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ORIGINAL RESEARCH

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# Short-term growth response of jack pine and spruce spp. to wood ash amendment across Canada

Caroline E. Emilson[1] | Nicolas Bélanger[2] | Suzanne Brais[3] | Colin E. Chisholm[4] | Amanda Diochon[5] | Ruth Joseph[5] | John Markham[6] | Dave Morris[7] | Ken Van Rees[8] | Michael Rutherford[9] | Lisa A. Venier[1] | Paul W. Hazlett[1]

[1]Great Lakes Forestry Centre, Natural Resources Canada, Sault Ste. Marie, ON, Canada

[2]Département Science et Technologie, Université TÉLUQ, Montréal, QC, Canada

[3]Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, QC, Canada

[4]University of Northern British Columbia, Aleza Lake Research Forest, Prince George, BC, Canada

[5]Department of Geology, Lakehead University, Thunder Bay, ON, Canada

[6]Department of Biological Sciences, University of Manitoba, Winnipeg, MB, Canada

[7]Centre for Northern Forest Ecosystem Research, Ontario Ministry of Natural Resources and Forestry, Thunder Bay, ON, Canada

[8]Department of Soil Science, University of Saskatchewan, Saskatoon, SK, Canada

[9]University of Northern British Columbia, Prince George, BC, Canada

**Correspondence**
Caroline E. Emilson, Great Lakes Forestry Centre, Natural Resources Canada, Sault Ste. Marie, ON, Canada.
Email: caroline.emilson@canada.ca

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**Abstract**

Wood ash amendment to forest soils contributes to the sustainability of the growing bioenergy industry, not only through decreased wood ash waste disposal in landfills but also by increasing soil/site productivity and tree growth. However, tree growth studies to date have reported variable responses to wood ash, highlighting the need to identify proper application rates under various soil/site conditions to maximize their benefits. We explored the influence of tree species, wood ash nutrient application rates, time since application, stand development stage, and initial (i.e., before wood ash application) soil pH and N on short-term tree growth response to wood ash amendment across eight unique study sites spanning five Canadian Provinces. Jack pine (*Pinus banksiana* Lamb) had the most positive response to wood ash amendment compared to white (*Picea glauca* Moench), hybrid (*Picea engelmannii* x *glauca* Parry), and black spruce (*Picea mariana* Miller), where increasing nutrient application rates increased height growth response. In comparison, black spruce had the most negative response to wood ash amendment, where increasing nutrient application rates slightly decreased height growth response. Site as a random effect explained additional variation, highlighting the importance of other unidentified site characteristics. By examining trends in short-term growth response across multiple studies with variable site characteristics, we found growth response differed by tree species and nutrient application rates, and that jack pine is a promising candidate for wood ash amendment. These results contribute to our knowledge of optimal wood ash amendment practices and environmentally sustainable bioenergy production.

**KEYWORDS**

bioenergy, forest amendment, sustainability, tree growth, waste reduction, wood ash

# 1 | INTRODUCTION

Wood ash amendment to forest soils is a common practice in some European countries and is of growing interest in Canada where bioenergy and associated wood ash waste production is on the rise (Hannam et al., 2018). When wood ash is applied to forest soils, it has the potential to contribute to the sustainability of the growing bioenergy industry, not only through decreased waste disposal in landfills but also by increasing soil/site productivity and tree growth (Augusto, Bakker, & Meredieu, 2008; Reid & Watmough, 2014). However, tree growth studies have reported variable responses to wood ash amendment, suggesting that the benefits of wood ash amendment depend on intrinsic soil/site conditions.

Enhanced tree growth following wood ash amendment has been most consistently documented on sites characterized by organic matter-rich soils, such as peatlands, where the alkalinity of wood ash raises the soil pH and increases mineralization of soil organic matter (Huotari, Tillman-Sutela, Moilanen, & Laiho, 2015). In contrast, results on upland forests have been less consistent. For example, individual wood ash amendment studies of coniferous species on mineral soils have reported positive (Hallenbarter, Landolt, Bucher, & Schutz, 2002; Omil, Piñeiro, & Merino, 2013; Saarsalmi, Smolander, Kukkola, & Arola, 2010; Saarsalmi, Smolander, Moilanen, & Kukkola, 2014; Solla-Gullón, Santalla, Pérez-Cruzado, Merino, & Rodríguez-Soalleiro, 2008; Solla-Gullón, Santalla, Rodríguez-Soalleiro, & Merino, 2006), negative (Bieser & Thomas, 2019; Brais, Bélanger, & Guillemette, 2015; Prescott & Brown, 1998; Shepard, 1997; Staples & Van Rees, 2001), and neutral (Jacobson, Lundström, Nordlund, Sikström, & Pettersson, 2014; Mandre, Pärn, & Ots, 2006; Saarsalmi, Derome, & Levula, 2005; Saarsalmi, Mälkönen, & Kukkola, 2004; Wang, Olsson, & Lundkvist, 2007) tree growth response. Although wood ash is typically enriched in calcium (Ca), magnesium (Mg), potassium (K), and phosphorus (P; Demeyer, Voundi Nkana, & Verloo, 2001), inconsistencies in tree growth responses to wood ash amendment have been attributed to the lack of nitrogen (N) in wood ash at sites with N limitations (e.g., Jacobson et al., 2014). In addition, an international meta-analysis by Reid and Watmough (2014) found time since wood ash application, tree species, and initial site pH prior to wood ash amendment helped to explain variation in tree growth response. Application rates and seasonality, physical form and chemical composition of wood ash, and quantity of precipitation following wood ash application are additional factors that have varied from study to study complicating the interpretation of the effects of wood ash amendment on tree growth (Aronsson & Ekelund, 2004).

Given the potential benefits of wood ash amendments for tree growth, there is a need to explore and define the site factors and conditions that are conducive to positive effects. Several individual wood ash amendment studies in Canada have reported tree growth results (Brais et al., 2015; Prescott & Brown, 1998; Sevean, 2014; Staples & Van Rees, 2001) or are currently measuring tree growth (see summary of Canadian studies in Emilson et al., 2018). Here, we analyze short-term tree growth results (≤6 years post wood ash amendment) across eight wood ash amendment studies spanning from British Columbia to Quebec. Our objectives were to: (a) describe the variability in short-term tree growth response; and (b) test if tree species, nutrient application rates, time since wood ash application, stand development stage, and initial soil pH and N concentration (i.e., before wood ash application) that varied across sites can explain some of the variability in short-term tree growth response. This summary of results across multiple studies provides a current synthesis of the response of Canadian forests to wood ash amendment, contributes to our knowledge of optimal wood ash amendment practices, and provides a baseline for future work and monitoring.

# 2 | MATERIALS AND METHODS

## 2.1 | Description of study sites and data

Short-term (i.e., ≤6 years post wood ash amendment) tree growth data were collected from eight unique wood ash amendment study sites that span from British Columbia to Quebec and from Cordilleran cool temperate to Boreal forest ecosystems (Figure 1). Soil type across the sites as assessed using the Canadian System of Soil Classification ranged from fine-textured Gray Luvisols (0%–45% sand) to coarse-textured Eutric and Dystric Brunisols (45%–100% sand; Soil Classification Working Group, 1998). All sites shared similar experimental design with the measurements of replicated control (no wood ash applied) and treatment plots where wood ash was applied. Loose wood ash was applied at all sites with the exception of one site that applied self-hardened,

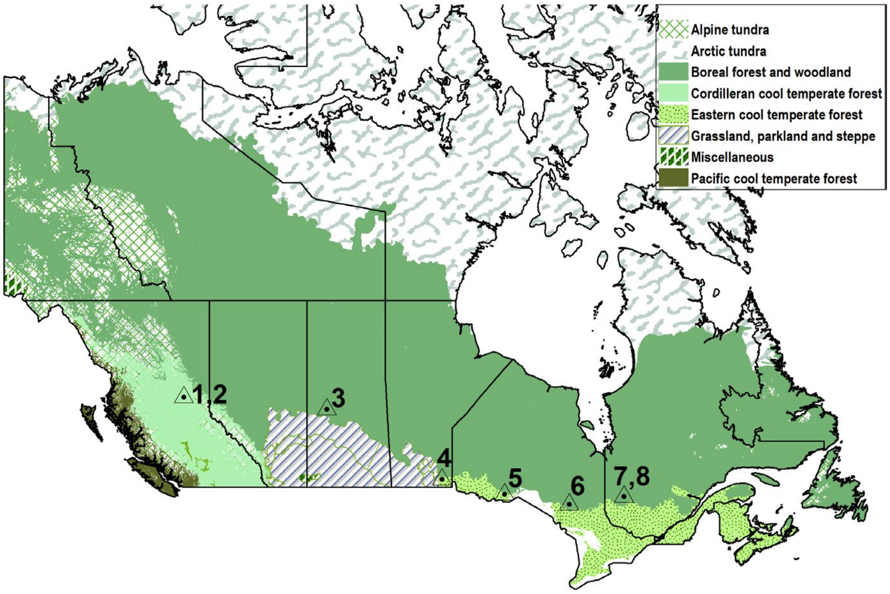


**FIGURE 1** Location of the wood ash study sites across Canada. Site names from left to right include Aleza Lake N, Aleza Lake S, Mistik, Pineland, 25th Sideroad, Island Lake, Senneterre 1, and Senneterre 3. The map is shaded by major forested Vegetation Zones of Canada (Baldwin et al., 2019)

crushed wood ash. See Table S1 for outline of experimental design and wood ash by site, and Emilson et al. (2018) for detailed site descriptions.

Only data for tree species represented at more than one site were included in the analysis. Tree species represented at more than one site included jack pine (*Pinus banksiana* Lamb), black spruce (*Picea mariana* Miller), white spruce (*Picea glauca* Moench), and hybrid spruce (*Picea engelmannii* × *glauca* Parry). Sites were newly planted with seedlings immediately following wood ash application ($n = 5$), or established stands that were between 18 and 53 years and either at crown closure or self-thinning stand stage at the time of application ($n = 3$). Tree height ranged from 0.18 to 10.06 m across the dataset and was measured at all but one site, whereas tree diameter was measured at all sites and ranged from 0.1 to 22.7 cm across the dataset.

Initial soil pH was determined for samples collected from the upper 10 cm of mineral soil prior to wood ash addition or from control plots where wood ash had not been applied and soil was not previously collected. Multiple plots were sampled at each site based on the total number of plots or control plots included in the study design ($n$ = 3–18) for an estimate of initial soil pH. Soil pH was measured in 0.01 M $CaCl_2$ (pH $CaCl_2$) at six sites. For two sites that only reported pH in distilled deionized water (pH $H_2O$), a conversion factor of $-1.3541 + (1.0028 \text{ *pH } H_2O)$ was used based on a relationship ($R^2 = .922$) between pH $H_2O$ and pH $CaCl_2$ for 320 soil samples collected from a wide range of organic and mineral boreal forest soils in Canada (Morris, unpublished data). At most sites, initial total soil nitrogen (N) and carbon (C) were not measured. Therefore, in order to assess site N status (total soil N and C:N) without the influence of wood ash, N and C concentrations were determined for forest floor and mineral soil samples (top 10 cm) collected from three to five replicate control plots in 2017 or 2018 for six of the eight sites. Samples were air-dried, sieved, and ground, and then analyzed on a CN elemental analyzer (Elementar vario EL cube) using flash combustion. For the remaining two sites, N and C values from control plots in the first year of the experiment were used. Estimates of C were obtained via loss on ignition (375°C for 16 hr) values multiplied by a conversion factor of 0.58, and total N was determined using the Kjeldahl N method (Bremner & Mulvaney, 1982) using an $HSO_4$–$H_2O_2$ digestion.

Across all sites, wood ash was applied to treatment plots at rates ranging from 0.7 to 15 Mg dry weight (DW)/ha (Table 1). Taking into consideration, large differences in the chemical composition of wood ash among studies due to factors such as type of feedstock and burn conditions, elemental application rates (i.e., kg nutrient/ha) were used to distinguish between the chemical signatures of wood ashes rather than just the applied amounts (i.e., Mg wood ash DW/ha). Application rates were calculated for K, P, and Ca based on their reported wood ash concentrations (Table S2). Potassium application rates were used as a surrogate for wood ash quality because K, P, and Ca application rates were all strongly correlated (Pearson $r$ = .789–.965; $p$ <.001), and the high solubility/mobility of K in soil makes it readily available for plant uptake (Huotari et al., 2015). For the sake of simplicity, K application rate is hereafter referred to as nutrient application rate. Nutrient application rates ranged from 9.0 to 432.7 kg K/ha (Table 1).

## 2.2 | Data handling

Mean values in height and diameter for each plot (i.e., plot was treated as the experimental unit) at a site were calculated for each tree species, measurement year, and nutrient

**TABLE 1** Summary of soil, wood ash, and tree growth. Values include all sites, years, treatment rates, stand development stages, and tree species. See Table S3 for a summary of soil and wood ash values for sites with height data only (i.e., seven of eight sites)

| Statistic | Min | Max | Mean (*SD*) |
|---|---|---|---|
| Initial[a] mineral soil pH $CaCl_2$ | 3.4 | 4.5 | 4.1 (0.4) |
| Initial[a] mineral soil TN (g/kg) | 0.4 | 1.7 | 1.1 (0.4) |
| Initial[a] forest floor C:N | 20.0 | 51.5 | 32.3 (10.5) |
| Wood ash application rate (Mg/ha) | 0.7 | 15.0 | 4.7 (4.0) |
| Wood ash Ca application rate (kg/ha) | 16.8 | 1,702.8 | 558.1 (597.8) |
| Wood ash P application rate (kg/ha) | 1.00 | 118.3 | 27.2 (38.1) |
| Wood ash K application rate (kg/ha) | 9.0 | 432.7 | 128.6 (137.5) |
| Height wood ash amended PAI[b] (cm) | 5.3 | 46.3 | 23.6 (14.2) |
| Height weighted ln response ratio | −69.1 | 73.3 | 4.5 (23.1) |
| Diameter wood ash amended PAI[b] (cm) | 0.1 | 0.9 | 0.4 (0.3) |
| Diameter weighted ln response ratio | −22.1 | 52.3 | 2.5 (12.3) |

Abbreviations: TN, total nitrogen.

[a]Before wood ash application.

[b]Periodic annual increment (PAI) values presented exclude one of the eight sites that only had measurements for 1 year.

application rate. These plot means were then used to calculate overall site means, followed by log response ratios (ln RR), variance, and weighted log response ratios based on the following equations (Hedges, Gurevitch, & Curtis, 1999):

$$\ln\ \mathrm{RR} = \log\left(\frac{\mathrm{Mean.t}}{\mathrm{Mean.c}}\right), \quad (1)$$

$$\ln\ \mathrm{RR\ variance} = \left(\frac{SD.\mathrm{t}^2}{nt \times \mathrm{Mean.t}^2}\right) + \left(\frac{SD.\mathrm{t}^2}{nc \times \mathrm{Mean.c}^2}\right), \quad (2)$$

$$\ln\ \mathrm{RR\ weighted} = \frac{\ln\ \mathrm{RR}}{\ln\ \mathrm{RR\ variance}}, \quad (3)$$

where t represents wood ash, treatment results and c represents control results for each study site. Response ratios account for potential differences in magnitude of results collected from different sites, and weighting the response ratios by variance accounts for uncertainty in results across sites, with more weight given to results with less variation than those with greater variation and therefore greater uncertainty (Hedges et al., 1999).

## 2.3 | Statistical approach

All statistical analyses were performed with R version 3.5.3 (R Core Team, 2019). To summarize the variation in short-term tree growth response, summary statistics (i.e., mean, standard deviation, and range) of height and diameter weighted response ratios, and periodic annual increment (PAI = measurement time point 2 − measurement time point 1/year time point 2 − year time point 1) of wood ash-treated plots were calculated. Mixed model regressions using restricted maximum likelihood were then computed for both height ($n = 57$ observations, seven sites) and diameter datasets ($n = 57$ observations, eight sites) to test if wood ash application and stand characteristics that varied across sites explained variation in short-term tree growth response. This was done with the function lmer in the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) and lmerTest package to generate p values using Satterthwaite's *df* (Kuznetsova, Brockhoff, & Christensen, 2017). Results of mixed model regression were visualized using the sjPlot (Lüdecke, 2018) and interactions (Long, 2019) packages.

The equation below was used to examine the effect of wood ash application and stand characteristics on tree growth response to wood ash amendment:

$$\begin{aligned}&\mathrm{Weighted\ response\ ratio} \sim \mathrm{tree\ species}\\&\quad \times \mathrm{nutrient\ application\ rate} + \mathrm{time\ since\ application}\\&\quad + \mathrm{initial\ soil\ pH} + \mathrm{initial\ soil\ TN}\\&\quad + \mathrm{stand\ development\ stage} + (1|\mathrm{site}),\end{aligned}$$

where weighted response ratio is the tree growth response variable, nutrient application rate (i.e., K as a proxy for P and Ca), tree species, time since application, initial pH and total nitrogen (TN) concentration of the mineral soil, and stand development stage are the fixed effect explanatory variables, and site is the random effect. Site as the random effect accounted for site-specific variation (i.e., random intercept model), while allowing for the analysis of the explanatory variables and interactions of interest represented by the combined dataset. An interaction term was included to assess the combined effect of nutrient application rate and tree species due to the potential for different tree species to respond differently to nutrient application rates. The influence of the interaction term on model fit was tested by comparing Akaike information criterion (AIC) values between the identical model with and without the interaction term. White and hybrid spruce were analyzed as one species group given the close relation of the two species.

Prior to conducting analyses, covariation of explanatory variables using the vif function in the car package (Fox & Weisberg, 2011) and normality of response and explanatory variables were assessed. All variance inflation factor values in the mixed models presented were <5. Initial C:N of the forest floor was not included in the mixed models due to covariation with pH values. However, when C:N was used in a separate model in place of pH, the same model results were found (Figures S1 and S2). Mixed model validation and fit were assessed by examining potential relationships between residuals and fixed effects, along with heteroscedasticity of model residuals using the plot_model function in the package sjPlot (Lüdecke, 2018). Finally, due to the fact that the dataset contained cases of multiple data points through time, the correlation between model residuals without time since application in the model and time since application was examined, along with a random slope model (i.e., random effect = time since application/site). Results remained consistent and no patterns in residuals or slopes across sites were observed supporting the use of the simplest mixed model (i.e., random intercept).

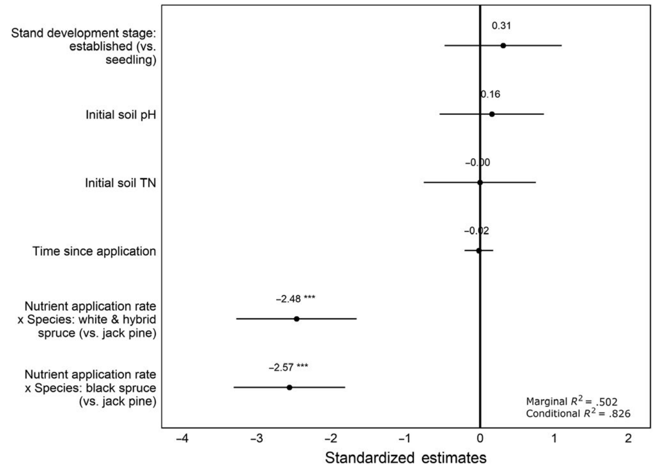


**FIGURE 2** Standardized estimates of the height growth response mixed model regression. Estimates that do not overlap the 0 line represent explanatory variables that explained significant variation in height growth response. The asterisks denote the level of significance (*<.05, **<.01, ***<.001). For the categorical variables, stand development stage and tree species estimates are shown in relation to seedling and jack pine results, respectively. Marginal $R^2$ values represent the amount of variation explained by the fixed-effect variables alone and conditional $R^2$ values represent the variation explained by the fixed-effects and random-effect variables together

## 3 | RESULTS

Weighted response ratios for height and diameter for all wood ash amended plots irrespective of site, tree species, nutrient application rate, and time since wood ash application ranged from negative to positive, with a positive mean value (Table 1). Height growth response ratios across sites varied more largely than diameter growth response ratios, and although not statistically significant, mean height growth response ratios tended to be more positive (Table 1). Mean tree growth PAI for all wood ash amended plots measured at multiple time points (i.e., including data from all but one site) was 23.6 cm with a coefficient of variation of 60.4% for height growth and 0.4 cm with a coefficient of variation of 68.1% for diameter growth (Table 1).

Fixed effect explanatory variables explained 50.2% of the variation in height growth response to wood ash (i.e., weighted response ratios), with a significant interaction between tree species and nutrient application rate (Figure 2; Table S4 for comparison between model with and without the interaction term: $\Delta AIC = -30.8$; $p < .001$).

Site as a random effect explained an additional 32.4% of the variation in tree growth response (i.e., conditional − marginal $R^2$). For the significant interaction between tree species and nutrient application rate, jack pine height growth response was positive in relation to increasing nutrient application rate and was significantly greater than the response of white and hybrid spruce spp. (Figure 3). Height growth response of white/hybrid spruce and black spruce, although not statistically significant, marginally increased

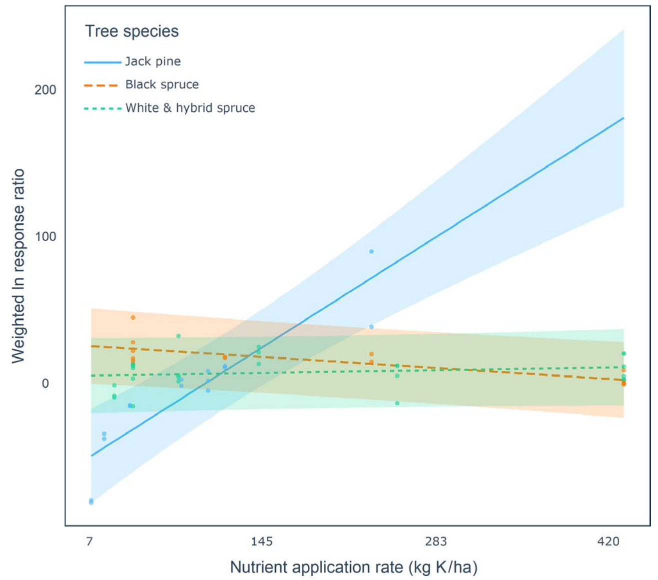


**FIGURE 3** Partial residual plot of the interaction between nutrient application rate and tree species for height growth response (weighted ln response ratio). Points are partial residuals and the shaded areas 95% confidence intervals around each slope

and decreased with increasing nutrient application rate, respectively (Figure 3).

Unlike height growth response, an interaction between tree species and nutrient application rate did not significantly

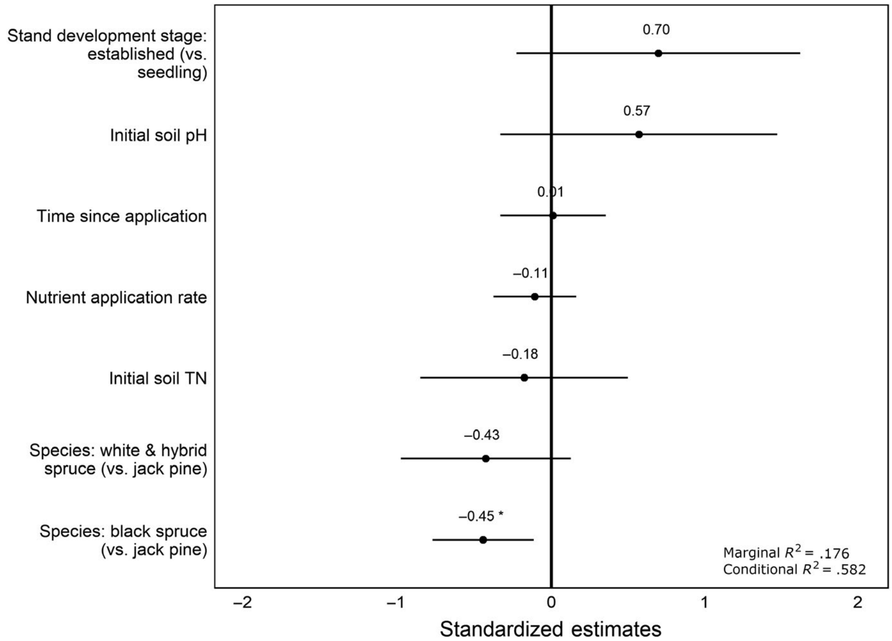


**FIGURE 4** Standardized estimates of the diameter growth response mixed model regression. Estimates that do not overlap the 0 line represent explanatory variables that explained significant variation in diameter growth response. The asterisks denote level of significance (*<.05, **<.01, ***<.001). For the categorical variables, stand development stage and tree species estimates are shown in relation to seedling and jack pine results, respectively. Marginal $R^2$ values represent the amount of variation explained by the fixed-effect variables alone and conditional $R^2$ represent the variation explained by the fixed-effects and random-effect variables together

explain variation or improve model fit for diameter growth response (Table S5: $\Delta$AIC = 3.64; $p$ = NS). Instead, tree species, irrespective of nutrient application rate, was the only variable that significantly explained variation in diameter weighted response ratios, with jack pine diameter growth response being significantly more positive than that of black spruce (Figure 4). The difference between mean PAI of treatment and control plot diameter growth for all sites with multiple years of data (i.e., seven of eight) was 0.115 cm for jack pine and −0.020 cm for black spruce. Tree species explained 17.6% of the variation in diameter growth response, whereas site as a random effect explained an additional 40.6% of the variation in diameter growth response. Stand development stage, initial soil pH and TN, and time since application did not significantly explain variation in either short-term height or diameter growth response.

# 4 | DISCUSSION

## 4.1 | Variability in short-term growth response by tree species and nutrient application rate

The relative magnitude (i.e., positive or negative) and direction (i.e., increasing or decreasing) of short-term tree growth response was found to vary by tree species, highlighting the importance of considering tree species when selecting stands for wood ash amendment. An international meta-analysis found that, in general, hardwood tree species responded more positively to wood ash amendment than coniferous species (Reid & Watmough, 2014). Beyond this comparison, we also found that the magnitude and direction of short-term growth response differed among different coniferous species in Canada. Jack pine benefited the most from wood ash amendment, whereas white/hybrid spruce and black spruce were less responsive. Although only the relative magnitude of growth response was explored in this study (i.e., calculation of response ratios to make findings comparable across multiple sites), results suggest that jack pine stands may be more suitable for wood ash amendment than other conifer species. Benefits of wood ash amendment to jack pine stands should be further explored, especially given previous research demonstrating that jack pine growth and nutritional status are susceptible to increasing intensity of biomass removals (Morris et al., 2019; Thiffault, Paré, Bélanger, Munson, & Marquis, 2006). In addition, although spruce species have the greatest total tree volume in Canada (~22,383 million $m^3$; Natural Resources Canada, 2018), pine species are the third most abundant nationwide (~5,611 million $m^3$; Natural Resources Canada, 2018), and in Ontario, jack pine are the second most harvested tree species by volume (~3,570,185 $m^3$; Ontario Ministry of Natural Resources & Forestry, 2018).

In the current study, black spruce height showed a marginal negative response to increasing amounts of nutrients applied via wood ash. A similar negative growth response for black spruce was found in a boreal forest stand in Quebec, where Brais et al. (2015) reported a negative growth response, in this case diameter, to increasing wood ash application rate for black spruce trees with diameters ≥10 cm. They argued that the negative response was likely due to the toxicity of trace metals contained in the ash and brought about by a root system that develops and absorbs most nutrients (and metals) in the surface organic soil horizons (Houle, Moore, Ouimet, & Marty, 2014). Another potential factor that may explain a negative growth response is increased competition with other plants that experience a positive growth response to wood ash amendment (e.g., Shepard, 1997). Investigation into the mechanism(s) driving this negative response as well as long-term monitoring to explore if this negative response persists (i.e., beyond the 6 years evaluated in this study) are needed to provide more conclusive evidence that wood ash amendment to black spruce stands should be limited to low application rates or avoided all together.

The positive linear relationship between nutrient application rate and height growth response for jack pine would not be expected to continue with higher wood ash application rates. The nutrient application rates at jack pine sites in this study (i.e., 10.2–232.5 kg K/ha, or 0.7–15 Mg DW/ha) can be considered moderate (Hannam, Deschamps, Kwiaton, Venier, & Hazlett, 2016). At higher application rates, a positive growth response of jack pine may become impeded by the high alkalinity and trace metal bioavailability that the wood ash brings about in the system (Huotari et al., 2015). No growth "plateauing" was observed with the higher application rates and as such, it is difficult to suggest a threshold application rate for jack pine from our study. Given the marginally negative response of black spruce, it can be speculated that the threshold for white/hybrid spruce is lower than jack pine. Most countries that allow wood ash amendment to forests do not recommend wood ash application rates >10 Mg/ha (Hannam et al., 2016; Pitman, 2006). However, it is important to note that no two ashes are identical given differences in feedstock and burn conditions. Therefore, the concentrations of potentially toxic metals in wood ash, such as Cd (e.g., Mortensen, Rønn, & Vestergård, 2018), should be considered along with nutrient concentrations when deciding on the total quantity of wood ash to apply. For example, in this study, the maximum overall quantity of wood ash applied was 15 Mg DW/ha (232.5 kg K/ha; 0.0300 kg Cd/ha), but this did not reflect the wood ash with the greatest K and Cd application rates (i.e., 432.7 kg K/ha; 0.0895 kg Cd/ha) which were applied at 10 Mg DW/ha. In addition to wood ash chemistry, soil chemical characteristics such as nutrient and trace metal concentrations and contents, and soil physical characteristics such as texture and water holding capacity at the receiving site should also be considered when planning application rates (Pitman, 2006).

### 4.2 | Unexplained site variability in short-term growth response

There was a large amount of variation explained by site as a random effect, suggesting that there are other intrinsic site characteristics that explain tree growth response. These factors could include nutrient retention in relation to the presence or absence of established vegetation at the time of wood ash application (Westling, Örlander, & Andersson, 2004), competition with other vegetation that benefit from wood ash applications (Huotari et al., 2015), and soil biology such as interactions with soil fauna, soil microbial communities, and plants (e.g., Liiri, Ilmarinen, & Setälä, 2007).

In this study, seedling versus established stands that were 18–53 years in age were examined. Jack pine and black spruce height growth responses were based on seedling results only, and thus, there was no bias in regard to stand age on height growth response. However, diameter growth response included data for both seedlings and established stands for all species groups. As such, growth response could differ due to potential differences in nutrient demand that could be present between different stand development stages (Chapin, Vitousek, & Cleve, 1986) and potentially increased sensitivity of seedlings to changes in the chemical and physical composition of the soil environment (Augusto et al., 2008). Because very similar results were found between height and diameter in this study, it is suggested that a finer examination of tree response to wood ash amendment that includes various growth developmental stages will likely be relevant in future studies. For example, Brais et al. (2015) found that black spruce of ≥10 cm diameter at breast height (DBH) had a greater response to wood ash than established black spruce with a DBH of <10 cm, demonstrating that growth response varies depending on the size of the trees within a stand.

Initial soil conditions, as described by pH and total N concentrations, did not explain variation in short-term tree growth response to wood ash amendment. In their meta-analysis, Reid and Watmough (2014) reported that tree growth at sites characterized by soils with pH $H_2O$ < 4.5 (i.e., pH $CaCl_2$~3.16) was less responsive to wood ash than at sites with soil pH $H_2O$ of 4.5–6.0. For all sites in the current study, soil pH was greater than this pH threshold (i.e., >3.16 $CaCl_2$), but across sites only ranged by less than one pH unit. Low soil pH was also associated with low (initial) forest floor C:N, and vice versa. The C:N ranged from 20.0 to 51.5 across the sites. Although initial forest floor C:N was not formally included in the analysis due to covariation with initial soil pH, replacing initial soil pH as an explanatory variable with forest floor C:N did not explain any additional variation in growth response (Figures S1 and S2). Three of the eight sites included in the analysis exhibited forest floor C:N ≥ 30, suggesting potential N limitations (Rosenberg, Persson, Högbom, & Jacobson, 2010). However, although initial soil conditions (i.e., pH, total N, and C:N) did not explain variation in short-term growth response across our dataset, N limitations can potentially play a role in tree growth response to wood ash amendment at nutrient-poor sites and over time frames greater than the 6 years evaluated in this study (e.g., Jacobson, 2003). Seven wood ash amendment research sites in Canada have been assessed (Brais et al., 2015) or are currently assessing if N additions in combination with wood ash amendment can enhance tree growth (see studies described in Emilson et al., 2018).

Tree growth measurements across the sites in this study were taken within 1–6 years following wood ash amendment. We identify these results as being indicative of short-term tree growth responses because previous research has demonstrated that there can be a lag time between time since wood ash application and growth response, with growth response increasing 10 years following wood ash amendment (Reid & Watmough, 2014). This identified lag time in response may be due to the slow vertical transfer of nutrients and pH effects down the soil profile (Hansen, Bang-Andreasen, Sørensen, & Ingerslev, 2017; van der Heijden et al., 2013). Therefore, it was not unexpected that the time since application did not explain variation in tree growth results in this study. However, time since application is expected to become increasingly relevant as these Canadian wood ash experiments progress.

Finally, specific factors that may influence the vertical transfer of nutrients and pH effects into the rooting zone, such as soil texture and forest floor depth, may help to further explain site-specific variability in short-term tree growth response to wood ash amendment (e.g., Ingerslev, Hansen, Pedersen, & Skov, 2014). In our study, black spruce and jack pine had different growth responses despite sharing similar soil textures (i.e., Brunisols with >45% sand), and although forest floor depth varied across sites with the same tree species (i.e., white and hybrid spruce 0–10 cm, jack pine 2–15 cm, black spruce 0–15 cm), differences in growth response by tree species were still evident. Therefore, in our study, soil texture and forest floor depth did not appear to be key factors influencing short-term growth response, but merit more detailed study in future research.

### 4.3 | Management implications

By examining short-term trends in growth response from multiple study sites with variable site characteristics, we found that tree species and the quantity of nutrients in ash applied are important considerations when planning forest wood ash applications. Jack pine, compared to spruce spp., showed the greatest potential for increased productivity following wood ash amendment. Increased nutrient application rate from wood ash was also found to positively influence the height growth response of jack pine, whereas white/hybrid spruce and black spruce were much less responsive to increasing application rates. These results provide a baseline for monitoring programs, and contribute to our knowledge of optimal wood ash amendment practices linked to the sustainability of bioenergy production. Future work is needed to assess if these trends continue as time since wood ash application increases, especially past 10 years.

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## ORCID

*Caroline E. Emilson* https://orcid.org/0000-0002-4770-1117
*Nicolas Bélanger* https://orcid.org/0000-0003-2696-5153
*John Markham* https://orcid.org/0000-0003-1060-496X
*Dave Morris* https://orcid.org/0000-0002-5739-0594
*Michael Rutherford* https://orcid.org/0000-0002-5065-7700
*Lisa A. Venier* https://orcid.org/0000-0002-7738-1361
*Paul W. Hazlett* https://orcid.org/0000-0003-2485-8426

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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