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The effect of boreal jack pine harvest residue retention on soil environment and processes

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A B S T R A C T

Forest residue left on the ground following harvesting (i.e., "slash") plays an important role in moderating the physical and chemical environment of the soil for future forest growth. Leaving too little slash can leave the soil exposed to extreme fluctuations in soil conditions and fewer nutrients that may hinder future forest growth, while leaving too much slash makes it difficult for new trees to establish or increases fire hazard. This study investigated the impacts of blading and different loadings of slash (0, 15, 30 and 60 Mg ha^{-1} dry mass) on soil physical (temperature and moisture), chemical (soil solution) and biological (soil respiration and net ecosystem exchange) processes over 4 summers at a harvested jack pine stand within the Island Lake Biomass Harvest Experiment in northeastern Ontario. Soil temperature and moisture were highest in the bladed and lowest in the 60 Mg ha^{-1} slash loading. Soil solution chemistry was generally similar among the 0, 15 and 30 Mg ha^{-1} slash loadings. However, total organic carbon and potassium had higher concentrations at 60 Mg ha^{-1} treatment and lower concentrations in the bladed treatment, the opposite trend occurred for pH and nitrate. Over three years the concentrations of cations decreased and nitrogen species increased for bladed to 30 Mg ha^{-1} treatments. The 60 Mg ha^{-1} treatment had increases in some solutes over time suggesting there is a lag effect as needles and bark are incorporated into the soil. The soil respiration data showed that lowest rates of CO_2 production occurred in the bladed treatment, but increased over time as the forest floor developed. CO_2 production was highest in the 60 Mg ha^{-1} slash loading, with high rates of soil respiration in the first year, as fine debris from slash deposited onto the soil, however little photosynthesis occurred in these treatments. Thus retention of small to moderate amounts of slash seem to be sufficient for maintaining a suitable balance of soil conditions for a regenerating forest over the short term.

1. Introduction

Approaches for managing non-commercial tree residues ("slash") remaining after forest harvest operations have varied across regions and over time. In the Canadian boreal forest context, prior to the 2000 s the common harvesting approaches included whole tree (WT) harvesting and de-limbing at road side and stem only (SO) harvest where de-limbing was done at the stump. In the former, slash was then either piled and/or burned at the roadside, and in the latter slash was left *in situ*, sometimes with or without piling and/or burning. In the last 20 years there has been movement towards greater use of tree biomass beyond just the bole, resulting in whole tree (WT) harvesting with larger portions of the formerly uncommercial slash being taken for biomass uses (e.g., bioenergy production, pellets, etc.) (Abbas et al., 2011). While there is a benefit to more fully using tree biomass in terms of carbon sequestration in harvested wood products and off-sets of fossil fuel use, there are also negative impacts of leaving less slash on site (Klockow et al. 2013; Egnell et al., 2016).

Slash that remains on-site plays an important function in terms of soil nutrition for the growth of the next generation forest (Ring et al., 2016; Ranius et al., 2018; Lim et al., 2020). Leaving slash on-site after harvesting influences the physical and biogeochemical processes within the soil (see recent summary by Page-Dumroese et al., 2021). Removing the slash removes the pool of woody debris available to decompose over time that would provide carbon (C) and nutrients to the soil and exposes the soil surface to greater temperature fluctuations (Harvey et al., 1976; Covington, 1981; Sinclair, 1992). However, leaving too much slash may result in increased risk of fires due to high fuel loads, as well as difficulties in planting and establishing trees (Jurgensen et al., 1997; Page-Dumroese et al., 2010; Harrington et al 2013). Finding the optimal

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amount of slash to leave on-site is challenging (Abbas et al., 2011). Many agencies recommend leaving one-third of harvest residues on site (Hendrickson et al., 1989; Mann et al., 1988; Hazlett et al., 2014; Thiffault et al., 2014), but a "one size fits all" approach may not be suitable for poor and productive sites alike (Klockow et al., 2013; Egnell et al., 2016).

Identifying approaches that optimize wood use while maintaining soil fertility and developing and validating indicators of site suitability for forest harvest residue are essential for ensuring sustainable forestry (Thiffault et al., 2015). Considerable work has focused on understanding impacts of slash removal on soil nutrient pools and tree regeneration and growth (e.g., Worrell and Hampson, 1997; Thiffault et al., 2011; Binkley et al., 2020), but there has been very little focus on understanding interacting physical, chemical and biological processes within soils. To better understand and accurately model the impacts of slash management, a better understanding of these soil processes occurring over short and long time scales is required. This is particularly of concern on nutrient poor soils that may be particularly sensitive to nutrient losses (Worrell and Hampson, 1997; Thiffault et al., 2011).

At the Island Lake Biomass Harvest Experiment (ILBHE, Kwiaton et al., 2014) the impacts of different levels of biomass removal (Stem Only [SO], Full Tree Biomass [FT_{bio}] where effort was made to remove as much slash as possible, Stumping [ST] and Blading [BL]) have been studied on various ecosystem components (e.g., soil microbes [Smenderovac et al., 2017], vegetation, macro invertebrates [Rousseau et al., 2019], food web structure [Laigle et al., 2021]) over a period of ten years in a boreal, jack pine dominated forest on sandy soil. One previous study (Webster et al., 2016) showed that soil respiration (surface CO_2 efflux) normalized to 15 °C (R_{15}) was lower in biomass harvest treatments than in the uncut stand and a mature 80-yr-old fire-origin natural stand. Among harvest treatments, R_{15} was positively related to the amount of C retained, with the general pattern of FT_{bio} plus blading $<FT_{bio}$ plus stumps removed $<FT_{bio} \sim$ SO harvest. Given the area constraints in the experimental design, no additional slash loading levels (i.e., greater than ~40 Mg ha^{-1} of the tree length treatment) could be tested at the plot scale. Furthermore, slash on large plots could not be evenly distributed to examine impacts at finer scale processes. To investigate physical, chemical and biological impacts on finer-scale soil processes over a wider range of slash loads (blading [forest floor removed], 0 [forest floor remains], 15, 30 and 60 Mg ha^{-1}) at a relatively nutrient poor (site index at 50 years = 19 m), a slash manipulation study was established within the FT_{bio} matrix of the ILBHE.

The goal of the manipulative study is to provide a better process-based understanding of the short-term impacts of a range of slash loadings on key physical, chemical and biological processes, including: soil temperature and soil moisture (soil environment), soil pore water chemistry (soil nutrient status), soil respiration (Rs, decomposition and nutrient cycling) and Net Ecosystem Exchange (NEE, understory productivity). The hypothesis is that intermediate amounts of forest residue left on a conifer-dominated, nutrient poor site will moderate soil environmental conditions, yet still provide sufficient inputs of C, nitrogen (N) and other nutrients to maintain soil processes. The expectation is that higher slash loadings, compared to lower slash loadings will result in: (1) cooler temperatures due to shading, (2) drier soil due to interception losses, (3) higher soil water concentrations of nutrients due to presence of residual biomass, (4) higher rates of soil respiration due to larger pools of decomposable substrate, although cooler and drier conditions may offset that increase, and; (5) lower NEE due to shading and reduced establishment. Having a more fulsome understanding of these interacting mechanisms will help to answer questions about the optimal levels of residue to leave after harvesting at nutrient poor sites, which will, in turn inform guidelines for slash management in the future.

2. Methods

2.1. Study area and experimental design

The ILBHE (Fig. 1) is situated on a 50 ha site near Chapleau, Ontario (N 47.7° W 83.6°). The mean annual temperature for the area is 2.0 °C, with 1444°days (>5 °C) and 92 frost free days, normally from early June to early September. The highest daily maximum temperatures are in July and the coldest are in January. Mean annual precipitation is 827 mm (545 mm in rainfall, 282 cm in snowfall) with September being the wettest month and February being the driest (Environment Canada, 2014). The soils in this area formed over rapidly-draining, coarse textured, glacial–fluvial deposits and are classified as Dystric Brunisols (Soil Classification Working Group, 1998). Details on pre- harvest soil conditions can be found in Kwiaton et al. (2014), and summarized in Table 1 and information on soil nutrients removed during the harvest treatments are summarized in Table 2.

The site was a 40-year old second growth jack pine stand that developed after clearcut harvesting in the 1960s. Following the harvest the site was prepared using Young's teeth (i.e., tooth blading) to expose mineral soil by uprooting trees and windrowing woody debris (Sutton and Weldon, 1995) and then hand seeded. It was subsequently harvested during December 2010 and January 2011 in preparation for the ILBHE. The site with the exception of the unharvested control block received a full tree biomass harvest [FT_{bio}], where the entire tree (including traditionally non-merchantable trees) was removed from the stump up. Site preparation (power disk trenching) was done in September 2011 followed by planting of jack pine in May of 2012. Jack pine were planted at 1.8 m spacing along the side of the trenches in the exposed mineral soil and at 2.1 m spacing between the trenches. Details related to the study site and other treatment applications in the main biomass trial can be found in Kwiaton et al. (2014).

The focus of this experiment was the slash manipulation study, installed on three adjacent flat rows between trench and spoil piles (i.e., turned over debris) created from the site preparation within the ILBHE FT_{bio} matrix ~30 m west of the control block (Fig. 2). The experimental design of the slash study was a complete randomized block design with three replicate blocks, each containing one plot (~5 m × 1.4 m) for each of the five treatments. While the small size of the plots allowed us to examine more (and higher) levels of loading in replicated blocks, it is recognized that there may be edge effects that wouldn't occur if the treatment replicates had been spread over a larger area.

The five treatments of slash loadings included bladed (FT_{bio}, stumping and removal of the forest floor), 0 Mg ha^{-1} (forest floor only, with any surface slash from FT harvest removed), 15, 30 and 60 Mg ha^{-1} of dry mass slash (Fig. 3). The treatments were deliberately ordered by applying the mass of forest floor (rounded to 40 Mg ha^{-1}) thus treatment levels were (with italics indicating the treatment name): 0 Mg ha^{-1} (*bladed* without forest floor), 40 (40 Mg ha^{-1} of forest floor only with *0 Mg* ha^{-1} slash), 55 (40 Mg ha^{-1} forest floor plus *15 Mg* ha^{-1} slash), 70 (40 Mg ha^{-1} forest floor plus *30 Mg* ha^{-1} slash), and 100 (40 Mg ha^{-1} forest floor plus *60 Mg* ha^{-1} slash).

The slash manipulation experiment increased the resolution of the slash loadings within and beyond those of the main treatments of the ILBHE. The highest slash manipulation loading (60 Mg ha^{-1}) is higher than the SO treatment (41 Mg ha^{-1}). The slash manipulation loadings of 15 and 30 Mg ha^{-1} are intermediate between the slash retention of the FT_{bio} (10 Mg ha^{-1} new residue) and SO (41 Mg ha^{-1} new residue) treatments, and the 0 Mg ha^{-1} is intermediate between the bladed and FT_{bio}. Many guidelines recommend leaving one-third of the biomass from pre-harvest live crown trees >10 cm as residue on the ground. For the ILBHE, the average pre-harvest live crown trees >10 cm (foliar + branches, i.e., the potential residue, so does not including stem wood or stem bark) was 26 Mg ha^{-1}, thus the one-third recommendation would be ~9 Mg ha^{-1} for this site. This is slightly less than what was left on the FT_{bio} treatment, even though attempts were made to clear any extra

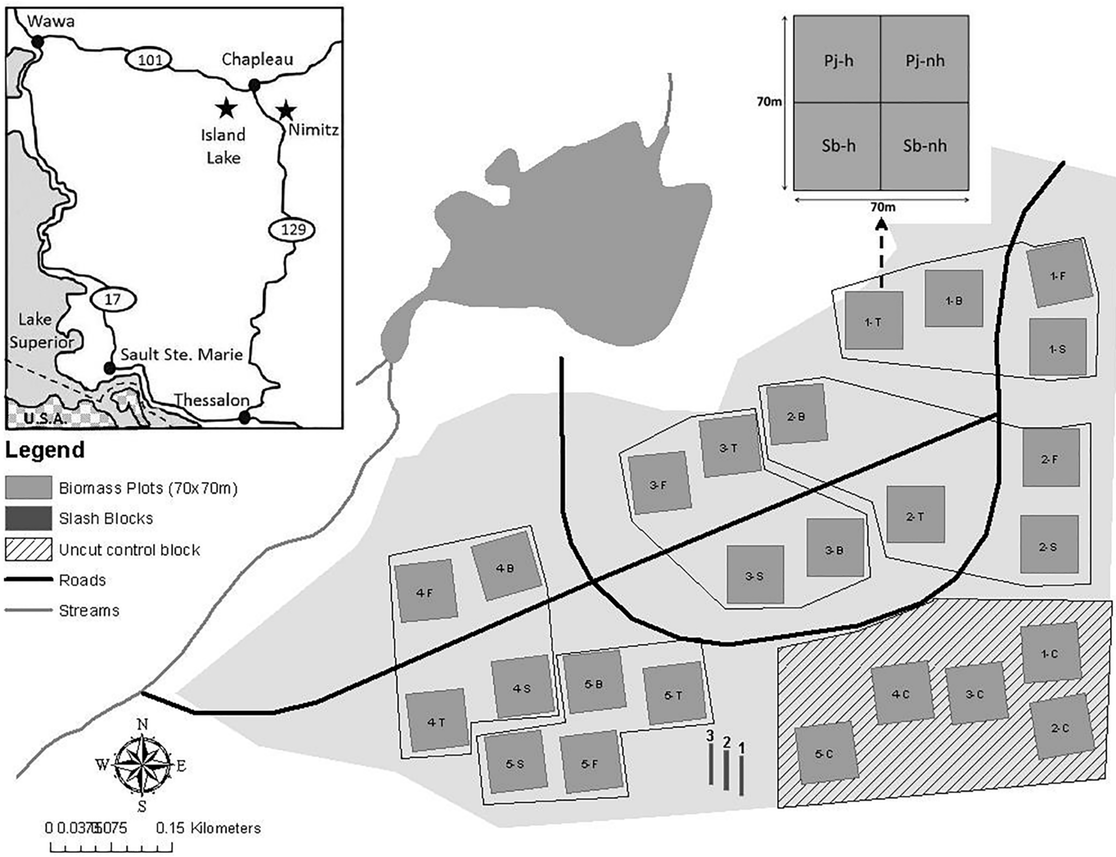

Fig. 1. Location of the Island Lake Biomass Harvest Experiment. The rows labelled 1, 2 and 3, situated just west of the uncut control block were the location of the slash manipulation study.

Table 1
Pre-harvest soil conditions at the Island Lake Biomass Harvest Experiment.

Soil horizon	Horizon depth (cm)	Coarse fragments (%)	Bulk density ($g \cdot cm^3$)	pH H_20	Horizon mass ($Mg \cdot ha^{-1}$)	Texture % Sand	% Silt	% Clay	Total C ($g \cdot kg^{-1}$)	Total N ($g \cdot kg^{-1}$)	Extr P (ppm)	Exch K ($cmol_c \cdot kg^{-1}$)	Exch Ca ($cmol_c \cdot kg^{-1}$)	Exch Mg ($cmol_c \cdot kg^{-1}$)
L	3.4			4.25	9.1				479.0	9.79	268.2	6.54	15.33	5.74
F	3.6			3.71	24.7				447.8	12.43	218.0	1.71	11.92	2.49
H/Ah	2.5	0.1	0.45	3.75	112.5				78.5	3.00	13.9	0.26	2.32	0.39
Ae	3.6	0.7	0.99	4.00	363.3	65.2	27.9	6.9	13.6	0.60	7.5	0.08	0.35	0.09
Bm_1	11.5	1.5	1.13	4.98	1282.2	57.3	32.9	9.8	20.4	1.02	6.1	0.04	0.22	0.05
Bm_2	14.5	3.9	1.30	5.24	1813.7	75.2	18.1	6.7	6.6	0.36	16.9	0.02	0.10	0.03
C	35.7	13.0	1.38	5.30	4053.7	92.1	2.9	5.0	1.9	0.09	43.7	0.00	0.04	0.02
IIC	20.4	29.0	1.13	5.65	1637.9	91.4	2.8	5.9	0.6	0.04	26.2	0.01	0.08	0.02
IIIC	14.2	1.0	1.34	5.70	1890.3	90.6	1.3	8.1	0.30	0.03	19.7	0.01	0.07	0.02

Table 2
Carbon and nutrient removal for biomass removal treatments (SO = stem only, FT_{bio} = full-tree biomass, and B = bladed).

	Nutrients removed ($kg\ ha^{-1}$, except C = $Mg\ ha^{-1}$)					
Treatment	C	N	P	K	Ca	Mg
SO	30.5	138.3	9.9	42.6	51.9	14.6
FT_{bio}	54.6	243.2	18	70.8	117.2	26.8
B	108.5	1119.1	20.6	137.6	296.6	54.1

residue from the FT_{bio} treatment.

2.2. Application of treatments and slash chemistry

The slash experiment did not start until 2016, almost five years (four growing seasons) after the initial harvest, site preparation and planting. The blading treatment for the experiment was applied in May 2016 and involved removing the entire forest floor layer. The 0 $Mg\ ha^{-1}$ treatment involved removing any excess residue from the plot. Given the time delay between the harvesting and site preparation and the initiation of the experiment there were minor amounts of vegetation (<50 cm height, primarily blueberry and sedges) on the 0 $Mg\ ha^{-1}$ treatment (see Fig. 3). The 15, 30 and 60 $Mg\ ha^{-1}$ loads of slash covered any existing vegetation on these plots. It is recognized that the delay in the initiation of the slash manipulation may cause some artefacts in the data compared to if the experiment had been done immediately after the site preparation, and although they are expected to be small, should be acknowledged.

The fresh slash applied to the 15, 30 and 60 $Mg\ ha^{-1}$ treatments were applied in June 2016. The slash used for the application was collected from live trees from an adjacent uncut area. Representative top and

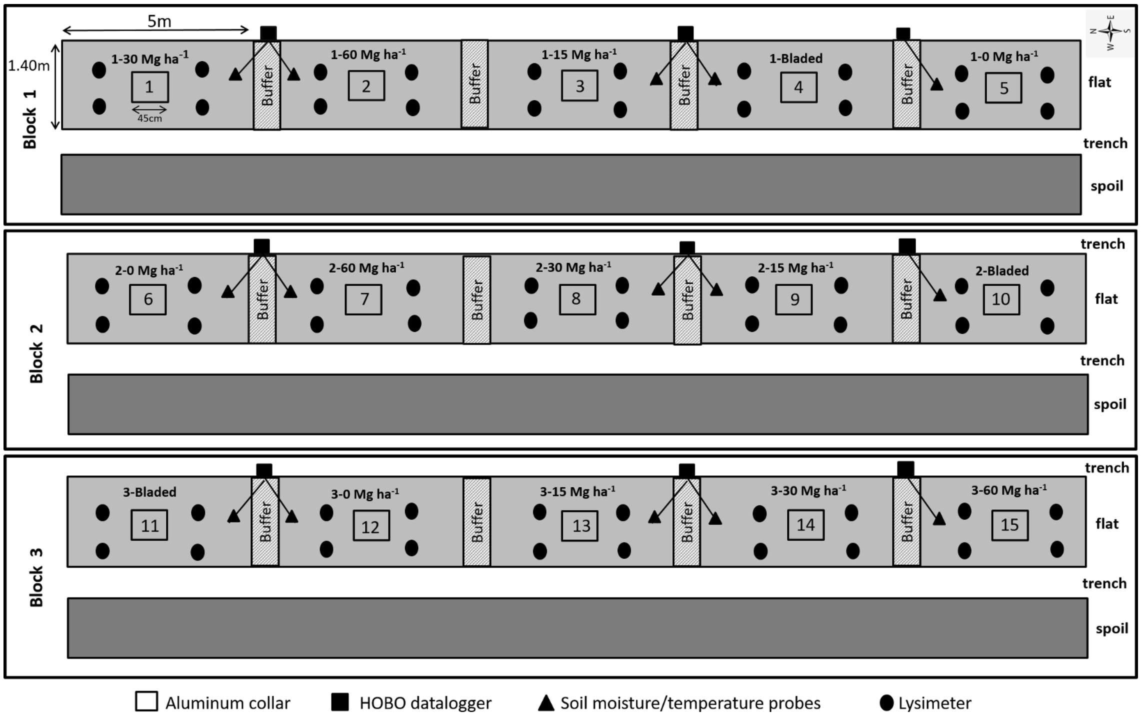

Fig. 2. Experimental design of the slash manipulation experiment. Buffer areas between treatments within each block were 0.5 m and distance between rows (i.e., flat areas) were 2.5 m, with area between rows occupied by trenches and spoil (i.e. debris) created as a part of the power disc trenching site preparation.

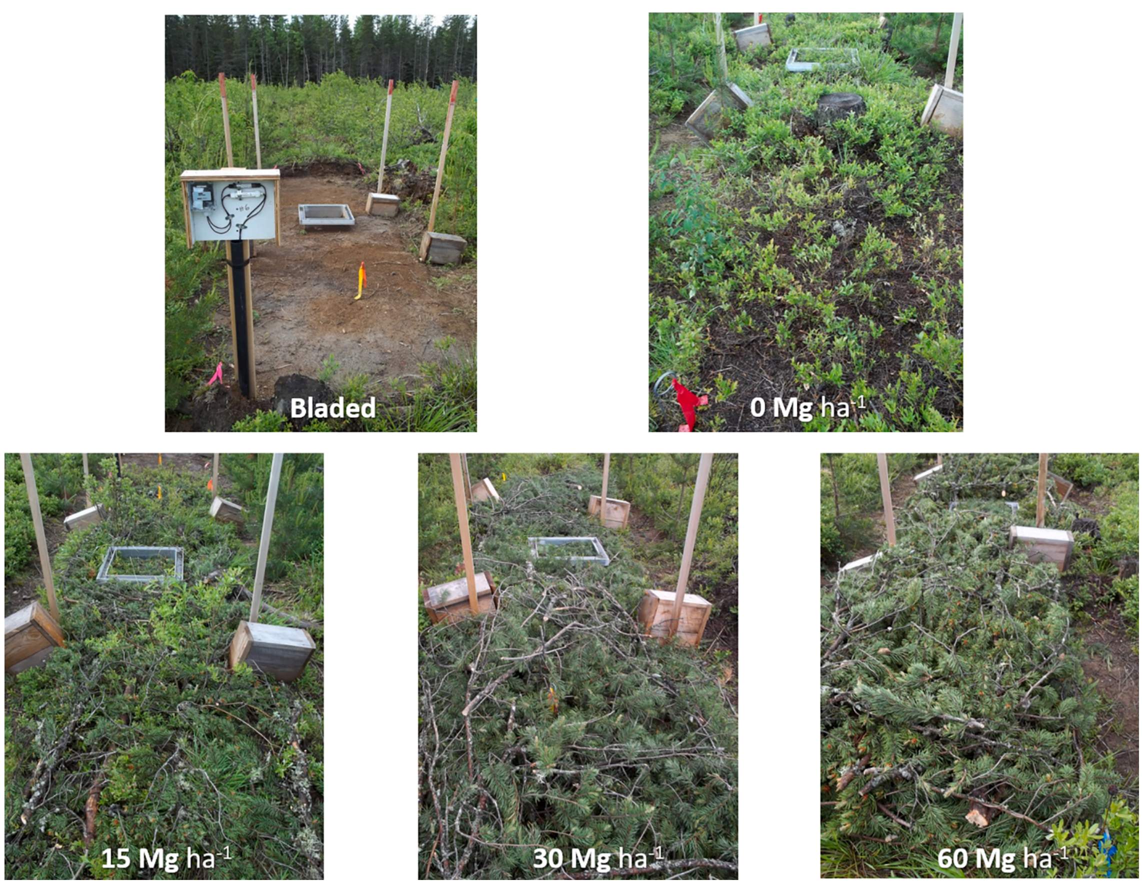

Fig. 3. Photos showing the slash loading on the different treatments.

bottom branches <5 cm in diameter were used to ensure uniform application on a small area. One upper and one lower branch was collected from each tree for separate chemical analyses. A wet weight of each sample was recorded as well as the plot that each tree was applied to. The weight of slash applied was determined using specific plot area and the given treatment for each plot, correcting for the amount of moisture in the fresh slash (48%). Slash was applied to the treatments in late June 2016. Of the tree components included in the slash (needle, cone, twig and branch), twigs made up the highest proportion of the slash mass, followed by needle, branch and cone with lowest percentage (Table 3). This is the same material and similar composition (i.e., % needles, twigs, branch) that was left in the SO treatment at the ILBHE (Kwiaton et al., 2014).

Samples of the individual components (needles, cones, twigs [0–1.99 cm diameter], branches [2–5 cm diameter]) from each of the live trees were taken. The components were dried, weighed, ground and then analyzed at the Soil and Plant Laboratory at the Great Lakes Forestry Centre, Canadian Forest Service, Sault Ste. Marie, Ontario, Canada. Total C and N concentrations were determined using a NCS combustion analyzer (Vario EL III, CHNOS Elemental Analyzer, Elementar Americas Inc. Mt. Laurel, NJ.). Elemental concentrations of Ca, Mg, K and P were determined with an inductively coupled plasma mass spectrometer (ICP-MS) (Agilent 7700X, Agilent Technologies, Santa Clara, CA) following high temperature microwave acid digestion (EPA standard method 3052). The chemistry of the slash by different components are presented in Table 4, and elemental load by plot in Table 5.

2.3. Soil environment

Soil temperature and moisture were monitored by HOBO USB micro station data loggers with EC5 soil moisture smart sensors and S-TMB-M006 12-Bit temperature smart sensors installed at 10 cm depths in May 2016, to reflect conditions within biologically active rooting zone of the soil. Data was read every 2 min and then averaged and recorded every hour continuously from May to October with monthly downloads. All 15 plots in the study were equipped with one soil temperature probe and one soil moisture probe with two adjacent plots sharing a HOBO data logger. No calibration was done for the moisture sensors and data are reported fractional water content.

2.4. Soil solution

Four porous cup tension lysimeters were used to collect soil solution in each plot (Fig. 2). Lysimeters (60 cm in length) were installed at a 30° angle to allow the porous clay sampling point to sit approximately 10 cm below the soil surface with the sampling tube access outside of the plot area. The holes were bored using a soil auger and a 30° wooden angled jig to maintain consistency across plots. Lysimeters were constructed with 2 bar standard ceramic cups with 1.3 μm pore size (Soil Moisture Equipment Corp., Santa Barbara, California). Prior to installation the lysimeters were acid washed with 1 M HCl and then rinsed repeatedly with deionized water. Rinsing was complete when the pH, conductivity, and base cation concentrations of solution passing through each lysimeter had reached the value of the deionized water. Lysimeters were installed in August 2015, were sampled three times with the solutions being discarded (Soil Moisture Equipment Corp., Santa Barbara, California) and allowed to equilibrate prior to the initiation of sampling during the snowmelt period in April 2016. Lysimeters were sampled from 2016 to 2018, monthly from May to November, with weekly sampling during the snowmelt period. Lysimeters were evacuated to 50 kPa and left to accumulate solution for the subsequent sampling and were largely still under suction when visited for the next sampling. Soil solution samples were bulked between the four lysimeters in each plot and refrigerated at 4 °C until processing and analysis. All samples were filtered through a coarse mesh filter (Fisher quantitative Q8 filter paper) with an aliquot passed through a 0.45 μm filter paper prior to nutrient analysis. Samples were analyzed at the Water Chemistry Laboratory at the Great Lakes Forestry Centre, Canadian Forest Service, Sault Ste. Marie, Ontario, Canada for pH, major ions and nutrients. The pH was

Table 3
Percentage of components making up slash loads by component (needle, twig, stem and cone) for each treatment (average of three replicates).

	Percentage			
Treatment	Needles	Twigs	Branch	Cones
15 Mg ha^{-1}	28	46	19	7
30 Mg ha^{-1}	27	51	11	10
60 Mg ha^{-1}	27	44	21	8

Table 4
Slash nutrient concentration by component (needle, twig, stem and cone) in lower and upper tree locations.

Location	Component	C (%)	N (%)	Ca (ppm)	K (ppm)	Mg (ppm)	P (ppm)
Lower	Branches	51	0.3	2813	718	369	206
Upper	Branches	51	0.3	1964	1121	426	307
Lower	Cones	52	0.5	656	703	298	426
Upper	Cones	53	0.5	472	1300	410	621
Lower	Needles	52	1.1	2642	2956	604	932
Upper	Needles	52	1.2	2238	3056	610	948
Lower	Twigs	52	0.4	2929	1440	503	385
Upper	Twigs	52	0.5	1943	2283	586	538

Table 5
Load of carbon, nitrogen, calcium, potassium, magnesium and phosphorus (kg ha^{-1} except for carbon in Mg ha^{-1}) in each treatment (average of three replicates).

	C (Mg ha^{-1})				
Treatment	Needles	Twigs	Branch	Cones	Total
15 Mg ha^{-1}	2	4	2	1	8
30 Mg ha^{-1}	4	8	2	2	16
60 Mg ha^{-1}	9	15	7	3	33
	N (kg ha^{-1})				
Treatment	Needles	Twigs	Branch	Cones	Total
15 Mg ha^{-1}	49	31	8	5	93
30 Mg ha^{-1}	96	70	9	10	185
60 Mg ha^{-1}	202	127	38	32	400
	Ca (kg ha^{-1})				
Treatment	Needles	Twigs	Branch	Cones	Total
15 Mg ha^{-1}	10	18	7	1	36
30 Mg ha^{-1}	20	43	9	1	73
60 Mg ha^{-1}	41	65	29	3	137
	K (kg ha^{-1})				
Treatment	Needles	Twigs	Branch	Cones	Total
15 Mg ha^{-1}	13	13	2	1	29
30 Mg ha^{-1}	27	28	3	2	60
60 Mg ha^{-1}	50	51	12	5	118
	Mg (kg ha^{-1})				
Treatment	Needles	Twigs	Branch	Cones	Total
15 Mg ha^{-1}	3	4	1	0	9
30 Mg ha^{-1}	6	9	1	1	17
60 Mg ha^{-1}	10	15	5	2	32
	P (kg ha^{-1})				
Treatment	Needles	Twigs	Branch	Cones	Total
15 Mg ha^{-1}	4	3	1	1	9
30 Mg ha^{-1}	8	7	1	1	17
60 Mg ha^{-1}	16	13	3	3	35

measured using a Man-Tech PC-Titrate (Mantech, Guelph, ON). Nitrate (NO_3^--N), ammonium (NH_4^+-N), total nitrogen (TN), and dissolved organic carbon (DOC) were measured with a Technicon Autoanalyser II (SEAL Analytical Inc., Mequon, WI) by the cadmium reduction, sodium nitroprusside, autoclave digestion, and potassium persulfate methods, respectively. Base cations were analyzed by an Agilent 7700X Inductively Coupled Plasma Mass Spectrometer (ICP-MS) (Agilent Technologies, Santa Clara, CA).

2.5. Soil respiration and net ecosystem Exchange

Rs and NEE were measured from July 2016 to October 2019 using the static chamber method (Livingston and Hutchinson, 1995). Measurements were made each time from a permanent square aluminum collar (0.21 m^2 measurement area) that was installed in August 2015 to allow equilibration before measurements commenced in July 2016. The measurements were obtained by placing an acrylic flux chamber (49.5 $\times$ 49.5 $\times$ 40 cm = 90.2 L volume) in a water-filled channel on the top of collars to create an air tight seal. The chambers were instrumented with a Vaisala CARBOCAP© CO_2 Probe GMP343 (Vaisala, Helsinki, Finland) attached to an infrared gas analyzer (IRGA) and a Vaisala HUMICAP© HM70 connected to a handheld Vaisala MI70 controller for logging. The chambers were also equipped with a small fan installed at the top to circulate the air within the chamber without disturbing the air–soil boundary layer. This system measured CO_2 concentrations, chamber humidity (50%), oxygen concentration (20.95%), pressure (101.3 kPa) and temperature. Soil respiration was measured monthly from May to October using a darkened chamber to capture bulk respiration of heterotrophic, root, and above ground biomass respiration, while NEE was measured monthly from June to September (growing season) using a clear chamber to measure photosynthesis minus respiration. All chamber measurements were made between 1000 h and 1400 h alongside manual soil moisture and soil temperature readings. Linear regression of the slope of CO_2 concentration within the chambers was used to calculate CO_2 fluxes for Rs and NEE. CO_2 fluxes were scaled according to the total volume determined by summing the volume of the chamber with the volume of each collar, adjusting for the topography of the surface within the collar, and corrected for chamber temperature and ambient pressure as described in Webster et al. (2016).

2.6. Statistical analyses

All variables were checked for normality and outliers using the Shapiro-Wilk W test. Soil temperature, soil moisture, Rs, NEE and pH met normality standards and were not transformed, whereas the various soil solution elements were log transformed prior to analysis to address normality. One outlier for each of Rs, NEE, log K, log NO_3^--N and log NH_4^+-N was removed before ANOVA. Mixed model repeated measures ANOVAs were then run on each variable using Restricted Maximum Likelihood in NCSS (ver 11.0.13). Three different variance structures were considered (Diagonal, Compound Symmetry and AR1), and the covariance model with the lowest AIC was chosen. Where statistically significant ($p < 0.05$, with few exception see Table 3) treatment or year effects occurred, responses were evaluated using linear and quadratic orthogonal polynomial contrasts. For log NO_3^--N, although there was a treatment effect, linear and quadratic contrasts were not significant, so an all-pairs comparison with a Bonferonni adjustment was performed. Where treatment $\times$ year interactions occurred, treatments were compared for individual years using one-way ANOVA, and when significant, were followed by similar treatment contrasts. For NEE in 2016, non-parametric ANOVA on ranks was preformed using the Kruskal-Wallis test to address heteroscedasticity. Exponential regressions of soil temperature to soil respiration were performed in Excel. R_{15} was calculated as the soil respiration at 15 °C using the fitted regression line equation. Linear regression of R_{15} as a function of slash loading was also performed in Excel.

3. Results

3.1. Physical environment

Soil temperature varied over the 4 years of the experiment with 2016 the warmest and 2019 the coldest (Table 6; Fig. 4). Among the treatments (Fig. 5A) the bladed treatment was always the warmest, except in October when it was the coldest (data not shown). Average soil temperatures (across all years and months) decreased in a linear or concave up manner with increasing slash loads (Table 6; Fig. 5A).

Soil moisture varied over the 4 years of the experiment with 2018 and 2019 drier than 2016 and 2017 (Table 6; Fig. 4). Among the treatments (Table 6; Fig. 5B) there was no significant difference in soil moisture. However, the 0 Mg ha^{-1} treatment typically had the lowest moisture, except in May when 60 Mg ha^{-1} treatment was the driest (data not shown).

3.2. Soil solution chemistry

Soil solution chemistry seemed to reflect the leaching of the slash components. Higher concentrations of solutes were generally observed at the highest slash loadings, with 0, 15 and 30 Mg ha^{-1} loadings having moderate concentrations and bladed having lowest concentrations (or similar to 0, 15 and 30 Mg ha^{-1} loadings) for TOC and K and concave up for Na (Table 6; Fig. 6). Higher concentrations of TOC and K was particularly noticeable in 60 Mg ha^{-1} treatment. The reverse pattern (higher in bladed and decreasing with increasing slash loading) occurred for pH (2017) and NO_3^--N. Spatial patterns were noisy for Ca, Mg, TN and NH_4^+-N. In terms of temporal changes, concentrations generally decreased over time for Ca, Mg and Na in the bladed, 0, 15 and 30 Mg ha^{-1} treatment, but typically increased in the 60 Mg ha^{-1} treatment (Table 6; Fig. 6). A notable exception to that trend are concentrations of N species. Concentrations of TN, NO_3^--N, and NH_4^+-N were higher in 2017 and 2018 than in 2016 (Table 6; Fig. 6). It is particularly notable that there was a strong NO_3^--N pulse in spring 2018, particularly in the bladed and 0 Mg ha^{-1} treatments (Fig. 7).

3.3. Rs and NEE

Overall Rs was highest from the 60 Mg ha^{-1} treatment, with average annual emissions decreasing in a linear or concave down fashion to the 0 Mg ha^{-1} slash loading and lowest in the bladed treatment (Table 6; Fig. 8A). Rs was highest in 2019 and lowest in 2018 for the 0, 15 and 30 Mg ha^{-1} treatments (Fig. 8A). For the bladed treatment the highest CO_2 emission occurred in 2019 and lowest in 2016, while for the 60 Mg ha^{-1} treatment the highest CO_2 emission was in 2016 and lowest in 2018 (Fig. 8A).

Average NEE decreased (became a stronger sink) from the 60 Mg ha^{-1} treatment in a concave up fashion to the 0 Mg ha^{-1} slash loading, with bladed near neutral (small source or sink) (Table 7; Fig. 8B). The 15, 30 and 60 Mg ha^{-1} treatments were net sources in 2016. The 60 Mg ha^{-1} treatment remained a source in 2017, and while it was a sink in 2018, it again became a small source in 2019. The 0, 15, and 30 Mg ha^{-1} treatments were sinks in the remaining years (except 15 Mg ha^{-1} treatment in 2017 which was near neutral) (Fig. 8B). The bladed treatment was near neutral (small source or sink) in all years (Fig. 8B). Understorey vegetation was a minimal component of all treatments, except for the 0 Mg ha^{-1} treatment which had some low growing (<50 cm height) plants (e.g., blueberry and sedges), with decreasing amounts with increasing slash loads. No quantitative measurement of vegetation biomass made, but qualitative observations of increasing amounts of blueberry and sedge is consistent with the NEE trend.

3.4. Drivers of Rs and NEE

Soil temperature was a strong driver of soil respiration explaining

Table 6
Results of ANOVA tests on soil environment and processes showing p values and trend direction. A positive linear trend is an increasing trend, and a negative linear trend is decreasing. A negative quadratic term is a parabola opening down (concave down) and a positive quadratic term is a parabola opening up (concave up).

	Treatment					Year				
Variable	Overall P	Linear trend	P	Quadratic trend	P	Overall P	Linear trend	P	Quadratic trend	P
Soil temperature	<0.001	–	<0.001	+	0.02	<0.001	+	<0.001		
Soil moisture						<0.001	+	<0.001	–	<0.001
LogTOC-2016										
LogTOC-2017	0.04	+	0.02							
LogTOC-2018[1]	0.06	+	0.01							
LogCa						0.03	–	0.03		
LogMg						0.03	–	0.01		
LogK-2016										
LogK-2017	0.04	+	0.005							
LogK-2018	0.03	+	0.005							
LogNa[1]	0.09			+	0.03	<0.001	–	<0.001		
LogNO_3^--N[2]	0.02					0.004	+	0.001		
LogNH_4^+-N						0.02	+	0.01		
LogTN						0.05	+	0.01	+	0.01
pH-2016										
pH – 2017[1]	0.06	–	0.01							
pH-2018										
Rs-2016	<0.001	+	<0.001							
Rs-2017	<0.001	+	<0.001	–	0.005					
Rs-2018	<0.001	+	<0.001	–	0.03					
Rs-2019	0.03	+	<0.001							
NEE-2016[3]	0.03	+	0.0005	+	0.02					
NEE-2017	0.004	+	0.01	+	0.01					
NEE-2018	0.04			+	0.01					
NEE-2019[1]	0.08			+	0.01					

[1] $P < 0.1$
[2] Linear and Quadratic contrasts not significant, All-pairs comparison ANOVA with Bonferonni adjustment used.
[3] ANOVA on ranks (Kruskall-Wallis test).

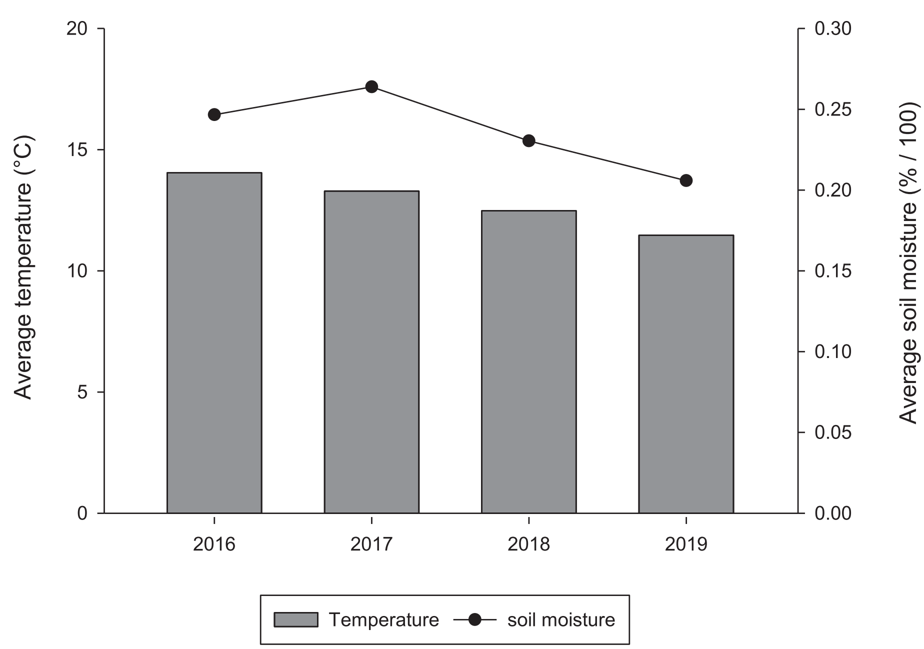

Fig. 4. Average soil temperature (°C) and soil moisture (%/100) across all treatments by year.

67–76% of the variation using an exponential relationship (Table 7). R_{15} was lowest in bladed and increased linearly from 0 to 60 Mg ha^{-1} slash loadings (Fig. 9). The R_{15} was not proportional to the increase in slash load such that a four fold increase in slash from 15 to 60 Mg ha^{-1} produced only a 1.5 times increase in R_{15}. While there was a quadratic response to moisture, the effect was not significant when included in a polynomial relationship with temperature (data not shown), reflecting collinearity with temperature response. Residuals from the temperature relationship did not consistently relate to any soil solution concentrations and thus not reported. In contrast to soil respiration, NEE did not show consistent relationships to any of the soil physical or chemical parameters measured.

4. Discussion

4.1. Physical environment

It was clear that the amount of slash left on the ground had a

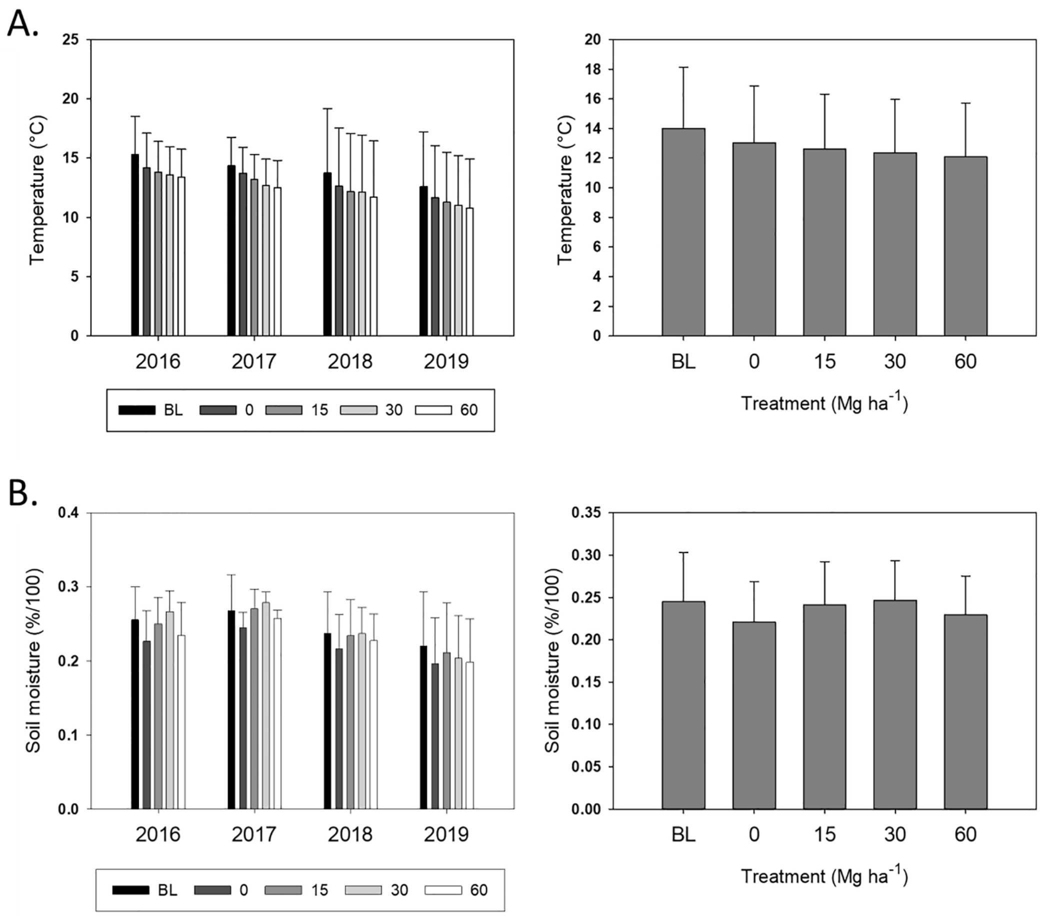

Fig. 5. Soil temperature (°C) in treatments in each year (left panel) and across all years (right panel) (A) soil moisture difference (%/100) in treatments in each year (left panel) and across all years (right panel) (B).

dramatic effect on the physical environment. The blading treatment was exposed to more extremes in temperature, having no insulated barrier from a forest floor or from slash. The forest floor only treatment (0 Mg ha^{-1} slash) showed warm and dry conditions likely due to drying and evapotranspiration in the forest floor. Intermediate levels of slash (15 and 30 Mg ha^{-1}) moderated both temperature and moisture conditions. The highest slash loading (60 Mg ha^{-1}) was cool, but also dry likely because of interception, follow by evaporation of precipitation (Trottier-Picard et al., 2014). These temperature observations are consistent with those in the literature, where logging debris has been shown to shade the soil surface, generally causing a reduction in soil temperature (Zabowski et al., 2000; Proe et al., 2001; Roberts et al., 2005; Devine and Harrington, 2007; Harrington et al., 2013; Trottier-Picard et al., 2014). Lieffers-Pritchard (2005) showed that daily mean soil temperatures during growing season were significantly lower under high levels of slash, resulting in shorter growing season length. Kranabetter and Chapman (1999) showed that temperatures were warmest in the bladed (during summer), moderate in WT and lowest in SO treatments. In contrast, Belleau et al. (2006) showed no change in temperature with higher amounts or slash. For soil moisture, our results are consistent with Ring et al. (2015) that showed water flux through logging residue decreased with an increasing amount of residue, a condition which persisted for 3 seasons. However, Trottier-Picard et al. (2014) found variability in moisture response over one year among five sites, with increases at one of the sites similar to that observed by Roberts et al. (2005), or no effect on soil volumetric water content, similar to that observed by Zabowski et al. (2000). Many site factors (e.g., evaporation, temperature, vegetation cover) likely contribute to the variability in response (Trottier-Picard et al., 2014).

4.2. Soil solution chemistry

Soil solution chemistry seemed to reflect the leaching of the slash components, as higher concentrations of solutes were observed at the highest slash loadings, with 0, 15 and 30 Mg ha^{-1} loadings having moderate concentrations and bladed having lowest concentrations or similar to 0, 15 and 30 Mg ha^{-1} loadings for the majority of solutes. This trend is particularly striking for DOC at 60 Mg ha^{-1}. Similarly, Hedwall et al. (2013) showed higher DOC in SO treatment compared to WT. This trend in solutes is generally consistent with that observed in the literature. Studies (usually comparing WT and SO harvest) have typically shown higher soil solution chemical concentrations with higher slash retention. This was a consistent trend with K^{+}, and often observed for other base cations (Ca^{2+}, Mg^{+} and Al^{3+}; e.g., (Staaf and Olsson, 1994; Titus et al., 1997; Bélanger et al., 2003; Belleau et al., 2006; Wang et al., 2010; Hedwall et al., 2013; Ring et al., 2015; Ring et al., 2016; Clarke et al., 2018). The nutrient increases with higher slash loads likely reflect mineralization, increased leaching and reduced plant uptake (Titus et al., 1997). It is suggested that higher base cation concentrations may benefit stands during the early stages of development (Bélanger et al., 2003).

Over the three years, cations and anions typically showed a decline in concentration in the low to moderate slash treatments, likely as a consequence of finer components of slash (needles, bark) falling to the ground and decomposing. Titus et al. (1997) observed at a moist birch site in Newfoundland that the elevated pore water concentrations didn't persist longer than three years. At the ILBHE site, however, conditions are more moisture-limited with variable inter-annual weather conditions (e.g., warmer and wetter conditions in second year and cooler and

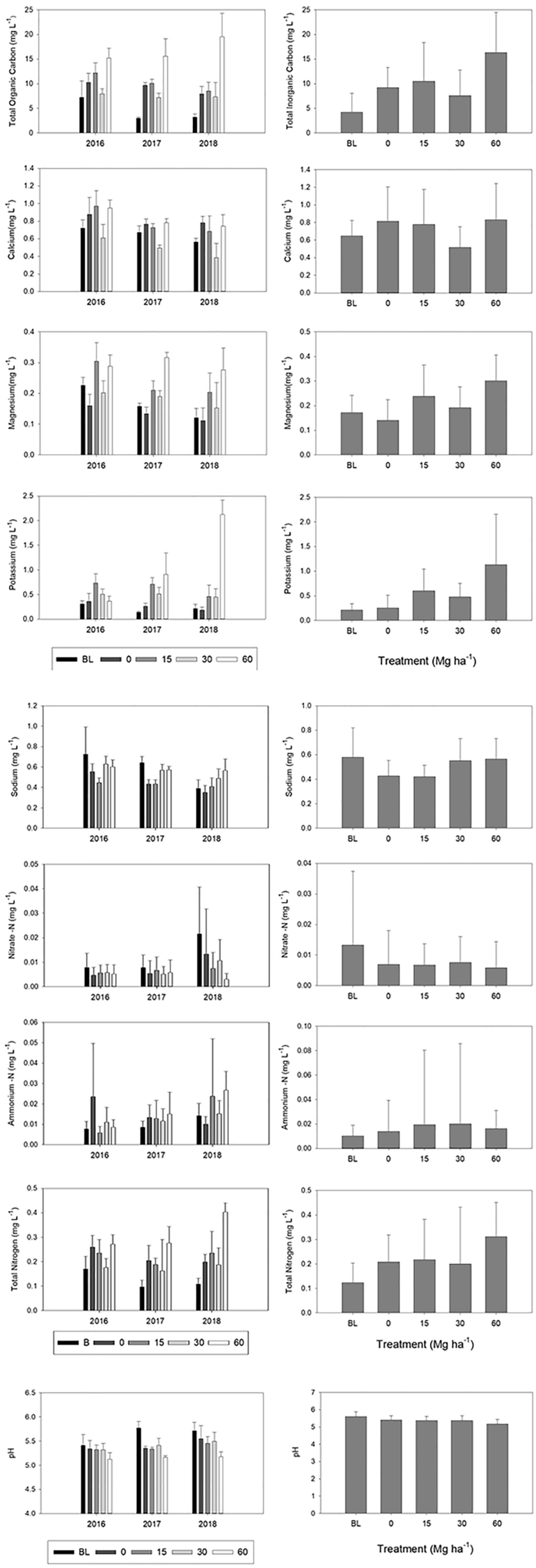

Fig. 6. Soil solution concentrations for selected solutes summarized by year (left panels) and average by treatment across all years (right panels).

drier in third year), thus it has been difficult to make clear inferences over the three years, given confounding factors at play (Trottier-Picard et al., 2014).

The patterns in nitrogen species showed that NO_3^--N was typically higher at bladed treatment compared to the other treatments. Concentrations of NO_3^--N rose in the spring of the third year, particularly in the bladed and 0 Mg ha^{-1} treatment. This is in contrast to Hendrickson et al. (1989), Staaf and Olsson (1994), Hedwall et al. (2013) and Ring et al. (2016) that showed increases in NO_3^--N with higher slash loads. NO_3^--N concentrations are influenced by environmental conditions (e.g., too dry or too wet may limit nitrification) and by uptake by new vegetation or advanced regeneration (Titus et al., 1997). However, less N leaching with SO compared to WT was also observed by Kļaviņš et al. (2019) which may be due to the N content of the residues and/or the mulching effect of residues on the underlying soil (Rosén and Lundmark-Thelin, 1987). In a litter decomposition experiment Symonds et al. (2013) showed immobilization of N in jack pine needles up to 4 years after litter was placed on the forest floor. NH_4^+-N showed general increases over time, particularly in the higher loadings (15, 30 and 60 Mg ha^{-1}), which is consistent with observations from Staaf and Olsson (1994) and Hedwall et al. (2013). Titus et al. (1997) also observed that SO harvesting on the rich birch site led to increased concentrations that persisted for 3 years. The complicated trajectories of nitrogen are consistent with N immobilization in the higher slash loadings (a "mulching effect") followed by increased N mineralization over time several year after harvesting (Hyvönen et al., 2000; Palviainen et al., 2004a,b; Hazlett et al., 2007; Kļaviņš et al., 2019). The pulse in NO_3^--N$^-$ in spring 2018 may also have been accentuated by warm and wetter conditions the previous year (2017). However, it should be noted that the slash experiment was initiated almost five years (four growing seasons) after the site preparation was done, so trends in treatments reflect the impact of slash additions, and not effects of harvesting (i.e., removal of trees).

The trend in pH showed a step function decline from BL to 0, 15 and 30 Mg ha^{-1} and 60 Mg ha^{-1} the lowest. This likely reflects increased acidity from presence of forest floor (0, 15, 30 Mg ha^{-1} treatments) as well as needle litter into soil water (60 Mg ha^{-1}). Titus et al. (1997) showed acidity increased after SO harvest, but the response was complicated by site nutrient richness. In contrast, Belleau et al. (2006) observed decreases in acidity in SO harvest treatments. These contrasting observations likely reflect differences in the chemistry of litter and slash, patterns of NO_3^--N and mobilization of base cations at the site (Titus et al., 1997).

4.3. Soil respiration and NEE

Soil respiration from the plots corresponded with increases in slash loadings, but the slope of the increase was disproportionally smaller than the amount of slash added. High rates of heterotrophic respiration require a source of labile organic matter, microbial decomposers and optimal environmental conditions. Twigs and needles made up a large component of the slash, with lower C:N than branches, which are easier to decompose. Siebers and Kruse (2019) showed that slash inputs led to increase in SOM, but this SOM was of lower thermal stability and did not contribute to general aggregate stability of the soil. Instead, these finer components were more easily broken down, leaching into soil water, and providing a labile substrate for respiration over the short term. Higher slash loadings provide a large source of labile material, consistent with the observed increase in DOC at high slash loadings in this experiment, however this material can take several years to make it into the soil as a substrate for microbial respiration. Furthermore, microbial activity is likely reduced under cooler conditions induced by high residue loads (Cassman and Munns, 1980). Sherman and Coleman (2020) summarized that studies on slash retention have shown inconsistent impacts on soil respiration results due to increased soil moisture, shading, and soil compaction (Hendrickson et al., 1989; Mattson and Swank, 1989; Slesak et al., 2010; Cheng et al., 2014; Kurth et al., 2014).

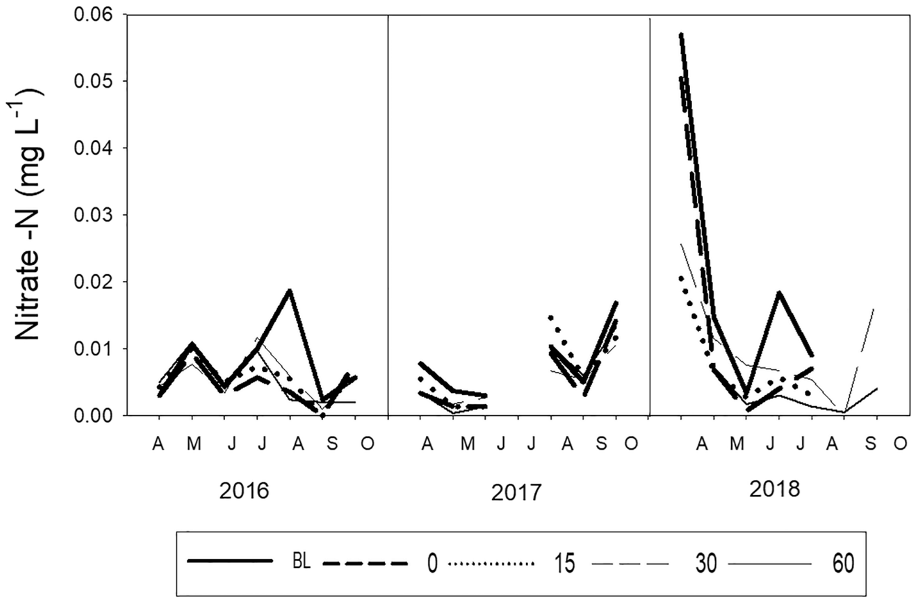

Fig. 7. Monthly NO_3^--N soil solution concentrations in each, highlighting high concentrations in the spring of 2018.

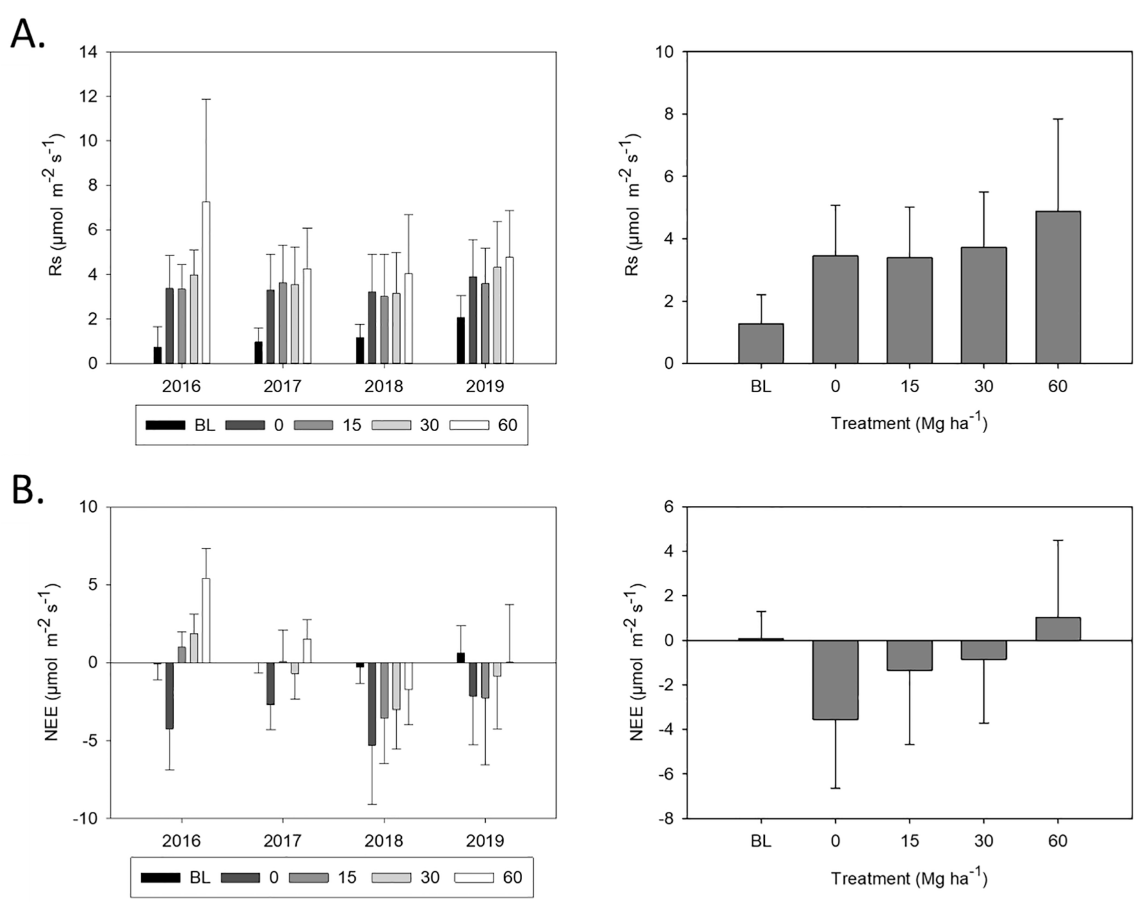

Fig. 8. Soil respiration (Rs; µmol m^{-2} s^{-1}), top, and Net Ecosystem Exchange (NEE; µmol m^{-2} s^{-1}), bottom, by year (left panels) and average by treatment across all years (right panels).

In a previous study from this site Webster et al. (2016) showed that respiration from SO (41 Mg ha^{-1}) and FT_{bio} (10 Mg ha^{-1}) treatments were roughly equivalent. Kurth et al. (2014) showed that the relative amount of biomass removed had a negligible effect on soil respiration in harvested areas, but treatment effects were probably obscured by heterogeneous slash configurations and rapid post-harvest regeneration of aspen in all of the treatments. Mattson and Swank (1989) showed there was no statistically significant difference in CO_2 efflux between the two types of residue treatments on clearcuts. However, Hendrickson et al. (1989) showed higher respiration from conventional harvest

Table 7
Regression equation to predict soil respiration from temperature and standardized soil respiration at 15 °C (R_{15}).

Treatment	Equation	R^2	R_{15}
Bladed	0.25 * EXP(0.09 * T)	0.19	1.0
0 Mg ha^{-1}	0.56 * EXP(0.13 * T)	0.67	3.8
15 Mg ha^{-1}	0.48 * EXP(0.14 * T)	0.76	4.1
30 Mg ha^{-1}	0.63 * EXP(0.13 * T)	0.73	4.6
60 Mg ha^{-1}	0.68 * EXP(0.15 * T)	0.76	6.1

(where tree branches and tops left on site) than WT in northern mixed forest, while Slesak et al. (2010) showed that high amounts (i.e., 80% coverage) of logging-debris retention reduce microbial respiration at these sites, although moderate amounts of debris had little effect or potentially a positive effect on microbial respiration.

Heterotrophic respiration by microbial communities breaking down soil organic matter in oxic conditions are primarily responsible for CO_2 emissions from forest soil. Smenderovac et al. (2017) in a study from the larger plots of biomass treatments at the ILBHE showed that microbial community function and structure was not influenced by intensification of clear-cut harvesting in the short term. Kersey (2020) also found little effect of management treatments at Pacific Northwest and Northern California LTSP on microbial activity indicators. Similarly, Sherman and Coleman (2020), showed biomass retention levels had no effect on exoenzyme activities. Instead, Sherman and Coleman (2020) showed that soil respiration and exoenzymes were driven by location, season, SOM, soil moisture content and soil temperature.

This study as well as a previous study (Webster et al., 2016) showed and that the presence of intact forest floor was the most important factor contributing to soil respiration. Removal of the forest floor has also been shown to reduce site productivity (Binkley et al., 2020). Kersey (2020) also noted the importance of importance of the forest floor layer in microbial activity in Pacific Northwest and Northern California Long-Term Soil Productivity (LTSP) sites. Similarly, Wilhelm et al. (2017), studying several LTSP sites, showed that removal of the forest floor had a strong impact on stress-tolerant taxa. This highlights the importance of the forest floor in shading and insulating underlying soil from temperature extremes. In this study 67–76% of the variation in soil respiration across all slash loading could be explained by temperature. This is comparable to 40 and 75% of the variation in bulk and microbial respiration explained by soil temperature in Slesak et al. (2010).

Bulk soil respiration also includes root respiration and while root respiration is near nil on bladed plots, it is also low on plots with high slash loads because of difficulties in establishing ground cover. While not measured directly, root respiration would only be an important component of in the 0 Mg ha^{-1} treatment where substantial ground cover existed, since there were no trees in the slash manipulation plots and likely minimal influence from smaller trees growing outside the plots. As such, NEE on plots with higher slash loadings were sources of CO_2 to the atmosphere because of higher rates of respiration and lower rates of photosynthesis. Photosynthetic rates will also be lower under cooler conditions (Lahti et al., 2002) imposed by higher slash loads. In addition, high amounts of slash are also a physical barrier to regeneration of understory vegetation, although this does not appear to be the case for species that form suckers (Frey et al., 2003; Belleau et al., 2006). However, at operational scales slash would not be consistently distributed, so the effect may not be as severe as observed in this experimental study.

5. Application and limitations

Many slash retention guidelines recommend leaving one-third of the biomass from pre-harvest live crown trees >10 cm as residue on the ground (Thiffault et al. 2015). For the ILBHE, the average pre-harvest live crown trees >10 cm (foliar + branches, i.e., the potential residue, so does not including stem wood or stem bark) was 26 Mg ha^{-1} (Kwiaton et al., 2014), thus the one-third recommendation would be ~9 Mg ha^{-1} for this site. This is slightly less than what was left on the FT_{bio} treatment within the ILBHE treatments and ~6 Mg ha^{-1} less than the 15 Mg ha^{-1} treatment in the slash manipulation experiment. Compared to the 0 Mg ha^{-1} slash loading, the 15–30 Mg ha^{-1} produced a moderated temperature and moisture environment, and moderate soil solution

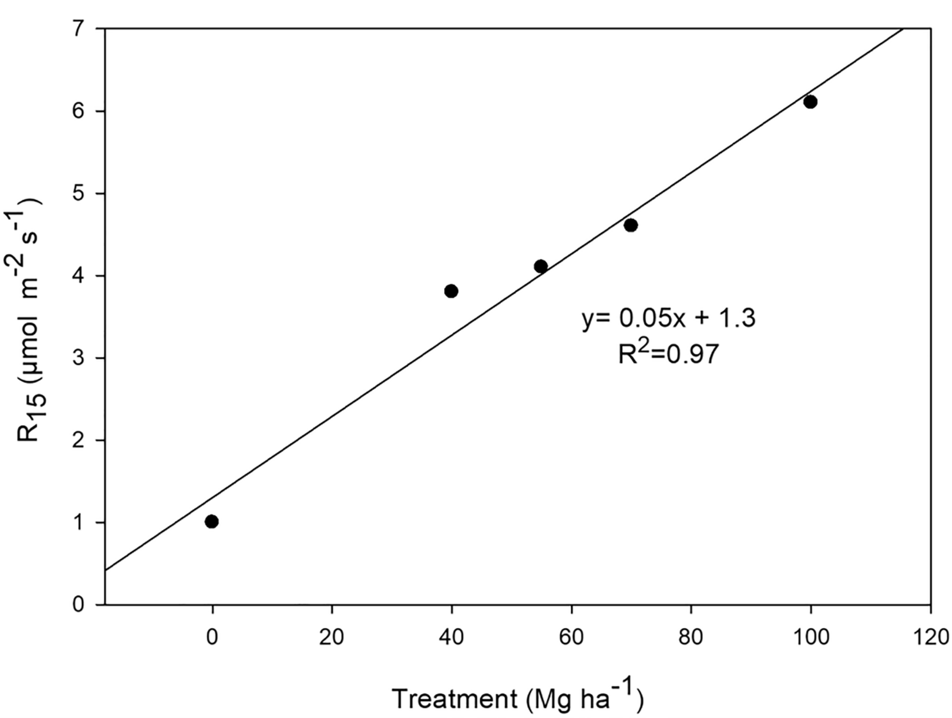

Fig. 9. Soil respiration normalized to 15 °C (R_{15}; μmol m^{-2} s^{-1}) as a function of slash loading (including forest floor mass of 40 Mg ha^{-1}, thus bladed = 0 Mg ha^{-1} and 0, 15, 30 and 60 Mg ha^{-1} slash loadings represented by 40, 55, 70 and 100 Mg ha^{-1}).

concentrations of nutrients. The most important factor was the retention of the forest floor, which creates warmer conditions, allows trees and understory vegetation to establish (creating a carbon sink) and provides sufficient mineralization to sustain soil nutrition over the short term. The 15–30 Mg ha^{-1} slash loading also produced moderate amounts of soil respiration and became a carbon sink after one year. The ecological role of logging residues on the microenvironment of plants appeared to be somewhat site-dependent (Trottier-Picard et al., 2014). Therefore, a one-third (~9–10 Mg ha^{-1}) recommendation is likely at the lower end of the amount of harvesting residues that should be retained on site. A one-third plus (i.e., one-third to two-third, i.e., 15–30 Mg ha^{-1}) approach may be useful when considering longer term benefits, particularly in nutrient poor soils which could not be assessed given the length of the study, or benefits to biodiversity which were not assessed. As noted by Hyvönen et al. (2012), long-term influences will take many more years to determine and re-measurements at this site are planned on a 5-year interval. Similarly, where there is inter-site heterogeneity in conditions, there may be benefit to distributing residue to areas prone to nutrient losses.

6. Conclusion

Retention of slash on site following harvesting performs many different ecosystem functions. One of the most important functions is ensuring a source of nutrients, which upon decomposition, can promote growth of regenerating forest. Over the short term (5 years), it is clear that the presence of forest floor is the dominant structural attribute that promotes ideal physical conditions (soil moisture and temperature) for decomposition (as measured by soil respiration). Although additional slash increased soil respiration it was not proportional to the load added and created a cooler, drier environment. Thus, over the short term the physical driver of soil temperature is more important to respiration and recycling of nutrients than either chemical or biological drivers. Therefore, using the heuristic of one-third residue retention seems appropriate over the short-term, but a one-third plus may be appropriate on particularly poor sites, particularly over long-term. Longer term studies are needed to continue to evaluate these recommendations on soil physical, chemical and biological processes and the overall ecosystem services that the forest provides.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: 'Kara Webster reports financial support was provided by Natural Resources Canada – Canadian Forest Service. Kara Webster reports a relationship with Natural Resources Canada – Canadian Forest Service that includes: employment'.

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