Amounts of logging residues affect planting microsites: A manipulative study across northern forest ecosystems

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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 corresponding seedling growth until the third growing season. In four experimental plantations across Quebec (Canada), we used a factorial design of four residue loads that were applied at the tree-level over three planted species: 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. 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.

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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) vs. 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 can be harvested 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

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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 8–12 years post-planting, most likely due to a nutrient effect, thereby emphasising the importance of a nutrient effect 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 also can 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 ameliorated 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 planted tree growth, and that the effects would be proportional to residue load. Because of the short timespan of the study, we anticipated no effect of residues on soil nutrients.

2. Materials and methods

2.1. Study sites

Four sites were selected that represented a range of contrasting soil characteristics and bioclimatic conditions across Quebec (Table 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 1). Soil pH was determined on distilled water (Table 1) (Pansu and Gautheyrou, 2006). Soil organic carbon, total nitrogen, and sulphur were determined on 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 (Table 1) (Soil Classification Working Group, 1998).

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 × *Populus balsamifera* L. (clone 915319) at Duparquet and Bouchette; bare root stock of *Populus* × *canadensis* Moench [*deltoides* 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 m² 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 aboveground biomass equations of Lambert et al. (2005). The corresponding load of residues for 9 m² 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 m²) were 20 kg, 40 kg and 80 kg,

Table 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°24′N, 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 (1971–2000) 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.

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 (1–9 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 m² 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 quantitative 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 spruces. A total of 408 plots (9 m²) were distributed over the four sites.

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 m²). 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).

2.4. 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 m² 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.

2.5. 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. We extracted the second sample for 30 min in 50 mL of 2 M KCl. Concentrations of NO_3^- and NH_4^+ in the KCl extracts were determined by flow-injection (QuickChem 8500, Lachat Instruments, Loveland, CO).

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.

2.7. 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 (ΔAICc) was calculated relative to the model with the lowest AICc and the AIC weight represented the ratio of the ΔAICc 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.

Table 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, 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
			Residue load (category) × Species	9.44	0.01	13	−156.37
Resin-NO$_3^-$	All data	None	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] + [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

All statistical analyses were conducted in R version 2.15.0 (R Core Team, 2012) using a significance level of α = 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 I 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.

3. Results

3.1. Micrometeorological measurements

For afternoon soil temperatures, the selected model contained a quadratic effect of residue load (Table 2). Soil temperature

significantly decreased with low residue load and remained stable when residue load increased (Fig. 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. 1). According to the full analysis, Residue load as a categorical factor (selected model, Table 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). 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
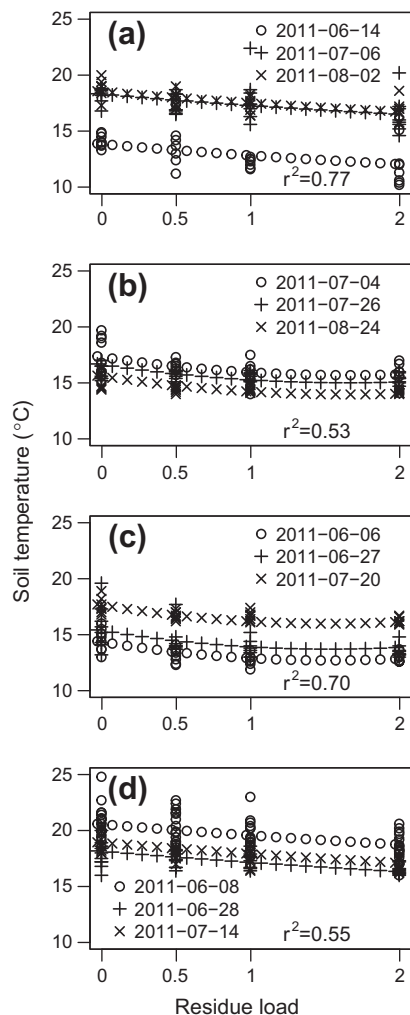

Fig. 1. Afternoon measurements and predicted values of soil temperature as a function of residue load and date of measurement on four experimental plantations in Quebec (Canada): Duparquet (a), Bouchette (b), Kamouraska (c), and Weedon (d). The selected model based on Akaike information criterion contains 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 1 for site descriptions.
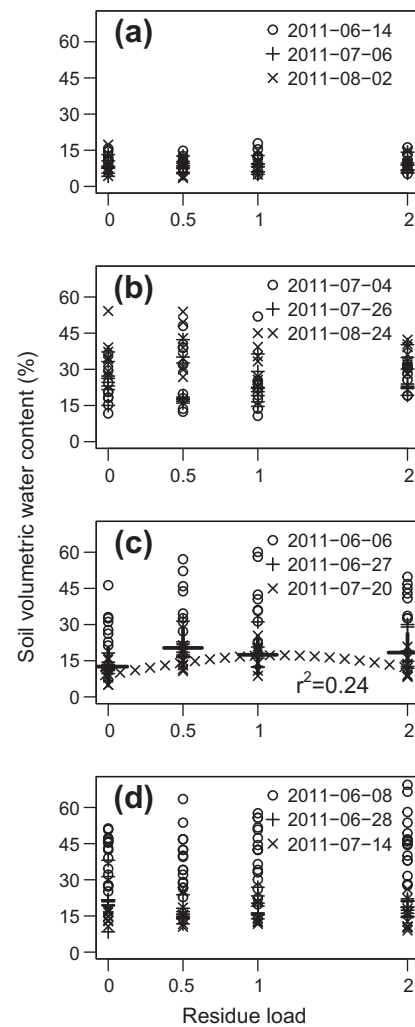

Fig. 2. Afternoon measurements of soil volumetric water content as a function of residue load and date of measurement on four experimental plantations in Quebec (Canada): Duparquet (a), Bouchette (b), Kamouraska (c), and Weedon (d). One model selection based on Akaike information criterion was run for 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 r^2 is presented. See Table 1 for site descriptions.

volumetric water content was highly variable, except at Duparquet, where the soil moisture remained below 20% (Fig. 2).

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 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 3).

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. 3). Strongest effects

Table 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 1 for site descriptions.

Factors	Maximum soil temperature (°C)			Minimum soil temperature (°C)		
	Estimate	SE	p-value	Estimate	SE	p-value
Spring (n = 7860)						
	$r^2 = 0.90$			$r^2 = 0.92$		
(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 = 8300)						
	$r^2 = 0.92$			$r^2 = 0.91$		
(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.

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. 3). For most of the winter, logging residues had a very weak effect on soil temperatures (Table 3), but over the winter of 2010–11 (Fig. 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.

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. 4). At Duparquet and Bouchette,
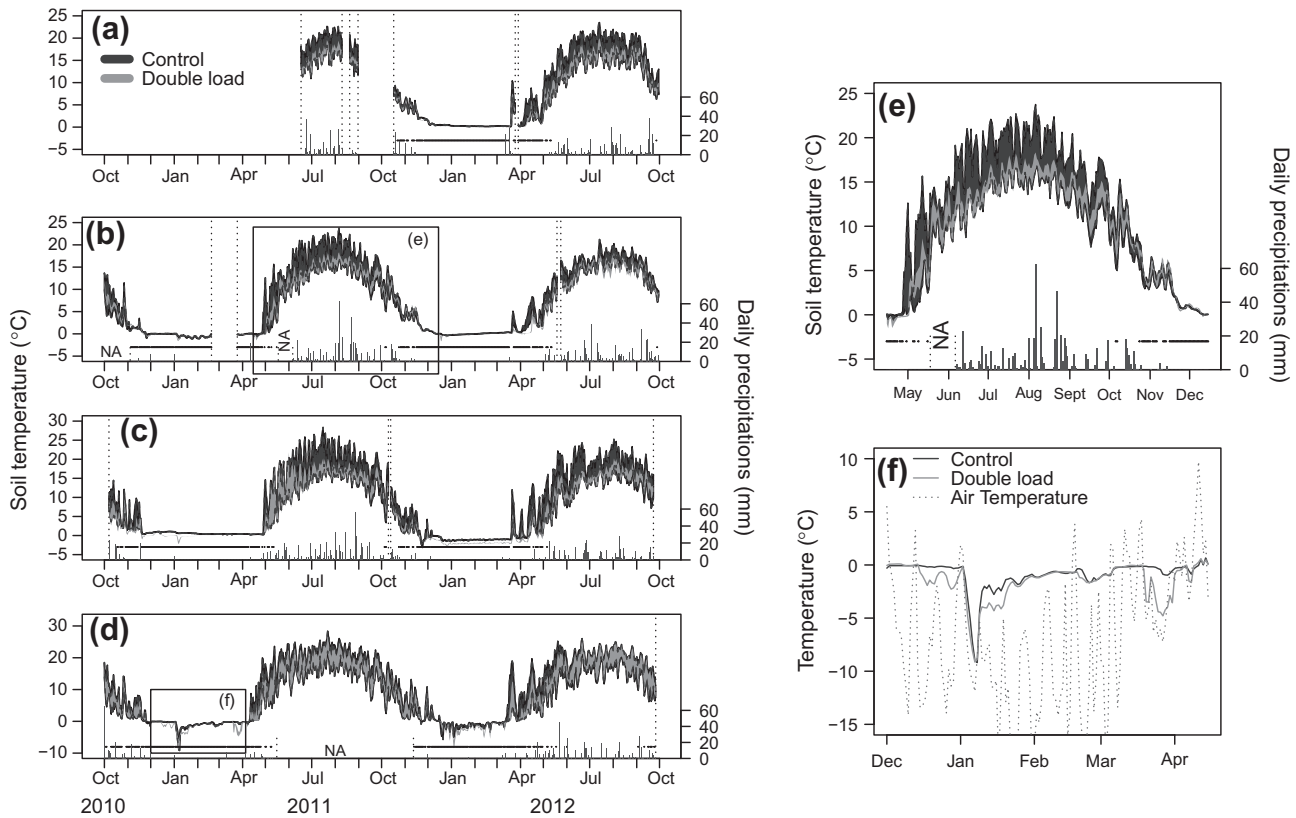
Fig. 3. Daily profiles of soil temperature at 5 cm depth under control and double load conditions, and precipitation over two years on four experimental plantations in Quebec (Canada). Panel (a) is Duparquet, (b) is Bouchette, (c) is Kamouraska, and (d) is Weedon. Panels (e) and (f) are more detailed 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 1 for site descriptions.
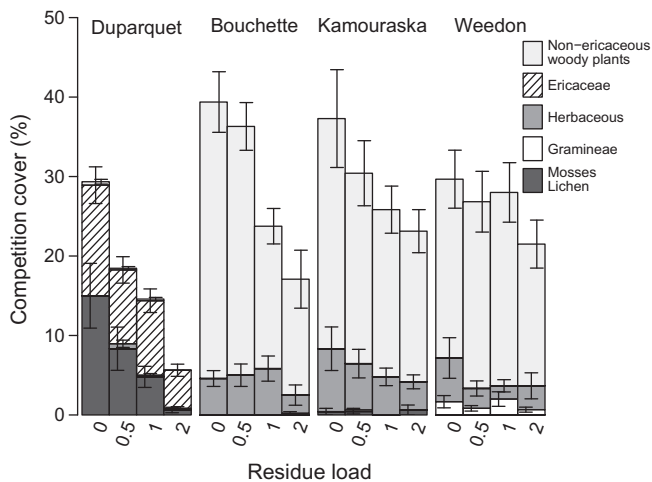
Fig. 4. Average percent cover (±SE) of the main groups of competing vegetation as a function of residue load, as evaluated during the second growing season following planting in four experimental plantations in Quebec (Canada). See Table 1 for site descriptions.

the selected models for total vegetation cover (Table 2) included a significant negative (Table 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), but these effects were not significant (Table 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).

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). 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 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.

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.

Table 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 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 1 for site descriptions.

Factors	Estimate	SE	*P*-value	Factors	Estimate	SE	*P*-value
	Duparquet				Bouchette		
	n = 94; *r*² = 0.36				*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				Weedon		
	n = 96; *r*² = 0.10				*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.

Table 5
Mean (±SE) soil available nutrients from resin bags installed during the second growing season, in four experimental plantations in Quebec (Canada). See Table 1 for site descriptions.

Site	Residue load	Soil available nutrients			
		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

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). 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 (see Table 6; 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 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).

4. Discussion

4.1. Microenvironment and growth

Microenvironmental measurements (soil temperature and water content, cover of competing vegetation, and soil nutrients)

Table 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 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

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 *P. 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; in Quebec (Canada), 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 decreased from 14% under control conditions to 5% under double load (Fig. 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.

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.

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 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.

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.

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