3.58	2.34	±	1.52
	Double	0.69	±	0.15	3.06	±	1.32	10.48	±	3.55	1.93	±	0.54
Bouchette	Control	6.28	±	5.72	9.00	±	4.25	7.20	±	1.62	6.71	±	2.24
	Half	0.81	±	0.33	9.17	±	4.72	9.75	±	1.77	7.54	±	3.71
	Single	14.26	±	8.02	12.67	±	3.08	17.71	±	8.57	10.40	±	3.68
	Double	2.36	±	1.11	52.08	±	43.12	11.90	±	4.47	6.62	±	2.25
Kamouraska	Control	2.36	±	1.63	4.27	±	2.32	2.09	±	0.87	1.73	±	0.72
	Half	0.68	±	0.21	0.82	±	0.45	2.22	±	0.97	3.08	±	1.05
	Single	5.01	±	2.93	2.03	±	1.55	1.95	±	0.9	2.77	±	0.77
	Double	3.53	±	1.65	1.08	±	0.28	1.42	±	0.6	1.71	±	0.5
Weedon	Control	0.44	±	0.14	0.13	±	0.06	0.28	±	0.12	0.20	±	0.04
	Half	2.09	±	0.83	0.54	±	0.30	0.51	±	0.19	0.34	±	0.05
	Single	1.50	±	0.62	1.71	±	1.28	1.03	±	0.35	0.66	±	0.12
	Double	2.88	±	1.68	1.43	±	0.68	0.42	±	0.09	0.33	±	0.09

2.3.4 Growth and survival

Growth data for hybrid poplar at Duparquet were excluded from statistical analysis. Mortality decreased the number of replicates below three and resprouting induced negative growth. Mortality was influenced not by residue load ($P = 0.900$), but rather by stock quality.

Selected models for basal diameter and height included a linear effect of residue load at Bouchette, Kamouraska and Weedon, and a quadratic effect of residue load at Duparquet (Table 2.2). At Kamouraska, residue load had no effect on basal diameter in 2010 (Residue load estimate = -0.26, SE = 0.76, $P = 0.730$) but it had a significant positive effect in 2011 and 2012 (Residue load × Year (2012) estimate = 2.55, SE = 0.83, $P = 0.003$). This significant effect was exhibited only by hybrid poplar (negative Residue load × Year × Species interaction for black and white spruce; e.g., for black spruce, Residue load × Year (2012) × Species (black spruce) estimate = -3.36, SE = 1.18, $P = 0.005$). Plant height at Kamouraska followed the same trend, although only the Residue load × Year (2012) interaction was statistically significant (log-scale linear estimate = 0.13, SE = 0.05, $P = 0.011$). Residue load had no significant effect on any other species, year, or site (Table 2.6).

Wildlife damaged hybrid poplars at Weedon, as well as with jack pine and black spruce at Bouchette (data not shown). At Weedon, damage was caused by white-tailed deer (*Odocoileus virginianus*), with residue load having no influence on the occurrence of wildlife damage ($P = 0.249$). Damage at Bouchette was caused by moose (*Alces alces*). Here, logging residues had no effect on damage incurred in black spruce ($P = 0.529$), but decreased occurrence of moose damage in jack pine ($P = 0.045$). In addition to damage incurred by moose, the western gall rust *Endocronartium harknessii* (J.P. Moore) Hirats infected jack pine at Bouchette, but the damage that was inflicted by this pathogen was independent of residue load ($P = 0.841$).

Table 2.6 Mean (± SE) heights and basal diameters of black spruce, jack pine, white spruce and hybrid poplars planted in spring 2010 and measured each autumn, for each tested residue load, in four experimental plantations in Quebec (Canada).
See Table 2.1 for site descriptions. Bold characters indicate significant effects of treatments.

Site	Residue load	Basal diameter (mm)			Height (cm)		
		2010	2011	2012	2010	2011	2012
				Black spruce			
Duparquet	Control	7 ± 0.4	8 ± 0.4	11 ± 1	40 ± 2	49 ± 2	56 ± 3
	Half	6 ± 0.3	8 ± 1	10 ± 1	38 ± 2	45 ± 3	54 ± 3
	Single	6 ± 0.3	8 ± 1	11 ± 1	43 ± 2	52 ± 3	61 ± 4
	Double	6 ± 0.5	7 ± 0.4	9 ± 1	36 ± 2	45 ± 2	53 ± 2
Bouchette	Control	8 ± 1	11 ± 1	15 ± 1	48 ± 2	69 ± 3	96 ± 6
	Half	8 ± 1	11 ± 1	14 ± 1	46 ± 3	57 ± 5	88 ± 7
	Single	8 ± 0.4	12 ± 1	14 ± 1	46 ± 1	69 ± 5	99 ± 9
	Double	7 ± 1	12 ± 1	15 ± 2	45 ± 2	66 ± 6	97 ± 9
Kamouraska	Control	8 ± 0.3	13 ± 1	17 ± 1	54 ± 1	76 ± 5	110 ± 7
	Half	7 ± 0.4	12 ± 1	16 ± 2	52 ± 2	68 ± 4	93 ± 8
	Single	8 ± 0.3	11 ± 0.5	15 ± 1	54 ± 2	76 ± 5	107 ± 7
	Double	8 ± 0.4	11 ± 1	16 ± 1	58 ± 2	78 ± 3	106 ± 6
Weedon	Control	7 ± 0.4	12 ± 1	17 ± 2	56 ± 3	79 ± 5	108 ± 9
	Half	8 ± 1	13 ± 1	19 ± 1	52 ± 4	83 ± 5	115 ± 6
	Single	11 ± 1	14 ± 1	20 ± 1	58 ± 3	86 ± 4	117 ± 8
	Double	8 ± 0.4	14 ± 1	20 ± 2	55 ± 3	81 ± 4	114 ± 8
				Jack pine			
Duparquet	Control	6 ± 0.3	8 ± 1	11 ± 1	31 ± 2	41 ± 4	56 ± 6
	Half	7 ± 0.4	9 ± 1	13 ± 1	30 ± 1	44 ± 2	65 ± 4
	Single	7 ± 0.4	9 ± 1	12 ± 2	33 ± 1	47 ± 3	68 ± 8
	Double	7 ± 0.2	8 ± 0.5	12 ± 1	30 ± 2	42 ± 2	61 ± 3
Bouchette	Control	10 ± 0.4	13 ± 1	14 ± 2	41 ± 3	44 ± 5	57 ± 11
	Half	10 ± 0.4	14 ± 1	19 ± 2	50 ± 2	69 ± 9	94 ± 17
	Single	10 ± 1	17 ± 2	19 ± 2	49 ± 4	63 ± 7	86 ± 14
	Double	10 ± 0.4	17 ± 1	22 ± 3	53 ± 2	71 ± 7	99 ± 16

				White spruce			
Kamouraska	Control	9 ± 0.4	15 ± 1	20 ± 1	56 ± 1	73 ± 5	107 ± 8
	Half	8 ± 1	13 ± 1	18 ± 1	51 ± 3	71 ± 3	97 ± 4
	Single	9 ± 0.4	14 ± 1	19 ± 1	55 ± 2	71 ± 5	107 ± 7
	Double	9 ± 0.1	13 ± 1	18 ± 1	51 ± 2	68 ± 4	103 ± 5
Weedon	Control	9 ± 0.4	13 ± 1	20 ± 1	64 ± 2	83 ± 4	107 ± 6
	Half	10 ± 0.4	15 ± 1	21 ± 1	61 ± 5	81 ± 5	113 ± 7
	Single	10 ± 0.2	16 ± 1	24 ± 1	58 ± 3	82 ± 3	113 ± 8
	Double	10 ± 0.2	15 ± 1	21 ± 1	58 ± 4	80 ± 4	115 ± 7
				Hybrid poplar			
Bouchette	Control	11 ± 1	15 ± 2	18 ± 3	97 ± 11	122 ± 14	172 ± 15
	Half	12 ± 1	18 ± 2	22 ± 2	104 ± 7	140 ± 14	188 ± 18
	Single	12 ± 1	20 ± 3	27 ± 5	103 ± 11	140 ± 30	215 ± 42
	Double	11 ± 1	17 ± 2	21 ± 3	106 ± 12	125 ± 12	175 ± 22
Kamouraska	Control	13 ± 1	**17 ± 2**	**20 ± 3**	92 ± 8	166 ± 19	**216 ± 28**
	Half	13 ± 0.5	**19 ± 1**	**24 ± 1**	86 ± 3	176 ± 23	**246 ± 20**
	Single	12 ± 1	**19 ± 1**	**23 ± 1**	84 ± 4	185 ± 13	**258 ± 13**
	Double	12 ± 0.4	**21 ± 2**	**26 ± 3**	91 ± 4	207 ± 28	**289 ± 32**
Weedon	Control	19 ± 1	25 ± 1	33 ± 2	149 ± 10	190 ± 11	252 ± 15
	Half	18 ± 1	25 ± 2	32 ± 3	149 ± 10	186 ± 16	235 ± 20
	Single	17 ± 1	24 ± 2	34 ± 3	159 ± 11	195 ± 14	240 ± 25
	Double	18 ± 1	25 ± 1	34 ± 2	160 ± 8	201 ± 9	258 ± 12

2.4 Discussion

2.4.1 Microenvironment and growth

Microenvironmental measurements (soil temperature and water content, cover of competing vegetation, and soil nutrients) were conducted for one year only. Our study is therefore a snapshot of the effects of logging residues on microenvironment one year after planting, and the integrated response of seedling growth over three years. Still, logging residues affected the microenvironment of planted seedlings in several ways which could drive a growth response of seedlings.

First, logging residues decreased summer soil temperatures, which has also been observed in other contexts (Zabowski et al. 2000, Proe et al. 2001, Roberts et al. 2005, Harrington et al. 2013). Soil temperatures below 15 °C can retard growth responses, especially those of the roots (Tryon and Chapin 1983, Kaspar and Bland 1992, Landhäusser et al. 1996). Many processes can explain decreased growth in cooler soils: 1) low soil temperatures decrease stomatal conductance and gas exchange (Lopushinsky and Kaufmann 1984, Landhäusser et al. 1996, Lahti et al. 2002); 2) photosynthetic rates are lower (Lahti et al. 2002); and 3) microbial activity is reduced, which negatively affects rates of mineralisation and decomposition, thereby decreasing nutrient availability to plants (Cassman and Munns 1980, Bonan and Shugart 1989, Brady and Weil 2001). Growth responses to soil temperatures depend upon species, with boreal deciduous species such as paper or white birch (*Betula papyrifera* Marsh.) and trembling aspen (*Populus tremuloides* Michx.) usually being more negatively affected by cold soils compared to boreal conifers such as *Picea mariana* and *P. glauca* (Landhäusser et al. 1996, 2001), although we found a difference for growth between hybrid poplar and the two spruces only at one site. Considering that the double residue load reduced the daily maximum of soil temperature by only 1.6 °C compared to the control, the importance of alterations to plant growth is likely to be negligible. Experimental studies often use at least a 3 °C difference to test for the effect of temperature on plant development (Landhäusser et al. 2001, Lahti et al. 2002).

Second, soil freezing episodes after periods of warmer air temperatures occurred more frequently under logging residues than in the control plots. A few freeze-thaw cycles can favour growth by speeding up carbon and nitrogen transformations, but multiple cycles can also reduce microbial populations (Campbell et al. 2005), thereby reducing organic matter decomposition and N mineralisation (Schimel and Clein,1996), and hampering N uptake and seedling growth thereafter. Schimel and Clein (1996) observed an increase in net N mineralisation rates for the first two freeze-thaw cycles between -5 °C and +5 °C, while that increase was inhibited at the third cycle. Considering that only two events led to temperatures close to -5 °C, net N mineralisation should have increased, which has not been observed in the resin extractions in the following summer. Therefore, freeze-thaw cycles were not likely to have had any effect on soil nutrients in this context. Our winter soil temperature results

differed from those of Proe et al. (2001) in the UK, who reported warmer soil temperatures under logging residues compared to bare soil. We suggest that the presence of a snow layer explains these contrasting results: in the absence of snow, logging residues insulated the soil surface and prevented soil temperature fluctuations in the UK; where a thick layer of snow typically insulates the forest floor, logging residues would have favoured the establishment of a looser and thinner snow pack, which was more likely to melt completely during short periods when air temperatures exceeded 0 °C. This process was aided by the low albedo of the logging residues relative to snow. If air temperature dramatically dropped afterwards, shallow soils under logging residues where the snow layer had melted were more likely to freeze than residue-free soil, where the snow still provided insulation.

Third, logging residues that dampened daily fluctuations of soil temperatures could also increase growth. By forming a physical barrier, logging residues can reduce energy exchanges between the soil surface and the above-ground environment (Fleming et al. 1998). As was observed in our study, maximum soil temperatures were lower under logging residues than in the control because solar radiation was reflected or absorbed and dissipated by logging residues (Fleming et al. 1998). Overnight, logging residues form a physical barrier that retains heat, which in turn buffers heat loss from the soil and limits daily temperate fluctuations. Low daily fluctuations can benefit populations of soil fauna (Uvarov 2003), thereby increasing decomposition and nitrification (Emmett et al. 1991, Fahey et al. 1991). Soil temperature fluctuations were reduced by 2.5 °C under the double residue load compared to the control, which is not comparable to changes in soil temperature fluctuations that were reported by Uvarov (2003) and which would lead to changes in soil faunal populations. However, our results are of similar magnitude to those observed by Fréchette et al. (2011), who reported increased photosynthetic activity of trees, with stronger responses from black spruce than from trembling aspen.

Fourth, logging residues reduced competing vegetation cover at Duparquet and Bouchette, consistent with previous observations (Stevens and Hornung 1990, Fahey et al. 1991, Harrington et al. 2013), which could increase growth and survival of planted seedlings by increasing access to light, water, and soil nutrients (Elliott and Vose 1993, Munson et al. 1993). At Duparquet, when excluding mosses and lichens, the cover of competing vegetation

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decreased from 14 % under control conditions to 5 % under double load (Fig. 2.4). At Bouchette, total vegetation cover decreased from 40 % under control conditions to 17 % under the double load treatment, although the residue effect was only significant for hybrid poplars. These values are just below the 20% competing herbaceous and woody vegetation threshold that was reported by Wagner (2000) and indicate that the magnitude of the logging residue effect on competing vegetation should have been sufficient to affect tree growth.

Fifth, logging residues increased soil volumetric water content on two occasions at Kamouraska. We compared the precipitation received during the five days before each of the three measurement events at this site. The days on which logging residues exerted a significant effect on soil moisture were characterised by lower absolute values of soil volumetric water content than the days on which no effect was observed, despite recent rainfall events. Thus, the data from Kamouraska suggest that logging residues could have only had an impact at low soil water contents and may depend on specific conditions prior to and on the day of measurement. Logging residues had no effect on soil volumetric water content on all measurements dates at Duparquet, Bouchette or Weedon. Since soil water depends on antecedent precipitation and measurements were all made within the same season, we assessed how far precipitation for summer 2011 departed from typical long-term average. When compared to 1970-2010 averages (Environment Canada 2012), precipitation was normal in June 2011 for Bouchette, Kamouraska and Weedon, but higher than usual at Duparquet. In contrast, values were lower than usual in July 2011 at Duparquet and Weedon, but normal at Bouchette and higher at Kamouraska. Precipitation was lower than the long-term averages in August 2011 at Duparquet, but higher than usual at Bouchette, Kamouraska and Weedon. Unusually high precipitation was observed in August 2011 at Bouchette, which led to slightly higher soil water content that could have masked the effects of residue load on this response variable. Thus, logging residues had either a positive effect on some conditions, supporting the findings of Roberts et al. (2005), or no effect on soil volumetric water content, which supported the findings of Zabowski et al. (2000).

Finally, logging residues had no effect on available nutrients, which was consistent with expectation, given the short time-span of our study (Titus and Malcolm 1999, Palviainen et al. 2004). Egnell (2011) found an effect of logging residue removal on foliar N, which only

commenced eight years after planting, suggesting that such an effect could appear later during stand development.

Considering the significant interaction of species and residue load on cover of competing vegetation, we cannot exclude the possibility that the planted species had an impact on its microenvironment, even at a very early stage of stand development. However, since this interaction was observed only on one site and since the effects of logging residues on soil temperature (daily maximum and fluctuations) has been observed on a wide range of sites (Fleming et al. 1998, Zabowski et al. 2000, Proe et al. 2001, Roberts et al. 2005, Harrington et al. 2013), maintaining the assumption that the planted species did not have a crucial effect on soil temperature one year after planting was reasonable, despite temperature measurements taken only under hybrid poplars.

The overall absence of growth response to logging residues could be attributed to logging residues having too weak of an effect on soil temperature and competing vegetation cover to induce a significant physiological response in the trees, or by counteracting effects on the drivers of tree growth (maximum soil temperature, "-"; temperature fluctuations, "+"; competing vegetation, "+"). In the case where effects of the logging residues on soil temperature were too weak to induce a growth response, as suggested in the literature, logging residues would modify seedling microclimate and competition and would improve the growing conditions for planted trees without the use of herbicides (Thiffault and Roy 2011). A more detailed analysis of physiological responses and a study over a longer timescale should provide more meaningful information regarding the growth of planted trees.

2.4.2 Residue load

Logging residues had a linear effect on soil temperature fluctuations at all sites, on competing vegetation at Bouchette and Duparquet, and on basal diameter of hybrid poplars at Kamouraska in 2011 and 2012, suggesting that effects of logging residues on these variables will be proportional to the quantity of residues within the range tested in this study. Logging residues had a quadratic effect on soil temperatures and on soil volumetric water content on one date at Kamouraska, and a non-linear effect on soil water content on another date on the same site, suggesting a peak response in the gradient of residue load.

2.4.3 Site differences

Logging residues had site-dependent effects for three response variables: soil volumetric water content, growth of hybrid poplars, and competing vegetation cover. Logging residue effects on soil water content and growth were both significant, but only at Kamouraska. Differences among sites may be a question of drainage, site preparation, type of residues, or specific conditions prior to and on the day of measurements. Logging residues had no effect on cover of competing vegetation at Kamouraska and Weedon. These two sites had the warmest climate (Table 2.1), possibly favouring vegetation growth, and had the most intensive mechanical site preparation, which could have had a stronger effect on competing vegetation cover than that of logging residues. Effects of logging residues on soil temperature (maximum and fluctuations) and on competing vegetation were as important at Duparquet, despite much smaller residue loads. This could be the consequence of the absence of site preparation, the climate, the low fertility of the soil, or perhaps the types of residues that had been applied to this site. The Duparquet site contained a high proportion of fine woody debris and foliage (jack pine) and, therefore, covered a large area per mass of residue.

2.5 Conclusions

We used a factorial design of three planted species and four residue loads that were applied at tree-level, on four experimental plantations in Quebec (Canada), to quantify logging residue effects on the microenvironment (soil temperature, soil volumetric water content, competing vegetation cover, and available nutrients) of planted seedlings one year after planting and to assess corresponding seedling growth over three growing seasons. Logging residues affected seedling microclimate and competing vegetation in contrasting ways, possibly neutralising each other's effect on growth. Logging residues decreased summer soil temperatures through a negative quadratic effect on all sites, possibly hampering growth; linearly decreased competing vegetation cover at two sites and ameliorated fluctuations in soil temperatures on all sites, effects which were likely to accelerate growth. Overall, seedlings showed little response to logging residues during the first three growing seasons. The ecological role of logging residues on the microenvironment of plants appeared to be somewhat site-dependent. Logging residues decreased fluctuations and daily maximum of soil temperatures and competing vegetation, two objectives of early site management. Our

study demonstrated that management of logging residues can be a tool to manipulate growing conditions of seedlings, depending on site conditions. This should be taken into account when evaluating their value as a forest bioenergy feedstock.

2.6 Acknowledgements

2.7 References

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CHAPITRE III

HOW FOREST LOGGING RESIDUES AFFECT PLANTING MICROSITES, INITIAL GROWTH AND PHYSIOLOGY OF HYBRID POPLARS IN BOREAL ECOSYSTEMS

Amélie Trottier-Picard, Annie DesRochers, Evelyne Thiffault, David Paré, Nelson Thiffault, Christian Messier

Abstract

Logging residues affect nutrition and growth of planted trees on harvested sites, but their indirect effects on tree physiology through changes to microclimate and competing vegetation remain to be understood. We studied three hybrid poplar plantations in Quebec, Canada, during their second growing season following planting. Three treatments representing different residue loads were applied to plantation microsites shortly after planting to quantitatively test the effects of logging residues on seedling physiology. In parallel, four additional treatments (Geotextile, Herbicide, Herbicide + Residue, and an untreated Control) were applied to create contrasting growth conditions and control specific environmental factors. Treatment comparisons and structural equation modelling were used to understand the effects of logging residues on height and basal diameter of trees through their effects on soil temperature, soil water content, and competing vegetation cover. Logging residues decreased soil temperature at all sites and cover of woody competing vegetation at one site out of three. Foliar $\delta^{13}C$, N concentrations and leaf mass increased with decreasing cover of woody plants but were not linked to soil nutrients or water content, suggesting that the main effect of woody competing vegetation were expressed through changes to above-ground conditions such as irradiance or air temperature. Effects of soil temperature on hybrid poplar physiology were site-dependent. Logging residues had no effect on hybrid poplar growth, neither globally nor through changes to soil temperature or cover of woody competing vegetation. A nutrition effect can be expected later during stand development.

Résumé

La présence de résidus de coupe affecte la nutrition et la croissance des arbres mis en terre suite à des coupes, mais leur effet indirect sur la physiologie de ces arbres à travers des modifications du microclimat et de la végétation compétitive demeure méconnu. Nous avons étudié trois plantations de peupliers hybrides au Québec, Canada à leur deuxième saison de croissance. Trois traitements représentant différentes charges de résidus ont été appliqués aux microsites de plantation peu après la mise en terre pour mesurer quantitativement l'effet des résidus de coupe sur la physiologie de peupliers hybrides. En parallèle, quatre traitements supplémentaires (Géotextile, Herbicide, Herbicide + résidus et un Témoin intouché) ont été appliqués au même moment pour créer des conditions d'environnement contrastées. La comparaison de traitements et la modélisation par équations structurelles ont été utilisées pour comprendre l'effet des résidus de coupe sur la hauteur et le diamètre à la base des arbres à travers des effets sur la température du sol, la teneur en eau du sol et la couverture de végétation compétitive. Les résidus de coupe ont diminué la température du sol à tous les sites et la couverture de compétition par des plantes ligneuses à un site sur trois. Le ratio foliaire $\delta^{13}C$, la concentration foliaire en N et la masse de feuilles ont augmenté avec une diminution de la couverture de compétition par des plantes ligneuses, mais sans être liés à la disponibilité des nutriments du sol ou à la teneur en eau du sol, suggérant que l'effet principal de la végétation compétitive ligneuse était à travers des modifications aux conditions au-dessus du sol comme la lumière ou la température de l'air. Les effets de la température du sol sur la physiologie du peuplier hybride dépendaient du site. Les résidus de coupe n'ont pas eu d'effet sur la croissance des peupliers hybrides, ni globalement, ni à travers des changements à la température du sol ou à la couverture de compétition par des plantes ligneuses. Un effet nutritionnel pourrait intervenir plus tard dans le développement du peuplement.

3.1 Introduction

As demand for forest biomass is increasing on the bioenergy market, consequences of logging residue extraction (branches and tops of trees) on stand productivity are inconsistent (Thiffault et al. 2011) and poorly understood. Precisely, we know that logging residues can modify soil nutrients, competing vegetation abundance, soil temperature and water content (Stevens and Hornung 1990, Proe et al. 2001, Harrington et al. 2013). What is lacking however, in understanding the effects of logging residues, is how competing vegetation abundance, soil temperature and water content influence the physiology of planted trees. In addition, these effects are time-dependent; Egnell (2011) suggested that removal of logging residues solely affected soil nutrients 8–12 years after planting, whereas Proe and Dutch (1994) suggested that microclimate and competition effects are visible shortly after planting whereas a nutrient effect becomes visible after crown closure.

At a very early stage of stand development, logging residues modify planting microsites mostly through light and water availability and soil temperature (Stevens and Hornung 1990, Proe et al. 1999, Harrington et al. 2013). Light and water availability can increase with the presence of logging residues that reduce competing vegetation cover (Stevens and Hornung 1990, Roberts et al. 2005). Increased light availability promotes higher photosynthetic rate, thereafter favouring growth (Raven et al. 2005). Logging residues can also affect soil water through a shelter effect that limits evaporation but intercepts precipitation (Roberts et al. 2005, Trottier-Picard et al. 2014). Increased water availability should decrease drought stress of planted trees, prevent stomatal closure and increase leaf conductance, increasing photosynthetic rates and growth over the long term (Farquhar et al. 1989). Apart from competing vegetation and soil water, logging residues can affect planting microsites by decreasing soil temperature (Zabowski et al. 2000, Proe et al. 2001, Roberts et al. 2005), and in turn reduce nutrient and water uptake of trees (Chapin et al. 1986, Clarkson et al. 1988, Landhäusser et al. 2001).

In the previous chapter, we evaluated if logging residues had a linear, quadratic or non-linear effect on environmental conditions (soil temperature and water content, competing

vegetation, and soil nutrients) and growth of four planted species. In the present study, we aimed at further assessing the physiological response and early growth of hybrid poplars to changes of environmental conditions due to logging residues. Hybrid poplar was selected as a case species because its specific requirements regarding competing vegetation control, water and nutrient availability, and soil temperature (Stettler et al. 1996) are expected to induce strong physiological responses to changes to microclimate, soil nutrients and competing vegetation cover due to logging residues. We hypothesised that (1) logging residues would have additive yet contradictory effects on hybrid poplar growth by decreasing competing vegetation and soil temperature; and more precisely that (2) a decrease of competing vegetation due to logging residues would increase resource availability; but that (3) a decrease of soil temperature due to logging residues would reduce water and nutrient uptake.

3.2 Materials and methods

3.2.1 Site description

Three hybrid poplar plantations representing different bioclimatic conditions and soil properties across Quebec were selected: Bouchette in Saguenay–Lac-Saint-Jean, Kamouraska in Bas-Saint-Laurent, and Weedon in Estrie. As described in the previous chapter, Bouchette is in the balsam fir–white birch bioclimatic domain, has an average annual precipitation of 1,030 mm (rainfall 700 mm, snowfall 330 mm) with an average daily temperature of 1.5 °C (Environment Canada 2012), has sandy loam soil texture (Soil Classification Working Group 1998) and imperfect drainage (Saucier et al. 1994). Kamouraska is in the balsam fir–yellow birch bioclimatic domain, has an average annual precipitation of 960 mm (rainfall 670 mm, snowfall 290 mm) with an average daily temperature of 4.1 °C (Environment Canada 2012), has sandy clay loam soil texture (Soil Classification Working Group 1998) and imperfect drainage (Saucier et al. 1994). Weedon is in the sugar maple–basswood bioclimatic domain, has an average annual precipitation of 1,140 mm (rainfall 870 mm, snowfall 270 mm) with an average daily temperature of 4.1 °C (Environment Canada 2012), has loam soil texture (Soil Classification Working Group 1998) and poor drainage (Saucier et al. 1994).

In 2009, sites were clear-cut by whole-tree harvesting before leaf fall, logging residues were piled along the roadside and mechanical site preparation for planting was performed in

autumn. Mechanical site preparation differed at each site (harrowing at Bouchette, shearing using a V-blade at Kamouraska, and mounding at Weedon) so that site characteristics are confounded with effects of mechanical site preparation. We planted hybrid poplars in spring 2010 at a density of 1,111 trees per hectare. Planted hybrid poplar clones were selected based on recommendations from provincial guidelines: at Bouchette, dormant bare root stock of *Populus maximowiczii* A. Henry × *P. balsamifera* L. (clone 915319); at Kamouraska, cuttings of *P. maximowiczii* × *P. balsamifera* (clone 915308); and at Weedon, bare root stock of *P. canadensis* Moench [*deltoides* Bartram ex H. Marshall × *nigra* L.] × *P. maximowiczii* (clone 915508).

3.2.2 Experimental design

Seven treatments representing contrasting conditions of soil temperature and competing vegetation cover were replicated shortly after planting in 2010 in each site, on 9 m^2 plots at the tree scale, with a minimum buffer of 3 m between plots. The seven treatments included: Control, where the plot was left untouched; Half residue load; Single residue load; Double residue load; Geotextile mulch; Herbicide; Herbicide + Single residue load. Half, Single, and Double residue loads were based on an estimation of stand basal area prior to harvest considering the species that had been harvested, site index, and stand density (Pothier and Savard 1998), and a consequent calculation of the average branch biomass per hectare that was expected from clearcutting of these forest stands, using above-ground biomass equations (Lambert et al. 2005). The corresponding load of logging residues for 9 m^2 was then estimated and designated as the single load. Therefore, Half, Single, and Double loads of logging residues were 20 kg, 40 kg, and 80 kg, respectively. The "Geotextile mulch", consisting in a square of 1.75 m × 1.75 m of grey textile (Texel 7609, Texel Géosol inc., Sainte-Marie, QC, Canada) centred on the tree, was used to mimic the physical effect of logging residues on soil temperature and competition cover compared to Control. We used the "Herbicide" treatment to decrease competition cover compared to Control, and Herbicide + Single residue load to capture the residue effect compared to Control while completely controlling competing vegetation. For both treatments requiring herbicide, we applied glyphosate (VisionMAX^{MC}, Monsanto Canada Inc., Winnipeg, MB, Canada) on the entire 9 m^2 plot in July of 2010 and 2011. Each treatment was replicated 8 times at Bouchette and

Kamouraska and 16 times at Weedon, following a completely randomised design, for a total of 224 plots distributed over three sites. All measurements (see below) were conducted during the second growing season since planting in 2011.

3.2.3 Environmental measurements

Competing vegetation cover was defined as the proportion of the plot area that was covered by the vertical projection of aerial competing vegetation parts. In July 2011, the same observer visually estimated the competing vegetation cover (5 % classes), using a 1 m^2 square plot centred on each hybrid poplar. Competing vegetation was recorded by species and aggregated in two groups: woody or herbaceous plants, the latter including ferns and gramineae. Measurements were conducted on all plots (n = 224), so that measurements on herbicided plots represented the July 2010 application only; the 2011 herbicide application started to be effective only after cover measurements were recorded.

We assessed soil nutrient availability with mixed bed ion exchange resins (Ionac NM-60, Lenntech, Delft, The Netherlands; H^+/OH^- Form, Type I, Bead) which we installed at a depth of 10 cm over the first two weeks of June 2011, recovered in October 2011, and extracted resin-NH_4^+, resin-NO_3^-, resin-P, and sum of exchangeable cations, following the method described in the previous chapter. Resin bags were installed < 50 cm from the planted seedlings and within all plots of Bouchette and Kamouraska but we randomly selected half of plots at Weedon so that 8 resin bags per treatment were installed within each site (56 resin bags per site).

Finally, we measured soil volumetric water content in the uppermost 12 cm by time-domain reflectometry (FieldScout TDR 300, Spectrum Technologies Inc., Plainfield, IL, USA) and soil temperature at 12 cm (DURAC 3818, H-B Instrument Company, Collegeville, PA, USA). We conducted measurements in 2011, within the same plots where resin bags were installed, at least 24 h after the last rain event, and between 13:00 and 15:00 hours EDT. Soil water content was measured and averaged three times within each plot for each measuring event. We measured soil water content and temperature three times at Bouchette (4 July, 26 July, and 24 August) and Kamouraska (6 June, 27 June, 20 July) but twice at

Weedon (8 June and 14 July), and averaged measurements by plot over the several measuring events.

3.2.4 Physiological measurements

To get a snapshot of water relations, we measured pre-dawn leaf water potential and midday leaf water potential within a 24 h period once at each site with a pressure chamber PMS Model 600 (PMS Instrument Company, Albany, OR, USA), following Turner (1981). Pre-dawn measurements were made between 2:00 and 5:00 EDT, and midday measurements were made between 13:00 and 16:00, at least three days after the previous precipitation. Considering the time constraints for sampling, only three replicates per treatment were randomly selected; the Half and Single residue load treatments were not sampled.

In August 2011, we sampled ten leaves from all hybrid poplars from top and bottom of the tree crown and from the four cardinal directions, and combined them into one composite sample which was oven-dried at 60 °C for 72 h, weighed, and ground. Previous studies have shown that individual leaf area and mass were correlated for hybrid poplars (DesRochers et al. 2006) and that individual leaf area was correlated with stem volume, hence growth (Ridge et al. 1986). Three subsamples per treatment per site were finely ground using a Mixer Mill MM301 ball grinder (Retsch Inc., Newtown, PA, USA) and carbon isotope ratio ($\delta^{13}C$), as influenced by stomatal behaviour and drought stress (Moreno-Gutiérrez et al. 2012), was determined (Stable Isotope Facility, University of California, Davis, CA, USA) using a PDZ Europa ANCA-GSL elemental analyser interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd, Cheshire, UK). The carbon isotope ratio was calculated according to Farquhar et al. (1989) and is expressed relative to Vienna PeeDee Belemnite. All samples were then used to determine total N and total P. Total N was determined on an elemental analyser (CNS-2000, LECO Corporation, St. Joseph, MI, USA). Total P was determined after overnight combustion at 500 °C and dilution in 0.1 M HCl, and analysed by inductively coupled plasma optical emission spectrometry (Optima 7300 DV, PerkinElmer, Waltham, MA, USA). Using sample biomass, nutrient content values were expressed as foliar concentrations. Finally, basal diameter and height of trees were measured in October 2011.

3.2.5 Statistical analyses

All statistical analyses were conducted in R version 3.0.1 (R Core Team 2013) using a significance level of $\alpha = 0.05$. We used analyses of variance (ANOVA) to detect if there was a difference between treatments within each site. Prior to ANOVA, data were verified for homogeneity and homoscedasticity of variances using standard graphical approaches; variables were transformed accordingly. If an effect of treatments or of Treatment × Site interaction was detected, multiple comparisons of means were computed using Tukey tests.

Structural equation modelling using the *sem* function of *lavaan* package (Rosseel 2012) complemented the analysis by treatment in order to understand the indirect effects of logging residues on height and basal diameter through environmental and physiological variables. Multigroup modelling was used to take account of and compare sites. Full information maximum likelihood was used to include all available data in the analysis, including those missing at random (Rosseel 2012), and to fit the structural equation model. The fit between the predicted and observed covariance matrix was assessed with a χ^2 test (Shipley 2002). When χ^2 test was associated with a *P*-value > 0.05, we had no good evidence to reject the model and it was assumed to be consistent with the data (Shipley 2002, Hershberger et al. 2003). The Bentler's comparative fit index (CFI) and the root mean square error of approximation (RMSEA) were also used to measure model fit, with CFI > 0.95 and RMSEA < 0.05 being considered as an acceptable fit (Shipley 2002, Tomer and Pugesek 2003, Rosseel 2012).

We used paired observations between tree physiological variables and the environmental measurements taken in close proximity to the sampled tree. Treatment was not a variable in this analysis except for residue load as a numerical value so that Control was 0, Half load 0.5, Single load 1, Double load 2. Geotextile, Herbicide, and Herbicide + Single residue load were not attributed any value for residue load. Pre-dawn and midday leaf water potential were finally excluded from structural equation modelling as we could not gather data at Weedon due to rainy meteorological conditions. Cover of competing vegetation was log-transformed to meet normality assumptions. We thus considered for inclusion in the structural equation models: residue load, cover of woody plants, cover of herbaceous plants,

soil temperature, soil volumetric water content, resin-NH_4^+, resin-NO_3^-, resin-P, sum of exchangeable cations, $\delta^{13}C$, leaf mass, foliar [N], foliar [P], basal diameter, and height.

A model saturated with the most biologically plausible relationships was tested as the starting point (Fig. 3.1). Soil available nutrients (resin-NH_4^+, resin-NO_3^-, resin-P, sum of exchangeable cations) were grouped into a latent variable. In structural equation modelling, covariances are correlations (non-causal relationships) between variables. A covariance was established between basal diameter and height to capture their strong correlation without establishing a causal relationship. When a causal relationship was possible in both directions, we tested a covariance to represent the bidirectional relationship between them, accepting that we would not obtain the detail of this effect in each direction. If this saturated model was rejected, an exploratory method was used to propose a model that was not rejected by our data: a relationship that was not significant ($\alpha = 0.05$) at a majority of sites was removed; an environmental variable (cover of woody or herbaceous plants, soil temperature, soil water content, and latent variable soil) that was not related to any tree physiological variable ($\delta^{13}C$, leaf mass, foliar [N] or [P], basal diameter, and height) was excluded from the analysis; or a tree physiological variable that was not related to any other tree physiological variable was excluded from the analysis. For every change, we checked that it did not induce any anomalies (negative s^2, negative r^2) and that it decreased the AICc of at least two units, based on the *AICcmodavg* package (Mazerolle 2013) and the *aictab.lavaan* function (Byrnes 2012). In the opposite case, the concerned relationship or variable was reintroduced into the model. We removed relationships or variables until a model had an acceptable fit (*P*-value of $\chi^2 >$ 0.05, CFI > 0.95, and RMSEA < 0.05). The resulting model was then compared to the same model, with path coefficients restricted to be the same across groups. These two models were compared using ANOVA, and the model without restrictions on path coefficients was kept only if it was better at $\alpha = 0.05$. The resulting model can only be hypothesised not to contradict data as the same data have been used to obtain the model.

3.3 Results

All treatments and all sites confounded, 2011 mean increment (standard deviation) was 0.9 (0.6) cm for basal diameter and 0.60 (0.55) m for height. Wildlife damages to hybrid poplars have caused negative growth in some cases (trees smaller in 2011 than 2010) and

high variability of data. However, we showed in the previous chapter that residue treatment had no effect on wildlife damages.

3.3.1 Treatment comparisons

For at least one site, we found differences between treatments (Tables 3.1 and 3.2) within for every variable except resin-NH_4^+, resin-P, and both pre-dawn and midday leaf water potential. However, soil temperature and foliar [N] were the only variables with a consistent treatment effect at all sites, with soil temperature being higher under Herbicide, Geotextile, and Control compared to Double residue load, and foliar [N] being higher for Herbicide + Single residue load compared to Control. Weedon was the only site with a plot treatment effect on basal diameter and height of trees, with Herbicide + Single residue load having a positive effect on these two variables compared to all other treatments. Again at Weedon, hybrid poplars under Herbicide + Single residue load also had increased leaf mass, foliar [N], and foliar [P] compared to Control and Double residue load (Table 3.2) but the distinction between Herbicide + Single residue load vs. Control and Double residue load was not consistent with any environmental measurements. Logging residues had no significant effect on any physiological measurements compared to Control, including basal diameter and height (Table 3.2).

Table 3.1 Mean (SE) of environmental variables measured in summer 2011 at each site as influenced by treatments. Different letters indicate significant differences between treatments within a site at $\alpha < 0.05$.

Treatment	Herbaceae cover (%)	Woody plant cover (%)	Resin-NH_4^+ (mg/kg)	Resin-NO_3^- (mg/kg)	Exchangeable base cations (cmol +/kg)	Resin-P (mg/kg)	Soil Temperature (°C)	Soil volumetric water content (%)
				Bouchette				
Control	5 (1) b	28 (7) c	9.0 (4.2)	6.3 (5.7)	6.7 (2.2)	7.2 (1.6)	16.3 (0.4) cd	27.4 (2.0)
Half load (residues)	3 (2) ab	26 (4) c	9.2 (4.7)	0.8 (0.3)	7.5 (3.7)	9.8 (1.8)	15.6 (0.1) abc	30.2 (3.7)
Single load (residues)	6 (4) b	19 (5) bc	12.7 (3.1)	14.3 (8.0)	10.4 (3.7)	17.7 (8.6)	15.3 (0.2) ab	25.7 (3.0)
Double load (residues)	1 (0.4) ab	8 (4) ab	52.1 (43.1)	2.4 (1.1)	10.4 (4.3)	11.2 (3.8)	15.1 (0.2) a	29.8 (1.4)
Geotextile	1 (0.3) a	3 (1) a	10.5 (4.5)	1.3 (0.4)	10.2 (4.4)	25.4 (14.9)	16.0 (0.2) bc	32.1 (3.5)
Herbicide	7 (5) b	5 (2) a	17.9 (8.3)	36.0 (20.1)	7.1 (1.7)	9.5 (3.0)	17.0 (0.2) d	30.9 (2.5)
Herbicide + Single load	3 (1) ab	4 (1) a	22.4 (14.4)	11.4 (4.9)	13.1 (2.3)	23.4 (6.3)	15.6 (0.2) abc	33.1 (2.6)
				Kamouraska				
Control	3 (2)	41 (12) b	4.3 (2.3)	2.4 (1.6)	1.7 (0.7)	2.1 (0.9)	15.8 (0.4) bc	17.6 (1.0) a
Half load (residues)	5 (2)	18 (4) b	0.8 (0.5)	0.7 (0.2)	3.1 (1.1)	2.2 (1.0)	14.8 (0.2) ab	25.6 (1.8) b
Single load (residues)	3 (2)	19 (6) b	2.0 (1.5)	5.0 (2.9)	2.8 (0.8)	1.9 (0.9)	14.4 (0.2) a	25.4 (2.4) b
Double load (residues)	4 (1)	16 (5) ab	1.1 (0.3)	3.5 (1.6)	1.7 (0.5)	1.4 (0.6)	14.3 (0.1) a	24.2 (1.5) ab
Geotextile	3 (1)	21 (8) b	2.4 (1.4)	5.9 (2.5)	0.6 (0.1)	0.7 (0.2)	16.2 (0.2) c	21.4 (1.1) ab
Herbicide	11 (9)	3 (1) a	2.7 (1.7)	38.2 (15.8)	1.8 (0.5)	1.3 (0.6)	16.3 (0.3) c	23.0 (1.8) ab
Herbicide + Single load	3 (1)	2 (1) a	8.3 (5.5)	12.1 (9.2)	1.7 (0.4)	1.7 (0.5)	14.8 (0.1) ab	22.1 (1.1) ab
				Weedon				
Control	11 (5) b	21 (5)	0.1 (0.1)	0.4 (0.1) a	0.2 (0.04) a	0.3 (0.1)	20.4 (0.4) cd	32.9 (2.8)
Half load (residues)	4 (1) ab	23 (5)	0.5 (0.3)	2.1 (0.8) ab	0.3 (0.1) ab	0.5 (0.2)	19.8 (0.4) bc	31.5 (2.2)
Single load (residues)	2 (1) ab	21 (4)	1.7 (1.3)	1.5 (0.6) ab	0.7 (0.1) b	1.0 (0.3)	19.0 (0.3) ab	33.6 (2.9)
Double load (residues)	7 (3) b	19 (4)	1.4 (0.7)	2.9 (1.7) ab	0.3 (0.1) ab	0.4 (0.1)	18.1 (0.3) a	36.9 (3.5)
Geotextile	1 (0.3) a	6 (2)	2.6 (1.5)	85.0 (54.0) c	0.5 (0.2) ab	0.4 (0.1)	19.9 (0.2) bcd	37.1 (2.5)
Herbicide	9 (3) b	7 (2)	0.6 (0.3)	15.9 (11.0) bc	0.3 (0.1) ab	0.3 (0.1)	21.2 (0.3) d	34.3 (3.7)
Herbicide + Single load	2 (1) ab	6 (1)	1.0 (0.9)	9.4 (6.7) abc	0.4 (0.1) ab	0.7 (0.3)	19.2 (0.3) abc	32.9 (3.3)

Table 3.2 Mean (SE) of physiological measurements of 2-year-old hybrid poplars as influenced by treatments. Different letters indicate significant differences between treatments within a site at $\alpha < 0.05$. Leaf mass represents the mass of 10 randomly selected leaves per tree.

Treatment	Pre-dawn leaf water potential (Mpa)	Midday leaf water potential (Mpa)	$\delta^{13}C$ (‰)	Leaf mass (g)	Foliar [N] (%)	Foliar [P] (g/kg)	Basal diameter (cm)	Height (m)
Bouchette								
Control	2.50 (0.29)	16.33 (1.96)	-30.24 (0.19)	1.74 (0.22)	1.24 (0.07) a	1.75 (0.16)	1.5 (0.2)	1.22 (0.14)
Half load (residues)	NA	NA	-30.02 (0.49)	2.40 (0.39)	1.36 (0.10) ab	1.99 (0.14)	1.8 (0.2)	1.40 (0.14)
Single load (residues)	NA	NA	-29.51 (0.43)	2.06 (0.38)	1.52 (0.13) ab	1.99 (0.19)	2.0 (0.3)	1.40 (0.30)
Double load (residues)	2.50 (0.50)	17.50 (1.89)	-29.20 (0.62)	1.98 (0.39)	1.52 (0.10) ab	1.97 (0.16)	1.7 (0.2)	1.25 (0.12)
Geotextile	1.83 (0.60)	17.33 (2.46)	-29.72 (0.10)	2.47 (0.24)	1.47 (0.09) ab	1.84 (0.17)	2.0 (0.1)	1.53 (0.10)
Herbicide	3.67 (1.01)	18.83 (5.57)	-29.29 (0.33)	3.11 (0.36)	1.66 (0.08) ab	1.73 (0.16)	2.6 (0.4)	1.66 (0.22)
Herbicide + Single load	1.50 (0.29)	25.00 (4.16)	-28.81 (0.38)	2.83 (0.42)	1.69 (0.07) b	2.24 (0.17)	1.8 (0.1)	1.53 (0.13)
Kamouraska								
Control	12.17 (3.03)	16.83 (0.44)	-30.34 (0.13) a	1.94 (0.42)	1.90 (0.09) a	1.69 (0.06) a	1.7 (0.2)	1.66 (0.19)
Half load (residues)	NA	NA	-29.31 (0.06) ab	2.36 (0.27)	1.85 (0.07) a	2.01 (0.13) ab	1.9 (0.1)	1.76 (0.23)
Single load (residues)	NA	NA	-29.28 (0.34) ab	2.75 (0.29)	1.88 (0.05) a	2.01 (0.08) ab	1.9 (0.1)	1.85 (0.13)
Double load (residues)	8.58 (2.39)	16.17 (4.64)	-29.24 (0.05) ab	3.28 (0.64)	1.99 (0.06) ab	2.26 (0.09) b	2.1 (0.2)	2.07 (0.28)
Geotextile	10.50 (3.69)	18.00 (3.04)	-28.99 (0.11) b	2.66 (0.26)	2.19 (0.06) abc	1.90 (0.15) ab	1.9 (0.1)	1.68 (0.19)
Herbicide	10.92 (2.90)	19.33 (1.45)	-28.91 (0.14) b	3.31 (0.27)	2.40 (0.14) c	1.98 (0.11) ab	2.1 (0.2)	1.76 (0.23)
Herbicide + Single load	8.33 (1.30)	19.67 (3.09)	-28.46 (0.61) b	2.92 (0.29)	2.36 (0.11) bc	2.01 (0.13) ab	2.3 (0.3)	1.92 (0.22)
Weedon								
Control	NA	NA	-30.26 (0.19)	2.28 (0.13) a	1.19 (0.04) a	1.15 (0.05) a	2.5 (0.1) a	1.90 (0.11) a
Half load (residues)	NA	NA	-29.95 (0.33)	2.33 (0.17) a	1.38 (0.08) a	1.30 (0.08) ab	2.5 (0.2) a	1.86 (0.16) a
Single load (residues)	NA	NA	-30.39 (0.15)	2.12 (0.14) a	1.43 (0.08) a	1.31 (0.08) ab	2.4 (0.2) a	1.95 (0.14) a
Double load (residues)	NA	NA	-30.22 (0.26)	2.44 (0.17) a	1.32 (0.05) a	1.17 (0.07) a	2.5 (0.1) a	2.01 (0.09) a
Geotextile	NA	NA	-29.75 (0.16)	2.68 (0.23) a	1.42 (0.07) a	1.29 (0.07) ab	2.9 (0.2) a	1.98 (0.12) a
Herbicide	NA	NA	-29.41 (0.28)	3.04 (0.48) ab	2.01 (0.08) b	1.66 (0.09) c	3.0 (0.2) a	1.86 (0.15) a
Herbicide + Single load	NA	NA	-29.73 (0.26)	4.03 (0.27) b	2.05 (0.08) b	1.58 (0.08) bc	3.8 (0.2) b	2.61 (0.11) b

3.3.2 Structural equation modelling

We first tested the full model saturated with the most biologically plausible relationships (Fig. 3.1), which was strongly rejected ($\chi^2 = 628$, degrees of freedom (df) = 189, $P < 0.001$). We hypothesised that the model resulting from our exploratory method (Fig. 3.2 and Table 3.3; $\chi^2 = 27.55$, df = 30, $P = 0.594$) would best describe our data. Starting from the causal structure presented in Fig. 3.2, we compared a model with path coefficients different between sites and one with path coefficients constrained to be equal across sites; the latter was strongly rejected ($P < 0.001$) so we allowed path coefficients to be different between sites (Table 3.3). This model excludes cover of herbaceae, latent variable soil (which included resin-NH_4^+, resin-NO_3^-, resin-P and sum of exchangeable cations), soil volumetric water content, and foliar [P], because all tested models containing these variables were strongly rejected ($P < 0.001$). Leaf mass was the main predictor of height and basal diameter among measured variables. The explained variations (r^2) of height and basal diameter by leaf mass were consistently above 0.5 except for height at Weedon where the r^2 was 0.33.
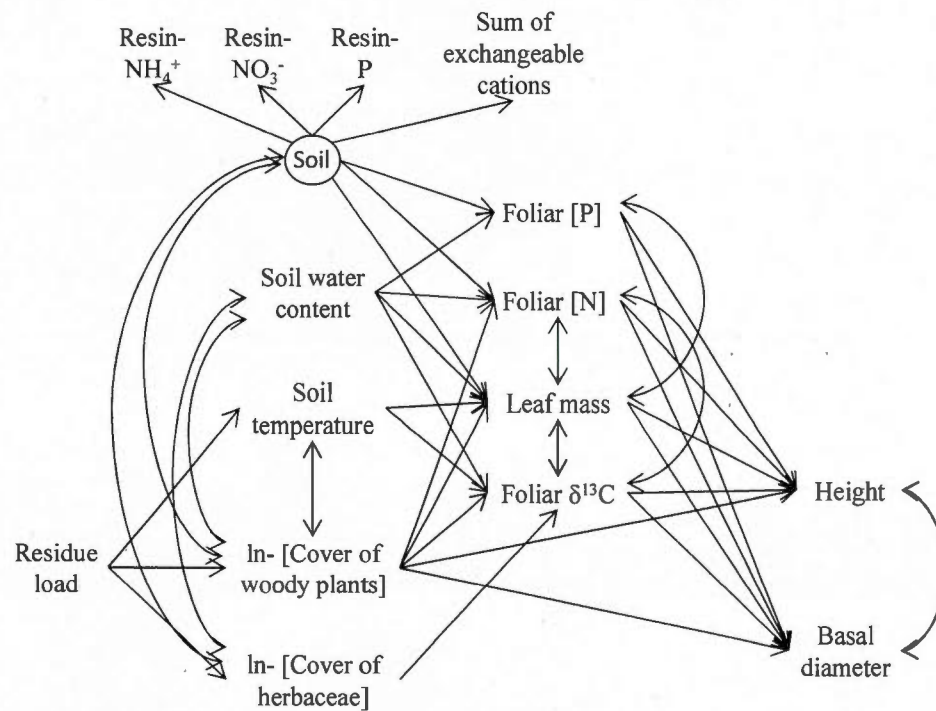
Figure 3.1 Full path diagrams of hybrid poplar physiological response to changes in microenvironment due to logging residues for three plantations in Quebec (Canada), proposed as a starting hypothesis.

Double-headed arrows represent correlations (non-causal relationships) and single-headed arrows represent causal relationships. Latent variable Soil is represented by a circle. Latent variable Soil was measured by resin-NH_4^+, resin-NO_3^-, resin-P, and sum of exchangeable cations, was correlated with cover of woody plants and cover of herbaceae, and influenced foliar [P], [N], and leaf mass.
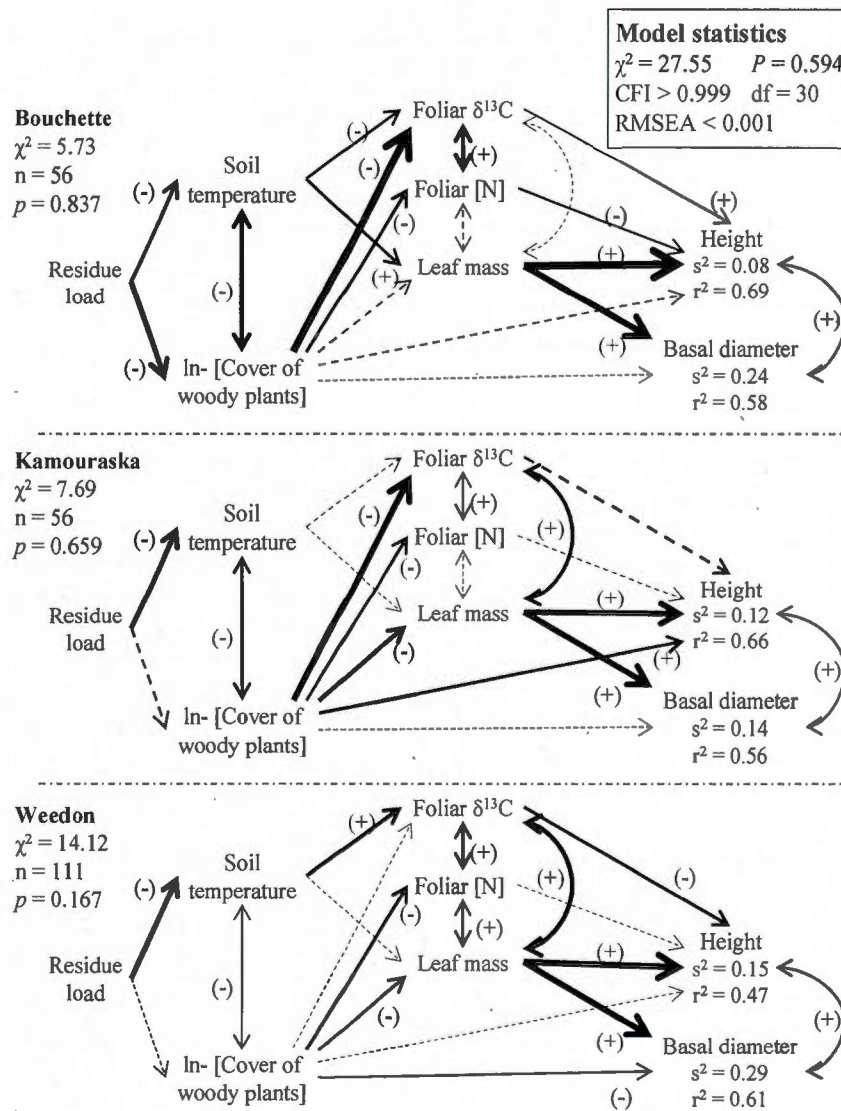
Figure 3.2 Selected path diagrams of physiological responses of hybrid poplars to changes in microenvironment due to logging residues for three plantations in Quebec (Canada).

Model χ^2, degrees of freedom (df), P-value, CFI, and RMSEA are presented, as well as site χ^2, n, and P-value, and residual variances (s^2) and explained variations (r^2) of response variables. Dashed lines represent relationships whose path coefficients are not significantly different from zero ($\alpha < 0.05$). The sign of path coefficients significantly different from zero are presented. Line widths are proportional to standardised path coefficients and represent their relative importance.

Table 3.3 Estimates (standard error) and *P*-values of regressions and covariances from the selected structural equation model at Bouchette, Kamouraska, and Weedon, three hybrid plantations from 2010 in Quebec (Canada). All measurements were made over summer 2011.

Explaining variable	Response variable	Bouchette		Kamouraska		Weedon	
		Estimate (SE)	*P*	Estimate (SE)	*P*	Estimate (SE)	*P*
Residue load →	Soil temperature	-0.44 (0.16)	**0.007**	-0.71 (0.22)	**0.001**	-1.10 (0.21)	**<0.001**
Residue load →	ln [Cover of woody plant]	-0.84 (0.19)	**<0.001**	-0.51 (0.37)	0.166	0.01 (0.20)	0.963
Soil temperature →	Foliar δ^{13}C	-0.28 (0.13)	**0.024**	-0.11 (0.09)	0.229	0.14 (0.05)	**0.005**
Soil temperature →	Leaf mass	0.45 (0.16)	**0.004**	-0.05 (0.14)	0.693	-0.06 (0.07)	0.395
ln [Cover of woody plant] →	Foliar δ^{13}C	-0.53 (0.13)	**<0.001**	-0.35 (0.06)	**<0.001**	-0.02 (0.06)	0.718
ln [Cover of woody plant] →	Foliar [N]	-0.10 (0.03)	**0.002**	-0.08 (0.03)	**0.004**	-0.13 (0.03)	**<0.001**
ln [Cover of woody plant] →	Leaf mass	-0.23 (0.12)	0.055	-0.34 (0.10)	**<0.001**	-0.30 (0.09)	**<0.001**
ln [Cover of woody plant] →	Height	0.09 (0.05)	0.073	0.17 (0.05)	**0.002**	-0.05 (0.04)	0.174
ln [Cover of woody plant] →	Basal diameter	0.01 (0.07)	0.897	-0.04 (0.04)	0.269	-0.15 (0.04)	**0.001**
Foliar δ^{13}C →	Height	0.19 (0.08)	**0.018**	0.28 (0.17)	0.103	-0.44 (0.14)	**0.002**
Foliar [N] →	Height	-0.49 (0.16)	**0.003**	-0.26 (0.16)	0.118	-0.04 (0.14)	0.770
Leaf mass →	Height	0.44 (0.05)	**<0.001**	0.39 (0.08)	**<0.001**	0.36 (0.05)	**<0.001**
Leaf mass →	Basal diameter	0.55 (0.07)	**<0.001**	0.37 (0.05)	**<0.001**	0.51 (0.05)	**<0.001**
ln [Cover of woody plant] ↔	Soil temperature	-0.43 (0.11)	**<0.001**	-0.50 (0.19)	**0.007**	-0.39 (0.18)	**0.030**
Foliar δ^{13}C ↔	Foliar [N]	0.10 (0.04)	**0.006**	0.05 (0.02)	**0.022**	0.07 (0.03)	**0.017**
Foliar δ^{13}C ↔	Leaf mass	-0.04 (0.14)	0.767	0.34 (0.10)	**0.001**	0.29 (0.11)	**0.009**
Foliar [N] ↔	Leaf mass	0.05 (0.03)	0.134	0.02 (0.04)	0.562	0.15 (0.04)	**<0.001**
Height ↔	Basal diameter	0.10 (0.02)	**<0.001**	0.08 (0.02)	**<0.001**	0.14 (0.03)	**<0.001**

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Effects of logging residues on height and basal diameter of trees were somewhat minor. Total indirect effect can be computed by multiplying the estimates given in Table 3.3 along the indirect path; if several indirect paths are possible, e.g., soil temperature can have an effect on height either through foliar $\delta^{13}C$ or through leaf mass, the total effect is given by the addition of all indirect paths. According to the model proposed in Fig. 3.2 and Table 3.3, when adding up all indirect paths, an increase of one unit of logging residues (one load, 40 kg/9 m^2) would have a positive effect on height and basal diameter at Kamouraska and Weedon: at Kamouraska, one load of logging residues led to an increase of 0.056 m in height and 0.097 cm in basal diameter; at Weedon, one load of logging residues led to an increase of 0.092 m in height and 0.030 cm in basal diameter. However, there was a slightly negative effect of indirect paths at Bouchette (one load of logging residues led to a decrease of 0.011 m in height and 0.011 cm in basal diameter). When partitioning the effects of logging residues on tree size through soil temperature and cover of woody plants, an increase of one unit (load) of logging residues decreased height and basal diameter through soil temperature only at Bouchette (respectively -0.064 m and -0.109 cm), and increased height and basal diameter through soil temperature at Kamouraska (0.036 m and 0.013 cm, respectively) and Weedon (0.092 m and 0.034 cm, respectively). An increase of one unit of logging residues increased height and basal diameter through a decrease of the cover of woody plants at Bouchette (0.053 m and 0.098 cm, respectively) and Kamouraska (0.020 m and 0.084 cm, respectively), but had no effect on height and basal diameter through cover of woody plants at Weedon ($<$ 0.001 m and -0.004 cm, respectively). Therefore, according to structural equation modelling (Fig. 3.2 and Table 3.3), changes in height and basal diameter of the magnitude likely to be caused by logging residues, were far below variability (as estimated by standard deviation) of height and basal diameter at all sites (respectively, changes $<$ 0.10 m and 0.10 cm, standard deviations $>$ 0.25 m and 0.3 cm).

3.4 Discussion

Logging residues had no significant effect on height and basal diameter of hybrid poplars after two growing seasons. However, the use of structural equation modelling highlighted the complex impacts of logging residues on resource availability and their resulting effects on growth. Our selected structural equation model did not support our first

hypothesis that decreased soil temperature and competing vegetation would have contradictory effects on growth of hybrid poplars. Treatment comparisons also not supported our first hypothesis about the expected contradictory effects of changes to soil temperature and competing vegetation. To support this hypothesis, low soil temperature and high competing vegetation should yield to lower growth than high soil temperature and low competing vegetation. In our study, the Herbicide treatment caused both low competing vegetation and high soil temperature (Table 3.1) which should have provided ideal growing conditions and should have improved growth compared to other treatments if water was not limiting. However, the Herbicide treatment led to the greatest height and basal diameter only at Bouchette where differences between any of the treatments were not significant (Table 3.2). The Half and Single residue loads resulted in high competing vegetation cover but also in low soil temperatures, which should have hampered growth compared to other treatments; however, we observed growth rates similar to those measured in the other treatments (Tables 3.1 and 3.2). Finally, the Herbicide + Single residue load had low competing vegetation and low soil temperature (Table 3.1), which, according to our initial hypothesis, should have led to average growth compared to other treatments. Instead, Herbicide + Single residue load led to increased tree size compared to other treatments, although the growth effect was only significant at Weedon (Table 3.2). This absence of response of hybrid poplars to logging residues support the findings of Egnell (2011) who found a significant effect of logging residues on tree growth only at least eight years after Norway spruce (*Picea abies* (L.) Karst) planting.

Leaf mass, the main predictor of height and basal diameter in this study, increased as a consequence of decreasing cover of woody plants. This could be due to increased irradiance associated with a low cover of woody plants, as leaves exposed to high irradiance are often thicker than leaves under the shade (Reich et al. 1998b, Raven et al. 2005). However, we did not measure incoming photosynthetically active radiation in the various treatments; as plausible as it is, this interpretation thus remains to be confirmed.

Leaf mass was significantly and positively correlated with foliar $\delta^{13}C$ (Fig. 3.2 and Table 3.3). Foliar $\delta^{13}C$ is the result of both stomatal behaviour, which influences CO_2 entry and water exit from the leaf, and carbon assimilation rate, which influences CO_2 demand from the

leaf (Duursma and Marshall 2006). Higher leaf mass suggests larger leaf area (DesRochers et al. 2006) and evapotranspiration, potentially leading to stomatal closure that in turn decreases leaf conductance and intercellular partial pressure of CO_2, and increases fixed ^{13}C (Farquhar et al. 1989). Considering that $\delta^{13}C$ integrates information from the whole growing season, higher $\delta^{13}C$ values could reflect some drought stress events due to changes to evapotranspiration without implying a constant drought stress throughout the whole growing season, which would have negatively affected growth. Higher $\delta^{13}C$ values could also result from higher assimilation rate (Farquhar et al. 1989), leading to increased biomass production and larger leaf mass.

Foliar $\delta^{13}C$ was in turn influenced by the cover of woody plants (Fig. 3.2 and Table 3.3). The negative relationship between the cover of woody plants and foliar $\delta^{13}C$ contradicted our second hypothesis that a decrease of competing vegetation would increase water availability, prevent stomatal closure and reduce drought stress. Treatment comparisons also contradicted this second hypothesis; the Herbicide and the Herbicide + Single residue load had higher (less negative) $\delta^{13}C$ values compared to Control (although treatment effect being significant only at Kamouraska), suggesting more drought stress in conditions of low competing vegetation without being associated with higher soil water content or any effect on growth (Tables 3.1 and 3.2). Again the balance between stomatal behaviour and assimilation rate to determine $\delta^{13}C$ could explain the negative effect of the cover of woody plants on foliar $\delta^{13}C$. Low cover of woody plants could have increased above-ground temperature and wind speed, leading to higher evapotranspiration and stomatal closure. On the other hand, less competition from woody vegetation could also have increased fixed ^{13}C by increasing available light, as foliar $\delta^{13}C$ is positively correlated with irradiance (Farquhar et al. 1989, Kranabetter et al. 2010). The negative effect of cover of woody plants on $\delta^{13}C$ was not significant at Weedon, where site preparation and size of trees at planting placed hybrid poplar foliage above most competition (personal observation), freeing the foliage from an above-ground effect. However, many other site characteristics (drainage, soil texture, precipitation, air temperature, etc.) could also explain this difference at Weedon compared to Bouchette and Kamouraska.

Soil temperature had a site-dependent effect on foliar $\delta^{13}C$ (significant positive effect at Weedon and significant negative effect at Bouchette), and leaf mass (positive effect but significant only at Bouchette; Fig. 3.2 and Table 3.3), not supporting our third hypothesis that a decrease in soil temperature would cause drought stress and low leaf nutrient concentrations by decreasing water and nutrient uptake. Treatment comparisons also did not support this third hypothesis; treatments with logging residues were associated with lower soil temperature compared to the Control or the Herbicide, but with no consistent effect on foliar [N], [P], $\delta^{13}C$, basal diameter or height (Tables 3.1 and 3.2). Peng and Dang (2003) found that the optimum soil temperature for trembling aspen production of biomass varied from 18.1 to 21.3 °C depending on plant component (optimal soil temperature for stem mass > root mass > foliage mass). Only in Weedon did soil temperatures reach values above 18 °C, suggesting that soil temperature may have remained limiting at Bouchette and Kamouraska. Indeed, at Bouchette, increases in soil temperature led to lower (more negative) $\delta^{13}C$ values and higher leaf mass, possibly explained by a higher rate of water absorption compared to low soil temperatures. At Weedon, an increase of soil temperature led to higher (less negative) $\delta^{13}C$ values, possibly suggesting a drought stress at high soil temperatures. Again at Weedon, changes in soil temperatures could explain the improved growth under Herbicide + Single residue load, which would have provided low competing vegetation but relatively lower soil temperatures than Herbicide or Control, protecting trees from drought stress.

Hybrid poplar nutrition was also consistently influenced by cover of woody plants which decreased foliar [N], without being linked to nutrients measured in soils (Fig. 3.2). This is supported by Kranabetter et al. (2010) and Kaelke et al. (2001) who found decreasing foliar [N] with decreasing light availability, attributed to shifts in root-shoot biomass allocation, assuming that available light was indeed correlated with cover of woody plants in this study. Foliar [N] was then positively correlated with $\delta^{13}C$, which could be explained by the reported positive correlation between foliar [N] and photosynthesis (Reich et al. 1998a, Kazda et al. 2004).

3.5 Conclusions

Logging residues decreased soil temperature and competing vegetation, which in turn influenced the physiological response of hybrid poplars during their second growing season

after planting. One important driver influencing leaf mass and tree growth seemed to have been changes to cover of woody plants. Foliar $\delta^{13}C$, N concentrations and leaf mass were linked to cover of woody plants but not to soil nutrients or water content, suggesting that changes to above-ground conditions (e.g., irradiance or air temperature) were the driving factors. Logging residues did not significantly influence hybrid poplar growth at this early stage of stand development: their effects on the microenvironment of the planted seedlings were apparently not significant enough to have an impact on growth drivers. The second growing season could be too soon during the stand development to observe a significant logging residue effect on hybrid poplar growth or stock and browsing problems could have masked a growth response. Monitoring of treatments in the upcoming years will provide valuable information about their longer term effects.

3.6 Acknowledgements

3.7 References

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CHAPITRE IV

CONCLUSION GÉNÉRALE

Le but de cette étude était d'évaluer l'effet des résidus de coupe sur l'établissement et le succès de plantation en conditions de forêt boréale et tempérée. Une étude sur le terrain a été mise en place sur quatre sites à travers la province : Weedon en Estrie, Kamouraska au Bas-Saint-Laurent, Lac-Bouchette au Lac-Saint-Jean et Duparquet en Abitibi–Témiscamingue. Tous les sites ont été récoltés en 2009 et trois espèces par site ont été mises en terre au printemps 2010 : le peuplier hybride et l'épinette noire à tous les sites, le pin gris à Lac-Bouchette et Duparquet et l'épinette blanche à Weedon et Kamouraska. Suite à la plantation, huit traitements, dont sept qui ont été retenus pour les analyses de cette étude, ont été appliqués en 2010 à l'échelle de l'arbre sur des parcelles de 9 m^2 réparties aléatoirement sur chaque site. Quatre traitements visaient à tester l'effet quantitatif des résidus, allant d'un témoin (sans résidu) à l'équivalent du double de la masse de branches sur 9 m^2 attendue selon le peuplement précédent. Quatre traitements visaient à détailler les mécanismes en œuvre dans l'effet des résidus sur la croissance de la régénération et étaient complémentaires au traitement témoin : un géotextile gris; un contrôle de la végétation; de la chaux dolomitique et de l'engrais; et une combinaison de la dose simple de résidus combinée au contrôle de la végétation. Le traitement incluant la chaux dolomitique et l'engrais a finalement été exclu des analyses à cause de valeurs anormalement élevées de ratio foliaire d'isotopes de carbone δ^{13}C par rapport à tous les autres traitements.

4.1 Résultats saillants et hypothèses

L'hypothèse selon laquelle les résidus de coupe diminueraient la température du sol et la couverture de végétation compétitive de manière à avoir des effets contradictoires sur la croissance a été rejetée. La modélisation par équations structurelles appliquée à trois sites a tout de même révélé que les variations de la température du sol et la couverture de compétition par des plantes ligneuses (comme sous-ensemble de la couverture de végétation compétitive totale) ont majoritairement dicté la réponse physiologique des peupliers hybrides.

Une diminution de la couverture de végétation ligneuse a mené à une augmentation de la masse des feuilles (significatif à $\alpha = 0,05$ à seulement deux sites sur trois), de $\delta^{13}C$ (valeurs moins négatives, significatif à seulement deux sites sur trois) et de la concentration foliaire de N (significatif à tous les sites). Les effets de la température du sol sur les variables physiologiques ont fortement dépendu du site : une diminution de la température du sol a mené à une augmentation de $\delta^{13}C$ à Lac-Bouchette, possiblement en raison d'une moins bonne absorption de l'eau, mais à une diminution de $\delta^{13}C$ à Weedon, possiblement à cause d'une réduction du stress hydrique. Une diminution de la température du sol menait également à une réduction de la masse de feuilles, mais seulement au site de Lac-Bouchette, le même effet n'étant pas significatif à Kamouraska et Weedon.

La modélisation par équations structurelles, en détaillant les effets des résidus de coupe sur la croissance à travers la température du sol et la couverture de végétation ligneuse, a toutefois révélé que les variations environnementales causées par les résidus de coupe étaient d'une magnitude trop faible pour induire une réponse de la croissance. La comparaison des traitements a également révélé que les résidus de coupe n'ont pas eu d'effet significatif sur la croissance en hauteur et le diamètre à la base des peupliers hybrides après la deuxième année de croissance. Seule la combinaison Herbicide + Dose simple de résidus a mené à une hauteur et un diamètre à la base plus élevés que le Témoin et tous les autres traitements, à seulement un site (Weedon).

Notre première hypothèse affirmait que les résidus de coupe n'auraient aucun effet sur les nutriments du sol à l'échelle de temps étudiée, hypothèse supportée par cette étude. La deuxième hypothèse affirmait que les résidus de coupe réduiraient, dans un premier temps, la température du sol et dans un deuxième temps, la couverture de végétation compétitive, hypothèse également confirmée par cette étude. Les résidus de coupe ont diminué la température du sol à tous les sites, supportant les conclusions de plusieurs études (Hendrickson 1988, Zabowski et al. 2000, Proe et al. 2001). L'effet de la quantité de résidus sur la température n'était pas linéaire, mais plutôt quadratique. Une diminution de la température du sol était associée à la dose simple (1) par rapport au témoin (0). La dose double (2) ne menait toutefois pas à une réduction significative de la température du sol par rapport à la dose simple. La dose simple a pu couvrir l'ensemble de la surface où étaient les

résidus de coupe et où la température du sol était mesurée, auquel cas des résidus supplémentaires ne conduiraient pas à une réduction supplémentaire de la température du sol. De plus, les fluctuations quotidiennes de température du sol (différence entre le maximum et le minimum quotidiens) ont été atténuées par les résidus de coupe, surtout l'été. Les résidus de coupe auraient ainsi agi comme tampon pour les échanges d'énergie entre la surface du sol et le climat au-dessus du sol, reflétant et absorbant la radiation solaire pendant le jour pour diminuer la température maximale du sol, mais retenant les pertes d'énergie du sol en période de refroidissement la nuit pour maintenir la température minimale du sol (Fleming et al. 1998).

Finalement, les résidus de coupe ont linéairement diminué la couverture de végétation compétitive, supportant encore une fois les conclusions de nombreuses études (Hendrickson 1988, Stevens et Hornung 1990, Proe et Dutch 1994, Roberts et al. 2005), mais seulement sur deux sites sur quatre. Les résidus de coupe n'ont eu aucun effet sur la couverture de végétation compétitive à Kamouraska et Weedon. Ces deux sites ont le climat le plus chaud, favorisant possiblement la croissance de la compétition malgré la présence de résidus, et avaient les préparations de terrain qui modifiaient le plus la microtopographie de la plantation. La préparation de terrain a possiblement eu un plus grand effet sur la végétation compétitive que les résidus de coupe.

4.2 Limites méthodologiques

Le traitement incluant la chaux dolomitique et l'engrais a été exclu des analyses parce que la dose appliquée était associée à des valeurs très élevées de ratio foliaire d'isotopes de carbone $\delta^{13}C$ par rapport à tous les autres traitements. Son inclusion aurait amélioré l'analyse de la nutrition foliaire en fonction des variations de nutriments du sol. Toutefois, ces données pourraient être analysées plus en profondeur pour comprendre comment l'engrais a pu mener à une telle réponse physiologique dans une étude sans lien avec les résidus de coupe.

De nombreuses données n'ont pas pu être incluses dans la modélisation par équations structurelles parce qu'elles n'avaient pas été mesurées sur un nombre suffisant d'arbres. Les mesures de température du sol en continu ont été exclues parce qu'elles avaient été mesurées

sur seulement deux peupliers hybrides par traitement par site. Pourtant, la pertinence des mesures de fluctuations quotidiennes de température de sol pour l'activité photosynthétique des arbres a été démontré en forêt boréal (Fréchette et al. 2011). Le potentiel hydrique des feuilles a également été exclu de la modélisation par équations structurelles tout en étant inclus dans la comparaison entre les traitements par site parce qu'il n'avait pas pu être mesuré à Weedon à cause d'averses répétées, mais aurait pu contribuer à expliquer les mesures de $\delta^{13}C$ foliaire en fournissant des informations sur l'utilisation de l'eau par la plante.

Cette étude présente un portrait en 2011 à la deuxième saison de croissance et est sensible aux variations climatiques de cette année. Également, cette étude s'est étendue à travers la province, si bien que les résultats qui sont constants entre les sites ont été testés à travers un gradient de la forêt québécoise. Par contre, puisque les sites étaient différents et ne se répétaient pas, les différences entre sites indiquent que les effets des résidus de coupe et de la régénération dépendent des conditions locales. Ces différences entre sites peuvent être constatées et des hypothèses ont été émises pour les expliquer. Le climat (température et précipitations), le sol (fertilité et texture), le drainage et la préparation de terrain, entre autres, différaient entre les sites, pour avoir une grande représentativité des sites forestiers du Québec, mais sans avoir des répétitions de sites.

4.3 Implications et recherche future

À court terme, la récolte de résidus de coupe pour la production de bioénergie a modifié les conditions de croissance des plants mis en terre –température du sol, couverture de végétation compétitive–, mais sans affecter leur croissance dans les conditions testées dans cette étude. Seule la combinaison d'herbicide et de dose simple a amélioré la croissance des peupliers hybrides lors de la deuxième saison de croissance à un site : Weedon. Toutefois, les résultats de croissance de la troisième saison de croissance ont suggéré que les résidus de coupe augmenteraient la croissance des peupliers hybrides à Kamouraska, suggérant un effet observable seulement après quelques années.

Ces résultats s'appliquent uniquement au peuplier hybride, puisque seule sa réponse physiologique spécifique aux résidus de coupe a été étudiée. De plus, le site de Duparquet a été exclu de l'analyse physiologique détaillée à cause de la forte mortalité des peupliers

hybrides sur ce site, possiblement causée par le drainage rapide associé à la texture grossière du sol ou à cause de la mauvaise qualité des plants (Guillemette et DesRochers 2008). La physiologie de l'épinette noire, blanche et du pin gris devra encore être étudiée pour déterminer si et comment la réponse physiologique à la présence et à la quantité de résidus de coupe dépend de l'espèce mise en terre. Alors qu'on pensait que le peuplier hybride aurait une réponse physiologique plus accentuée aux résidus de coupe et au microenvironnement, Fréchette et al. (2011) ont trouvé que l'activité photosynthétique de l'épinette noire avait davantage varié en fonction des fluctuations de température du sol que le peuplier faux-tremble, espèce analogue au peuplier hybride, suggérant une réponse spécifique.

Même si aucune conclusion ne peut être tirée des différences observées entres les sites, les hypothèses qui en découlent peuvent mener à de nouvelles études et questions de recherche. Notamment, l'effet de modifications à la température du sol sur la physiologie des peupliers hybrides a été opposé à Weedon et Bouchette. Une hausse de température du sol à Weedon a augmenté le $\delta^{13}C$ foliaire, suggérant un stress hydrique, tandis que le même changement a diminué le $\delta^{13}C$ foliaire et augmenté la masse de feuilles à Bouchette. À Weedon, les températures du sol étaient plus élevées qu'à Bouchette, suggérant un gradient dans la réponse du peuplier hybride à la température du sol. Une hausse de température du sol pourrait être bénéfique, tel qu'observé à Bouchette, jusqu'à un certain optimum après lequel toute hausse de température du sol pourrait être néfaste, ce qu'on aurait peut-être observé à Weedon. Peng et Dang (2003) ont observé un tel optimum dans la réponse du peuplier faux-tremble à la température du sol, mais cette information serait déterminante pour le peuplier hybride dans un contexte où une productivité élevée est désirée, et pourrait varier selon le clone. Si un tel optimum était confirmé, des sites avec des températures du sol élevées, soit à cause du climat, soit à cause d'une préparation de terrain qui expose davantage le sol au soleil, pourraient requérir des mesures de contrôle de la température du sol pour y limiter le stress hydrique. Une manière d'y arriver serait d'utiliser les résidus de coupe, tout en gardant en tête que la dose simple a été aussi efficace pour réduire la température du sol que la dose double.

Une autre différence entre les sites qui pourrait mener à des recherches futures est la réponse du peuplier hybride à la couverture de végétation ligneuse à Weedon. Une

augmentation de la couverture de végétation ligneuse n'a pas mené à une diminution du $\delta^{13}C$ foliaire, contrairement aux autres sites. L'eau du sol n'était pas du modèle final d'équations structurelles, mais des analyses préliminaires ont montré l'association suivante : une humidité du sol élevée était associée à une faible végétation compétitive, qui était associée à des valeurs élevées de $\delta^{13}C$ foliaire, suggérant un stress hydrique malgré l'humidité du sol élevée. Cette particularité de Weedon pourrait s'expliquer, entre autres, par l'humidité élevée du sol à ce site, réduisant l'impact d'une sécheresse; par la grandeur des arbres plantés (presque deux mètres à la plantation); ou par la préparation de terrain en monticules avec plantation au sommet, deux facteurs qui ont placé le feuillage des peupliers hybrides au-dessus de la compétition (observations personnelles). La contribution de la taille des peupliers hybrides à la plantation, de la préparation de terrain et de l'humidité du sol pourrait être déterminée par un dispositif avec des répétitions de site (plusieurs types de plants mis en terre, plusieurs préparations de terrain et plusieurs sites avec différents drainages).

Une seconde explication vient de la mesure du $\delta^{13}C$ foliaire; le $\delta^{13}C$ foliaire dépend de la conductance stomatique, qui détermine le ratio de $^{13}C/^{12}C$ que la feuille peut assimiler (entrée dans le système), mais également du taux d'assimilation du CO_2 des feuilles dans le cadre de la photosynthèse (sortie du système). Ainsi, la fermeture des stomates augmente le ratio de $^{13}C/^{12}C$ dans les stomates en augmentant le ^{13}C fixé par la feuille (Farquhar et al. 1989). Une augmentation du taux d'assimilation du carbone augmenterait la demande de CO_2 de la feuille et favoriserait l'absorption de ^{13}C notamment quand les stomates sont fermés, mais encore davantage que l'effet induit seulement par la fermeture des stomates (Duursma et Marshall 2006). Une telle augmentation du taux d'assimilation du carbone pourrait découler d'une radiance solaire accrue, par exemple à cause d'une faible couverture par la végétation compétitive. La part de variations du $\delta^{13}C$ foliaire en fonction du climat au niveau du feuillage et en fonction du taux d'assimilation est encore l'objet de discussions dans la communauté scientifique (voir notamment : Duursma et Marshall 2006, Kranabetter et al. 2010) et pourrait être déterminée en mesurant la conductance stomatique et l'activité photosynthétique des feuilles.

L'absence d'effet des résidus de coupe sur les nutriments du sol, l'effet significatif des résidus de coupe sur la température du sol et la couverture de compétition semble supporter

l'hypothèse (Proe et Dutch 1994, Fleming et al. 1998) que l'effet à court terme des résidus de coupe sur la régénération n'est pas lié à une augmentation des stocks d'éléments nutritifs disponibles dans le sol. Au cours des premières années suivant l'établissement de la plantation, l'influence des résidus de coupe se fait plutôt par le biais de variations du microclimat (incluant la température du sol) et de la végétation compétitive. Toutefois, les variations de la nutrition foliaire, de la masse de feuilles et du ratio foliaire d'isotopes de carbone $\delta^{13}C$ induites par les résidus de coupe n'ont pas été suffisantes pour causer une différence de la hauteur ou du diamètre à la base des peupliers hybrides étudiés, contredisant l'hypothèse avancée. De plus, alors que les résidus de coupe ont eu un effet plus constant sur la température du sol, les variables physiologiques mesurées ont montré une plus forte réponse à des variations de la couverture de végétation compétitive, démontrant son importance dans les premières années d'établissement des plantations. Puisque cette étude offre la possibilité d'évaluer l'effet quantitatif des résidus de coupe, sur un gradient d'espèces et de conditions de site, elle a le potentiel d'apporter dans les années à venir des connaissances scientifiques sur l'effet de différentes quantités de résidus de coupe sur la nutrition d'arbres mis en terre à travers le Québec. Surtout, cette étude propose une approche, la modélisation par équations structurelles, qui permet de détailler l'effet indirect des résidus de coupe sur la croissance de la régénération. Cette approche permettra de tester l'influence relative sur la régénération des changements à la température du sol, à la couverture de compétition et aux nutriments du sol dus aux résidus de coupe.

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