Effects of A Second Wood Ash Application to Soil on *Picea mariana* (Mill.) B.S.P. and *Picea glauca* (Moench) Voss Growth and Foliar Nutrition and Soil Chemistry

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Abstract

As the Canadian biomass energy sector grows, so too does its production of by-products such as wood ash from the combustion of wood biomass for energy. Wood ash can be land applied with the goal of increasing the productivity of a site through an increase in soil pH and available nutrients. Most studies have focused on a single ash application to the soil. The purpose of this study is to investigate the effects of re-applying wood ash on the chemistry of a forest soil and the growth and foliar nutrition of two commercially important tree species (*Picea mariana* (Mill.) B.S.P. and *Picea glauca* (Moench) Voss). A low and high carbon wood ash sourced from vibrating power boilers at the Resolute Forest Products facility in Thunder Bay were re-applied in 2019 to plots established in 2012 at the Ministry of Natural Resources, Northwest Science and Technology Center, 25th Side Road. The wood ashes were applied at 0, 1000, and 10 000 kg ha^{-1} alone and in combination in 5 replicate blocks. Tree height and diameter were measured in the Fall of 2019 and 2020 and soil and foliar samples were collected at the same time for chemical analyses. A second application significantly affected concentrations of soil C, C:N, conductivity, pH, total soil Ca, S, Sr, and exchangeable Ca, K, Mg, Na, and extractable Cu, Mn, and Zn concentrations. Differences attributable to species were observed for soil C concentrations, conductivity and exchangeable K concentrations. Concentrations of soil C, conductivity, exchangeable K and extractable Zn differed between years. Three trends were observed in soil chemistry: 1) low C ash had a greater effect on measured parameters than the high C ash, 2) applying ash at higher rates had a greater effect, and 3) applying low C ash in addition to high C ash had greater impact on soil than when high C ash was applied alone. Foliar and growth response from wood ash re-application were species dependant. *Picea marianna* (black spruce) showed a negative foliar Mn response and a non-significant but negative height growth response to ash where *Picea glauca* (white spruce) did not show any effect of ash application. Lower foliar Al and black spruce foliar Mn were observed when higher amounts of ash were applied and when low C ash was applied. Foliar S responded to ash application after the first growing season and low C ash had the greatest effect. Comparing these results to the first ash application in 2012: 1) high C ash had a greater impact on soil chemistry after the second ash application, 2) the concentration of some soil metals (extractable Cu, Zn, and Mn, and total Sr and Ca) increased with the second application, though not to toxic concentrations. This study shows that a repeat ash application to soils can increase concentrations of Ca, K, Mg, and S in soil, reduce the impact of soil acidification, and combat soil C depletion that follows whole tree harvesting, at least in the short term, while having no significant immediate negative effects on black and white spruce growth and foliar nutrition.

Keywords: wood ash, soil amendment, boreal forest, *Picea mariana*, *Picea glauca*, soil chemistry

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Chapter 1- Introduction

Behind hydro-electric and wind energy, bioenergy is Canada's third largest renewable source of electricity generation accounting for 1.4% of generated electricity in 2014 (Natural Resources Canada, 2017). From 2005 to 2015 bioenergy production doubled and produced 13,000 GWh of power (Hannam et al., 2019), and is anticipated to grow due to the effort to reduce our reliance on fossil fuels in the face of a rapidly changing climate. The majority of biomass sourced for bioenergy production comes from the Canadian forest industry (Roach and Berch, 2014). Biomass for bioenergy production is sourced from many different avenues within forestry: harvested trees unsuitable for lumber, harvest residue, by-products of the forestry industry (paper pulp, sawmill shavings), and bio-energy crops such as short rotation poplar (Ventura et al., 2019; Natural Resources Canada, 2020). Using bio-residuals, i.e., the by-products of the forest industry, offers perhaps the most opportune fuel source for bioenergy, by turning manufacturing waste into profit. In fact, it's estimated that forest residues from existing sustainably managed British Columbian forests could replace 21% of the fossil fuel energy demand for the province (Roach and Berch, 2014). This opportunity has already been seized by many of Canada's pulp and sawmills, who burn their residuals and sell electrical energy to the grid (Natural Resources Canada, 2017).

Burning solid biofuel on an industrial scale generates wood ash, a by-product of the combustion process. Canada produced over 1 million tons of wood ash in 2018 alone (IEA Bioenergy et al., 2019). As bio-energy production continues to grow, so will the production of wood ash. Production of wood ash in large quantities creates both an economic burden for the energy producer and presents risks to the health of the environment. Land application of wood ash in Canada is regulated due to its strong alkalinity, high reactivity, and concentration of metals (Demeyer et al., 2001; Emilson et al., 2019), and is commonly landfilled at a cost to the producer. Disposing of this ash is becoming problematic due to increases in quantity being produced, landfill costs and landfill site regulations (Staples and Van Rees, 2001). However, research into the beneficial uses of wood ash, such as concrete production and as a soil amendment, has shown that wood ash can be a useful resource (Santalla and Omil, 2011; Ayobami, 2021)

Bioenergy generation from burning forestry residuals and by-products from pulp and paper production in power boilers produce two types of ash, fly and bottom ash (Santalla et al., 2011; Scheepers and du Toit, 2016). Fly ash is generated from the fine particles that rise with the flue gas and condense, where bottom ash is heavier and collects at the bottom of the boiler (Scheepers and du Toit, 2016). The different formative conditions produces physically and chemically unique ashes. Fly ash is captured in boiler emissions by filtration and consists of finer particles with high specific surface area, where bottom ash is a coarser material (Scheepers and Toit, 2016). This in turn means that fly ash has higher reactivity and can have a faster and greater chemical response in the environment than bottom ash (Scheepers and du Toit, 2016). All ash however is porous, with polar surface functional groups that can form organo-mineral complexes (Lehmann and Kleber, 2015; Basile-Doelsch et al., 2020).

The differences between ashes are evident in their chemical composition (Table 1.1). Wood ash pH typically ranges from 9 to 13.5 (Scheepers and du Toit, 2016), but is dependant on feedstock, combustion temperature, particle size, and ash collection method (Etiégni and Campbell, 1991; Demeyer et al., 2001; Scheepers and Toit, 2016). Fly ashes tend to be more alkaline because the ash is formed from the recondensation of volatilized alkali and alkaline earth metals (Kuokkanen et al., 2006) into very fine-grained water-soluble crystalline mineral

Table 1.1. Chemical properties for 8 different wood ashes applied to soils in Canada. Notes: Organic Carbon (OC), Inorganic Carbon (IC), below detectable limit (<dl).

Study		Pugliese et al., 2014		Couch et al., 2021		Domes et al., 2018		This Study	
Feed Stock		Spruce-Pine-Fir Bark		Soft Wood Chips and Pressed Secondary Effluent Sludge		Softwood Saw Mill Residue	Wood Chips, Bark, Sawdust	Soft Wood Chips and Pressed Secondary Effluent Sludge	
Ash Type		Mill A Bottom	Mill A Fly	High Carbon Fly	Low Carbon Fly	Gasifier Bottom	Boiler Bottom	High Carbon Mixed	Low Carbon Mixed
pH		10.91	11.92	8.04	11.99	11.27	12	12.7	12.8
Total OC	(weight %)	1.76	1.08	-	-	3.58	28.5	57.4	26.8
Total IC	(weight %)	1.85	0.63	-	-	-	-	0.74	1.35
Total C	(weight %)	-	-	39.16	11.63	7.31	29.7	58.1	28.1
Total N	(weight %)	0.02	0.23	0.34	0.15	0.08	0.09	0.18	0.15
P	(weight %)	0.01	0	0.09	0.76	0.64	0.27	0.21	0.91
K	(weight %)	0.14	0.37	0.25	2.5	5.06	1.59	1.28	2.22
Ca	(weight %)	2.85	5.04	2.9	14	19.4	6.7	3.24	11.3
Mg	(weight %)	0.93	1.45	0.3	1.8	2.5	0.66	0.59	1.11
Fe	(mg kg^{-1})	27.38	40.56	7320	19 600	-	-	-	-
Cu	(mg kg^{-1})	61.37	9.93	12	122	63	27.6	81	85
Mn	(mg kg^{-1})	1778	3579	917	3710	9280	1710	-	-
Zn	(mg kg^{-1})	136	467	65	1500	435	439	1	1300
Al	(mg kg^{-1})	55159	72901	4300	28 000	-	-	-	-
Na	(mg kg^{-1})	18194	20601	900	6000	7400	1800	997	7770
S	(mg kg^{-1})	0.05	0.26	300	28500	18 000	28 000	-	-
As	(mg kg^{-1})	12.16	16.66	-	-	6.21	1.23	0.87	3.3
Cd	(mg kg^{-1})	2.12	6.11	-	-	2.08	2.9	0.66	11
Co	(mg kg^{-1})	15.89	24.32	-	-	7.95	4.61	3.2	6.3
Cr	(mg kg^{-1})	39.31	66.62	-	-	23.9	14.5	56	58
Mo	(mg kg^{-1})	2.08	4.13	-	-	4.58	5.48	0.53	3
Ni	(mg kg^{-1})	21.41	36.44	<dl	31	38.1	18.9	67	45
Pb	(mg kg^{-1})	30.87	54.31	-	-	1.4	3	-	-
Se	(mg kg^{-1})	3.58	10.43	-	-	2.2	1.4	<dl	0.64
Si	(mg kg^{-1})	221	305	-	-	-	-	-	-

phases, such as oxide, hydroxide, carbonate chloride, and sulphate phases (Demeyer et al., 2001; Vassilev and Vassileva, 2019). Cadmium, Pb, Mo, S, and Hg are particularly susceptible to volatilization and therefore are concentrated in fly ash more than in bottom ash (Kuokkanen et al., 2006). Wood ash, more generally, is composed of the following elements in order of decreasing abundance: C, Ca, K, Al, Mg, Fe, P and lesser amounts of other elements (Demeyer et al., 2001; Hannam et al., 2019). Typically, fly ash has a lower C content and is associated with higher metal content (Demeyer et al., 2001). Bottom ash has higher C content and lower concentrations of metals.

Research has shown that applying wood ash to soil increases the soil's water holding capacity, pH, mineral nutrient availability, retention of nutrient cations, and microbial activity and biomass (Etiégni and Campbell, 1991; Bååth & Arnebrant, 1994; Sollins et al., 1996; Demeyer et al., 2001; Bieser and Thomas, 2019; Guo et al., 2020). The effect wood ash has on soils have the potential to resolve many of the issues associated with intensive tree harvesting, such as soil acidification (Jacobson et al., 2014; Hannam et al., 2019), soil C depletion (Bieser and Thomas, 2019), organic matter reduction (Bieser and Thomas, 2019; Hannam et al., 2019), and mineral nutrient removal (Bieser and Thomas, 2019). However, wood ashes differ in their chemistry and forest trials on boreal tree species across Canada's forests have had mixed results depending on the tree species present, and the amount and type of ash applied (Reid and Watmough, 2014; Hannam et al., 2019).

Wood ash application to the soil can affect the growth of plants, and the soil's microbiome, which cycles nutrients necessary for plant growth. Biederman and Harpole (2013), who performed a meta-analysis of 371 studies, found that the pool of microbial biomass increased across a wide variety of ecosystems and agricultural systems with wood ash application. Adding wood ash to a boreal soil has also been reported to increase the phylogenetic diversity of bacterial communities in boreal forest soils (Perkiömäki and Fritze, 2002; Noyce et al., 2016). Though these are signs of a thriving microbiome, a larger microbial community needs energy to sustain itself which generally comes from the decomposition of soil organic matter, which results in the emission of CO_2 as a by-product into the atmosphere (Bååth and Arnebrant, 1994). An increase in the bacterial community is ubiquitous when liming acidic soils to more neutral pH ranges; both the abundance and diversity of bacteria nearly double from raising pH from 4 to 8 (Rousk et al., 2010).

Soil pH is also a master variable in controlling soil organic carbon retention (Bailey et al., 2019). Changing pH can lead to solubilizing mineral aggregate cements, thus destroying the aggregate, or reintroducing mineral encapsulated soil organic matter to the soil solution where it becomes available for microbial consumption (Sollins et al., 1996; Bailey et al., 2019). Wood ash's main constituent is C, with most of that C being held in organic forms that may be used by the microbial community (Table 1.1). Most field studies have shown that wood ash application to forest soils does not cause measurable change in soil C 2 – 20 years after application (Clarke et al., 2017; Hannam et al., 2019). The combined effect of raising pH and adding nutrients, i.e., ions by amending soils with wood ash, results in greater availability of micro- and macronutrients to organisms (Bieser and Thomas, 2019). There is also a risk of heavy metals leaching from wood ash creating toxic soil conditions. This could lead to shifts in the microbial community to more pathogenetic organisms and less soil fungi (Sullivan and Gadd, 2019). Metals are micronutrients and essential for life, but if they occur at levels above biological threshold concentrations, can be toxic to life (Sullivan and Gadd, 2019).

In addition to providing nutrition for the soil microbial community, the influx of mineral nutrients into the soil provides readily dissolved nutrients for plants to absorb through their roots. Wood ash has shown to increase concentrations of exchangeable Ca, Mg, K and P (Pugliese et al., 2014). In a plantation trial, wood ash positively affected soil exchangeable Ca and K, and total S, Fe, Mn, and Zn (Couch et al., 2021). Studies have also shown wood ash's ability to neutralize acid forest soils and improve tree growth (Hannam et al., 2019; Arseneau et al., 2020; Couch et al., 2021). It is also evident that tree species differ in their growth and foliar responses to ash application. White spruce (*Picea glauca* (Moench) Voss) growth has shown no response to wood ash application (Emilson et al. 2019). Black spruce (*Picea mariana* (Mill.) B.S.P.) tends to exhibit a negative growth response to wood ash application (Emilson et al. 2019). The growth response of black spruce to wood ash application might also be dependent on tree size and age; larger, older trees had a negative linear growth response with increasing rate of ash application (Brais et al., 2015) and younger smaller trees were unaffected (Brais et al., 2015). Picea all together have shown negative growth effects from ash addition due to their slow conservative growth compared to other species such as jack pine (Bélanger et al., 2021). Foliar nutrition for black spruce was unaffected by wood ash application (Brais et al., 2015).

Investigating wood ash application to forest soils on soil chemistry and tree growth and nutrition focuses on the immediate effects i.e., several months to 5 years after a single application (Arvidsson and Lundkvist, 2002; Brais et al., 2015; Domes et al., 2018; Bieser and Thomas, 2019; Couch et al., 2021). Meta-analysis of forest fire and bioenergy ash on boreal soils found that wood ash's effect on soil exchangeable chemistry is strongest within the first 5 years following application (Omil et al., 2013; Hannam et al., 2019). Although ash chemistry and application rates differ, the general finding is that pH, cation exchange capacity (CEC), and exchangeable concentrations of Ca, K, Mg, extractable Al, and other nutrients increase with application rate immediately after application (Brais et al., 2015; Couch et al., 2021). Longer term studies reveal that wood ash effect on soil pH, C and N tend to return to initial levels within 20 years after application (Hannam et al., 2019).

An area that has received little attention is the effect of repeated application of wood ash to forest soils on soil chemistry and tree growth and foliar nutrition. One study that re-applied mixed fly and bottom wood ash reported increased concentrations of exchangeable P, Ca, and K after the second ash application (Omil et al., 2013). Repeated application of mixed wood ash had limited effects on foliar element contents, only raising Mn in Monterey pine (*Pinus radiata* D. Don) after the third ash application (Omil et al., 2007). Increases in stand volume was observed after three mixed ash applications in a sandy soil (Omil et al., 2013).

Re-applying wood ash to soil presents an opportunity to further divert wood ash from the landfill with the potential benefit of improving soil properties and the growth and nutrition of trees. Some concerns around repeated application of ash would be negative effects on tree growth, which has already been observed in black spruce after a single wood ash application (Emilson et al. 2019), and heavy metal concentrations and metal toxicity (Demeyer et al., 2001; Sullivan and Gadd, 2019). The goal of this study is to determine if a second wood ash application to soil has any beneficial, or at least no negative effects on two commercially important boreal tree species, and some soil properties. The objectives of this study are to determine how a second application of a low and high carbon wood ash affects: 1) the growth and foliar nutrition response in black and white spruce, and 2) some soil chemical and physical properties. Similar to the first application at this site, I hypothesize that the measured soil properties, seedling growth and foliar nutrient contents will be significantly affected by the application of wood ash and that: i) low carbon ash will have a greater effect than high carbon ash because it is more reactive, ii) higher loading rates will elicit stronger responses, and iii) responses will differ when the application is of a single ash type versus when it is applied in combination.

Chapter 2- Materials and Methods

2.1 Site History & Design

This experiment was established in May 2012 at the Ontario Ministry of Natural Resources Northwest Science and Technology Center, located at 48º22’N 89º23’W, Thunder Bay, Ontario, Canada. The soil is a Dystric Brunisol (Soil Classification Working Group 1998), which developed over glacial fluvial sediments with a sandy loam texture containing 74% sand, 20% silt, and 6% clay (Couch et al., 2021). From 1946 until 1992 the site functioned as a bare root nursery growing jack pine and black spruce. Over this time, soils were tilled and treated with a range of soil amendments and fertilizers. From 1992 – 2012, soil beds were mostly fallow.

The experimental design consists of a factorial design with replication (5 blocks) (Figure 2.1). Each plot is 148.5 m^2 (Figure 2.2). The ash treatments include two factors, ash type (low and high C ash) and ash application rate (0, 1000, or 10 000 kg ha^{-1}) creating the following 9 wood ash treatments (low C/ high C): 0/0, 0/1000, 0/10 000, 1000/0, 10 000/0, 1000/1000, 1000/10 000, 10 000/1000, 10 000/10 000 kg ha^{-1}. In 2012, prior to ash application, the soil was roto-tilled. After the ash was applied, black and white spruce seedlings were planted with a grid spacing of 0.5 m. Each plot was divided into two sub-plots, with 16 white spruces planted in one sub-plot and 16 black spruces planted in the other. The subplots were bordered by a perimeter of jack pines (Figure 2.2). A random number generator was used to situate the plots and subplots within each block.

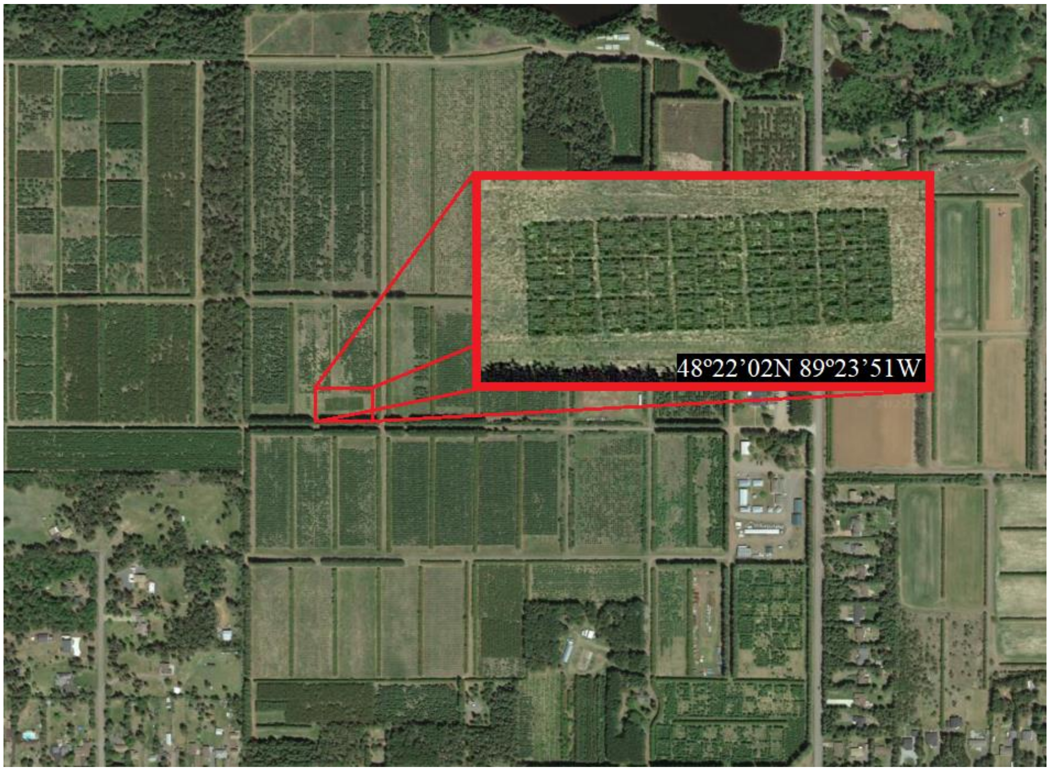

Figure 2.1. Satellite imagery of the Ontario Ministry of Natural Resources Northwest Science and Technology Center Thunder Bay, Ontario, Canada. (Google Earth).

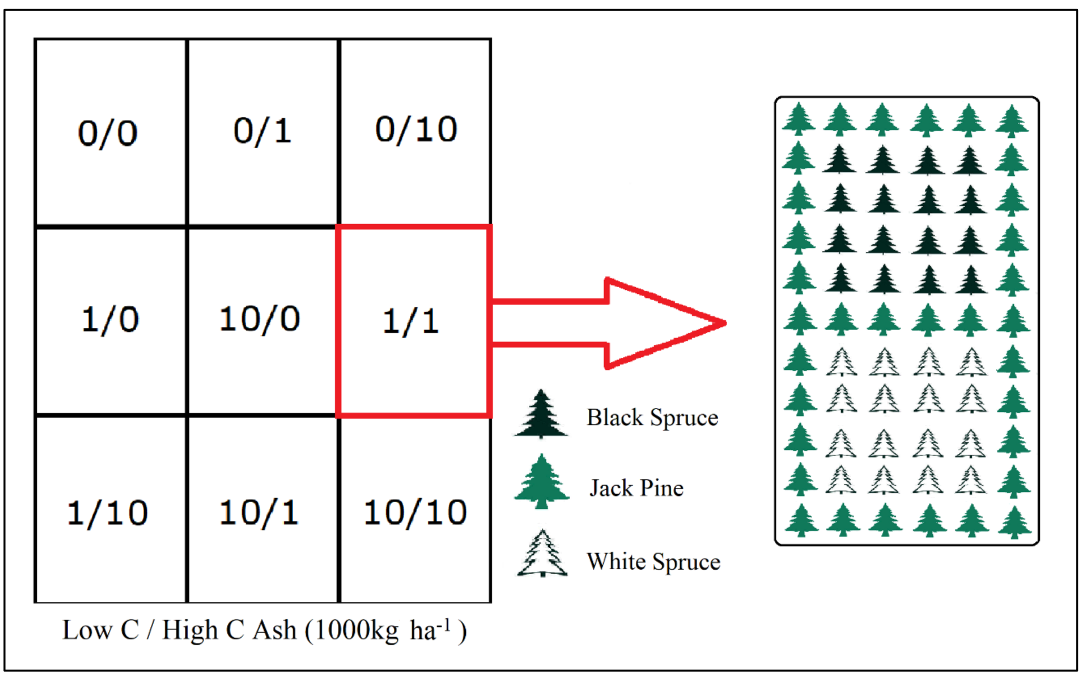

Figure 2.2. Illustration of wood ash treatment arrangement in a single block.

In 2019, two wood ashes sourced from boilers at Resolute Forest Products Thunder Bay operation were applied at the same low and high C ash loading rates as in 2012. Prior to application, the plots were thinned so that nine trees remained in each subplot. Removal was done randomly. The soil surface was also scarified using hand rakes. Wood ash dry weight equivalents for the nine treatments were weighed into bags before application. Ash was evenly distributed across the plot's soil surface by hand on a calm weather day to facilitate spreading and then incorporated at the surface using hand rakes.

2.2 Wood Ash

The wood ashes used in this study for both applications were sourced from Resolute Forest Products No.3 and No.6 vibrating power boilers. The No.3 vibrating grate power boiler was the source of the high-carbon ash (58.1% C), and the No.6 power boiler supplied the low C fly ash (28.1% C). The ash produced in these boilers is formed from a feedstock of mainly wood-chips, saw dust, and mill waste of softwood species, with additions of 8%-14% pressed secondary effluent sludge into boiler No.6. Though the source and application rates were the same for the 2012 and 2019 applications, the chemistry of the ashes differed slightly (Table 2.1).

2.3 Sampling Techniques & Methods of Analysis

2.3.1 Soils

Soil bulk density samples were collected in September of 2019 and October of 2020 by driving a cylinder of known volume (183.9 cm^3) into the soil profile of each sub-plot to collect a sample from the Ap horizon at 0-15 cm in the mineral soil. In the laboratory, the fresh soil was weighed into a pan and dried in a forced-air convection oven at 105 ºC to a constant weight.

Soils were sieved to 2 mm and the < 2 mm fraction was used to determine the bulk density (dry soil mass/volume; Cully, 1993).

Table 2.1. Chemical properties the wood ashes that were applied to our study site in 2012 and 2019. Notes: Organic Carbon (OC), Inorganic Carbon (IC), below detectable limit (<dl).

Study		Couch et al., (2021)		This Study	
Feed Stock		Soft Wood Chips and Pressed Secondary Effluent Sludge		Soft Wood Chips and Pressed Secondary Effluent Sludge	
Ash Type		High Carbon Fly	Low Carbon Fly	High Carbon Mixed	Low Carbon Mixed
pH		8.04	11.99	12.7	12.8
Total OC	(weight %)	-	-	57.4	26.8
Total IC	(weight %)	-	-	0.74	1.35
Total C	(weight %)	39.16	11.63	58.1	28.1
Total N	(weight %)	0.34	0.15	0.18	0.15
P	(weight %)	0.09	0.76	0.21	0.91
K	(weight %)	0.25	2.5	1.28	2.22
Ca	(weight %)	2.9	14	3.24	11.3
Mg	(weight %)	0.3	1.8	0.59	1.11
Fe	(mg g^{-1})	7320	19 600	-	-
Cu	(mg g^{-1})	12	122	81	85
Mn	(mg g^{-1})	917	3710	-	-
Zn	(mg g^{-1})	65	1500	1	1300
Al	(mg g^{-1})	4300	28 000	-	-
Na	(mg g^{-1})	900	6000	997	7770
S	(mg g^{-1})	300	28500	-	-
As	(mg g^{-1})	-	-	0.87	3.3
Cd	(mg g^{-1})	-	-	0.66	11
Co	(mg g^{-1})	-	-	3.2	6.3
Cr	(mg g^{-1})	-	-	56	58
Mo	(mg g^{-1})	-	-	0.53	3
Ni	(mg g^{-1})	<dl	31	67	45
Se	(mg g^{-1})	-	-	<dl	0.64
Ag Index				25	30

All other soil analyses were conducted using soils collected using 1.91 cm diameter Oakfield soil probe also in September of 2019 and October of 2020. Ten soil cores were collected from the top 15 cm of the soil and composited into a single sample to represent the plot. Samples were air dried inside a ventilated laboratory for a minimum of one week. Dry soils were sieved to 2 mm, and all subsequent analyses were carried out on the <2 mm fraction. A subsample of each soil was pulverized and homogenized in a SPEX Mixer Ball Mill and passed through a 250 μm sieve prior to analysis of C and N concentrations by flash combustion on an elemental analyzer (Elementar, VarioCube).

Soil electrical conductivity was determined by thoroughly mixing soil at 1:2 soil-to-water ratio using a Fisher Accumet conductivity probe (Rhoades, 1982). Soil pH was determined in a saturated paste of 1:2 soil-to-water ratio and measured with a Fisher Accumet Ion Analyzer pH meter (Kalra and Maynard, 1991). Soil total metal content was determined after using 3:1 HNO_3:HCl acid ratio digestion using a Varian Vista Pro Radial inductively coupled plasma atomic emission spectrometer (ICP-AES) (US EPA Method 3050B) (US Environmental Protection Agency (US EPA) 1996). Soil analyses included Al, As, Ca, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, Pb, S, Sr, and Zn. Exchangeable Ca, K, Mg, and Na were determined using a 1 M ammonium acetate solution, with pH adjusted to 7, and analysed by ICP-AES (Simard, 1993). Extractable Fe, Cu, Mn, and Zn were determined using a 1:2 soil to 0.005 M DTPA extraction analysed by ICP-AES (Liang and Karamanos, 1993). Extractable P was determined using the Bray-P method with analysis done using and a Skalar continuous flow analyzer (Olsen and Sommers, 1982).

2.3.2 Trees

The heights of all trees in each sub-plot were measured using a telescoping measuring rod and the diameter at breast height or root crown diameters at the soil surface were measured with a digital caliper in September of 2019 and October of 2020. Volumes were calculated using the diameter at breast height or root crown diameters using Honer's (1967) stand volume equations.

Growth was determined by the difference in height or volume of an individual. Foliar samples were collected from the branch tips (i.e., year needles) from the center four trees in each subplot. Foliar samples were placed in paper bags in a forced-air convection oven at 60 ºC until a constant weight was achieved. The mass of 100 dry needles was weighed and foliar samples were ground to <1 mm for elemental analysis. Metals in foliage were extracted using a microwave assisted acid digestion (concentrated HNO_3) and concentrations of metals were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES) analysis (US EPA Method 3051A) (US Environmental Protection Agency (US EPA) 2007. Foliage analyses included total concentrations of Al, B, Ba, Ca, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, S, Si, Sr, and Zn. Foliar N was determined by flash combustion using an elemental analyzer (Elementar VarioCube). Foliar nutrient contents were calculated as foliar concentration*needle dry weight per 100 needles.

2.4 Statistical Approach

Foliar and soil data were analysed as a randomized design using split plots using a linear mixed effects model. Ash application treatment, species, year, and their interaction were the fixed effects, and the interaction between treatment and replicate was the random effect. Tree height and volume data were analysed using a two-way repeated measures ANOVA as a mixed model where treatment, species and their interaction are fixed effects, and the interaction of treatment and replicate is the random effect. Treatment by replicate accounted for the split-plot effect in the design (Federer and King, 2007).

Shapiro-Wilk's tests were performed on the residuals to assess normality and Levene's tests for homogeneity of variance were used to confirm the assumptions of ANOVA. Square root and log data transformations were performed as needed. For this study, a p-value less than 0.05

is considered to be significant. Where a significant effect of wood ash treatment was found, orthogonal contrasts (Snedecor and Cochran, 1989) were used to examine the effects of ash type, loading rate and mixtures on the measured parameters (Table 2.2). Orthogonal contrasting enables direct questioning of data and allows for grouped comparisons that other post-hoc tests can not offer. Statistical analyses were completed in R version 4.0.3 using the lme4, lmerTest, and dplyr packages, and graphics were created using the ggplot2, ggarrange and ggpubr packages.

Table 2.2. Orthogonal contrasts used to examine the effects of ash type, loading rate and mixtures on the measured parameters.

Question	Orthogonal Contrasts (high-carbon/low-carbon ash loading rate (000 kg ha-1))
L1: Does the application of wood ash affect the response variable?	(0/0) - 1/8* (0/1 + 0/10 + 1/0 + 10/0 + 1/1 + 1/10 + 10/1 + 10/10)
L2: Does the response differ between the low and high carbon ash loading?	(0/1 + 0/10) - (1/0 + 10/0)
L3: Does the response differ between the low and high loading rate when low C ash is applied?	(0/1) - (0/10)
L4: Does the response differ between the low and high loading rate when high C ash is applied?	(1/0) - (10/0)
L5: Does the response differ when the low carbon ash is applied at the low rate with or without the high carbon ash?	(0/1) - 0.5*(1/1 + 10/1)
L6: Does the response differ when the low carbon ash is applied at the high rate with or without the high carbon ash?	(0/10) - 0.5*(1/10 + 10/10)
L7: Does the response differ when the high carbon ash is applied at the low rate with or without the low carbon ash?	(1/0) - 0.5*(1.1 + 1/10)
L8: Does the response differ when the high carbon ash is applied at the high rate with or without the low carbon ash?	(10/0) - 0.5*(10/1 + 10/10)

Chapter 3- Results

3.1. Soil Parameters

Statistical outputs of soil parameters can be found in tables 3.1-3.6, found on page 47–53.

3.1.1. Treatment by year by species interaction effect: Total soil C and C:N

There was a significant interaction between treatment, year and species for total C concentrations and soil C:N (Table 3.1). In 2019, there was a significant effect of wood ash application on total C concentrations in the soil that did not differ between species (Table 3.2). Concentrations of soil carbon were higher when the low carbon and high carbon ashes were applied at a rate of 10 000 kg ha^{-1} than when applied at 1000 kg ha^{-1} (L3 and L4; Figure 3.1).

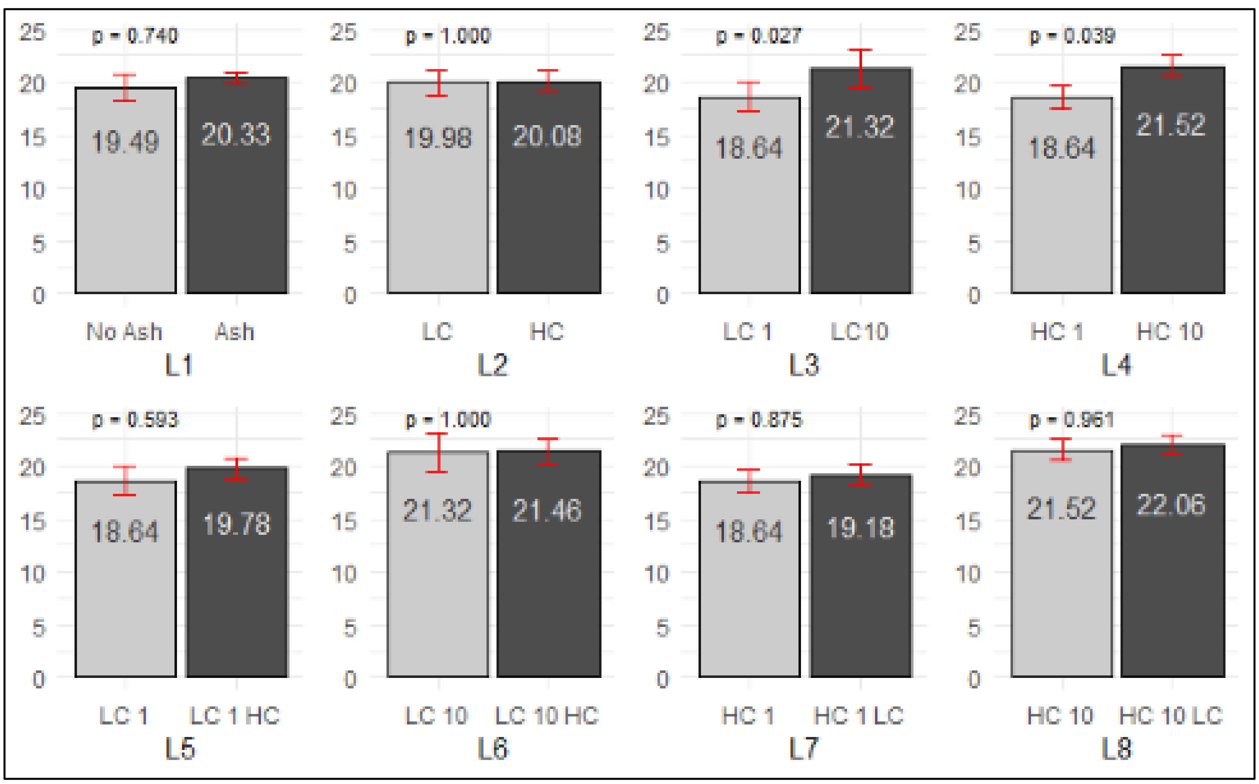

Figure 3.1. Orthogonal contrasts for the year 2019 (means and standard error of means (red bar)), for total soil C (g kg^{-1} soil), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

In 2020, there was significant interaction between treatment and species on total C concentrations (Table 3.2). The carbon concentration in soils under white spruce and black spruce were significantly affected by the application of wood ash in 2020 (Table 3.3). For soils under black spruce in 2020, no differences in total soil C concentrations were identified in the orthogonal contrasts (Figure 3.4). However, for soils under white spruce in 2020 the application of ash to the soil had a significant effect but only at the level $p<0.10$ (L1; Figure 3.3). Application of the high carbon ash at the 10 000 kg ha^{-1} rate resulted in significantly higher soil carbon concentrations than when the ash was applied at 1000 kg ha^{-1} (L4; Figure 3.4).

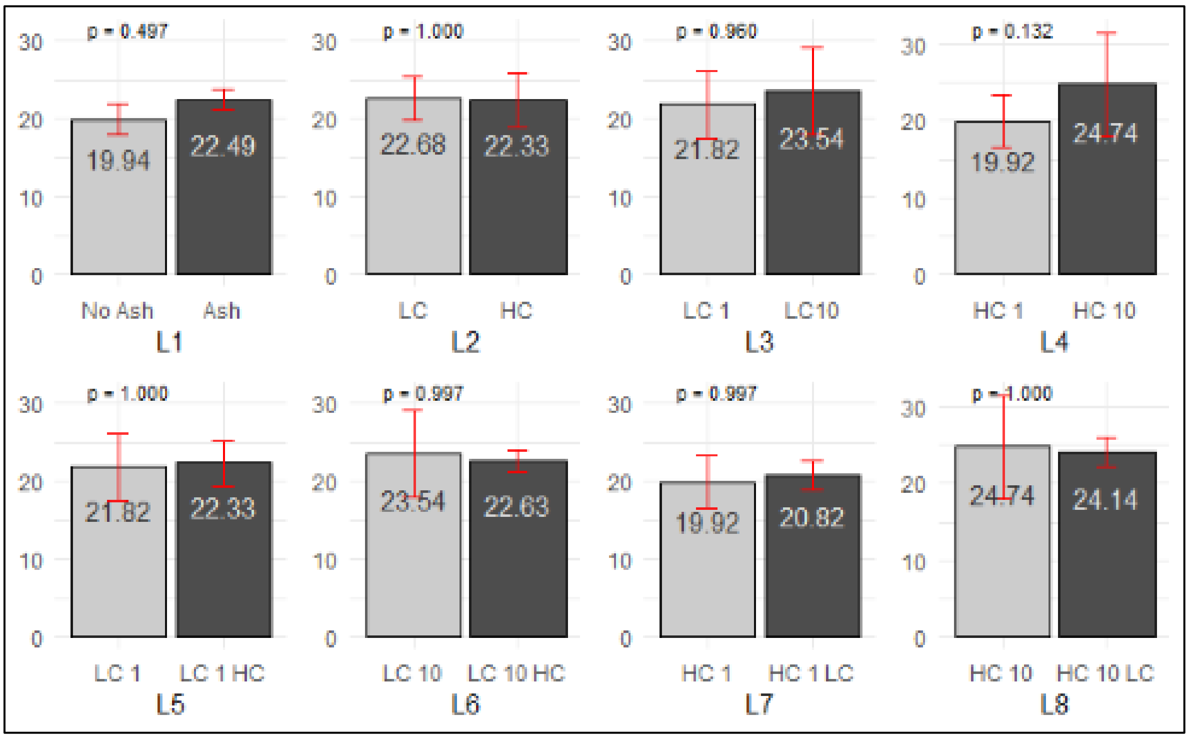

Figure 3.2. Orthogonal contrasts for the year 2020 in soils under black spruce (means and standard error of means), for total soil C (g kg^{-1} soil), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

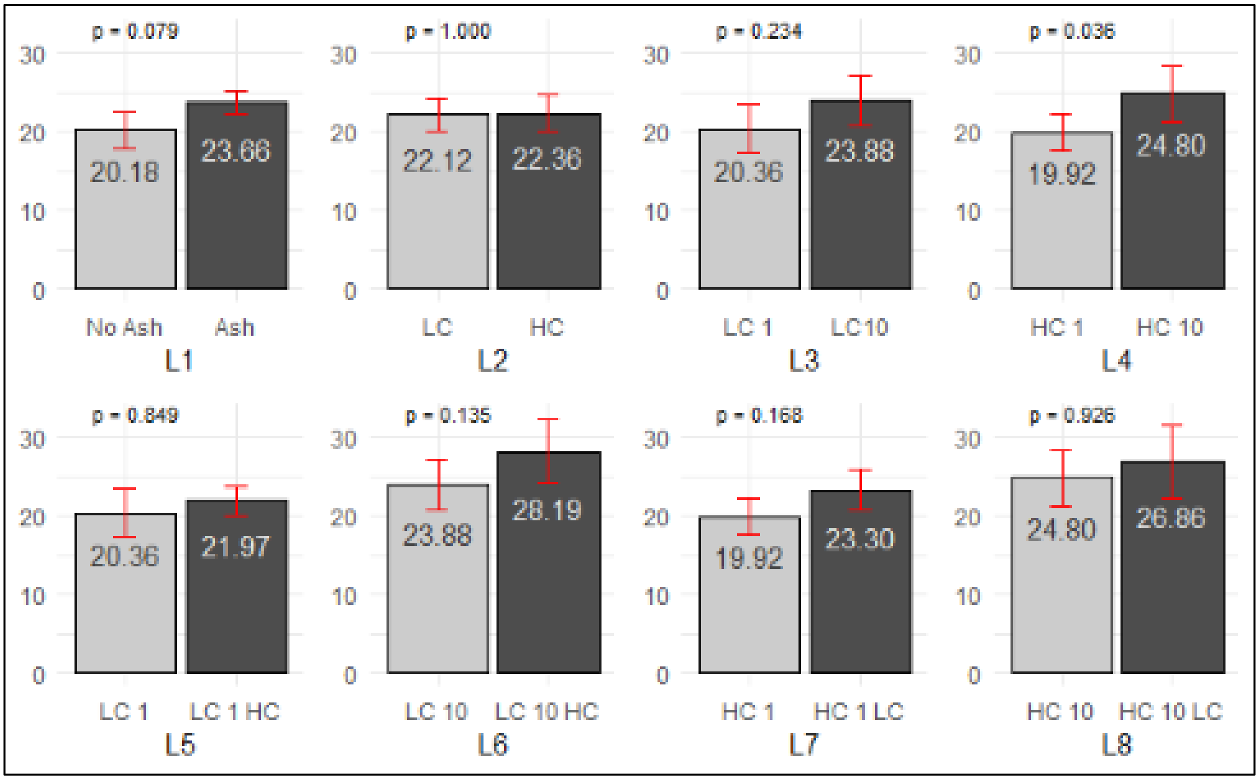

Figure 3.3. Orthogonal contrasts for the year 2020 in soils under white spruce (means and standard error of means), for total soil C (mg kg^{-1} soil), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

In both 2019 and 2020, treatment was the only significant effect on soil C:N (Table 3.2), with greater mean values in 2020. There was no species effect on soil C:N in 2020. In 2019, the application of ash resulted in significantly wider C:N and the C:N was significantly wider with the application of the high carbon ash at 10 000 kg ha^{-1} compared to the application of this ash at 1000 kg ha^{-1} (L1; Figure 3.4). In 2020, the application of the high carbon ash at the high loading rate compared to the low loading rate was still significantly wider and when the high carbon ash was added with the low carbon ash, the C:N was significantly wider (L4, L5; Figure 3.5).

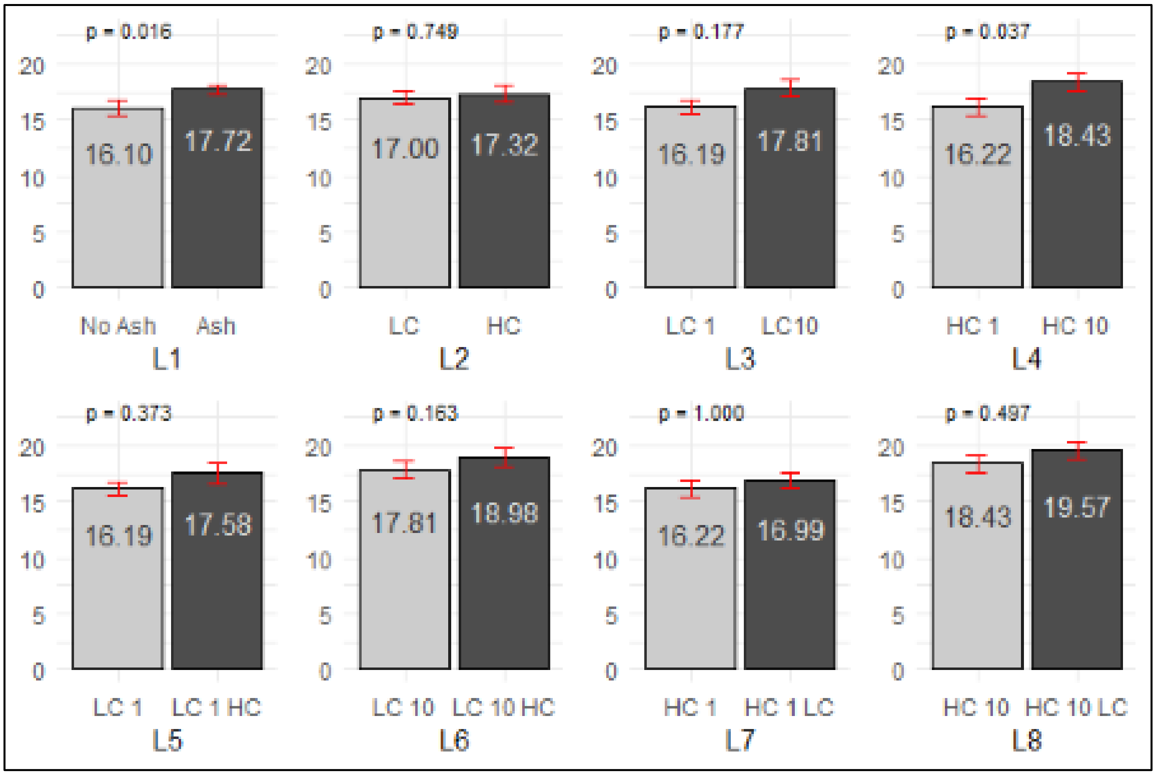

Figure 3.4. Orthogonal contrasts for the year 2019 (means and standard error of means) for soil C:N ratio, (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

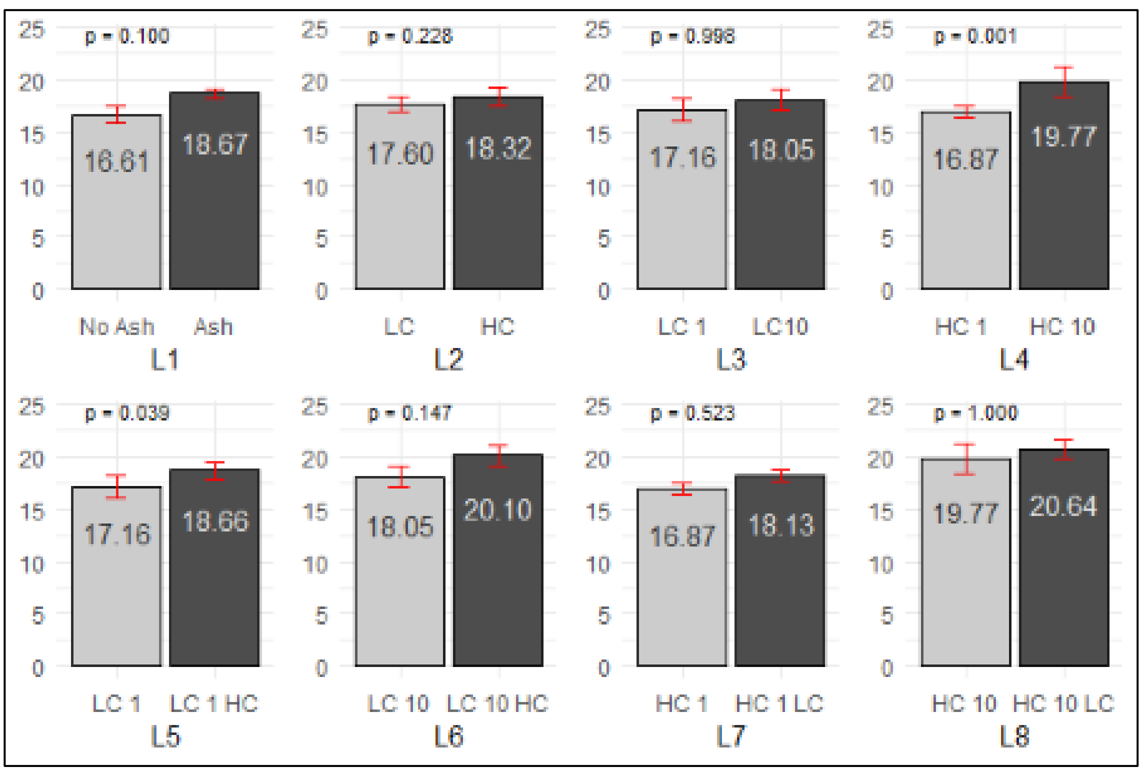

Figure 3.5. Orthogonal contrasts for the year 2020 (means and standard error of means), for soil C:N ratio, (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

3.1.2. Treatment by year and treatment by species interaction effects: Bulk density, conductivity, exchangeable Fe, K, P, and Zn

Significant treatment by year interactions were identified for bulk density, conductivity, extractable Fe, P and Zn, and exchangeable K (Table 3.1). There was also a significant treatment by species interaction effect for conductivity and exchangeable K (Table 3.1). There was no significant effect of treatment in 2019 or 2020 on exchangeable Fe and P (Table 3.5).

In 2019, there was no effect of treatment on bulk density (Table 3.5). There was an effect of wood ash treatment on bulk density in 2020 (Table 3.5) but linear contrasts were unsuccessful in finding significant variation (Figure 3.6). Application of ash generally decreased bulk density (Figure 3.6).

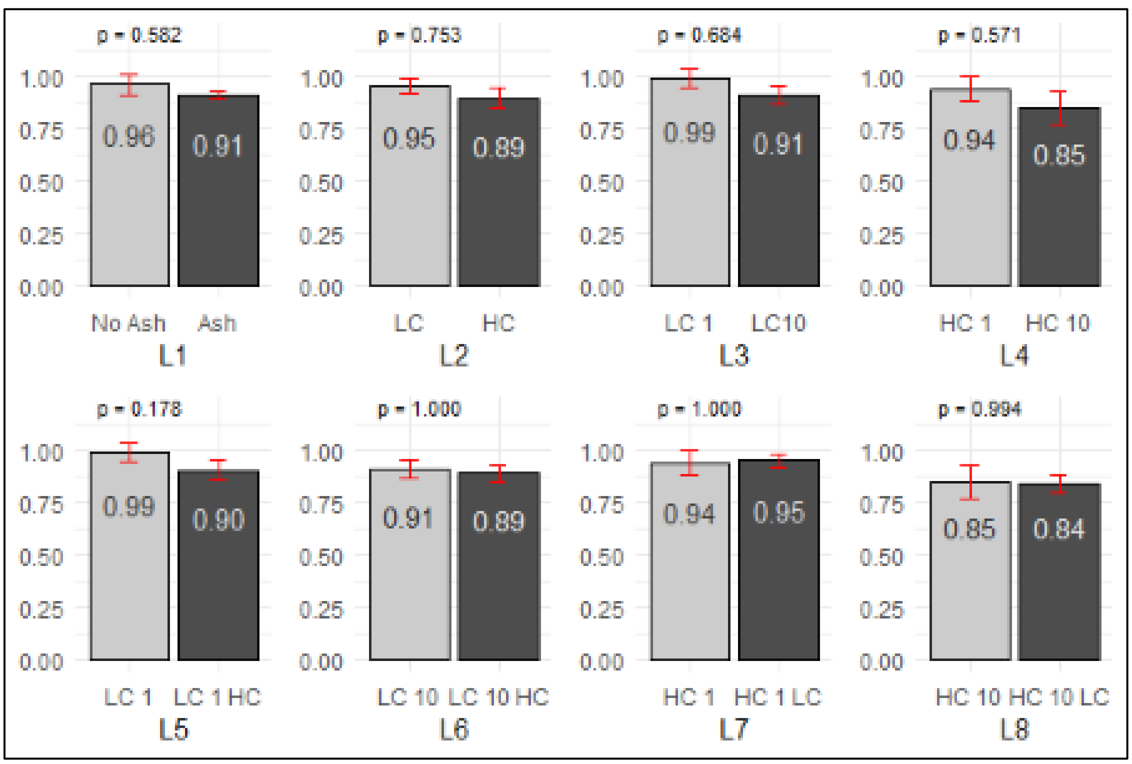

Figure 3.6. Orthogonal contrasts for 2020 (means and standard error of means), for soil bulk density (g/cm^3), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

There were significant wood ash treatment effects in 2019 and 2020 for conductivity, exchangeable K and extractable Zn (Table 3.5). In 2019 ash application to soil significantly increased conductivity (L1; Figure 3.7) and soils treated with low C ash had significantly higher conductivity than those that were treated with high C ash (L2; Figure 3.7). There was a significant difference in conductivity between low and high loading rates when either ash is applied alone to soil, where for both low and high C ash, higher loading rates resulted in higher conductivity (L3, L4; Figure 3.7). Low C ash applied at 1000 kg ha^{-1} had significantly lower conductivity than when it was applied in combination with high C ash (L5; Figure 3.7). High C ash applied at the low rate had significantly lower conductivity than when it was applied in combination with low C ash (L7; Figure 3.7). Finally, high C ash applied at 10 000 kg ha^{-1} loading rate had significantly lower conductivity than when it was applied in combination with low C ash (L8; Figure 3.7).

In 2020, soils receiving ash still had significantly higher conductivity than soils that did not receive ash (L1; Figure 3.8). Soils receiving the low carbon ash maintained significantly higher conductivity than the soils that received high carbon ash (L2; Figure 3.8). For low C ash, conductivity was significantly lower when 1000 kg ha^{-1} wood ash was applied compared to10 000 kg ha^{-1} (Figure 3.8). Finally, L7 and L8 contrasts show that soils where high C ash was applied at the low rate had significantly lower conductivity than when it was applied in combination with low C ash (L7, L8; Figure 3.8).

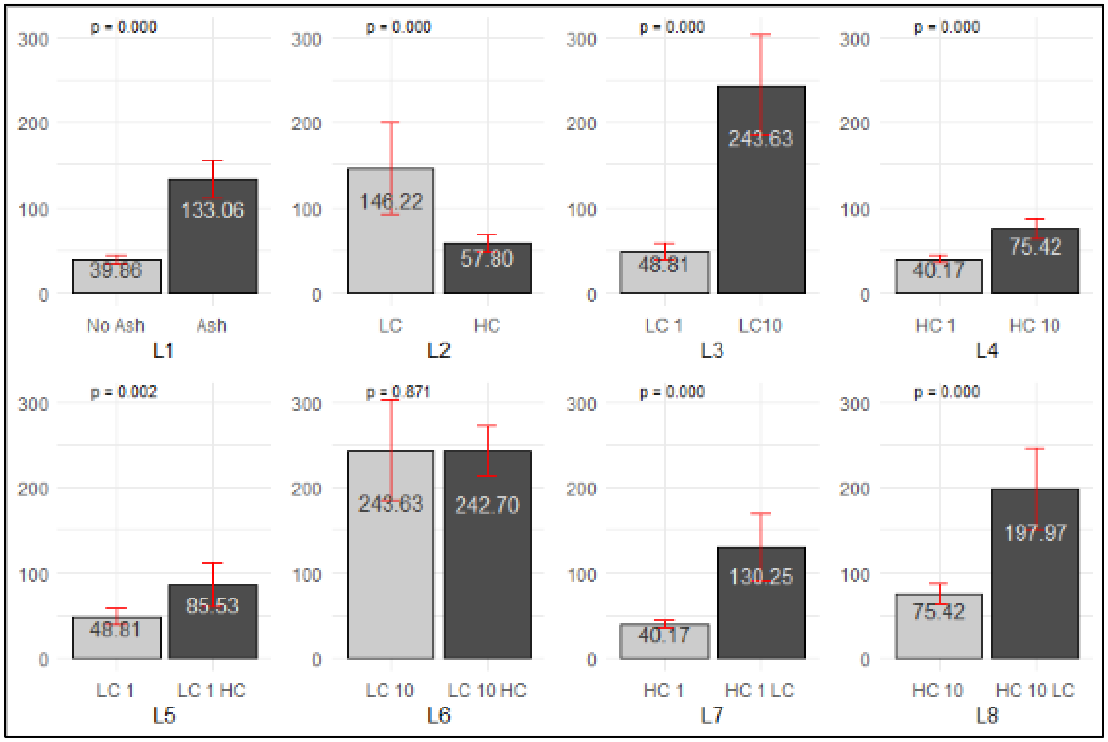

Figure 3.7. Orthogonal contrasts for the year 2019 (means and standard error of means) for soil conductivity (µS cm^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

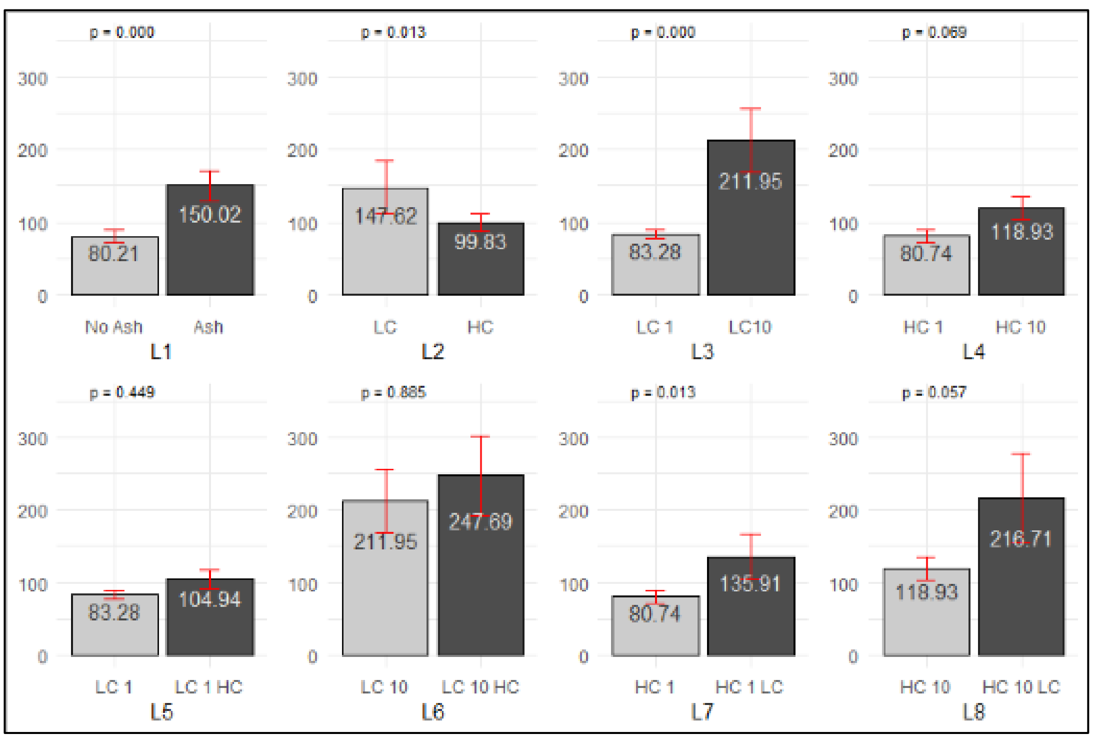

Figure 3.8. Orthogonal contrasts for the year 2020 (means and standard error of means) for soil conductivity (µS cm^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

Soils under both black and white spruce had significantly higher conductivity when wood ash was applied than when there was no ash application (L1; Figures 3.9 & 3.10). Soils under both species had lower conductivity when the high C ash was applied vs when low C ash was applied (L2; Figures 3.9 & 3.10). Under both species, soils that received the 10 000 kg ha^{-1} of either ash had higher conductivity than when that ash was applied at 1000 kg ha^{-1} (L3, L4; Figures 3.9 & 3.10). Under both black and white spruce, soils where low C ash was applied at 1000 kg ha^{-1} had significantly lower conductivity than where it was applied in combination with high C ash (L5; Figures 3.9 & 3.10). Both soils under white and black spruce which received high C ash application at low rate had significantly lower conductivity than when it was applied in combination with low C ash (L7; Figures 3.9 & 3.10). Finally, the L8 contrasts for soils under both species discovered that, high C ash applied at 10 000 kg ha^{-1} had significantly lower conductivity than when it was applied in combination with low C ash (L8; Figures 3.9 & 3.10).

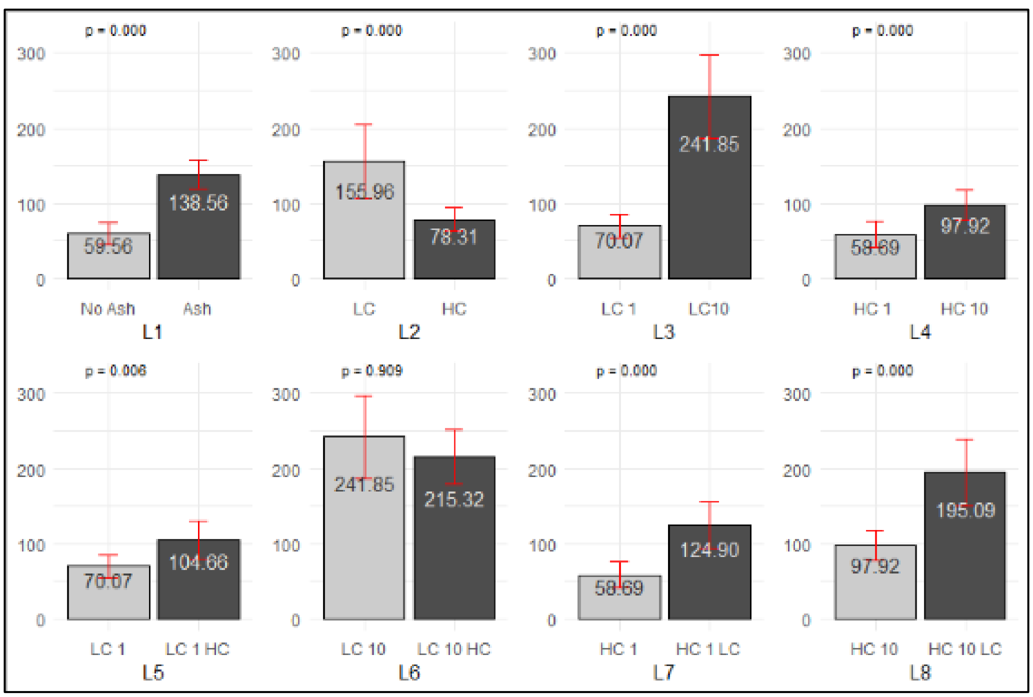

Figure 3.9. Orthogonal contrasts for soils under black spruce (means and standard error of means) for soil conductivity (µS cm^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

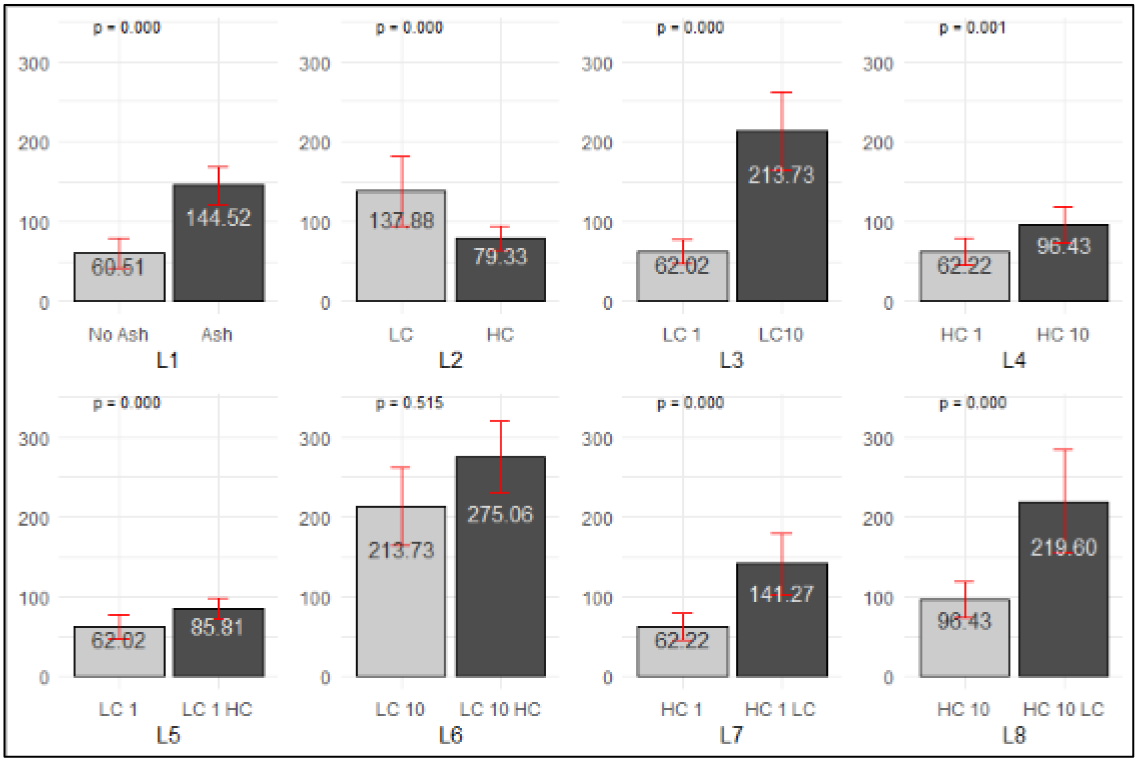

Figure 3.10. Orthogonal contrasts for soils under white spruce (means and standard error of means) for soil conductivity (µS cm^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

In 2019, wood ash application did not significantly affect exchangeable K concentrations when compared to soils that received no treatment (L1; Figure 3.11). Low C ash applied at 10 000 kg ha^{-1} resulted in higher exchangeable K concentrations than when the ash was applied at 1000 kg ha^{-1} but only at $p<0.10$ (L3; Figure 3.11).

In 2020 wood ash application significantly increased soil exchangeable K concentrations when compared to soils that received no ash (L1; Figure 3.12). Soils receiving low C ash had significantly higher exchangeable K concentrations than those where the high C ash was applied but only at $p<0.10$ (L2; Figure 3.12). Additionally, when applied at 10 000 kg ha^{-1}, both low and high C ash had significantly higher exchangeable K concentrations than when applied at 1000 kg ha^{-1} (L3, L4; Figure 3.12). When 1 000 kg ha^{-1} of high C ash is applied in combination with low

C ash, exchangeable K values are significantly greater than when 1000 kg ha^{-1} high C ash is applied alone (L7; Figure 3.12). Finally, when 10 000 kg ha^{-1} of high C ash is applied in combination with low C ash, soil exchangeable K values are significantly higher than when 10 000 kg ha^{-1} is applied alone (L8; Figure 3.12).

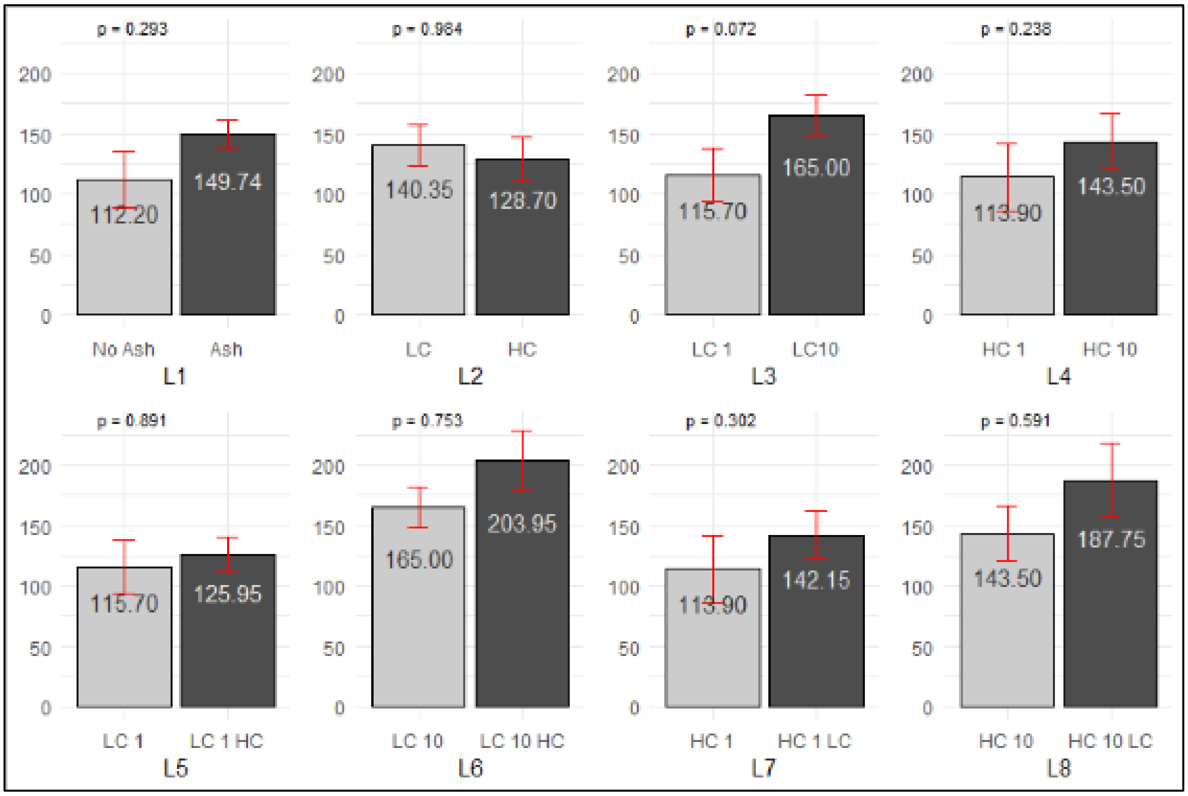

Figure 3.11. Orthogonal contrasts for the year 2019 (means and standard error of means) for exchangeable potassium (mg kg^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

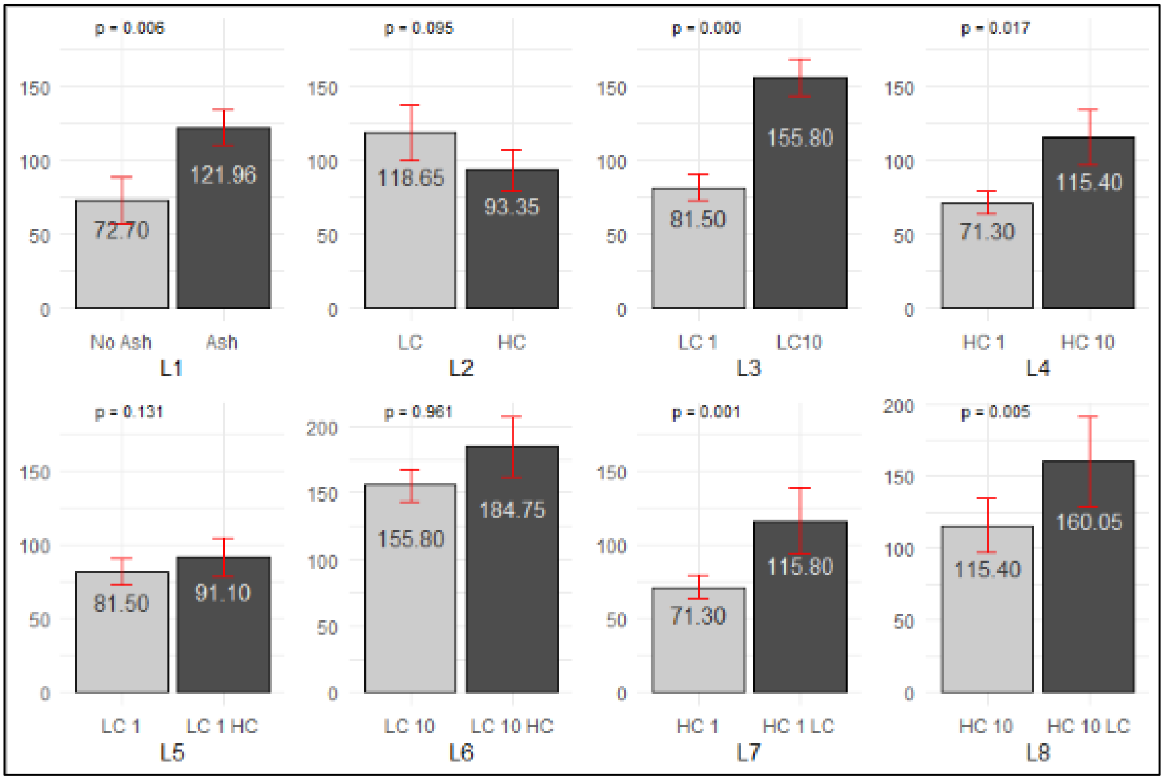

Figure 3.12. Orthogonal contrasts for the year 2020 (means and standard error of means) for exchangeable potassium (mg kg^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

In soils under black spruce, wood ash significantly increased exchangeable K concentrations compared to soils where no ash was applied but only at level $p<0.10$ (L1; Figure 3.13). Soils under black spruce receiving low C ash had significantly higher exchangeable K concentrations when ash was applied at 10 000 kg ha^{-1} when compared to 1000 kg ha^{-1} (L3; Figure 3.13). The same result was found for high C ash, however only at level $p<0.10$ (L4; Figure 3.13). Under black spruce when high C ash was applied at 1000 kg ha^{-1} in combination with low C ash, exchangeable K was significantly greater at $p<0.10$ than when 1000 kg ha^{-1} high C ash was applied alone (L7; Figure 3.13). Lastly, exchangeable K concentrations in soils under white spruce were significantly higher, at $p<0.10$, when ash was applied compared to soils that received no ash (L1; Figure 3.14).

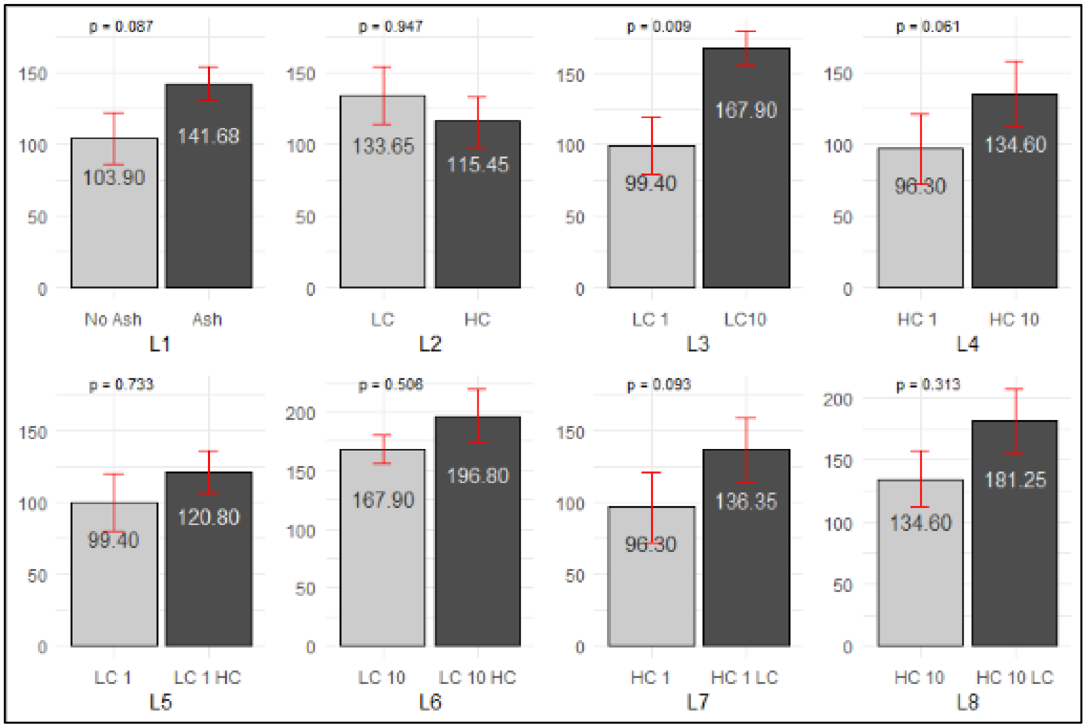

Figure 3.13. Orthogonal contrasts for soils under black spruce (means and standard error of means) for exchangeable potassium (mg kg^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

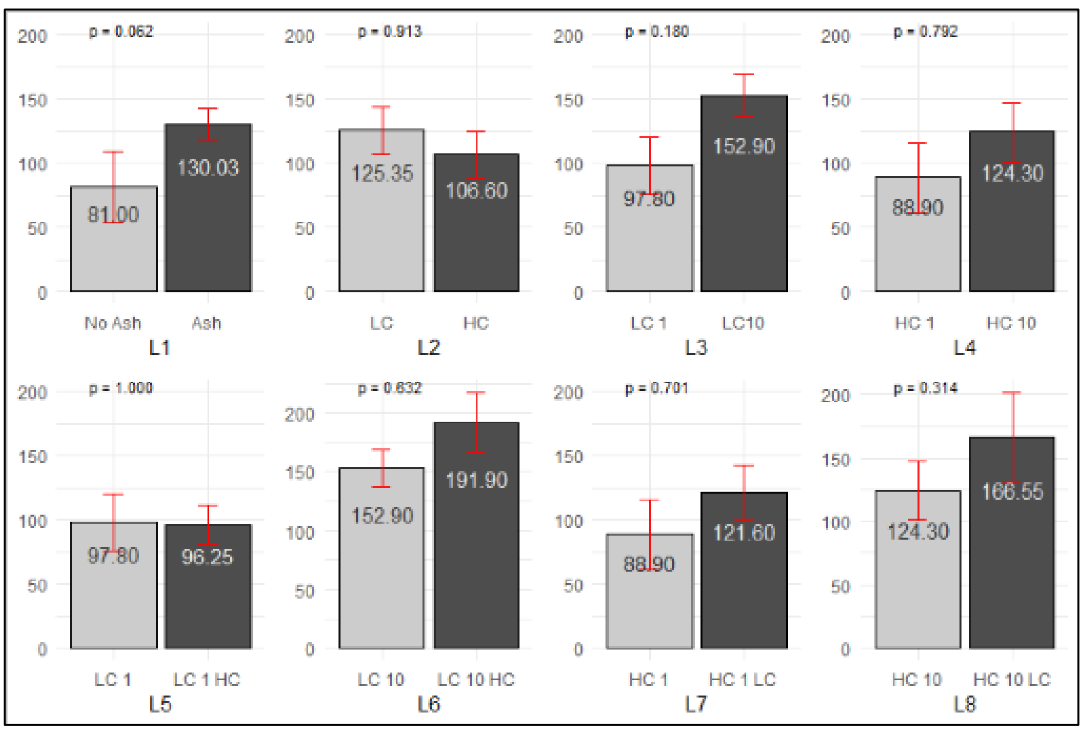

Figure 3.14. Orthogonal contrasts for soils under white spruce (means and standard error of means) for exchangeable potassium (mg kg^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

Orthogonal contrasts for soil extractable Zn in 2019 and 2020 data showed similar effects between years among the ash application treatments. The difference between years was that in 2020, soils receiving ash had significantly higher concentrations of extractable Zn than soils that did not receive ash (L1; Figures 3.15 & 3.16). In both 2019 and 2020 soils treated with low C ash had significantly greater extractable Zn concentrations (L2; Figures 3.15 & 3.16). In both years, the low C ash treatment resulted in significantly higher extractable Zn concentrations when applied at the 10 000 kg ha^{-1} compared to 1000 kg ha^{-1} (L3; Figures 3.15 & 3.16). Extractable Zn concentrations were significantly higher in 2019 and in 2020 when the high C ash was applied at 1000 kg ha^{-1} in combination with low C ash than when applied alone (L7; Figures 3.15 & 3.16). Finally, high C ash application at 10 000 kg ha^{-1} in both years resulting in significantly higher extractable Zn when applied in combination with low C ash than when applied alone (L8 Figures 3.15 & 3.16).

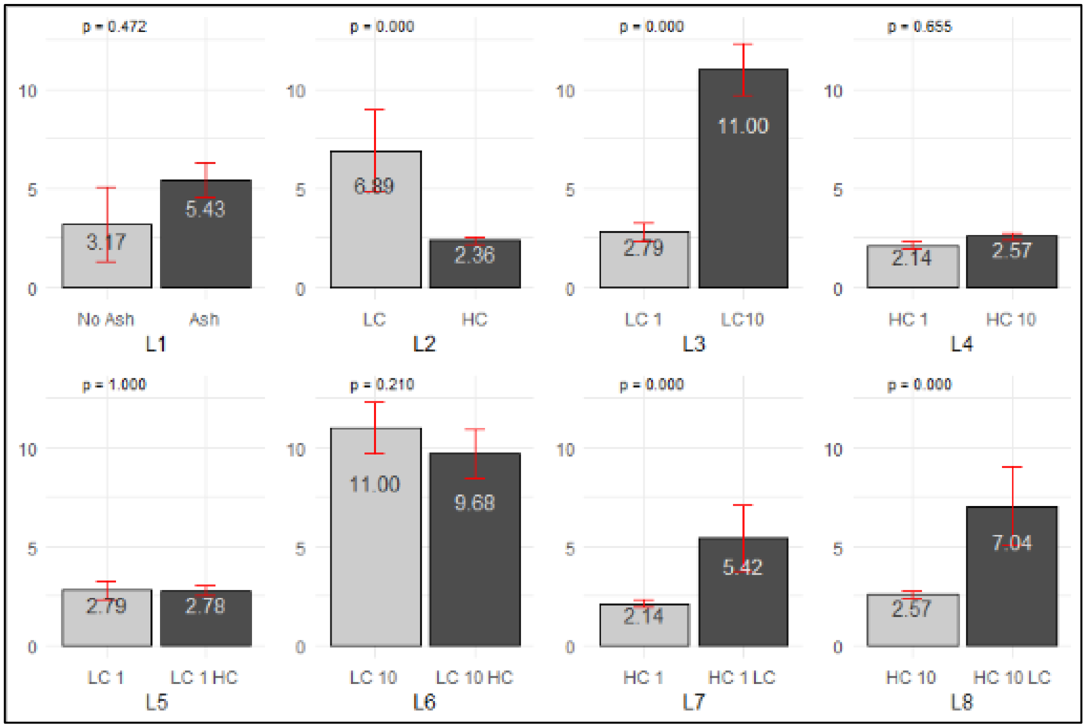

Figure 3.15. Orthogonal contrasts for soil in 2019 (means and standard error of means) and its extractable zinc (mg kg^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

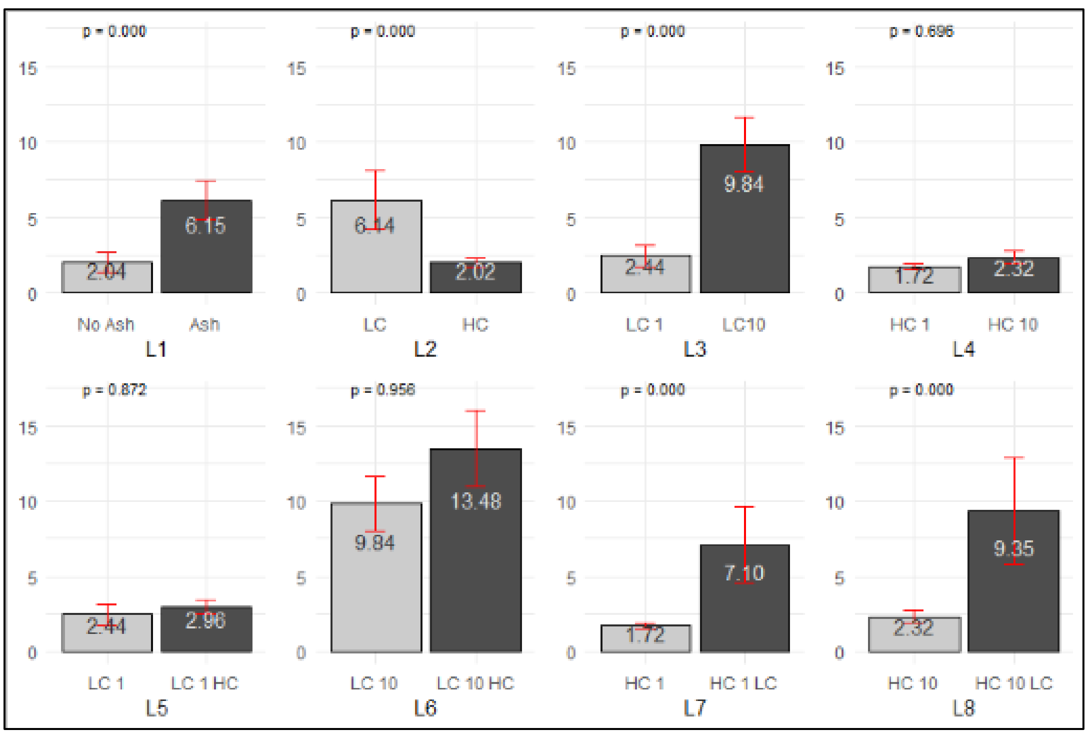

Figure 3.16. Orthogonal contrasts for soil in 2020 (means and standard error of means) and its extractable zinc (mg kg^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

3.1.3. Treatment Effects: pH, Extractable Cu and Mn, Exchangeable Ca and Na and Total Ca, S, and Sr

There was a significant effect of wood ash treatment on soil pH, extractable Cu and Mn, exchangeable Ca and Na, and total Ca, S, and Sr concentrations (Table 3.1).

Application of wood ash significantly increased soil pH compared to soils that received no ash (L1; Figure 3.17). There was no difference in soil pH between the low C and high C ash treatments (L2) but soil pH increased significantly at the higher loading rates for both ashes (L3-4, Figure 3.17). The application of a combination of ashes generally increased soil pH (L5, L7-8, Figure 3.17).

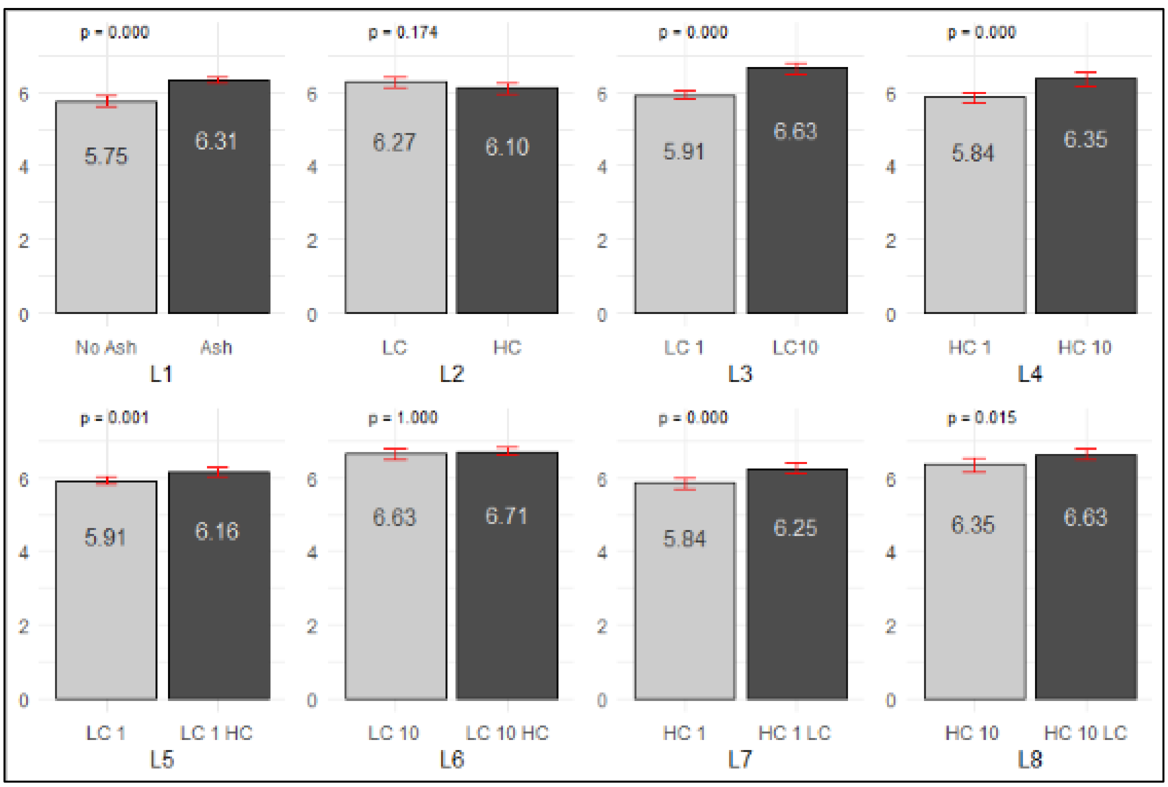

Figure 3.17. Orthogonal contrasts for soil pH (means and standard error of means), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

Concentrations of extractable Cu and Mn, exchangeable Mg, and total concentrations of Ca and Sr were significantly higher when the low carbon ash was applied at 10 000 kg ha^{-1} compared to 1 000 kg ha^{-1} (L3; Figures 3.18-3.22).

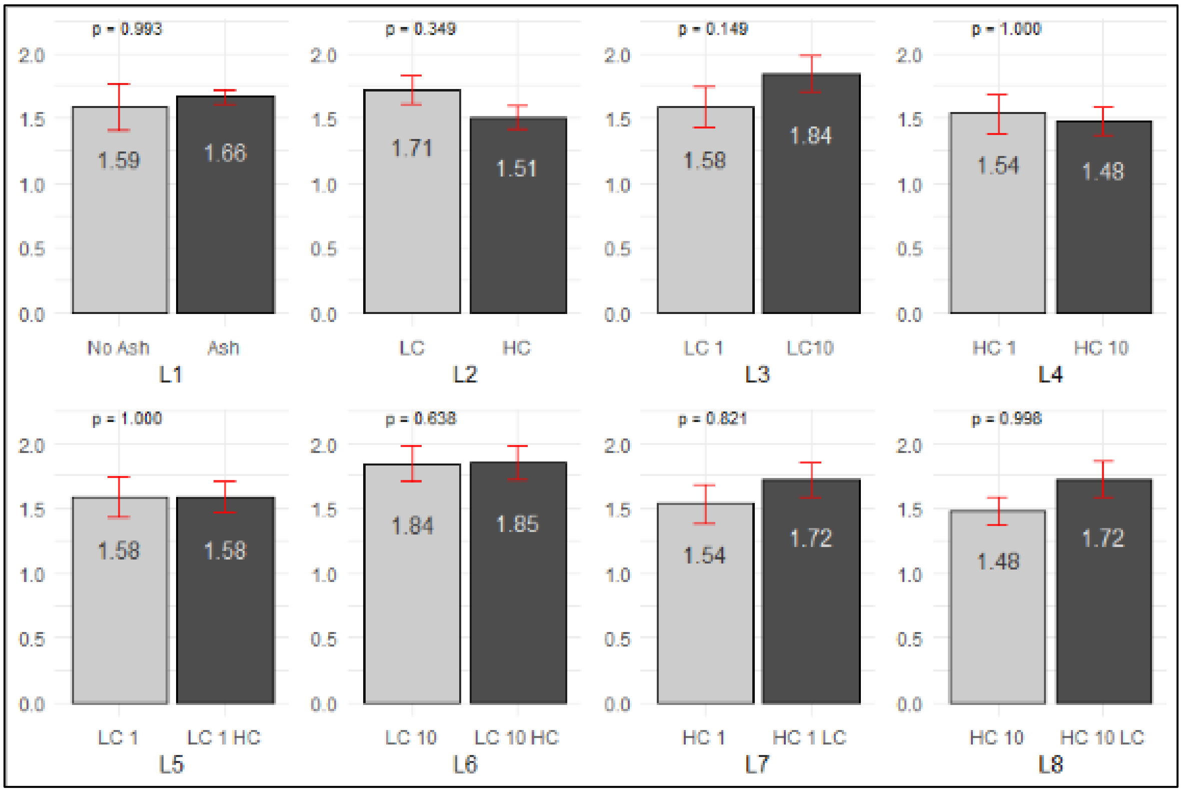

Figure 3.18. Orthogonal contrasts for soil extractable copper (mg kg^{-1}) (means and standard error of means), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

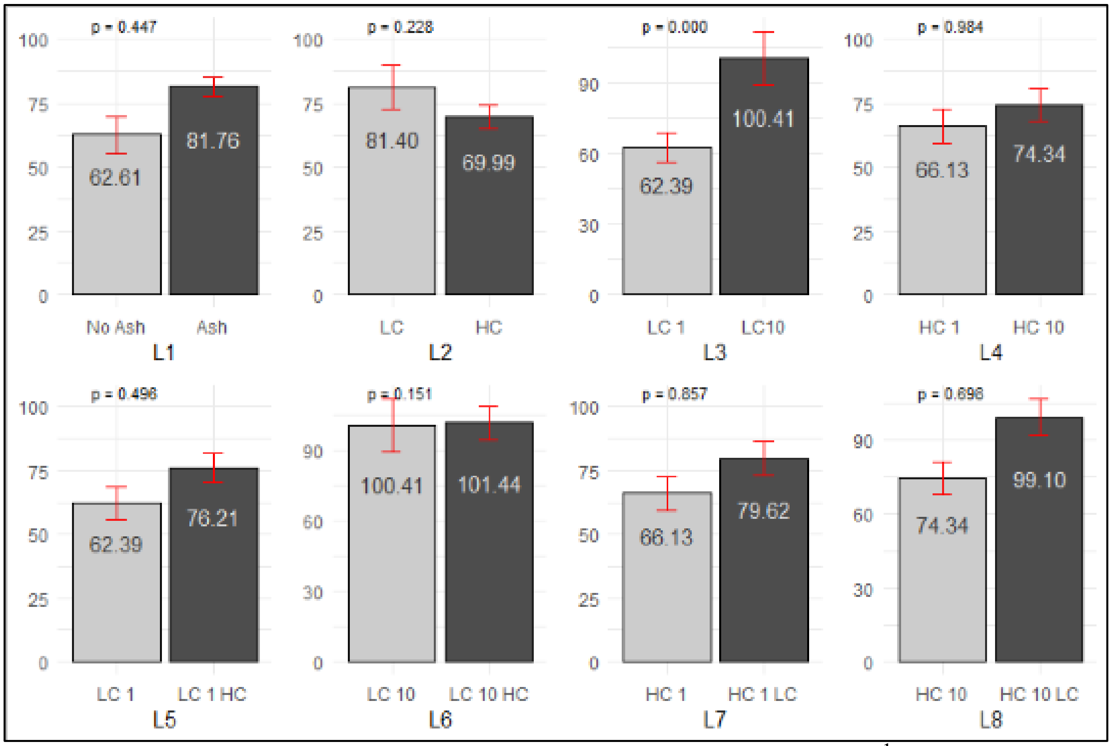

Figure 3.19. Orthogonal contrasts for soil extractable manganese (mg kg^{-1}) (means and standard error of means), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

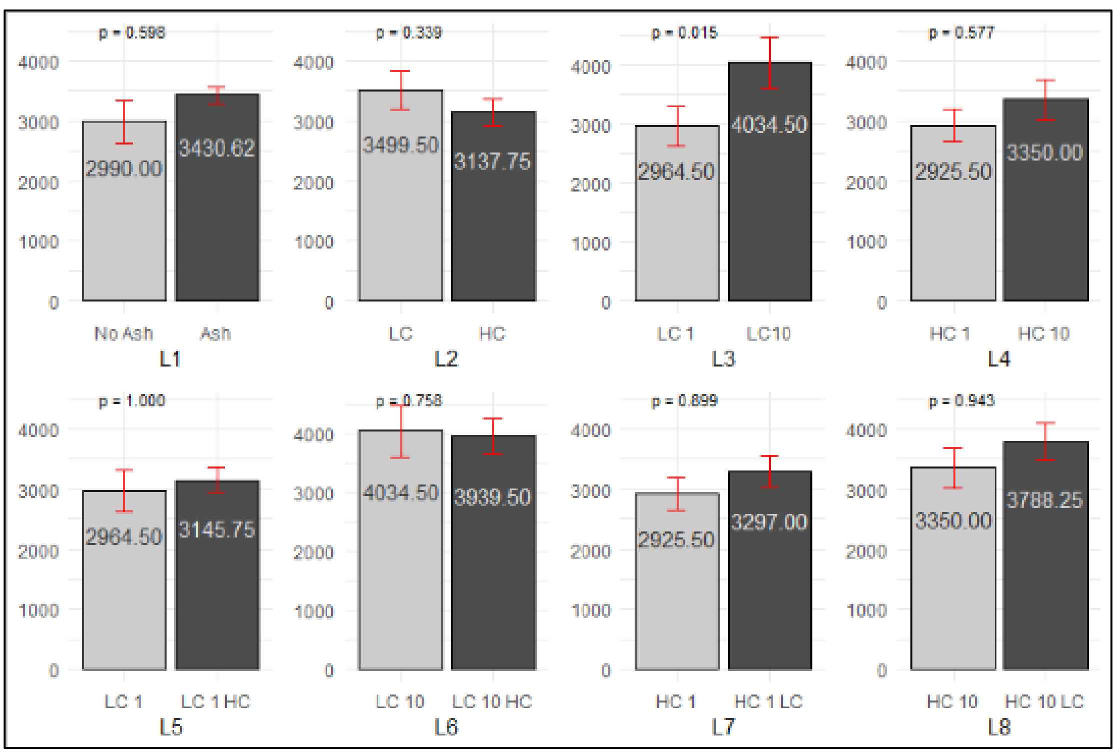

Figure 3.20. Orthogonal contrasts for soil total calcium (means and standard error of means) (mg kg^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

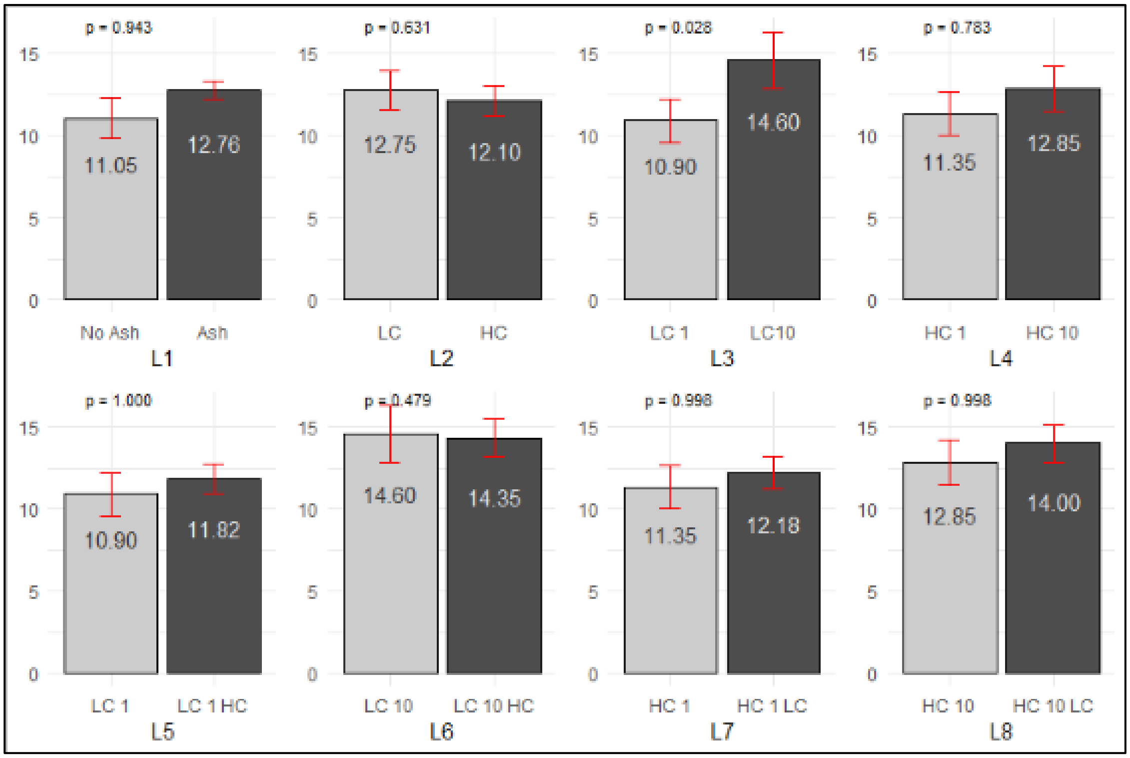

Figure 3.21. Orthogonal contrasts for soil total strontium (means and standard error of means) (mg kg^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

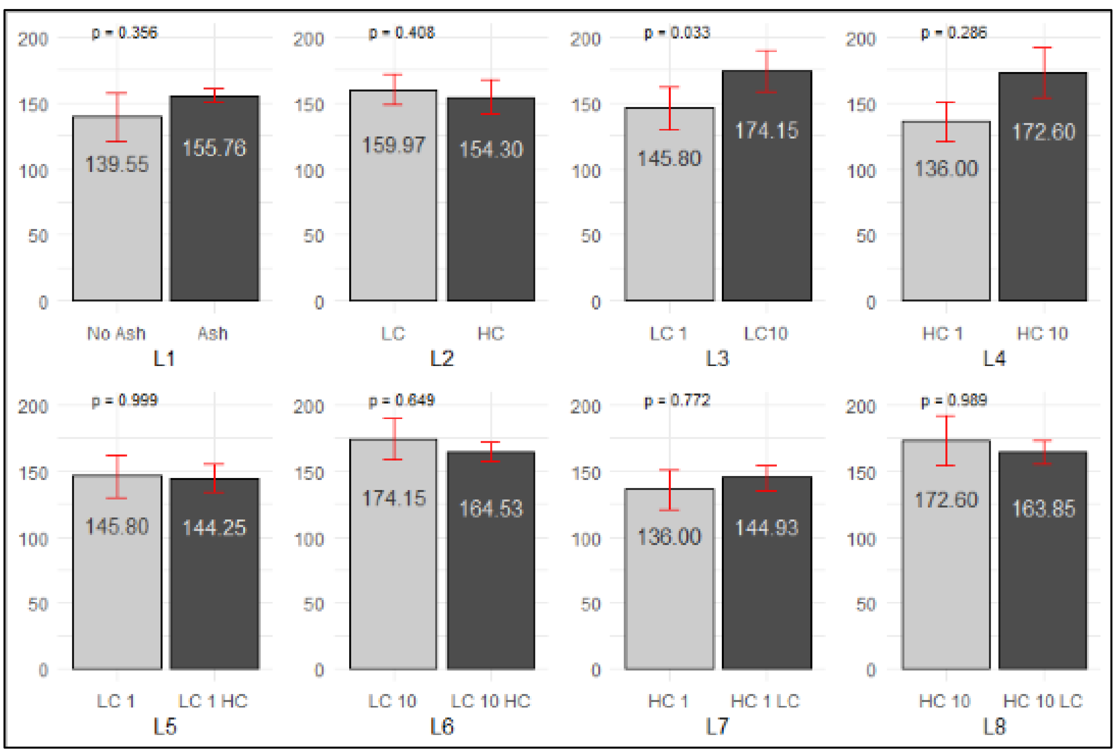

Figure 3.22. Orthogonal contrasts for soil exchangeable magnesium (means and standard error of means) (mg kg^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

Concentrations of total S in the soil were higher when low carbon ash was applied than when high carbon ash was applied (L2, Figure 3.23). Low carbon ash application at 10 000 kg ha^{-1} also resulted in significantly higher total S concentrations than when the low carbon ash was applied at 1000 kg ha^{-1} (L3, Figure 3.23).

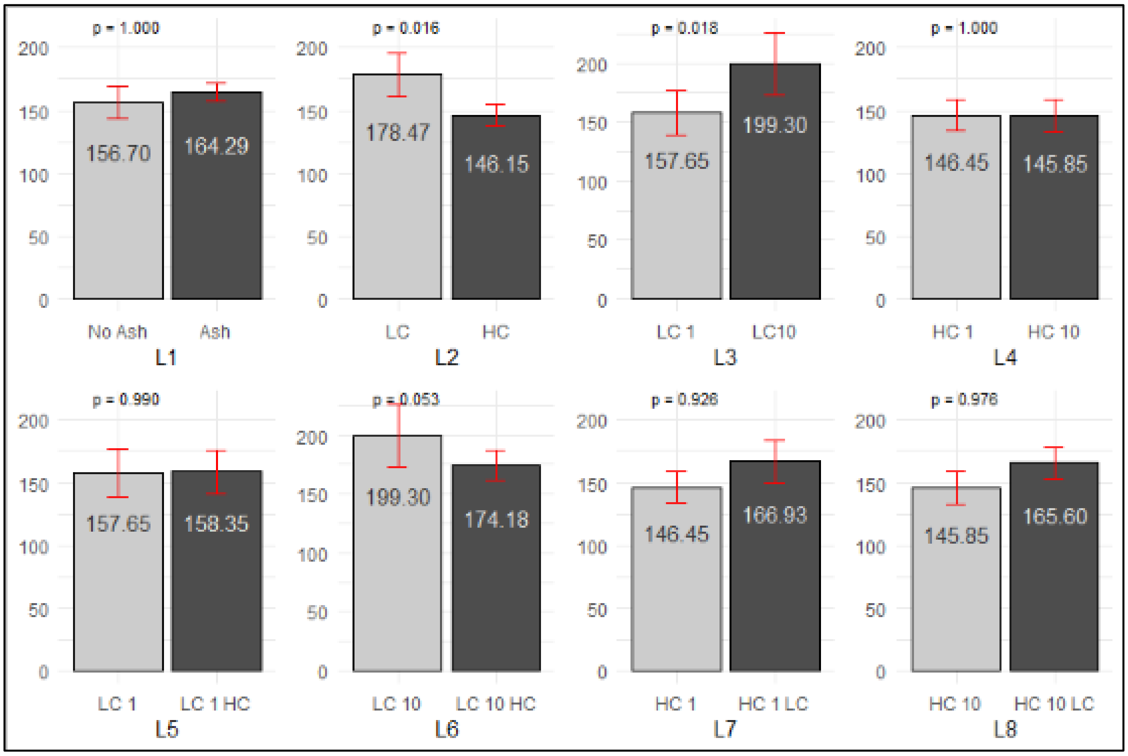

Figure 3.23. Orthogonal contrasts for soil total sulfur (means and standard error of means) (mg kg^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

Concentrations of exchangeable Ca in the soil were significantly higher when wood ash was applied to the soil than when it was not (L1, Figure 3.23) and were higher when the low carbon ash was applied compared to the high carbon ash (L2, Figure 3.23). Concentrations of exchangeable Ca were also significantly higher when ash was applied at the higher loading rate (L3-4, Figure 3.23). When the low carbon ash was applied with the high carbon ash at the low loading rate, concentrations of exchangeable Ca were higher than when the high carbon ash was applied alone at the same rate (L7, Figure 3.23). Finally, high C ash applied at 10 000 kg ha^{-1} had lower exchangeable Ca than when it was applied in combination with low C ash at $p > 0.10$ (L8, Figure 3.23).

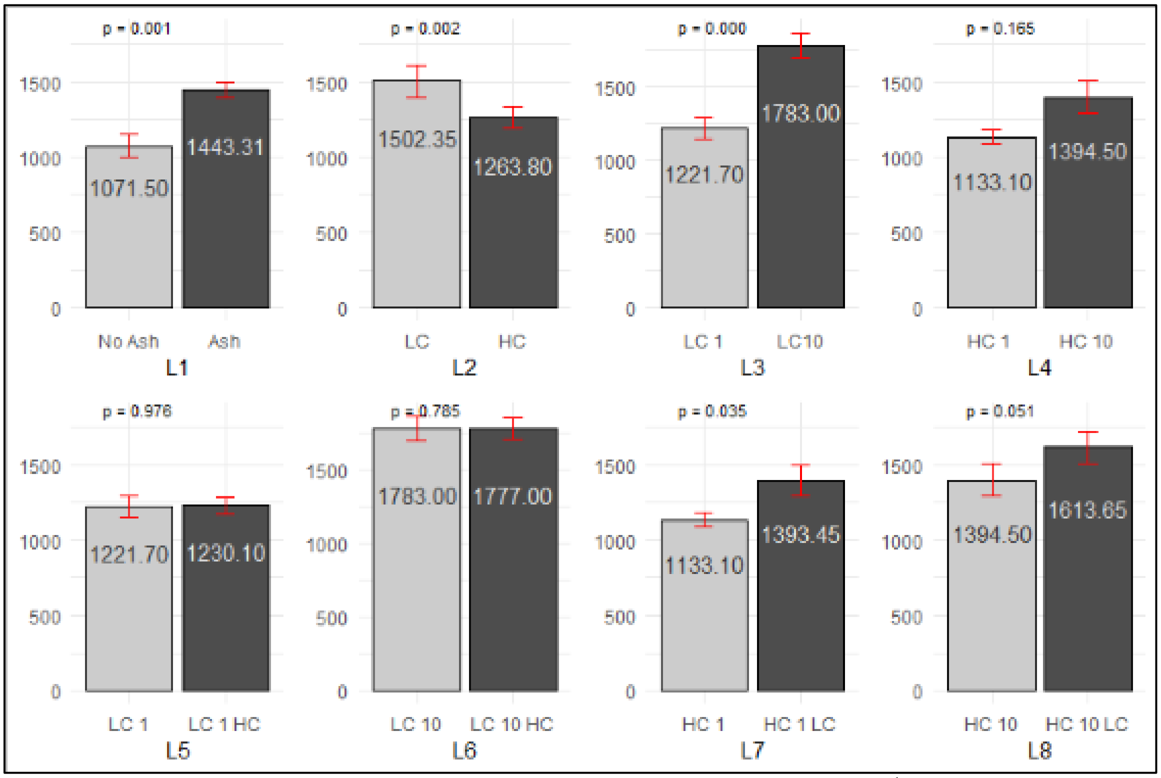

Figure 3.24. Orthogonal contrasts for soil exchangeable calcium (mg kg^{-1}) (means and standard error of means), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

Soil exchangeable Na was significantly higher when wood ash was applied to soils, though only at $p > 0.10$ (L1, Figure 3.25). Significantly greater exchangeable Na was observed in low C ash application of 10 000 kg ha^{-1} than at the 1000 kg ha^{-1} application rate (L2, Figure 3.25). Finally, high C ash applied at the high loading rate was significantly higher exchangeable Na when mixed with low C ash (L8, Figure 3.25).

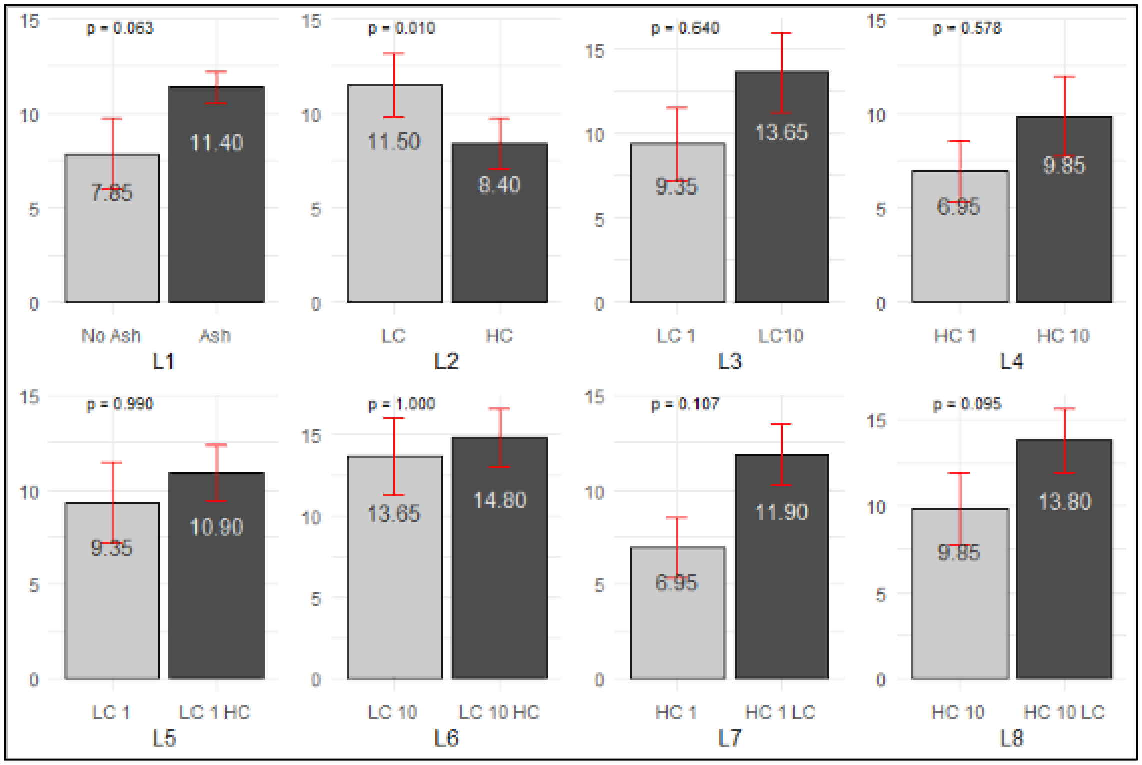

Figure 3.25. Orthogonal contrasts for soil exchangeable sodium (means and standard error of means) (mg kg^{-1}), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

3.1.4. Species by Year Interaction Effect: Conductivity, Total N, Extractable Fe, Mn and P, Exchangeable Ca and Mg, Total S, Al, Co, Cu, Mg, Mn, Ni, P, Pb

There was a significant species by year interaction effect for conductivity, extractable Fe, Mn, and P, exchangeable Ca and Mg, total S, Al, Co, Cu, Mg, Mn, N, Ni, P, Pb and (Table 3.1).

Conductivity, total N, extractable Fe, exchangeable Ca, and total Co were significantly higher values in 2020 than in 2019 for at least one species (Figure 3.26). Species had a significant effect on soil conductivity in both 2019 and 2020, and soil conductivity under both species was significantly affected by the year sampled (Table 3.6, Figure 3.26a). Total N concentrations were only significantly different between years for soil under white spruce (Table 3.6, Figure 3.26b). In both years, the concentration of soil N was higher in soils under black spruce than white spruce (Table 3.6, Figure 3.26b). Extractable Fe only differed significantly between species in 2020 (Table 3.6, Figure 3.26c), and extractable Fe in soil under both species were significantly affected by the year sampled (Table 3.6, Figure 3.26c). Total Co concentrations in soils under white spruce differed significantly between years (Table 3.6, Figure 3.26 e). In 2019, total Co concentrations were significantly higher under white spruce than black spruce (Table 3.6, Figure 3.26 e). There was no significant effect of either year on species or species on year for exchangeable Ca (Table 3.6).

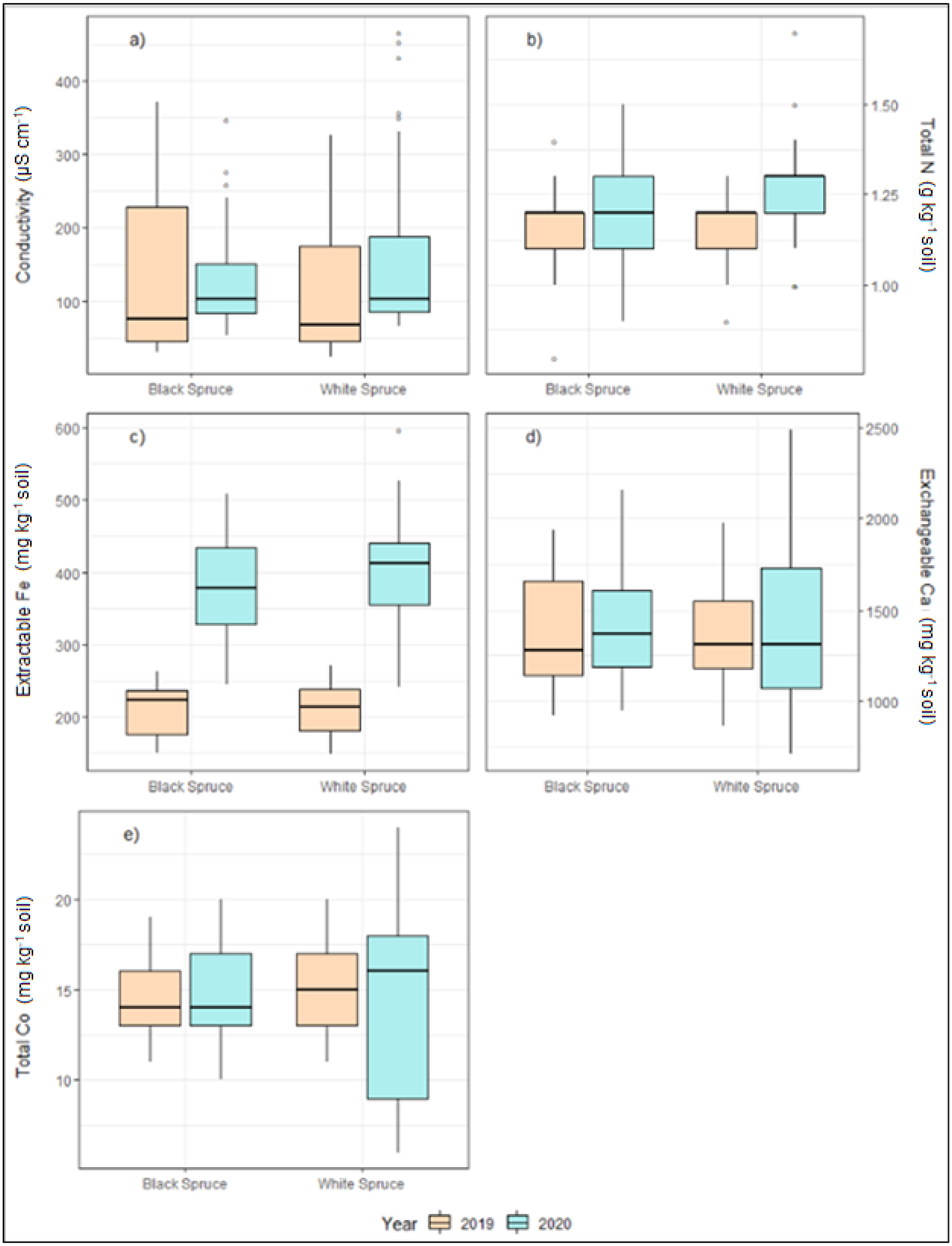

Figure 3.26. Boxplots of soil a) conductivity, b) total N, c) extractable Fe, d) exchangeable Ca, and e) total Co between species and years.

Exchangeable Mg, extractable Mn and P, and total Al, Cu, Mg, Mn, Ni, P, Pb, and S were greater in 2019 than in 2020 under at least one species (Figures 3.27, 3.28). Exchangeable Mg differed significantly between years in soils under white spruce (Table 3.6, Figure 3.27a). Both species had higher mean exchangeable Mg concentrations in 2019, and generally soils under black spruce had higher concentrations of exchangeable Mg (Figure 3.27a). In 2020, species had a significant effect on extractable P concentrations (Table 3.6). P concentrations in soils under white spruce differed significantly between years (Table 3.6, Figure 3.27b). Soil P concentrations were lower and less variable in 2020 than 2019 (Figure 3.27b). There was a significant effect of year for extractable Mn concentrations in soils under both species (Table 3.6, Figure 3.27c), but the concentrations only differed between species in 2019 (Table 3.6, Figure 3.27c). There was a significant effect of year on total soil Al concentrations in soils under both black and white (Table 3.6, Figure 3.27d). Total Cu concentrations under white spruce differed significantly between years and total Cu concentrations were generally higher than in soils under black spruce. (Table 3.6, Figure 3.27e). Concentrations of total Mg in soils under white spruce were significantly lower in 2020 than in 2019 (Table 3.6, Figure 3.27f) where soils under black spruce were un-affected by year sampled (Table 3.6). Additionally, in 2020, tree species had a significant effect on soil Mg, with higher concentrations under black spruce (Table 3.6, Figure 1.46b).

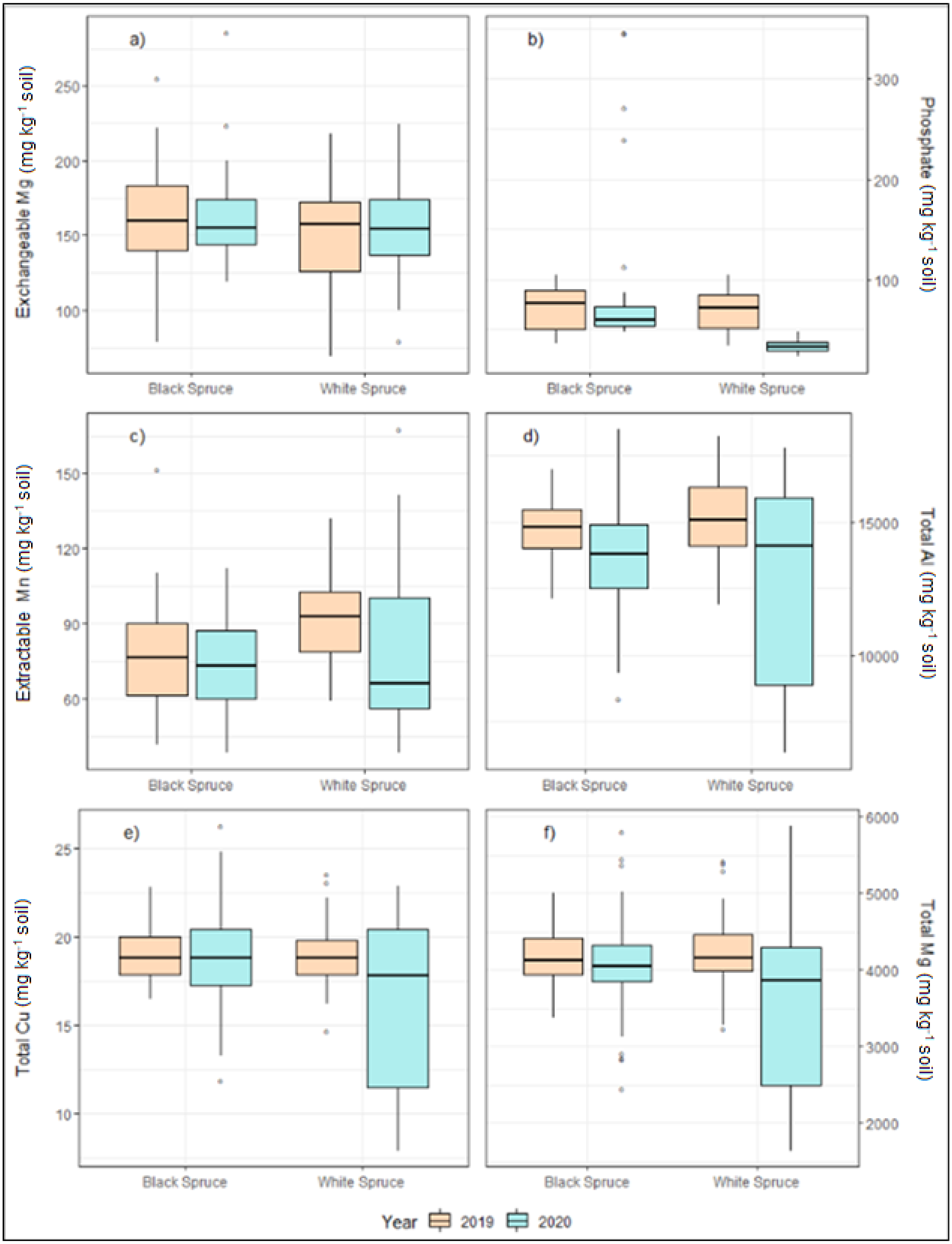

Figure 3.27. Boxplots of soil a) exchangeable Mg, b) extractable P (phosphate), c) extractable Mn, d) total Al, e) total Cu, and f) total Mg between species and years.

Concentrations of total Mn did not differ between years in soils under black spruce, but concentrations were significantly lower in 2020 than in 2019 for white spruce (Table 3.6; Figure 3.28a). Total soil Ni concentrations were significantly higher in 2020 than in 2019 under white spruce but there was no difference between years under black spruce (Table 3.6, Figure 3.28b). In 2020, there was a significant species effect on total soil P concentrations (Table 3.6), with lower means and broader interquartile ranges found under white spruce (Figure 3.28c). Total soil P concentrations under white spruce were significantly affected by which year they were sampled (Figure 3.28c), where soils under black spruce were un-affected by year sampled (Table 3.6). The concentration of total Pb in soils under white spruce differed significantly between years (Figure 3.28d). Total soil Pb concentration in 2020 differed significantly between species (Table 3.6), with lower mean values and greater interquartile range found under white spruce species (Figure 3.28d). Finally, total S in soils only under white spruce varied significantly with the year of sampling (Figure 3.28e) and in 2019 S in soils under black and white spruce varied significantly (Table 3.6), with greater concentrations in white spruce (Figure 3.28e).

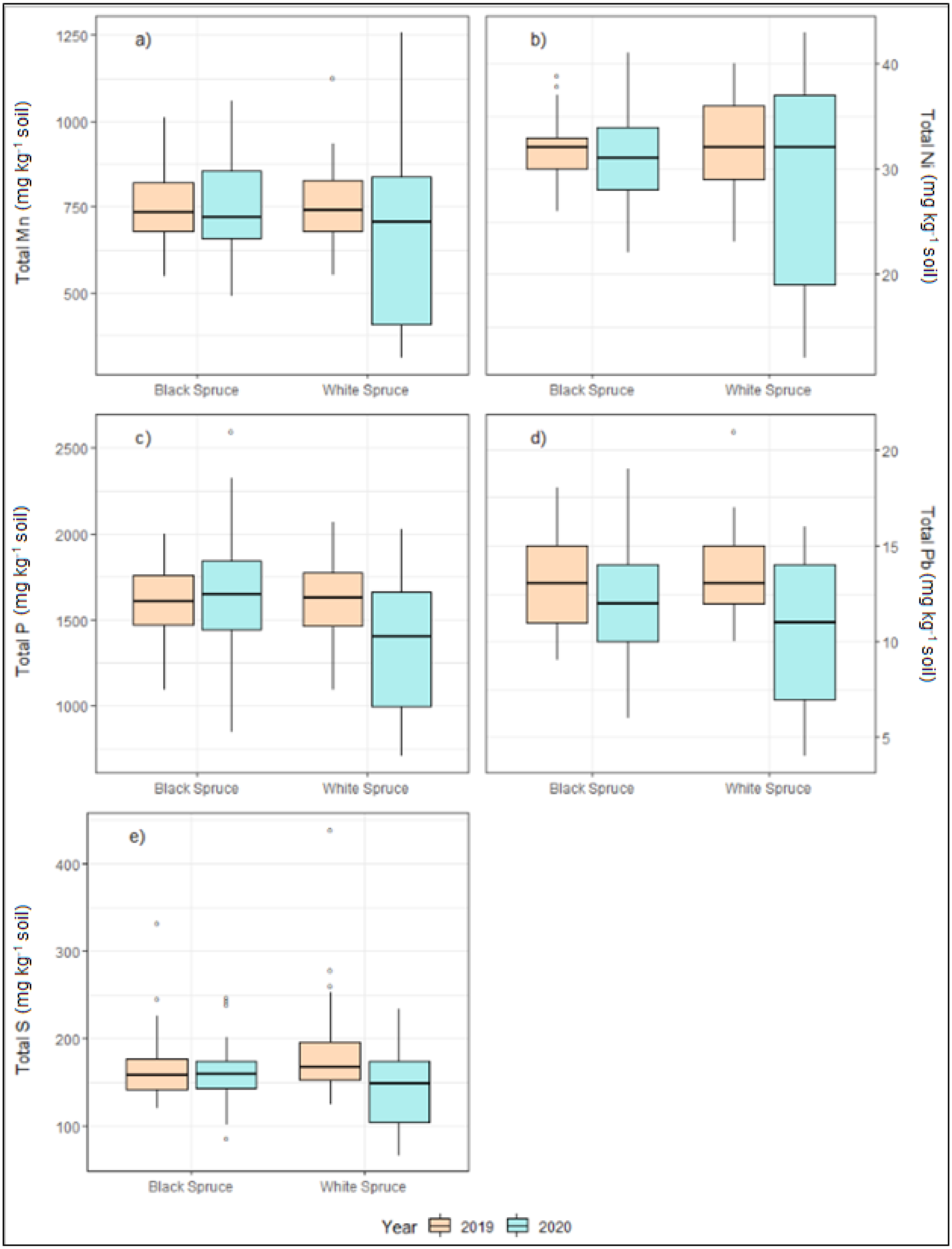

Figure 3.28. Boxplots of soil a) total Mn, b) total Ni, c) total P, d) total Pb, and e) total S, between species and years.

3.1.5. Year Effect: Extractable Cu, P, and Zn, Exchangeable K and Na, and Total soil As, Ca, Cr, K, Na, Sr, and Zn

There was a significant difference between years for bulk density, soil pH, extractable Cu, P, Zn, exchangeable K and Na, and total soil As, Ca, Cr, K, Na, Sr, and Zn (Table 3.1). Bulk density, extractable Cu and P and total As were significantly higher in 2020 (Figure 3.29). Soil pH, exchangeable Na, K, and total Ca, Cr, K, Na, Sr, and Zn were all significantly greater in 2019 (Figures 3.30, 3.31).

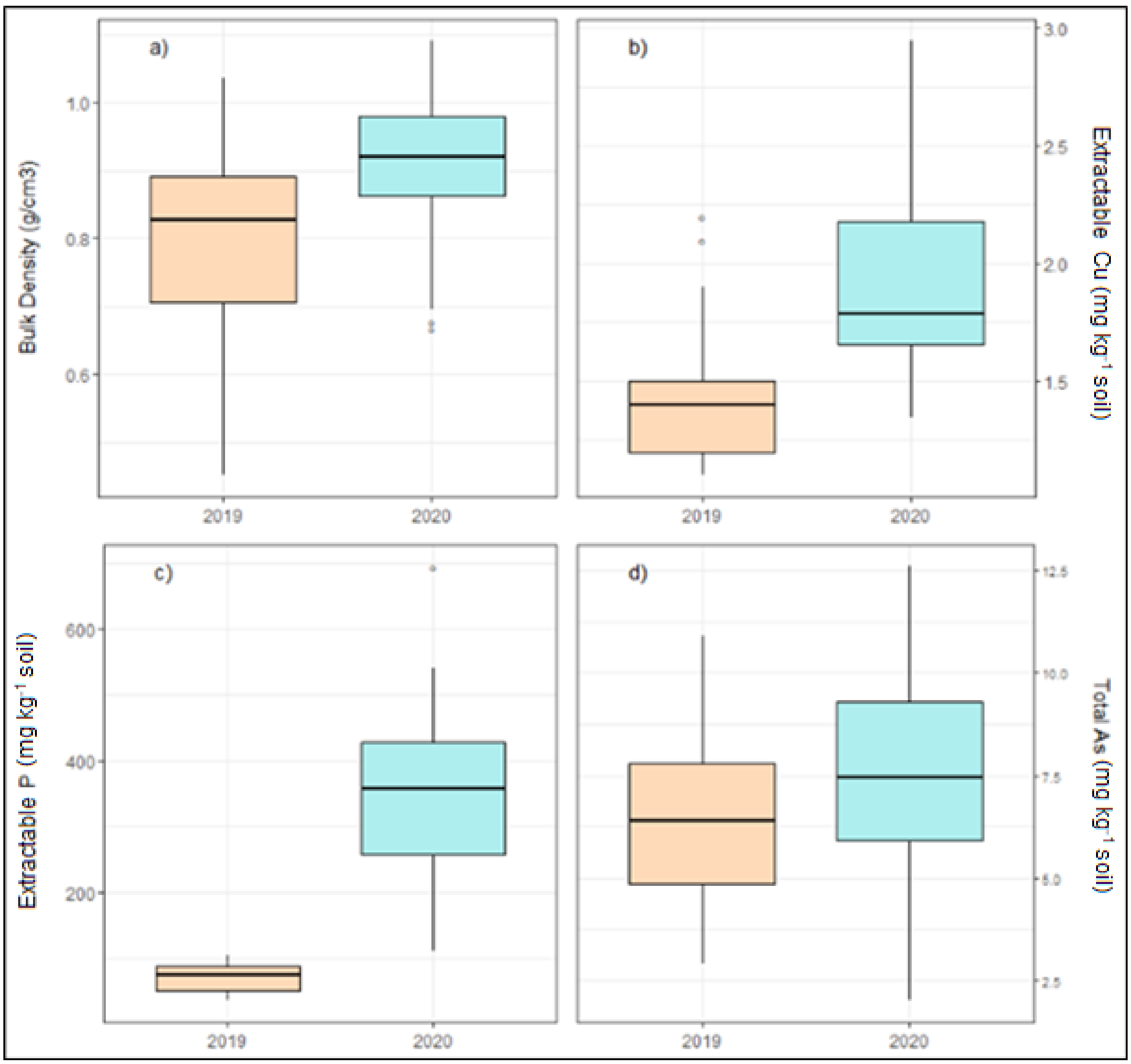

Figure 3.29. Boxplots of soil a) bulk density, b) extractable Cu, c) extractable P, and d) total As between years.

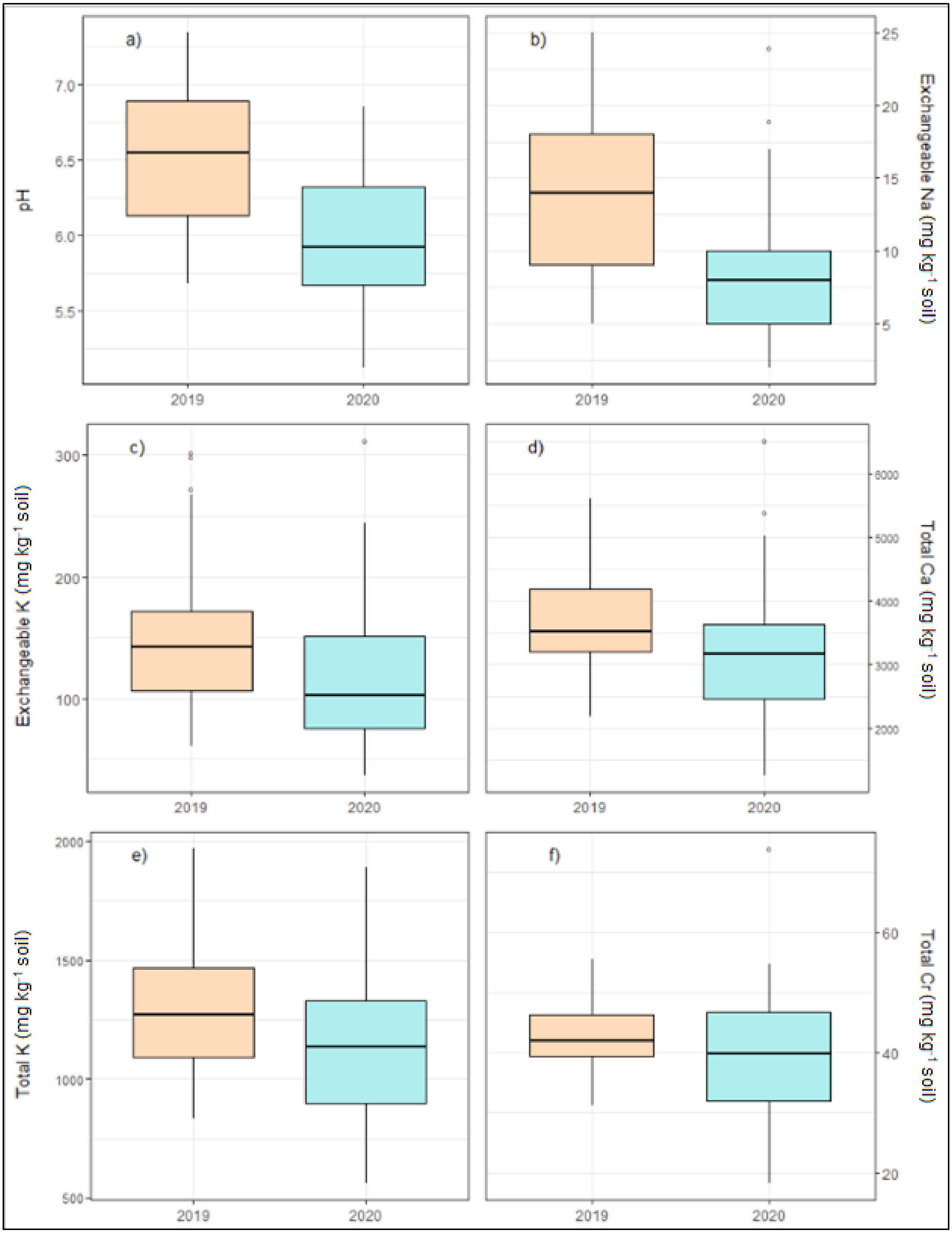

Figure 3.30. Boxplots of soil a) pH, b) exchangeable Na, c) exchangeable K, d) total Ca, e) total K, and f) total Cr in 2019 and 2020.

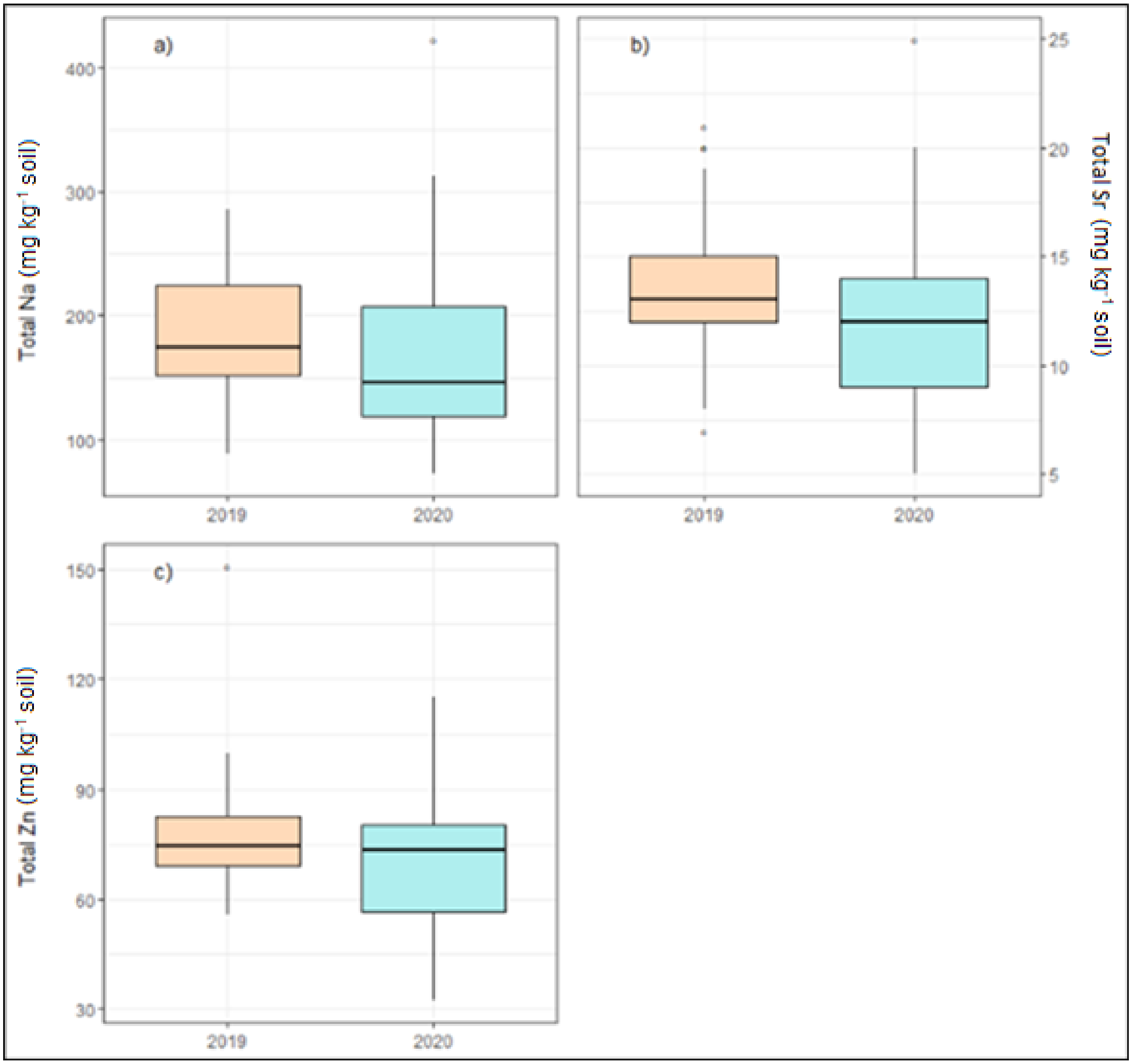

Figure 3.31. Boxplots of soil a) total Na, b) total Sr, and c) total Zn in 2019 and 2020.

3.1.6. Species Effect: Exchangeable K and Total Na

Concentrations of exchangeable K and total soil Na differed significantly between species (Table 3.1). Greater exchangeable K was observed under black spruce, where greater total Na was found under white spruce (Figure 3.32).

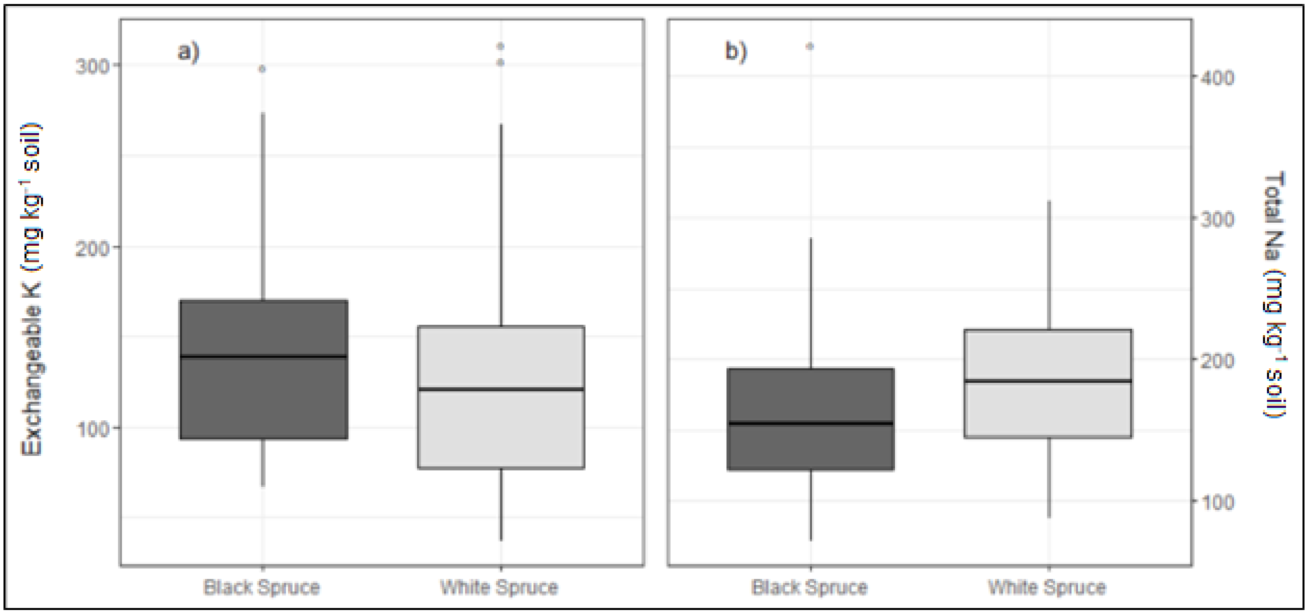

Figure 3.32. Boxplots of soil a) exchangeable K, and b) total Na under black and white spruce.

Table 3.1. The F-statistics and probability levels from the mixed linear model to test for the effects of ash addition treatment, tree species, year and their interaction on soil properties and chemistry. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator. e=extractable or exchangeable

	Treatment				Species				Year			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Bulk density	8	36	1.20	0.324	1	108	1.69	0.196	1	108	57.17	0.000
Conductivity	8	144	139.59	0.000	1	144	0.01	0.928	1	144	77.52	0.000
Phosphate	8	36	0.48	0.860	1	108	74.48	0.000	1	108	54.07	0.000
TN	8	36	0.74	0.659	1	108	5.86	0.017	1	108	28.38	0.000
TC	8	36	5.56	0.000	1	108	1.27	0.262	1	108	68.67	0.000
C:N	8	36	19.48	0.000	1	108	1.85	0.177	1	108	27.02	0.000
pH	8	36	67.31	0.000	1	108	1.39	0.242	1	108	648.90	0.000
eCa	8	36	18.80	0.000	1	108	2.31	0.132	1	108	1121.53	0.000
eCu	8	36	3.61	0.004	1	108	1.50	0.223	1	108	264.96	0.000
eFe	8	36	0.38	0.926	1	108	2.90	0.092	1	108	1909.54	0.000
eK	8	36	19.87	0.000	1	108	24.77	0.000	1	108	98.24	0.000
eMg	8	36	3.32	0.006	1	108	0.08	0.784	1	108	186.63	0.000
eMn	8	35.1	9.43	0.000	1	78.04	16.99	0.000	1	91.75	28.32	0.000
eNa	8	36	10.36	0.000	1	108	2.82	0.096	1	108	124.47	0.000
eP	8	36	0.71	0.683	1	108	0.19	0.664	1	108	5919.69	0.000
eZn	8	36	61.64	0.000	1	108	0.00	0.958	1	108	0.67	0.416
Al	8	144	0.11	0.999	1	144	0.50	0.480	1	144	26.08	0.000
As	8	36.6	0.73	0.666	1	107	0.17	0.679	1	107	16.10	0.000
Ca	8	144	7.92	0.000	1	144	0.63	0.429	1	144	26.98	0.000
Co	8	36	0.05	1.000	1	108	0.28	0.600	1	108	1.94	0.167
Cr	8	36	0.06	1.000	1	108	1.25	0.267	1	108	10.65	0.001
Cu	8	36	0.29	0.966	1	108	7.82	0.006	1	108	8.30	0.005
Fe	8	36	0.09	0.999	1	108	1.54	0.218	1	108	1.85	0.177
K	8	144	1.70	0.102	1	144	2.05	0.154	1	144	14.93	0.000
Mg	8	36	0.27	0.971	1	108	4.14	0.044	1	108	15.79	0.000
Mn	8	36	0.13	0.997	1	108	6.80	0.010	1	108	7.08	0.009
Na	8	144	1.01	0.430	1	144	7.21	0.008	1	144	10.94	0.001
Ni	8	36	0.06	1.000	1	108	2.74	0.101	1	108	10.86	0.001
P	8	36	0.74	0.658	1	108	10.07	0.002	1	108	8.51	0.004
Pb	8	36	0.23	0.982	1	108	2.73	0.102	1	108	26.40	0.000
S	8	144	3.11	0.003	1	144	1.12	0.292	1	144	16.97	0.000
Sr	8	144	5.46	0.000	1	144	0.22	0.637	1	144	15.42	0.000
Zn	8	36	0.87	0.547	1	108	2.11	0.149	1	108	21.86	0.000

Table 3.1. continued. The F-statistics and probability levels from the mixed linear model to test for the effects of ash addition treatment, tree species, year and their interaction on soil properties and chemistry. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator. e=extractable or exchangeable

	Treatment*Species				Treatment*Year				Species*Year			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Bulk density	8	108	0.36	0.939	8	108	2.68	0.010	1	108	0.20	0.659
Conductivity	8	144	2.64	0.010	8	144	10.27	0.000	1	144	16.21	0.000
Phosphate	8	108	0.46	0.880	8	108	1.43	0.192	1	108	66.80	0.000
TN	8	108	1.55	0.147	8	108	1.47	0.178	1	108	8.44	0.004
TC	8	108	1.44	0.187	8	108	1.19	0.312	1	108	4.59	0.034
C:N	8	108	0.93	0.498	8	108	0.70	0.692	1	108	0.17	0.684
pH	8	108	1.16	0.328	8	108	1.37	0.216	1	108	0.67	0.413
eCa	8	108	1.46	0.180	8	108	1.57	0.143	1	108	5.30	0.023
eCu	8	108	1.05	0.404	8	108	1.21	0.298	1	108	1.10	0.296
eFe	8	108	1.12	0.355	8	108	2.51	0.015	1	108	4.63	0.034
eK	8	108	2.28	0.027	8	108	3.53	0.001	1	108	0.78	0.378
eMg	8	108	0.84	0.572	8	108	0.93	0.493	1	108	12.41	0.001
eMn	8	78.04	0.78	0.625	8	89.80	1.24	0.287	1	78.04	7.74	0.007
eNa	8	108	1.23	0.287	8	108	0.70	0.695	1	108	0.59	0.443
eP	8	108	0.70	0.688	8	108	2.69	0.010	1	108	2.12	0.148
eZn	8	108	1.78	0.089	8	108	3.93	0.000	1	108	1.56	0.215
Al	8	144	0.71	0.685	8	144	0.25	0.981	1	144	4.47	0.036
As	8	106.98	1.38	0.216	8	106.98	1.22	0.292	1	107	3.49	0.064
Ca	8	144	0.26	0.978	8	144	0.34	0.947	1	144	1.60	0.208
Co	8	108	0.75	0.649	8	108	0.17	0.995	1	108	4.55	0.035
Cr	8	108	0.77	0.629	8	108	0.23	0.985	1	108	2.84	0.095
Cu	8	108	0.66	0.722	8	108	0.35	0.946	1	108	8.32	0.005
Fe	8	108	0.81	0.599	8	108	0.35	0.943	1	108	2.36	0.128
K	8	144	0.36	0.938	8	144	0.35	0.946	1	144	0.24	0.622
Mg	8	108	0.98	0.455	8	108	0.28	0.971	1	108	7.58	0.007
Mn	8	108	0.67	0.719	8	108	0.26	0.977	1	108	8.44	0.004
Na	8	144	0.47	0.877	8	144	0.17	0.995	1	144	0.87	0.354
Ni	8	108	0.81	0.595	8	108	0.24	0.982	1	108	5.90	0.017
P	8	108	0.80	0.604	8	108	0.37	0.935	1	108	12.77	0.001
Pb	8	108	0.70	0.690	8	108	0.90	0.520	1	108	9.73	0.002
S	8	144	0.47	0.873	8	144	0.88	0.537	1	144	12.92	0.000
Sr	8	144	0.30	0.966	8	144	0.25	0.980	1	144	0.36	0.552
Zn	8	108	0.72	0.672	8	108	0.32	0.957	1	108	1.90	0.171

Table 3.1. continued. The F-statistics and probability levels from the mixed linear model to test for the effects of ash addition treatment, tree species, year and their interaction on soil properties and chemistry. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator. e=extractable or exchangeable

	Treatment*Species*Year			
Parameter	NDF	DDF	F	Sig.
Bulk density	8	108	0.12	0.998
Conductivity	8	144	1.58	0.135
Phosphate	8	108	0.36	0.938
TN	8	108	1.67	0.114
TC	8	108	2.52	0.015
C:N	8	108	2.22	0.032
pH	8	108	0.61	0.768
eCa	8	108	1.68	0.112
eCu	8	108	1.00	0.440
eFe	8	108	0.78	0.618
eK	8	108	1.19	0.312
eMg	8	108	0.99	0.449
eMn	8	78.041	1.13	0.354
eNa	8	108	0.70	0.695
eP	8	108	0.40	0.920
eZn	8	108	1.36	0.224
Al	8	144	1.10	0.370
As	8	106.98	1.29	0.254
Ca	8	144	0.43	0.899
Co	8	108	0.90	0.521
Cr	8	108	1.43	0.194
Cu	8	108	1.06	0.395
Fe	8	108	1.48	0.173
K	8	144	0.65	0.738
Mg	8	108	1.43	0.193
Mn	8	108	1.51	0.163
Na	8	144	0.29	0.969
Ni	8	108	1.02	0.423
P	8	108	1.20	0.306
Pb	8	108	1.44	0.189
S	8	144	0.60	0.773
Sr	8	144	0.56	0.809
Zn	8	108	0.58	0.793

Table 3.2. The F-statistics and probability levels from the linear model to test for the effects of ash addition treatment and species in 2019 and 2020, as well as the effect of treatment and year by species on soil properties and chemistry on total carbon (TC) and the ratio of carbon to nitrogen. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator.

	2019											
	Treatment				Species				Treatment*Species			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
TC	8	36	4.22	0.001	1	36	0.96	0.334	8	36	0.76	0.636
C:N	8	36	13.13	0.000	1	36	0.51	0.479	8	36	0.75	0.650

	2020											
	Treatment				Species				Treatment*Species			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
TC	8	36	4.90	0.000	1	36	3.68	0.063	8	36	2.45	0.032
C:N	8	36	13.61	0.000	1	36	1.26	0.269	8	36	2.00	0.074

	Black Spruce											
	Treatment				Year				Treatment*Year			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
TC	8	36	3.28	0.007	1	36	18.10	0.000	8	36	0.95	0.490
C:N	8	36	10.60	0.000	1	36	13.83	0.001	8	36	1.31	0.268

	White Spruce											
	Treatment				Year				Treatment*Year			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
TC	8	36	6.01	0.000	1	36	85.47	0.000	8	36	4.27	0.001
C:N	8	36	14.17	0.000	1	36	15.63	0.000	8	36	1.94	0.084

Table 3.3. The F-statistics and probability levels from the linear model to test for the effects of ash addition treatment in each year and under each species on total carbon (TC). Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator.

Data Group:	White Spruce 2019				White Spruce 2020			
Effect Measured:	Treatment				Treatment			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
TC	8	32	3.79	0.003	8	36	6.51	0.000

Data Group:	Black Spruce 2019				Black Spruce 2020			
Effect Measured:	Treatment				Treatment			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
TC	8	32	3.90	0.003	8	36	2.22	0.049

Table 3.4. The F-statistics and probability levels from the linear model to test for the effects of ash addition treatment by species on soil properties and chemistry. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator. e=extractable or exchangeable

	Black Spruce				White Spruce			
	Treatment				Treatment			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Conductivity	8	81	29.32	0.000	8	81	48.54	0.000
eK	8	36	16.82	0.000	8	81	15.13	0.000

Table 3.5. The F-statistics and probability levels from the linear model to test for the effects of ash addition treatment by year on soil properties and chemistry. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator. e=extractable or exchangeable

	2019				2020			
	Treatment				Treatment			
Parameter	NDF	DDF	F	p	NDF	DDF	F	p
Bulk Density	8	36	0.46	0.877	8	36	4.45	0.001
Conductivity	8	81	95.51	0.000	8	81	31.79	0.000
eFe	8	36	0.77	0.628	8	36	0.34	0.946
eK	8	36	7.77	0.000	8	81	33.52	0.000
eP	8	36	0.77	0.629	8	36	0.78	0.626
eZn	8	81	62.66	0.000	8	36	46.61	0.000

Table 3.6. The F-statistics and probability levels from the linear model to test for the effects of species by year on soil properties and chemistry. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator. e=extractable or exchangeable

	2019				2020			
	Species				Species			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Conductivity	1	44	8.30	0.006	1	44	4.85	0.033
Phosphate	1	44	1.93	0.171	1	44	105.73	0.000
TN	1	44	0.13	0.722	1	44	10.98	0.002
eCa	1	44	0.72	0.399	1	44	1.42	0.240
eFe	1	44	0.20	0.660	1	44	5.50	0.024
eMg	1	44	14.87	0.000	1	44	4.52	0.039
eMn	1	29	22.29	0.000	1	44	0.86	0.358
Al	1	88	3.06	0.084	1	88	2.64	0.108
Co	1	44	8.59	0.005	1	44	1.66	0.205
Cu	1	44	0.02	0.894	1	88	9.66	0.003
Mg	1	88	0.66	0.420	1	88	7.28	0.008
Mn	1	44	0.14	0.715	1	44	9.83	0.003
Ni	1	44	1.54	0.221	1	44	4.02	0.051
P	1	44	0.61	0.438	1	88	13.32	0.000
Pb	1	44	2.67	0.110	1	44	7.13	0.011
S	1	44	8.27	0.006	1	88	6.67	0.011

Table 3.6. continued. The F-statistics and probability levels from the linear model to test for the effects of year by species on soil properties and chemistry. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator.

	Black Spruce				White Spruce			
	Year				Year			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Conductivity	1	44	4.71	0.035	1	44	73.65	0.000
Phosphate	1	44	0.19	0.663	1	44	290.80	0.000
TN	1	44	3.06	0.087	1	44	33.39	0.000
eCa	1	44	0.49	0.490	1	44	0.20	0.659
eFe	1	44	0.00	0.000	1	44	877.33	0.000
eMg	1	44	1.26	0.268	1	30	36.01	0.000
eMn	1	35	4.43	0.043	1	30	36.01	0.000
Al	1	44	10.53	0.002	1	44	32.48	0.000
Co	1	44	0.53	0.470	1	44	6.32	0.016
Cu	1	44	0.00	0.996	1	44	13.18	0.001
Mg	1	88	1.28	0.260	1	44	23.56	0.000
Mn	1	44	0.00	0.999	1	44	17.43	0.000
Ni	1	44	0.78	0.383	1	44	15.22	0.000
P	1	44	0.10	0.750	1	44	18.66	0.000
Pb	1	88	1.95	0.166	1	44	35.93	0.000
S	1	44	0.31	0.582	1	88	20.99	0.000

3.2 Foliar Nutrient Contents

There was no effect of wood ash application of foliar N, B, Ba, Ca, Cr, Cu, Fe, K, Mg, Na, Ni, P, Si, Sr, or Zn contents (Table 3.7). Statistical outputs of foliar nutrient content can be found in tables 3.7 - 3.11, found on page 66–71.

3.2.1 Treatment by Year by Species interaction: Foliar S

A significant treatment by species by year interaction was detected for foliar S (Table 3.7). There was a significant treatment by year interaction effect for white spruce and black spruce foliar S content (Table 3.8). Further analysis showed that white spruce foliar S contents were significantly affected by wood ash application in 2019, but there was no significant effect in 2020 (Table 3.9).

There was no significant effect of wood ash application to soil on foliar S in white spruce in the year 2019 when compared to white spruce that received no wood ash soil treatment (L1; Figure 3.33). However, when high C ash was applied to soil at 1000 kg ha^{-1}, foliar S contents were significantly higher than when this ash was applied at 10 000 kg ha^{-1} (L4; Figure 3.33). Contents of foliar S were also significantly higher when the low carbon ash was applied at 10 000 kg ha^{-1} with the high carbon ash at a rate of 1000 kg ha^{-1} than when the low carbon ash was applied alone (L6; Figure 3.33). Black spruce foliar S contents were significantly affected by the wood ash treatments in both 2019 and 2020 (Table 3.11). In 2019, applying ash to the soil significantly increased foliar S contents in black spruce (L1; Figure 3.34). Also, soils under black spruce treated with low C ash had significantly higher foliar S contents in 2019 than those that received the high C ash (L2; Figure 3.34). Additionally, when high C ash was applied at both the

1000 kg ha^{-1} and 10 000 kg ha^{-1} application rate with low carbon ash the foliar S contents were higher than when the high C ash was applied alone (L7, L8; Figure 3.34).

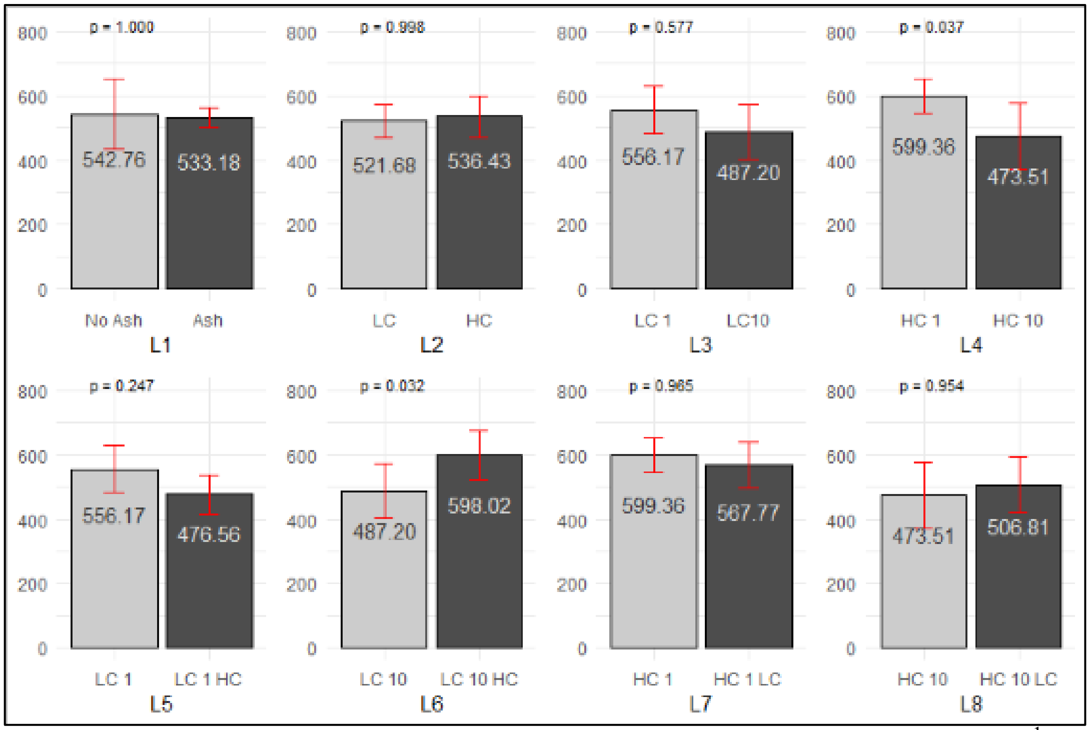

Figure 3.33. Orthogonal contrast of white spruce foliar sulfur content (µg 100 $needles^{-1}$) in 2019 (means and standard error of means (red bars)), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

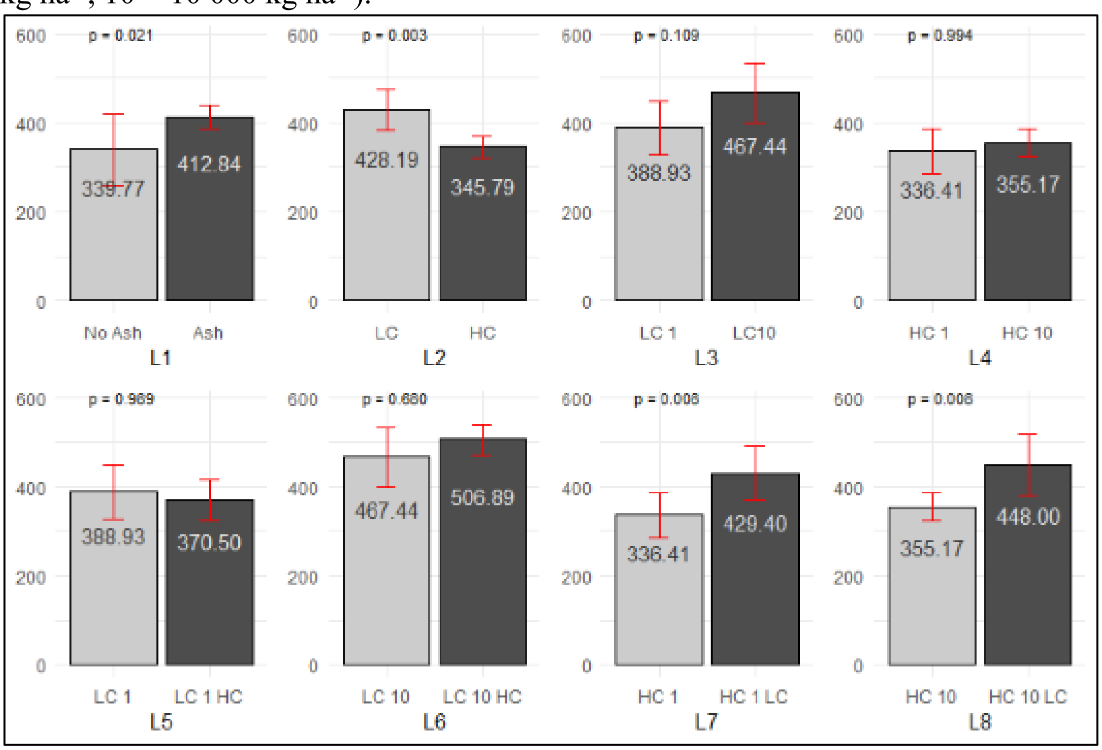

Figure 3.34. (Previous page) Orthogonal contrast of black spruce foliar sulfur content (µg 100 needles^{-1}) in 2019 (means and standard error of means), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

In 2020, there was no difference in foliar S content in black spruce between soils that received wood ash and those that did not (L1; Figure 3.35). However, when high C ash was applied at the 10 000 kg ha^{-1} application rate in combination with the low carbon ash, foliar S contents were significantly higher than when this ash was applied alone (L8; Figure 3.35).

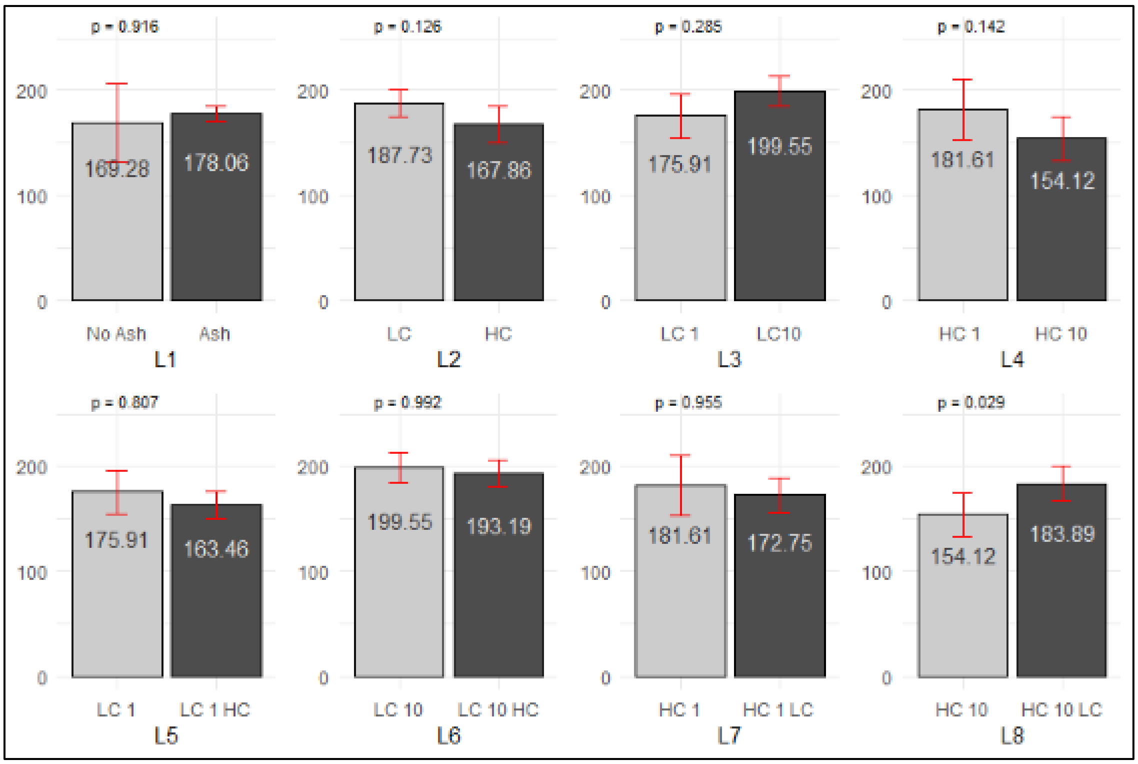

Figure 3.35. Orthogonal contrast of black spruce foliar sulfur content (µg 100 needles^{-1}) in 2020 (means and standard error of means), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg/ha, 10 = 10 000 kg ha^{-1}).

3.2.2 Wood Ash Application Effect: Foliar Al and Mn

There was a significant effect of ash application on foliar Al contents (Table 3.7) and orthogonal contrasts showed that Al contents were higher when the low carbon ash was applied at 1 000 kg ha^{-1} than when this ash was applied at 10 000 kg ha^{-1} (L3; Figure 3.36).

There was a significant treatment by species interaction for foliar Mn contents (Table 3.7). There was no effect of wood ash application on foliar Mn contents for white spruce but there was a significant effect on foliar Mn contents for black spruce (Table 3.10). Foliar Mn contents were higher when the low carbon ash was applied at 1000 kg ha^{-1} than when this ash was applied at 10 000 kg ha^{-1} but only at a $p<0.10$ level of significance (L3; Figure 3.37).

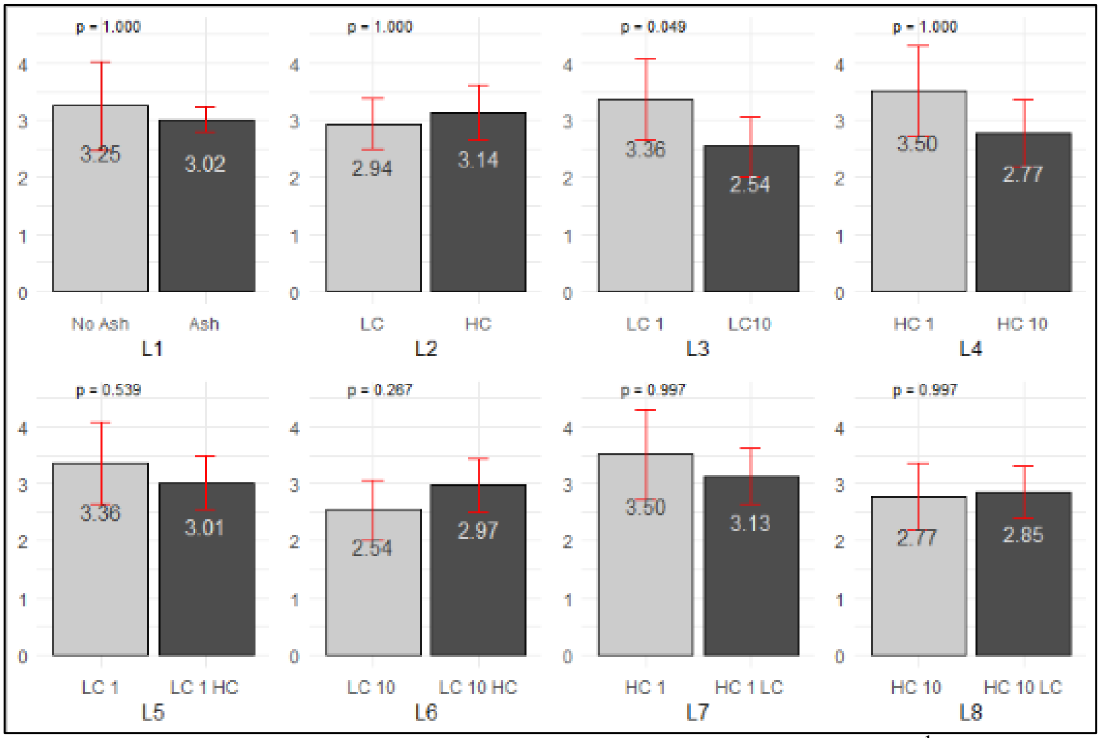

Figure 3.36. Orthogonal contrast of foliar aluminum content (µg 100 needles^{-1}) (means and standard error of means), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

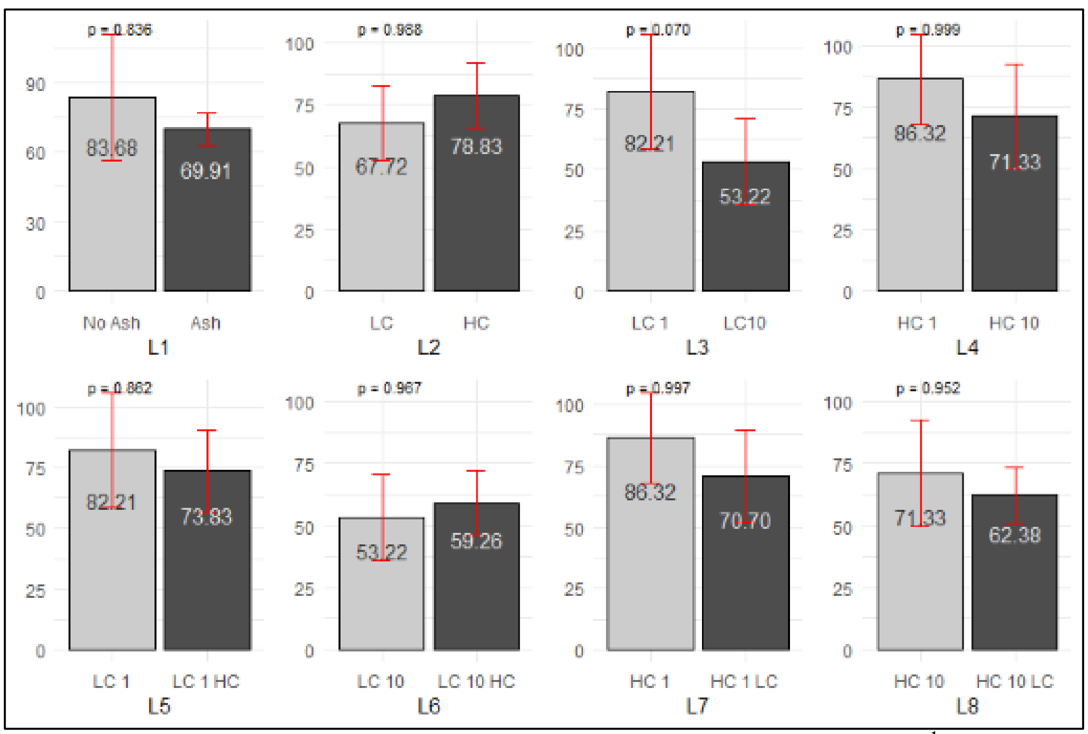

Figure 3.37. Orthogonal contrast of foliar manganese content (µg 100 needles^{-1}) in black spruce (means and standard error of means), (LC, low-carbon ash; HC, high-carbon ash; 1 = 1000 kg ha^{-1}, 10 = 10 000 kg ha^{-1}).

3.2.3. Species by Year Interaction Effect: Foliar B, Ca. Cu, Fe, Mg, N, P, Zn

There was a significant species by year interaction effect for foliar N, B, Ca, Cu, Fe, Mg, N, P, and Zn contents (Table 3.7). Foliar N content was higher in 2020 than in 2019 and in white spruce compared to black spruce (Table 3.11, Figure 3.38). Foliar B differed between years but only for black spruce, where B was greater in 2020, additionally foliar B was significantly higher in black spruce than white spruce in 2020 (Table 3.11, Figure 3.38). Foliar Ca, Cu, Fe, Mg, P, and Zn, contents were higher in 2019 than in 2020 and in both years were higher in white spruce than in black spruce (Table 3.11, Figure 3.39).

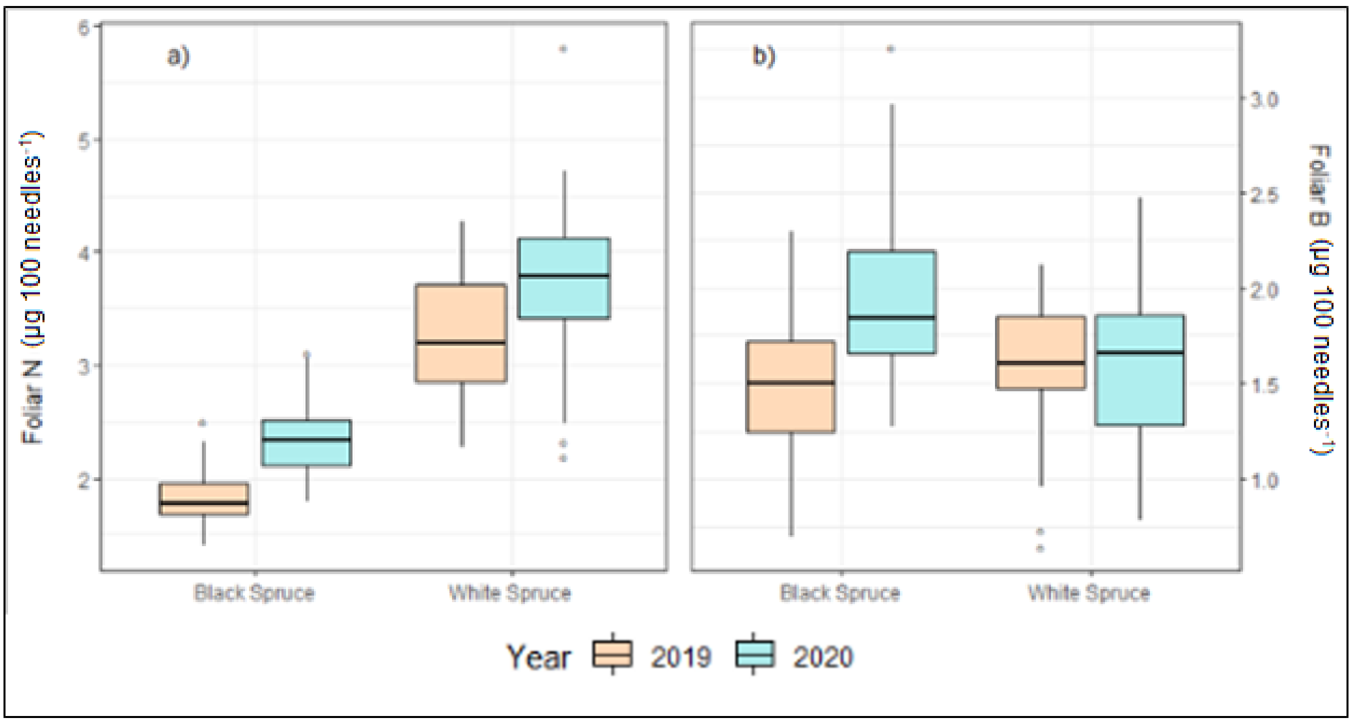

Figure 3.38. Boxplots of a) foliar N, and b) foliar B between species and years.

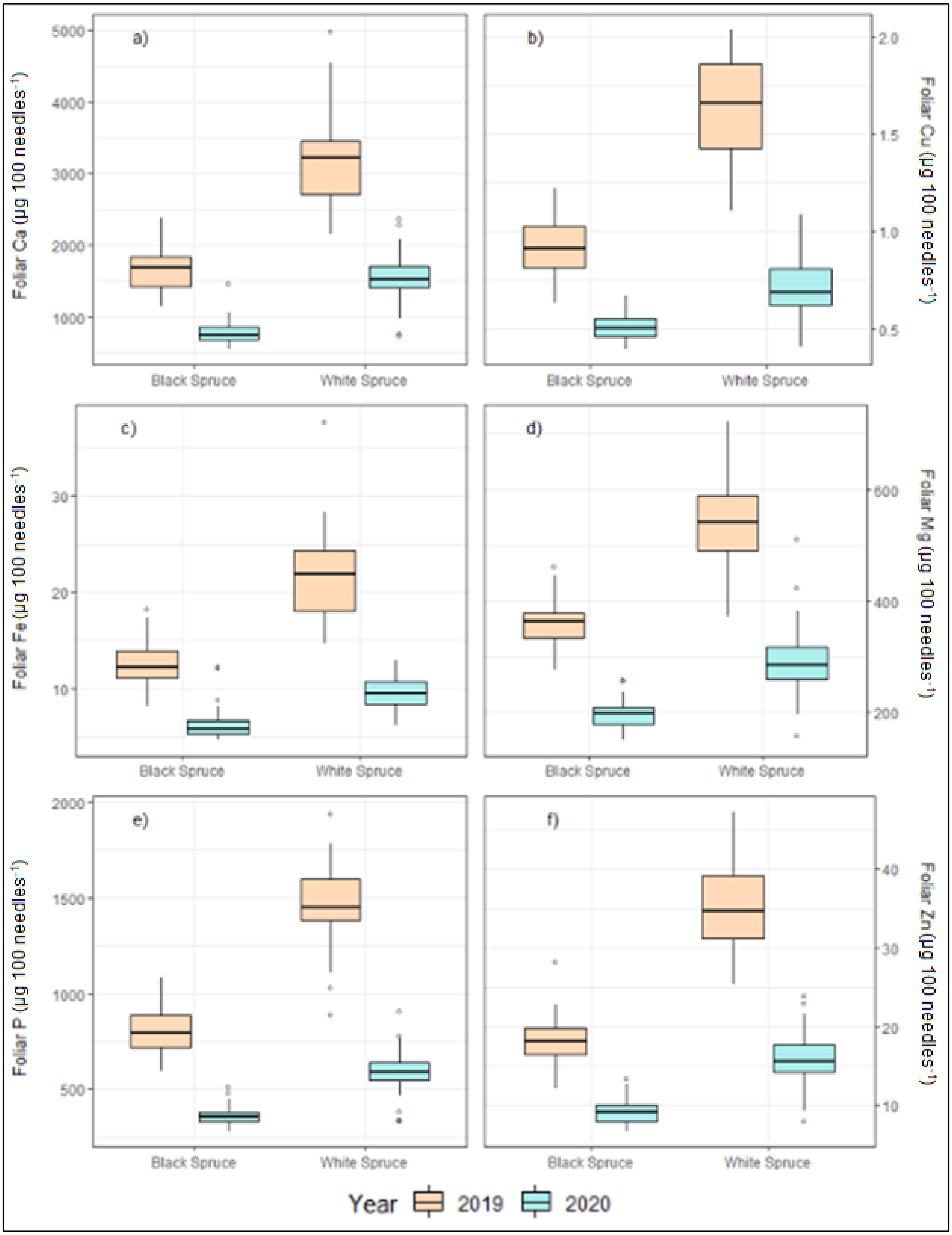

Figure 3.39. Boxplots of a) foliar Ca, b) foliar Cu, c) foliar Fe, d) foliar Mg, e) foliar P, and f) foliar Zn between species and years.

3.2.4. Species Effect: Foliar Al, Ba, Cr, K, Mn, Ni, Si, and Sr

Foliar contents of Al, Ba, Cr, K, Mn, Ni, Si, and Sr differed significantly between species (Table 3.7) and were higher in white spruce than black spruce (Figures 3.40, 3.41).

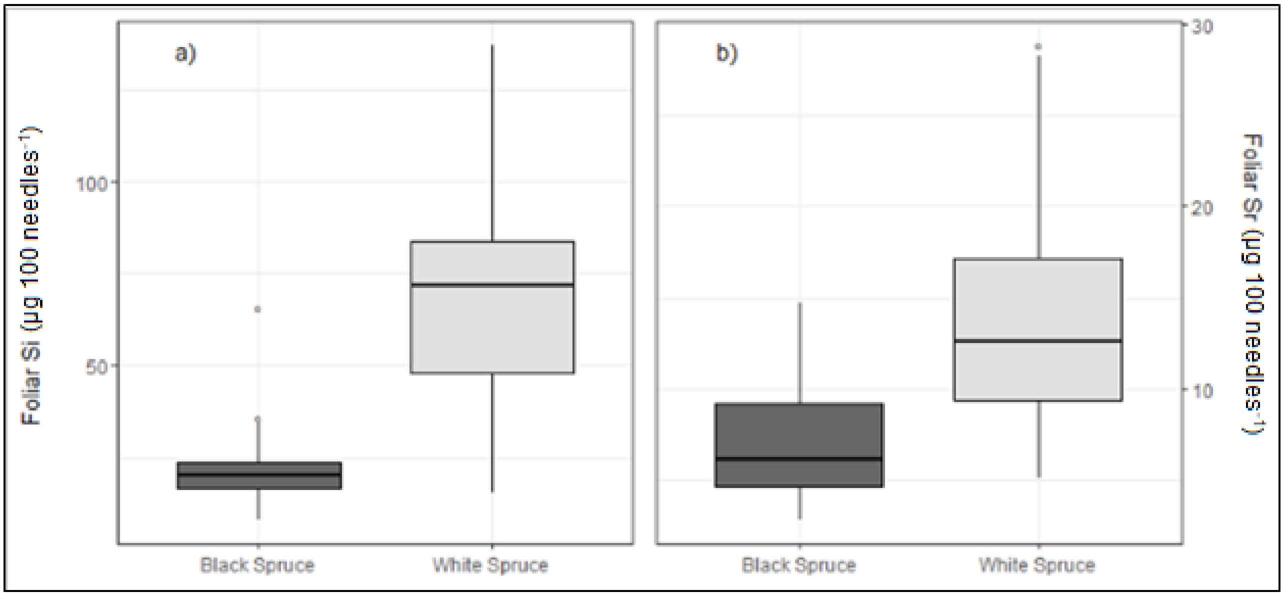

Figure 3.40. Boxplots of a) foliar Si, and b) foliar Sr in black and white spruce.

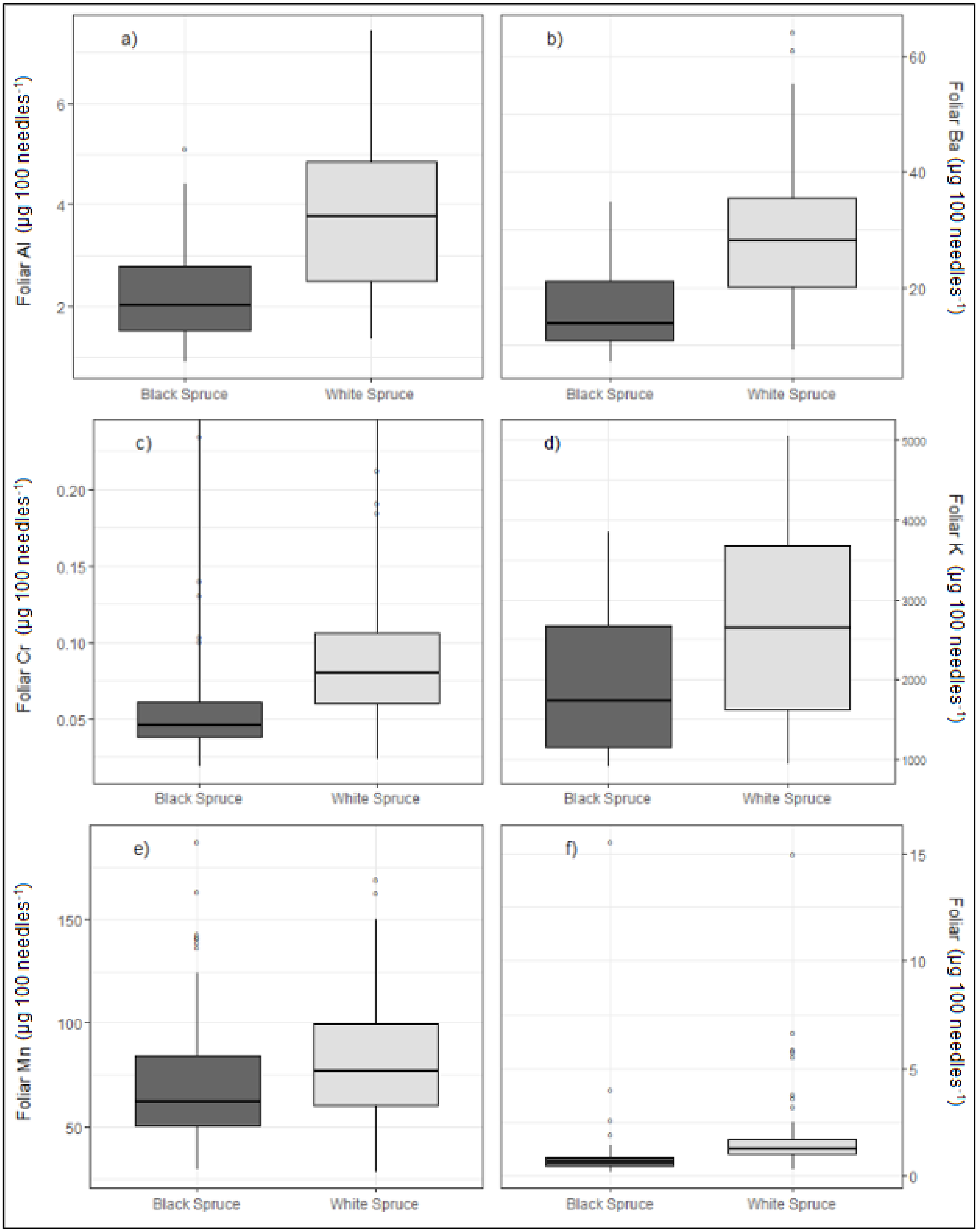

Figure 3.41. Boxplots of a) foliar Al, b) foliar Ba, c) foliar Cr, d) foliar K, e) foliar Mn, and f) foliar Ni in black and white spruce.

3.2.5. Year Effect: Foliar Al, Ba, Cr, K, Mn, Ni, Si, and Sr

Foliar contents of Al, Ba, Cr, K, Mn, and Ni were higher in 2019 than in 2020, while Si and Sr were higher concentrations in 2020 than 2019 (Table 3.7, Figures 3.42, 3.43). There was no significant difference between years in foliar element contents of Ni or Si.

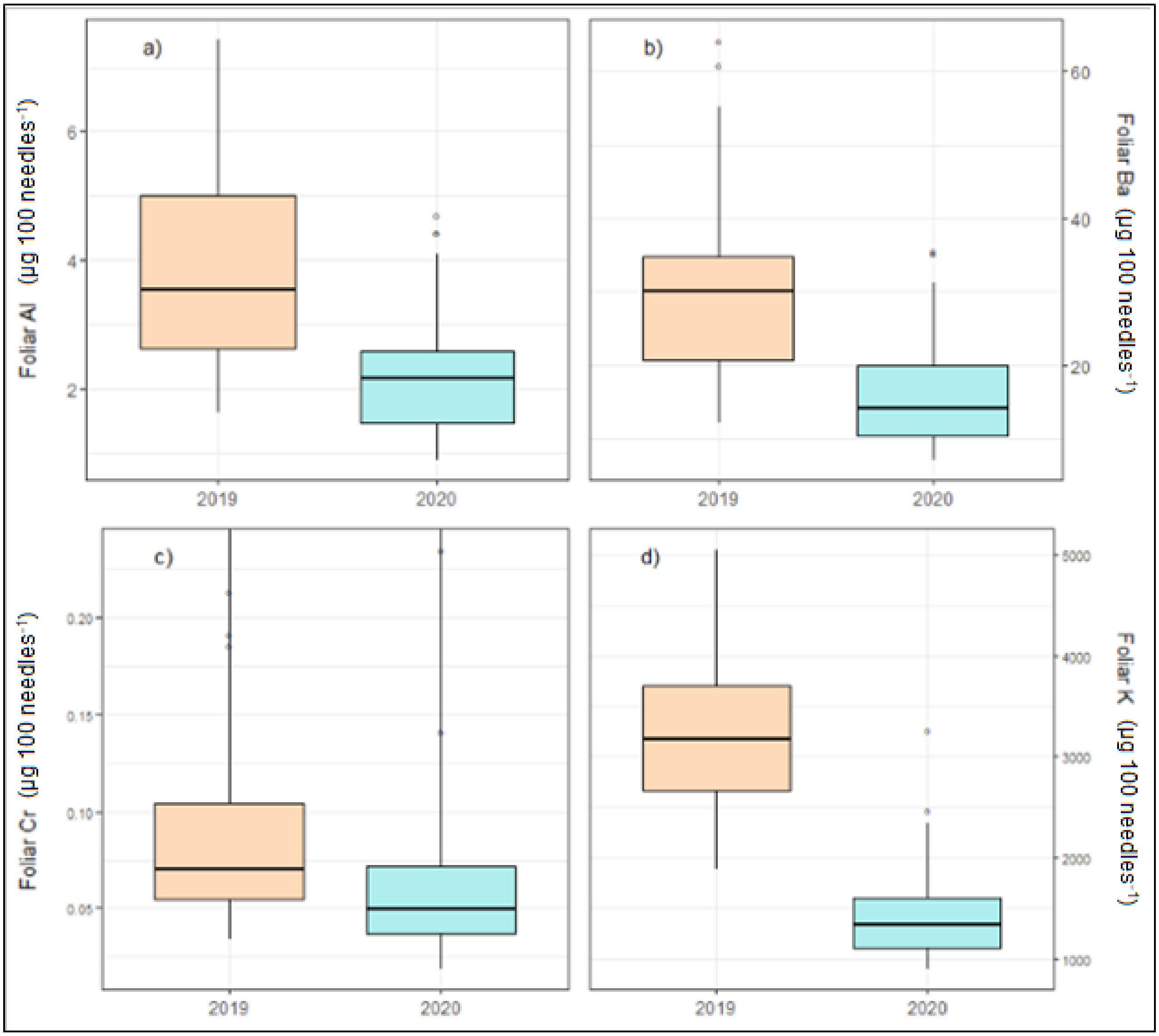

Figure 3.42. Boxplots of a) foliar Al, b) foliar Ba, c) foliar Cr, and d) foliar K in 2019 and 2020.

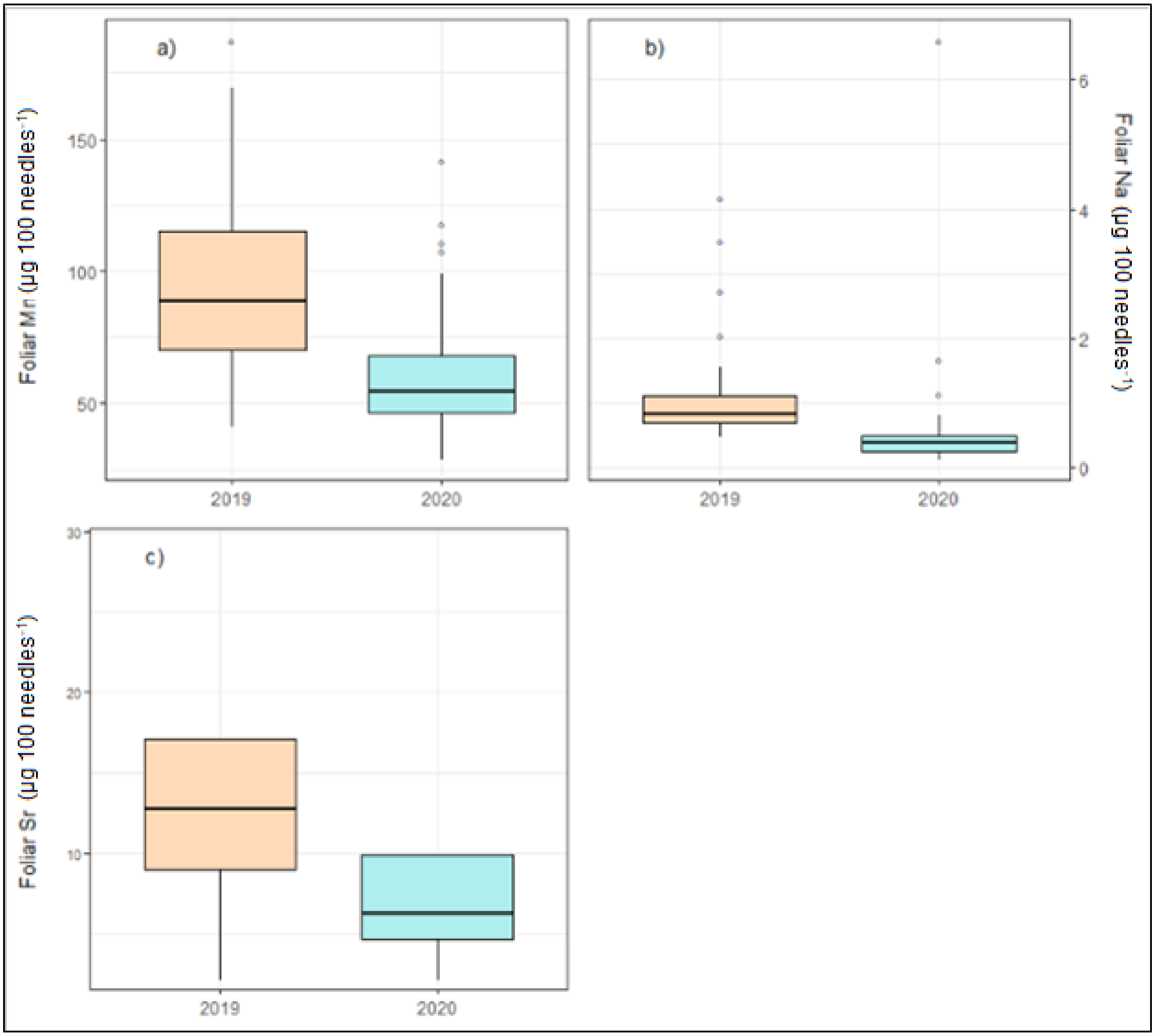

Figure 3.43. Boxplots of a) foliar Mn, b) foliar Na, and c) foliar Sr in 2019 and 2020.

3.3 Tree Growth Response

3.3.1 Species Effect on Height and Volume Growth

Wood ash treatment had no significant effect on white and black spruce volume ($F_{(8,69.86)}$ = 0.873 p = 0.543) or height ($F_{(8,71.98)}$ = 0.719, p = 0.674). There was significant variation between species in tree volume ($F_{(1,69.86)}$ = 10.381 p = 0.002) and height ($F_{(1,71.98)}$ = 32.627, p = 0.000), where white spruce on average had greater growth than black spruce (Figure 3.44).

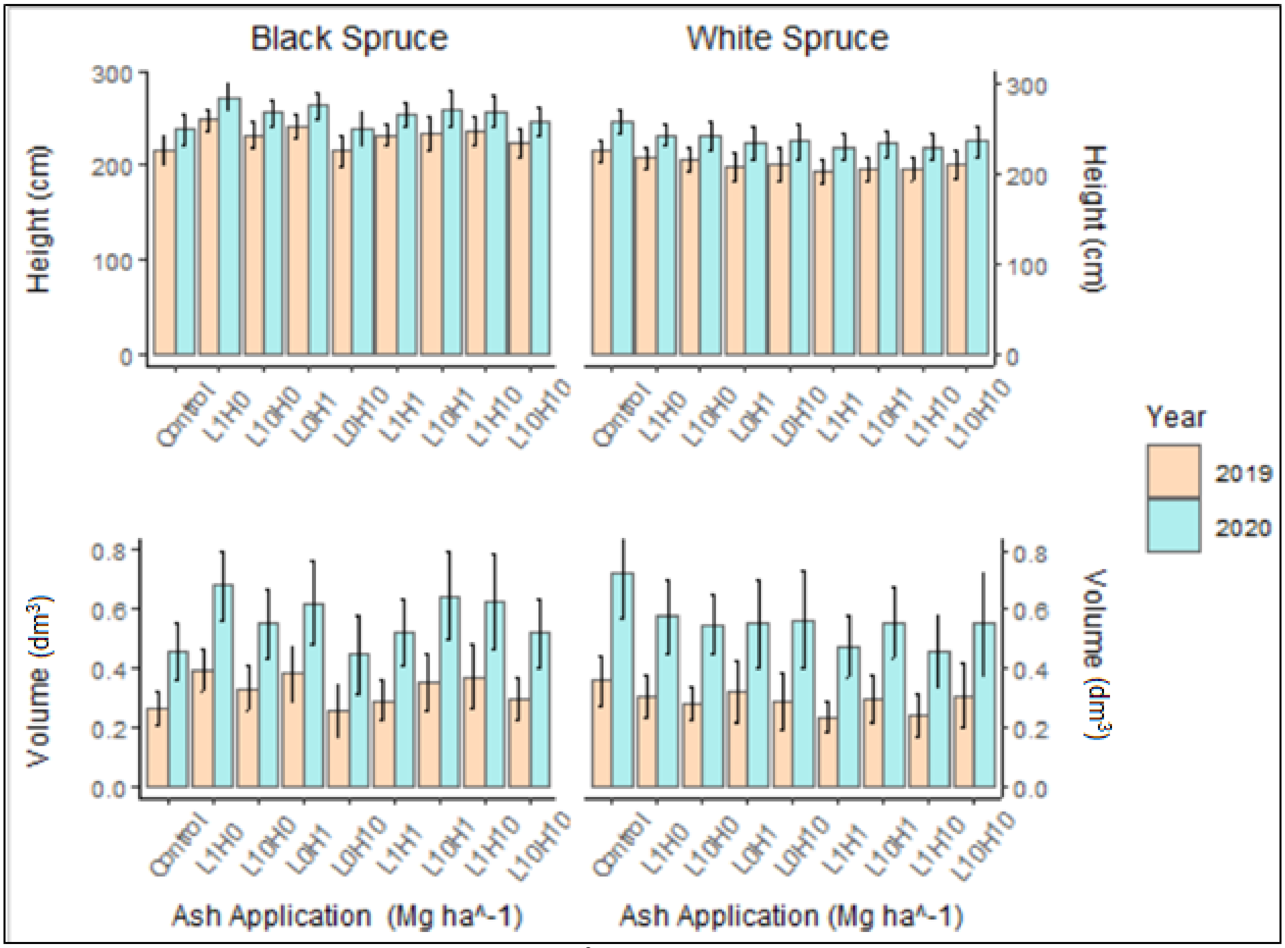

Figure 3.44. Height (cm) and volume (dm^3) response between years and species. (Cumulative growth is the difference between years).

Table 3.7. The F-statistics and probability levels from the mixed linear model to test for the effects of ash addition treatment, species, year and their interaction on foliar nutrient contents. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator.

	Treatment				Species				Year			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Foliar N	8	36	1.12	0.371	1	108	579.21	0.000	1	108	73.76	0.000
Foliar Al	8	35.8	2.46	0.031	1	107.1	240.28	0.000	1	107.1	231.65	0.000
Foliar B	8	36	1.57	0.169	1	108	4.81	0.031	1	108	18.24	0.000
Foliar Ba	8	36	0.48	0.866	1	108	284.21	0.000	1	108	310.91	0.000
Foliar Ca	8	36	0.47	0.871	1	108	562.39	0.000	1	108	703.99	0.000
Foliar Cr	8	131	1.43	0.191	1	131	56.36	0.000	1	131	31.55	0.000
Foliar Cu	8	36	1.37	0.241	1	108	385.13	0.000	1	108	965.68	0.000
Foliar Fe	8	36	1.79	0.112	1	108	355.82	0.000	1	108	863.27	0.000
Foliar K	8	36	1.60	0.159	1	108	189.59	0.000	1	108	1264.66	0.000
Foliar Mg	8	36	0.48	0.860	1	108	288.05	0.000	1	108	697.90	0.000
Foliar Mn	8	36	2.07	0.065	1	108	20.95	0.000	1	108	180.66	0.000
Foliar Na	8	36.9	0.81	0.599	1	71.57	0.88	0.351	1	74.49	61.63	0.000
Foliar Ni	8	132	1.16	0.329	1	132	33.74	0.000	1	132	0.94	0.335
Foliar P	8	36	1.40	0.229	1	108	690.86	0.000	1	108	1675.63	0.000
Foliar S	8	36	3.94	0.002	1	108	157.17	0.000	1	108	1655.81	0.000
Foliar Si	8	144	0.55	0.817	1	144	442.06	0.000	1	144	0.52	0.473
Foliar Sr	8	36	0.69	0.698	1	108	362.63	0.000	1	108	336.39	0.000
Foliar Zn	8	36	1.80	0.109	1	108	561.15	0.000	1	108	876.77	0.000

Table 3.7. continued. The F-statistics and probability levels from the mixed linear model to test for the effects of ash addition treatment, species, year and their interaction on foliar nutrient contents. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator.

	Treatment*Species				Treatment*Year				Species*Year			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Foliar N	8	108	1.28	0.259	8	108	0.63	0.753	1	108	5.44	0.022
Foliar Al	8	107	0.80	0.603	8	107.1	1.07	0.392	1	107.2	3.39	0.068
Foliar B	8	108	1.22	0.294	8	108	1.34	0.232	1	108	21.24	0.000
Foliar Ba	8	108	1.11	0.361	8	108	0.42	0.909	1	108	1.85	0.177
Foliar Ca	8	108	1.08	0.382	8	108	0.34	0.947	1	108	15.44	0.000
Foliar Cr	8	131	1.45	0.181	8	131	1.00	0.440	1	131	3.56	0.061
Foliar Cu	8	108	1.50	0.165	8	108	1.31	0.245	1	108	26.65	0.000
Foliar Fe	8	108	0.52	0.838	8	108	1.39	0.207	1	108	5.33	0.023
Foliar K	8	108	0.89	0.531	8	108	0.42	0.907	1	108	0.47	0.496
Foliar Mg	8	108	1.03	0.420	8	108	0.36	0.938	1	108	6.47	0.012
Foliar Mn	8	108	2.08	0.043	8	108	0.91	0.510	1	108	0.33	0.568
Foliar Na	8	71.7	0.48	0.864	8	74.62	1.01	0.436	1	70.32	3.36	0.071
Foliar Ni	8	132	1.23	0.285	8	132	0.43	0.903	1	132	0.02	0.897
Foliar P	8	108	1.46	0.180	8	108	1.22	0.296	1	108	60.64	0.000
Foliar S	8	108	4.05	0.000	8	108	2.99	0.005	1	108	15.09	0.000
Foliar Si	8	144	0.67	0.715	8	144	0.24	0.983	1	144	2.49	0.117
Foliar Sr	8	108	1.01	0.430	8	108	0.60	0.776	1	108	0.02	0.900
Foliar Zn	8	36	1.80	0.109	1	108	561.15	0.000	1	108	876.77	0.000

Table 3.7. continued. The F-statistics and probability levels from the mixed linear model to test for the effects of ash addition treatment, species, year and their interaction on foliar nutrient contents. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator.

	Treatment*Species*Year			
Parameter	NDF	DDF	F	Sig.
Foliar N	8	108	1.39	0.208
Foliar Al	8	107.2	0.69	0.698
Foliar B	8	108	1.04	0.413
Foliar Ba	8	108	0.39	0.922
Foliar Ca	8	108	0.52	0.839
Foliar Cr	8	131	0.53	0.831
Foliar Cu	8	108	0.85	0.557
Foliar Fe	8	108	1.15	0.335
Foliar K	8	108	0.76	0.639
Foliar Mg	8	108	0.83	0.579
Foliar Mn	8	108	0.38	0.929
Foliar Na	8	71.14	0.77	0.630
Foliar Ni	8	132	1.56	0.144
Foliar P	8	108	0.80	0.606
Foliar S	8	108	2.33	0.024
Foliar Si	8	144	0.66	0.728
Foliar Sr	8	108	0.24	0.981
Foliar Zn	8	108	0.63	0.753

Table 3.8. The F-statistics and probability levels from the linear model to test for the effect of ash addition treatment, species, and their interaction, as well as the effect of ash addition treatment, year and their interaction for each species on foliar S content. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator.

	2019											
	Treatment				Species				Treatment*Species			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Foliar S	8	36	4.20	0.001	1	36	140.01	0.000	8	36	5.64	0.000

	2020											
	Treatment				Species				Treatment*Species			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Foliar S	8	72	1.45	0.191	1	72	45.78	0.000	8	72	0.96	0.471

	Black Spruce											
	Treatment				Year				Treatment*Year			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Foliar S	8	72	10.15	0.000	1	72	976.27	0.000	8	72	2.15	0.042

	White Spruce											
	Treatment				Year				Treatment*Year			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Foliar S	8	36	1.60	0.159	1	36	859.94	0.000	8	36	2.13	0.058

Table 3.9. The F-statistics and probability levels from the linear model to test for the effect of ash addition treatment on foliar S contents in each year by each species. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator.

	Black Spruce 2019				Black Spruce 2020			
	Treatment				Treatment			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Foliar S	8	32	9.42	0.000	8	32	3.87	0.003

	White Spruce 2019				White Spruce 2020			
	Treatment				Treatment			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Foliar S	8	32	3.62	0.004	8	32	0.41	0.904

Table 3.10. The F-statistics and probability levels from the linear model to test for the effects of ash addition treatment by year on foliar Mn contents. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator.

	Black Spruce				White Spruce			
	Treatment				Treatment			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Foliar Mn	8	36	2.43	0.033	8	81	1.16	0.333

Table 3.11. The F-statistics and probability levels from the mixed linear model to test for the effect of year by species on foliar nutrient contents. Significance is the probability that the null hypothesis of difference holds. NDF is the degrees of freedom in the numerator; DDF is the degrees of freedom in the denominator.

	Black Spruce				White Spruce			
	Year				Year			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Foliar N	1	44	95.32	0.000	1	44	17.82	0.000
Foliar B	1	44	39.87	0.000	1	44	0.03	0.867
Foliar Ca	1	44	489.76	0.000	1	44	481.45	0.000
Foliar Cu	1	44	364.30	0.000	1	44	562.07	0.000
Foliar Fe	1	44	362.80	0.000	1	44	610.66	0.000
Foliar Mg	1	44	602.74	0.000	1	44	468.45	0.000
Foliar P	1	44	898.74	0.000	1	44	651.88	0.000
Foliar Zn	1	44	567.80	0.000	1	44	651.88	0.000

	2019				2020			
	Species				Species			
Parameter	NDF	DDF	F	Sig.	NDF	DDF	F	Sig.
Foliar N	1	44	485.45	0.000	1	88	188.91	0.000
Foliar B	1	44	2.87	0.098	1	44	20.20	0.000
Foliar Ca	1	44	402.43	0.000	1	88	217.88	0.000
Foliar Cu	1	44	349.71	0.000	1	88	71.06	0.000
Foliar Fe	1	44	271.76	0.000	1	88	104.35	0.000
Foliar Mg	1	44	187.16	0.000	1	88	111.52	0.000
Foliar P	1	44	587.42	0.000	1	88	178.06	0.000
Foliar Zn	1	44	558.18	0.000	1	88	169.15	0.000

Chapter 4- Discussion

The purpose of this study was to determine if a second wood ash application to soil has any beneficial, or at least no negative effect on black and white spruce, and in soil chemical and physical properties. The results showed that a second application of a low and high carbon wood ash affected foliar nutrition in both tree species, and several soil properties that will be discussed below.

4.1 Soil Physical Properties

Soil bulk density was significantly affected by the year of sampling, with higher bulk densities in 2020 in soils under both species. The application of either ash at any amount did not significantly affect bulk density but increasing the amount of ash added of either type resulted in lower soil densities. Wood ash contains large, porous particles making them less dense relative to soil (Etiégni and Campbell, 1991). This factor along with mixing action used to incorporate ash into soil at the time of treatment would lower the bulk density (Sarrantonio et al., 1996). Bulk density was higher in 2020, this could potentially be due to the transport of the fine, soluble, and porous mineral content in wood ash (Etiégni and Campbell, 1991; Demeyer et al., 2001) deeper into the mineral soil, resulting in higher density relative to previous year's sampling. It may also be from settling after application i.e., compaction or the binding of ash particles together.

4.2 Conductivity

The response of soil conductivity to ash addition was dependent on species and differed between years. Conductivity was higher in soils receiving ash under both species in 2020 compared to 2019. In both 2019 and 2020 conductivity was higher in soils under black spruce than those under white spruce. Though not always significant, low C ash, higher quantities of ash, and mixing ash resulted in higher conductivity. A rapid change in conductivity, such as what was observed in this study, is common when liming material, such as wood ash, is applied to soil (Sarrantonio et al., 1996; Bang-Andreasen et al., 2017). Low C ash was finer and produced at a higher temperature and was therefore more chemically reactive. It also contained higher concentrations of common electrolytes such as Ca, Na, K, and Mg; characteristics that would contribute to raising conductivity of the soil solution. Higher conductivity has been linked to shifts in a soil's microbiome (Bang-Andreasen et al., 2017). Bang-Andreason et al. (2017) observed that wood ash additions of 22 000 kg ha^{-1} shifted mildly acidic soils to neutral, increased conductivity, and increased copiotrophic bacteria while decreasing oligotrophic bacteria (Bang-Andreasen et al., 2017). Copiotrophic bacteria are those who exhibit high population growth rates in nutrient rich conditions, where oligotrophic bacteria are those that have sustainable growth rates in nutrients poor environments. A root's rhizosphere (i.e., zone of chemical, biological, and physical influence from root growth) harbours the sustained growth of bacteria responsible for mineralizing nutrients necessary for the tree. Increased oligotrophic bacteria may coincide with a tree's ability to control the bacterial species within the rhizosphere and inhibit the tree's desired and controlled release, and subsequently absorption, of specific nutrients that it needs to survive (Bang-Andreasen et al., 2017).

4.3 Soil pH

Soil pH was higher in 2019, the year of ash application, which is common in ash treated soils (e.g., Clarke et al., 2017). Soil pH is the ratio of hydrogen protons to hydroxyl molecules in the soil solution. Soil pH can be raised by the addition carbonate and bicarbonate, found in many wood ashes (Etiégni and Campbell, 1991), as these minerals dissociate to produce free hydroxyl, aqueous Ca and carbonic acid. In acidic forest soils, pH tends to respond quickly to ash addition because of a) free H^+ decomposing carbonates into bicarbonate ions, and b) base cations become readily available for sorption to mineral exchange sites liberated of H^+ after ash addition (Bélanger et al., 2021). The result of higher pH in 2019 is likely due to being closer to the time of ash application. After the ash was applied, dissolution of carbonates and bicarbonate begins immediately; this combined with continual eluviation of ash particles/solutes over time and cumulative precipitation of minerals would eventually shift the pH back down to its initial level.

All rates and ashes applied increased soil pH, a result that has been well documented in many other wood ash and biochar amendment trials (Etiégni and Campbell, 1991; Demeyer et al., 2001; Biederman and Harpole, 2012; Scheepers and du Toit, 2016). There was no difference between the types of ash applied and their effect on soil pH. Though mean pH was higher in low C treated soils, it was not significantly higher. This was unexpected as the low C ash has a smaller grain size, is more alkaline, and therefore has higher reactivity. When applied at the higher rate (10 000 kg ha^{-1}), both low and high C ash applied alone resulted in higher pH. Higher quantities of ash application resulting in higher pH is consistent with other acidic forest soil wood ash treatment research (Perkiömäki and Fritze, 2002; Voundi Nkana and Brümmer, 2006; Li et al., 2017). Additionally, mixing low and high C wood ash resulted in higher soil pH, this is also expected as applying more ash means greater alkalinizing potential.

Untreated soils had an average soil pH of 5.75 and treated soils ranged from 5.84 (HC 1) to 6.71 (LC 10 HC). The transition of soil pH through pH 6.3 marks an important threshold for soil C stability (Rowley et al., 2017). This threshold is due to Al/Fe oxide and oxyhydroxide mineral phases exiting their stable pH range and potentially releasing C containing organic molecules that were sorbed to the mineral surface into soil solution (Rowley et al., 2017). This pH threshold was crossed when the following wood ash treatments were applied to a soil: LC 10 (pH=6.63), HC 10 (pH=6.35), LC 10 HC (pH=6.71), and HC 10 LC (pH=6.63). Adding wood ash could influence carbon storage in the soils of the boreal forests soil, which are acidic and coarse grained, with the finer silt and clay fraction dominated by allophane clays and Fe and/or Al oxyhydroxides (Basile-Doelsch et al., 2020). It has been estimated that this stable organo-mineral complexed pool contains 60% to 90% of a soil's organic matter content (Paustian et al., 1992). Considering that soil C is the largest terrestrial C pool (Batjes, 1996; IPCC, 2007), and that the boreal forest represents the world largest forest by area; applying wood ash to northern soils could have unintended effects on soil C storage and stability.

An increase is soil pH can have immediate beneficial effects to plant species through the destabilization and release of soil organic matter (Rowley et al., 2017; Bailey et al., 2019) and subsequent abundance of bacterial mediated mineralized nutrients for plant uptake. However, this comes at the cost of potentially depleting soil organic matter stores (Bååth and Arnebrant, 1994) through increased soil microbial activity (Biederman and Harpole, 2012; Bieser and Thomas, 2019). Additionally, increases in microbial activity (i.e., mineralization of organic matter) is known to cause production and subsequent release of CO_2 (Bååth and Arnebrant, 1994) into the atmosphere, thus potentially contributing to climate change.

4.4 Soil C and N

Ash application to soil affected concentrations of total soil C, but the effect was dependant on the time since ash was applied and which tree species was growing in the soil. Wood ash application to soils resulted in an increase in 2019 and in 2020, but differed between species, though this was not statistically significant. In 2019 both low and high C ash applied alone at a rate of 10 000 kg ha^{-1} resulted in greater total soil C concentrations (Figure 3.1). These results are consistent with other studies who found increased C in boreal clear cuts and in bioenergy cropping when soils were amended with wood ash (Bieser and Thomas, 2019; Ventura et al., 2019). This was anticipated as C is the main constituent in wood ash (Table 1.1; Demeyer et al., 2001).

In 2020 soils under black spruce had greater mean C concentrations when ash was applied, though this effect was not significant. Under white spruce this effect was weakly significant (p=0.079). In 2020, the soils that received low or high C ash at the higher loading rates resulted in greater soil C, though this was not significant under either species. Except under white spruce where soil treated with high C ash applied at 10 000 kg ha^{-1} had significantly greater soil than when applied at 1000 kg ha^{-1}.

Soil C concentrations in untreated plots did not differ significantly between years, increasing slightly from 19.49 g kg^{-1} in 2019 to an average of 20.06 g kg^{-1} in 2020. In soils treated with ash, their mean soil C concentration increased from 20.33 g kg^{-1} in 2019 to an average of 23.08 g kg^{-1} in 2020. This shows that C concentrations in untreated soils were stable between years, while soils treated with ash accumulated additional carbon from 2019 to 2020. In contrast, boreal soil response to forest fire and bio-energy wood ash found soil C stocks in the mineral soil (0-10 cm) remained relatively unchanged for 2 years (Clarke et al., 2017) up to 20 years after ash incorporation to soil (Hannam et al., 2019). Though environmental factors differ, wood ash addition to soils of short rotation cropping of poplar species transformed soil from a C source to a C sink just 2 years after application (Ventura et al., 2019). Additional years of observations on soil C at the 25^{th} Side Road site are required to determine the longevity of this observed effect.

Soil N concentrations were higher in 2020 for soils under both species than in 2019 and were unaffected by wood ash treatment. Nitrogen is a major growth limiting factor in boreal ecosystems (Häkkinen et al., 2010). No effect of wood ash application on soil N concentrations was observed in a meta-analysis, a trend that persisted up to 15 years following ash application (Hannam et al., 2019). The C:N was affected by ash treatments. This effect seems inevitable since wood ashes contain significantly more C than N (Table I). Wider C:N were observed in 2019 when any ash was applied, when high C ash was applied at high rates as well as when applied in combination with 10 000 kg ha^{-1} low C ash. Wood ash application continues to have some influence on soil C:N the following year where high C was applied at 10 000 kg ha^{-1} and where low C was applied in combination with high C ash. Typical soil C:N in boreal forest's soil range from 9.3:1 – 34:1 (Hume et al., 2016; Karhu et al., 2016). The 25^{th} Side Road falls within this range with lower and upper limits of 16.1:1 – 20.64:1 C:N. Soil C, N and C:N in forest soils following fire were affected by the time since fire occurred, with C:N increasing up to 98 years after forest fire (Hume et al., 2016). This trend was also observed in this study, with wider ratios in 2020. Like total C concentrations, further sampling would be needed to determine if this effect persists.

4.5 Total Soil Elements

Concentrations of all measured soil element concentrations, excluding As, were greater in 2019 than 2020, with some variation between canopy species. All soils had higher concentrations of total soil Al, Ca, Cr, K, Na, Sr, and Zn in 2019 regardless of species. Concentrations of Co, Cu, Mg, Mn, Ni, P, Pb, S were higher in 2019 in soils under white spruce, where under black spruce concentrations of these elements remained constant between years. This trend is directly associated with the timing of application of wood ash to the soil. Wood ash is chemically complex and adds many elements to soil. Additionally, the ash used in this experiment was composed from 40% – 48% of particles less than 250 μm, making it reactive because of the large surface area. Increased reactivity in this case means that elements contained in the ash are more readily dissolved and subsequently either absorbed by plants or eluviated from the mineral soil, with these effects likely diminishing with time since application.

Total Ca, S, and Sr soil concentrations were significantly affected by specific wood ash treatments, independent of species or year. Soil Ca and Sr concentrations both increased with wood ash application, and the effect was greater when low C ash was applied, though this difference was not statistically significant. Behind C, Ca was the second most abundant element i.e., had the highest concentration in the wood ashes applied, containing 113 000 mg kg^{-1} and 32 400 mg kg^{-1} in the low and high C ash respectively (Table 1.1). Unfortunately, Sr concentrations were not measured in low or high C ash, however, typical ash from residual boreal coniferous forest biomass biofuel range from 405 mg kg^{-1} in high C ash (Bieser and Thomas, 2019) to 93 mg kg^{-1} – 428 mg kg^{-1} in low C fly ash (Pugliese et al., 2014). Higher soil Ca concentrations is an effect that has been documented in many forest wood ash amendment trials (Demeyer et al., 2001; Domes et al., 2018; Bieser and Thomas, 2019).

Soil Ca and Sr concentrations were highest when higher amounts of ash were applied alone or in combination, excluding LC 10 HC. Soils treated with low C ash had significantly higher mean Ca and Sr concentrations when this ash was applied at 10 000 kg ha^{-1} than at 1000 kg ha^{-1}. Soil Ca concentrations have been positively related to the quantity of Ca ash applied to soil that is untreated prior to application (Hannam et al., 2019). Un-treated ash is ash that has not been granulated, self hardened, or pelleted which is what was used in this study. Reports of soil Sr concentrations are scarce in the literature; however, Sr tends to be more concentrated in fly ash than in bottom ash (e.g., Pugliese et al., 2014). This is due to the volatilization of alkaline and alkaline earth metals during combustion (Kuokkanen et al., 2006). Given that Ca and Sr are both alkaline earth metals and are both concentrated into the fly ash (Kuokkanen et al., 2006), it would be reasonable to assume that Sr concentrations are proportional to Ca in our mixed ash and thus would increase soil concentrations with greater application rate. The key to Sr's persistence in soil may be linked to its shared characteristic of bivalency with other alkaline earth metals such as Ca. Sr is well known to substitute for Ca in carbonate mineral (Kim et al., 2021), and could also participate in cation bridging.

Sr is known for being a toxin for bacterium (Kim et al., 2021), therefore elevated levels in a soil could have adverse effects on that soil's microbiome if Sr is soluble. Nieminen et al. (2005) analysed ash particles collected 3-5 years after application to mineral soil and found that heavy metals in ash were highly insoluble and had remained in ash particles. The precipitation of carbonates, through both physio-chemical and biologic reactions (Kim et al., 2021), could effectively absorb aqueous Sr and sequester it in mineral form, removing it from the biosphere. It's important to note that Sr in this form would only be meta-stable, as carbonates are pH sensitive (Rowley et al., 2017) and will dissolve back into soil solution if pH conditions change.

Soil total S concentrations increased with low C ash application and decreased with the application of high C ash. This suggests that the high C ash increases the mobility of S, enabling S to be lost through eluviation. Sulfur concentrations in ash derived from coniferous feedstock ranges from 160 mg kg^{-1} to 4300 mg kg^{-1} to in bottom ash (Nieminen al., 2005; Kuokkanenen et al., 2006) and 3780 mg kg^{-1} to 28 500 mg kg^{-1} in fly ash (Kuokkanenen et al., 2006; Couch et al., 2021). After combustion, ash retains 40-90% of the feedstock's original sulfur content (Kuokkanenen al., 2006), and therefore concentrations increase as the fuel is burned more completely and/or at higher temperatures. This effect, along with increased reactivity, may explain higher S concentrations when low C ash is applied. However, S enrichment is often short lived as high rates of S leaching are found to occur after ash fertilization (Nieminen al., 2005).

4.6 Soil Extractable and Exchangeable Elements

Concentrations of soil extractable and exchangeable elements were generally higher in 2019, the year of ash application, but extractable Cu (eCu; prefix "e" denotes extractable or exchangeable pool of an element), eFe, and eP were higher in 2020. Tree species had little effect on the soil's exchangeable chemistry, only significantly affecting eFe, eMg, eK and eMn. Interestingly, soil under black spruce had higher concentrations of exchangeable alkali and alkaline earth metals (eK and eMg), whereas soils under white spruce soils had higher concentrations of exchangeable transition metals (eFe and eMn). This could indicate that white spruce has greater ability to counteract pH increase from ash, maintaining lower pH and higher Fe and Mn solubility.

Exchangeable K and Zn both exhibit characteristics of a slower release into soil solution. Whereas in 2019 ash treated soils showed no significant difference from the control, only application of low C ash at high rate resulted in significant changes in eK and eZn. In 2020 however, both these metals showed significant variation across treatments, which implies the selective removal of other exchangeable elements over K and Zn.

Significantly greater concentrations of exchangeable elements are observed when: low C ash was applied, when greater quantities of ash were applied, and where high C ash was mixed with low C ash. These observations reflect the chemistry of the ash. Concentrations of Ca, Mg, K, Cu, Na, and Zn were higher in the low C ash (Table 1.1). Enrichment of metals in ash is caused when the feedstock is subjected to more complete combustion and higher combustion temperatures (i.e., low C ash), and has been measured in many different biofuel ash products (Etiégni and Campbell., 1991; Kuokkanen et al., 2006; Domes et al., 2018; Bieser and Thomas 2019). During combustion, organic matter decomposes, and alkaline and alkaline earth elements are volatilized, and later recondense in fly ash (Kuokkanen et al., 2006) in oxide, hydroxide, carbonate (Demeyer et al., 2001), chloride, and sulphate phases (Vassilev and Vassilera, 2019). This trend would also explain the increased mean exchangeable metals values when high C ash was applied to soil in combination with low C ash for eCa and eZn.

Metals are micronutrients and are essential for life, but if present at levels above biological threshold concentrations, all metals can be toxic to life (Sullivan and Gadd, 2019). Although extractable Cu, Mn, and Zn, and exchangeable Ca, K, Mg, and Na, and total soil Ca and S concentrations were higher in soils where wood ash was applied this did not translate into an effect on the foliar contents of these elements (excluding eMn). Thus, the primary hazards wood ash associated eCa, eCu, eK, eMg, eMn, eNa, and eZn pose to the soil at this site is on its microbiome. A secondary hazard could form from a change in the soil's natural microbial community as a result from ash addition, which may affect a plant's rhizosphere and limit the microbial community's ability to mineralize nutrients required for growth. As noted by Sullivan and Gadd (2019), metal contamination to toxic levels shifts the micro-community to one that houses more pathogenetic organisms and soil fungi. When soils are subjected to elevated metal concentrations (Pb, Zn) there is a measurable decrease in enzyme activity, N and P in both the rhizosphere and bulk soil (Yang et al., 2017; Sullivan and Gadd, 2019). This effect was partially seen in this study, where concentrations of soil N and eP were lower in 2019 when eCa, eK, eMg, eMn, and eNa concentrations were higher. Since a soil's microbiome is diverse, it is difficult to draw a line when a metal's concentration in soil solution becomes toxic and detrimental, as some species exhibit greater sensitivity/tolerance than others (Giller et al., 2009; Sullivan and Gadd., 2019). Soil Zn concentrations higher than 100ppm have been shown to have a negative effect on rhizobia and individual cell counts (Giller et al., 2009). Heavy metals (Cu, Zn) have been shown to persist almost indefinitely in soils, yet there has been little progress in building environmental regulations on soil heavy metal content with respect to soil micro-organisms (Giller et al., 2009).

4.7 Foliar Nutrient Response

Apart from foliar N and B, the concentrations of all other measured foliar elements were higher in 2019 and in white spruce. The year effect can be attributed to the date/timing of wood ash application, which would result in more solubilized nutrients for root uptake in the year of ash application. This effect was also observed by Domes et al. (2018).

Foliar Al, Mn and S contents were significantly affected by wood ash treatment. Interestingly Al and Mn showed a very similar foliar responses across the contrast of treatments. This response was consistent between years and species for Al, however foliar Mn was only affected when ash was applied to soils under black spruce. A negative relationship was observed between ash application of either type, and foliar concentrations of Al and Mn. Both low and high C ash application resulted in lower foliar Al and Mn, this effect was further enhanced with increasing application load. Additionally, adding low C ash to high C ash at low and high rates lowered mean foliar Al and Mn concentrations.

All plants are negatively affected by exposure to aqueous Al, either by interference with cation nutrient uptake, or by damage to plant cells (Cronan and Grigal, 1995). Lower Al concentrations in foliar tissue is beneficial, as greater amounts on Al absorbed by roots have been linked to toxicity and stress in plants (Cronan and Grigal, 1995). These reduced foliar Al and Mn concentration appear to be inversely related to the increase in pH. Soil pH is proportional to the amount of H^+ dissolved in a solution, and at a lower pH more H^+ protons are found in solution. These positively charged protons compete with other dissolved cations for sorption cites on negatively charged surfaces in soil called colloids (both mineral and organic). The H^+ ions do not remain as exchangeable cations for long, instead they react with mineral surfaces and release Al and Mn bound in mineral forms into the soil solution in the process (Brady and Weil, 2008). At this point they are free to be absorbed by roots or sorbed to surfaces. This is likely the reason foliar Al and Mn concentrations are higher in the soils with a lower pH. A phenomenon that would lower foliar Al is that Al solubility decreases as pH increases, forcing the precipitation of Al as $Al(OH)_3$ (Tipping, 2005), thereby removing Al from a plant root's consumable pool. This same process applies to Mn, precipitating as hydroxy ions $Mn(OH)^{2-}$, and further bonding with OH^- to form insoluble hydroxides and oxides ($Mn(OH)_3^-$, MnO) with increasing pH (Brady and Weil, 2008). Plant growth is commonly limited in alkaline soils by Zn, Cu, Fe and Mn deficiencies (Brady and Weil, 2008) due to these elements being stabilized in hydroxide and oxide minerals. This precipitation is thought to be the reason for the decrease in foliar Mn concentrations in wheat crops with increasing pH (Sillanpaa, 1982).

Our results also indicate that foliar S was affected by ash treatment, however this effect differed between species and years. Sulfur enrichment was also observed in short term wood ash trials 5 months after ash application in boreal setting (Domes et al., 2018). In conifers S has a strong controlling influence on N uptake (Domes et al., 2018). It has been suggested that a foliar N:S less than 15 implies no deficiency for spruce in interior British Columbia (Brockley, 2012).

On average, black spruce had a N:S of 4.2:1 in 2019, 12.6:1 in 2020, suggesting no deficiency, while white spruce showed signs of deficiencies in 2020 (6:1 in 2019, 17.6:1 in 2020).

In 2019, black and white spruce had nearly opposite foliar S responses to wood ash application. White spruce showed no significant effect of ash application when compared to control, where black spruce had a significantly greater foliar S response with ash application. Foliar S in black spruce had a significantly greater response to low C ash, where white spruce recorded no difference between low and high C ash. Foliar S in black spruce increased with ash loading rate, though not significantly. Foliar S contents in white spruce were lower with increasing loading rate, significantly so with high C ash. The two species also displayed different responses to the mixing of ashes. Adding low C ash to high C ash resulted in significantly higher foliar S for black spruce. In 2019 black spruce exhibited N:S as low as 3.68:1 when low C was applied at high rate, and as high as 5.36:1 in control. White spruce was much less impacted in 2019, with N:S ranging from 5.7:1 when 10 000 kg ha^{-1} low C ash was mixed with high C ash, and 6.63:1 in control. Any effect ash had on white spruce was gone in 2020, where no difference was observed between any treatments. In 2020 black spruce responded with a similar pattern as 2019, although with fewer significant observations. The 2020 N:S ratios in in black spruce ranged from 11.56:1 when low C ash was applied at 10 000 kg ha^{-1}, and 14.48:1 when high C ash was applied at 10 000 kg ha^{-1}.

4.8 Growth Response

The only significant variation in tree height and volume was between species. No significant effect of wood ash treatment was found on the growth of either species. Although wood ash had no significant effect on height and volume, there is a clear pattern in response to ash addition and growth between species. Black spruce grew taller and had larger increases in volume when compared to control, except for 1000 kg ha^{-1} low C ash in combination with 10 000 kg ha^{-1} high C ash which performed very similar to control. The best performance in growth was seen in plots treated with 10 000 kg ha^{-1} low C ash in combination with 1000 kg ha^{-1} high C ash where black spruce on average grew 26.1 cm in a growing season. White spruce on the other hand showed a somewhat negative relationship between ash application and growth where the control pots experienced the greatest growth in height and volume across all treatments. Soils treated with 1000 kg ha^{-1} low C ash had the smallest response in height growth (25.3 cm average) and soils treated with 10 000 kg ha^{-1} low C ash in combination with 1000 kg ha^{-1} high C ash had the most positive response from ash addition (28.4 cm on average).

A negative or no response of white spruce growth to wood ash application has been observed in several other studies. This is attributed to the slow and conservative growth strategies that spruce species exhibit, where species such as jack pine have a more rapid nutrient acquisition strategy and have more positive growth response to ash addition (Bélanger et al., 2021). Staples and Van Rees (2001) observed significantly lower growth in white spruce 2 years after 5000 kg ha^{-1} wood/sludge ash application. Wood ash application to soils under white spruce in boreal forests across Canada ranged from 700-1500 kg ha^{-1} application resulted in little to no growth response (Emilson et al., 2019). This same meta-analysis found marginal negative growth rate response in black spruce of all ages with wood ash addition (Emilson et al., 2019). Brais et al. (2015) found that larger (diameter breast height > 10 cm) height growth decreased linearly with application rate, where younger black spruce (diameter breast height < 10 cm), growth was not affected by ash. The current study has shown the opposite, where black spruce showed insignificant additional growth where ash was applied, with stronger response from low C ash.

More years of observations are needed to determine if this growth effect is significant through time.

4.9 Wood Ash Influence Through Time

After the first application of wood ash in 2012, soil pH, conductivity, exchangeable Ca, exchangeable K, total S, total Zn, total Fe, total Mn, black and white spruce height, black and white spruce foliar S, and white spruce foliar B were significantly affected by ash application in the first growing season after application (Couch et al., 2021). After the second application there were several responses not detected after the first application such as: soil C, soil C:N, exchangeable Mg, exchangeable Na, total Sr and foliar Al.

Three trends in both the 2012 ash application and the 2019 re-application observed in the soil data are: 1) low C ash had a greater impact on soil chemistry than the high C ash (conductivity, eCa, eK, eZn, total Ca and S), 2) applying ash at higher rates had a greater effect on soil (pH, conductivity, eCa, eK), and 3) mixing low C ash with high C ash had greater effects than high C ash alone (pH, eCa, eK). Another two trends observed in the soil are: 1) high C ash had a greater impact after the second ash application, 2) concentrations of soil metals (extractable Cu, Zn, and Mn, and total Sr and Ca) are higher in the soil with the second application. The province of Ontario has set regulations imposing maximum acceptable concentrations of ten soil metals (As, Cd, Co, Cr, Cu, Pb, Hg, Mo, Ni, Se, and Zn; O. Reg. 338/09, s 70). The Cu and Zn limit for soils are 100 mg kg^{-1} for Cu and 220 mg kg^{-1} for Zn (O. Reg. 338/09, s 70). Total Cu and Zn concentrations in the soils at this site have a maximum value of 21 mg kg^{-1} and 150 mg kg^{-1} respectively, including the soils receiving two applications of ash. This indicates that these metals have not yet accumulated in the soil at levels that compromise environmental quality. The results presented here show that that Cu and Zn are accumulating in the extractable (plant accessible) pool which could pose a hazard to plants, though differences of these metals were not detected in either black or white spruce and are likely of no significant threat.

Increased exchangeable Ca and K concentrations in the soil were also observed after the second mixed ash application by Omil et al. (2013). Omil et al. (2013) also observed increased P; however, this was not the case at the 25th Side Road. Differences between studies could be attributed to multiple factors including different ash chemistry and loading rates, and time since application.

Tree growth and foliar nutrient contents response to ash application is much less consistent between tree species in this study. Only foliar S in black spruce showed a consistent response after the first and second ash application. Foliar Mn, white spruce foliar S, and black spruce height growth show no consistent treatment effects with ash application. The sole consistency between these is that greater application rates trend to lower the response i.e., less of a difference. Additionally, black spruce foliar S, white spruce foliar S, and black spruce height growth all had stronger responses after the first round of treatments than the second application seven years later, where few significant variations in treatment are detected.

Black spruce has been found to have a neutral growth response to ash at young ages, and negative responses in mature individuals (Brais et al., 2015). In this experiment black spruce may have matured from a period where there would be some benefit from ash into a stage where ash is beginning to limit growth. It's been argued that the negative response of black spruce to wood ash could be due to toxic concentrations of Mn causing reduction in needle chlorophyll as it does in white spruce (Brais et al., 2015). Elevated foliar Mn contents were reported in Monterey pine species after 3 mixed wood ash soil applications at 4500 kg ha^{-1} (Omil et al., 2007), and in hybrid larch and white spruce 8 years after ash application (Bélanger at al., 20121). Black spruce would be especially susceptible to ash derived toxicity, as ash would have the strongest impact near the soil surface where black spruce tends to root (Houle et al., 2014). Elevated soil exchangeable Mn and variable black spruce foliar Mn only occurred seven years after the first application, which is in line with the finding that Mn concentrations in ash decline with time since application (Nieminen et al., 2005). Black spruce in the control plots and in plots with the lowest ash application rates have the highest foliar Mn contents, even though concentrations of extractable Mn in the soil are higher in the soils receiving high rates of ash. This suggests that Mn is initially held in high pH dependant phases, which may later dissolve when pH declines. In years to come as the soil pH returns to its baseline, it is possible that plants could experience Mn toxicity as Mn is released from minerals and desorbed from soil colloid exchange sites. Further pH and foliar Mn monitoring with time would be needed to understand the stability of ash derived Mn in soil and the pH dynamics that control plant uptake. Repeated ash application may result in initial Mn deficiencies in black spruce, but on the other hand if pH conditions return to pre-application levels plants could be exposed to toxic concentrations of Mn.

Chapter 5- Conclusions

This study investigates the effects of a second application of two different wood ashes in varying amounts and mixtures on tree growth, foliar nutrient, and soil chemistry of a sandy loam soil. The second application produced significant changes in total soil chemistry, soil exchangeable and extractable chemistry, and the foliar nutrition of black and white spruce.

Wood ash's effect on soil chemistry included increased: exchangeable Ca, K, Mg, Na, extractable Cu, Mn, Zn, total soil C, Ca, S, Sr, soil conductivity, and pH. These soil effects were all observed within the first year of re-application and were clearly influenced to a greater degree when 1) low C ash was applied, 2) greater amounts of ash were added to soil, and 3) when low C ash was mixed into high C ash. These soil parameters were predominantly affected by the low C ash, which contains greater quantities of these elements (excluding C) than the high C ash. Ash re-application resulted in significant changes in soil parameters (soil C, soil C:N, exchangeable Mg, exchangeable Na, and total Sr) that showed no difference after the initial application in 2012.

Elevated extractable Cu, Mn and Zn, along with total Sr concentrations in soil are factors that may pose issues when considering ash application, though no metals are present in toxic concentrations according to Ontario Regulation 338/09 section 70 on regulated metals. Concentrations of these heavy metals observed in soil are more affected by the low C ash, which would indicate that low C ash should be used in moderation in order to reduce risk of metal contamination. High C ash does not have this effect and could therefore be used in greater amounts with less associated heavy metal risks. Though these metals are elevated in soil from low C ash application, they do not translate into the foliar content of the trees growing in the soil.

Both the first and second applications had some effect on foliar S concentrations which varied between species, suggesting that both black and white spruce see some benefit from repeated applications. Ash's effect on foliar S is short lived with most of its effects seen only after one growing season. Foliar Mn and Al contents were lower where low C ash was applied and where ash was applied at greater rates. This is likely due to the increase in soil pH creating a new regime of stable Mn and Al oxide/hydroxides phases that remove these elements from the available pool. When pH returns to pre-application levels it is possible that Mn may increase because it will become soluble and available for plant uptake.

Black spruce appears to be sensitive to surface ash applications, as its rooting structure is closer to the soil surface than white spruce. This conclusion is corroborated by black spruce having a greater chemical change in foliar Mn, S contents with ash application and a waning growth response from ash application. Our study shows that black spruce may not be a suitable candidate for ash application, though further foliar and growth analysis as the plots mature would be beneficial to determine how ash and time affect black spruce health.

No immediate negative effects were observed in the re-application of low and high C wood ashes in varying amounts and combinations. This is an encouraging outcome. Landfilling ash comes at a financial cost for the producer, and a potential environmental cost if the ash is improperly landfilled. Using ash as a forest soil amendment could help reduce the effects of intensive forestry on soil. This study shows that ash re-application to soils can increase concentrations of Ca, K, Mg, and S in soil, as well as reduce the impact of soil acidification and C depletion that follows tree harvesting.

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Appendix A

2020 Soil and Foliar Data from Sub-Plots Containing Black Spruce

Plot	Block	Treatment (LC/HC)	Bulk Density g/cm^3	Field Moisture (g H2O / g soil)	Conductivity (µS cm^{-1})	pH	Total N (g kg^{-1})	Total C (g kg^{-1})	C:N
1	1	10/0	0.90	16.0	154.5	6.52	1.3	20.9	16.1
2	1	0/10	0.87	15.2	137	6.32	1.3	23.8	18.3
3	1	1/0	1.04	13.1	74	5.63	1.3	21.2	16.3
4	1	10/10	1.01	16.3	277	6.67	1.1	21.9	19.9
5	1	0/0	0.91	13.2	79.5	5.6	1.1	17.3	15.7
6	1	10/1	0.98	17.8	191.7	6.53	1.2	21.3	17.8
7	1	0/1	1.09	14.5	92.4	5.52	1	16	16.0
8	1	1/1	0.96	15.2	78.5	5.56	1	17.9	17.9
9	1	1/10	0.82	19.7	92.2	6.12	1.4	29.3	20.9
10	2	10/0	0.87	18.2	135.5	6.12	1.4	25.4	18.1
11	2	1/1	0.89	20.2	94.5	5.56	1.2	21.2	17.7
12	2	0/1	0.94	19.8	73	5.57	1.2	20.1	16.8
13	2	1/0	1.05	18.7	76.9	5.67	1.3	25.9	19.9
14	2	0/0	1.09	19.0	80.5	5.47	1.2	20.7	17.3
15	2	10/1	0.84	26.9	102.4	6.16	1.3	24	18.5
16	2	1/10	0.94	20.3	176.4	6.42	1.2	26.8	22.3
17	2	0/10	0.83	28.1	75.1	5.87	1.1	19.6	17.8
18	2	10/10	1.00	23.9	175.9	6.23	1.1	22.5	20.5
19	3	0/10	0.86	17.7	108.4	6.11	1.1	23.3	21.2
20	3	1/1	0.98	16.1	80.9	5.85	1.1	19.8	18.0
21	3	10/10	0.74	24.8	140.1	6.55	1.1	22.4	20.4
22	3	0/1	1.02	16.6	84	5.49	1.2	20.1	16.8
23	3	0/0	0.98	17.4	58.5	5.13	1.2	20.2	16.8
24	3	10/1	0.95	22.0	175.8	6.08	1.3	23.3	17.9
25	3	1/10	0.80	29.3	102.7	5.84	1.1	21.2	19.3
26	3	10/0	0.86	23.3	240	6.32	1.5	30.7	20.5
27	3	1/0	0.88	19.0	101.4	5.73	1.4	24.9	17.8
28	4	10/1	0.91	22.4	202	6.38	1.1	18.4	16.7
29	4	1/10	0.86	16.5	130.8	6.04	1.2	22.6	18.8
30	4	10/10	0.84	21.9	111.3	6.34	1.2	24.8	20.7
31	4	0/1	0.92	16.8	90.8	5.69	1.3	23.8	18.3
32	4	0/10	1.02	17.7	114.9	5.81	1.4	34	24.3
33	4	0/0	0.98	15.4	81	5.56	1.2	20.4	17.0
34	4	1/0	1.01	17.7	87.4	5.69	1.3	19	14.6
35	4	10/0	1.01	17.4	207	6.33	1.2	21.2	17.7
36	4	1/1	0.98	17.9	96.9	5.68	0.9	16.3	18.1
37	5	10/0	0.95	15.1	259	6.32	1.2	19.5	16.3
38	5	10/10	0.81	19.6	347	6.46	1.2	24.1	20.1
39	5	1/0	1.00	14.3	87.2	5.68	1	18.1	18.1
40	5	1/10	0.67	22.3	150.3	6.2	1.2	25.8	21.5
41	5	0/1	0.80	18.8	53.1	5.48	1.1	19.6	17.8
42	5	1/1	1.09	13.6	86.7	5.78	1.2	22.4	18.7
43	5	0/10	0.77	18.7	138.2	6.06	1.1	23	20.9
44	5	0/0	0.94	17.1	88.1	5.54	1.1	21.1	19.2
45	5	10/1	1.01	17.0	105.9	6.37	1.1	23.6	21.5

Plot	Al (mg kg^{-1})	As (mg kg^{-1})	Ca (mg kg^{-1})	Co (mg kg^{-1})	Cr (mg kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	K (mg kg^{-1})	Mg (mg kg^{-1})	Mn (mg kg^{-1})
1	14200	7.4	4760	20	46.2	21.5	57100	1170	3930	918
2	12900	7.6	3250	18	41.4	17.7	53300	970	3630	854
3	13800	9.3	2660	17	45.2	20.4	64200	1030	4130	975
4	14500	10.8	3940	17	48	19.2	54300	1360	4470	809
5	13400	6.3	2550	19	48.9	20.5	64200	890	3960	888
6	13500	10.3	3850	18	49.4	20.4	74600	1130	3850	1060
7	8370	3.9	1740	12	27.5	11.9	36000	560	2460	542
8	12000	4.9	2370	16	39.5	16.6	47500	760	3460	735
9	13800	6.2	3450	17	44.7	19.5	56700	1020	4180	823
10	13500	8.5	3020	15	45.7	18.9	52300	1140	4330	781
11	9340	5.6	1740	13	32.3	13.3	36100	870	2910	563
12	15200	7.3	2670	17	46.2	19.6	51800	1100	4360	794
13	14000	10.7	2550	17	45.8	20.3	69200	950	3850	966
14	13900	8.2	2140	16	45.1	19.6	55700	990	4170	810
15	12700	7.1	2830	12	39.3	17.3	46500	950	4400	608
16	12500	6.1	3150	14	39.8	17.3	44500	1010	3530	715
17	11200	4.7	2460	13	36.1	17.5	50800	840	4470	719
18	15700	10.2	2780	17	49.9	24.7	67600	1170	5370	857
19	14200	9.3	3560	16	43.8	20.6	54400	1200	4300	848
20	14900	8.4	3310	15	42.6	21.3	56800	1050	5010	876
21	15500	12.6	3250	17	50.2	23.1	69800	1120	5460	959
22	11500	5.8	3180	13	35.2	16.8	39700	1030	3510	588
23	11800	6.3	3640	12	32	17	35500	1090	3550	602
24	9650	5.8	2100	10	29.8	14.1	35000	660	2860	491
25	12500	5	2450	14	37.4	17.3	45700	820	4050	635
26	11600	7.1	3180	13	36.6	17.4	41200	970	3240	644
27	16200	9.3	3650	18	50.4	24.8	64000	1310	4940	926
28	18500	10.9	5020	19	54.7	26.3	67400	1530	5810	1030
29	10200	8.1	2410	12	33.7	18.1	52100	700	2840	738
30	13700	9.6	3470	13	46.7	19.9	51700	1160	4770	689
31	13400	8.6	3050	13	37.2	19.1	46800	920	4000	679
32	13300	8.7	3060	13	35.9	18.1	46300	920	4110	720
33	11500	6	2270	12	30.7	16	36300	780	3130	589
34	14300	7.1	3180	15	40	21	50500	1190	4030	794
35	13500	6.3	3540	13	36.3	18.2	43700	1290	4220	659
36	14700	9.7	2790	14	38	21	51400	1080	4320	721
37	12700	6.6	3490	13	33.9	16.7	41100	1080	3900	608
38	17700	9.8	6520	18	43.9	20.8	46500	1840	4120	903
39	15100	5.3	3170	13	39.6	16.6	43300	1320	4230	636
40	15600	10.7	4080	13	38.5	18.8	46000	1600	4260	673
41	16800	7.8	3560	16	41	18.1	46700	1440	3840	755
42	15400	10.4	3350	14	38.6	19.5	47900	1360	3980	665
43	13800	9	3330	13	38.4	18.2	47300	1280	3860	697
44	16100	9.7	3350	14	41.9	17.7	45700	1440	4070	685
45	14900	8.1	4100	14	37	17.9	41800	1420	3910	659

Plot	Na (mg kg^{-1})	Ni (mg kg^{-1})	P (mg kg^{-1})	Pb (mg kg^{-1})	S (mg kg^{-1})	Sr (mg kg^{-1})	Zn (mg kg^{-1})
1	186	41	1690	14	244	16	98.1
2	135	37	1510	14	154	12	76.6
3	113	34	1730	18	164	9	76.9
4	153	38	1440	14	180	14	82.1
5	137	38	1440	12	169	9	77.1
6	128	35	1860	18	202	12	83.0
7	92	22	907	8	88	6	45.6
8	117	33	1220	12	143	9	65.2
9	130	37	1390	12	170	12	79.0
10	128	33	1390	14	181	10	75.6
11	92	25	845	9	121	6	54.2
12	131	35	1690	15	159	10	78.2
13	122	32	1290	15	144	9	76.2
14	97	34	1510	14	149	8	74.7
15	123	30	1600	9	134	10	56.7
16	122	30	1690	12	172	11	74.5
17	93	26	1010	11	101	8	56.9
18	95	35	1850	15	128	11	83.6
19	125	33	1840	13	174	12	80.5
20	115	34	1840	14	156	11	79.8
21	114	33	2320	17	166	12	75.1
22	121	28	1560	8	143	11	63.1
23	133	26	1440	6	158	12	62.1
24	77	22	1260	9	122	7	48.3
25	95	31	1700	12	137	9	60.4
26	124	28	1590	11	175	11	63.6
27	160	38	2280	19	202	14	86.5
28	166	41	2600	16	240	19	93.9
29	72	23	1650	11	151	9	54.6
30	117	33	1960	12	163	12	64.3
31	151	29	1720	11	152	11	60.5
32	145	29	1680	13	161	11	60.1
33	118	25	1390	10	154	8	54.3
34	176	33	1690	10	160	12	65.0
35	181	29	1410	9	153	12	67.0
36	169	30	1450	12	149	11	64.8
37	147	27	1850	10	161	13	67.9
38	423	35	2220	10	248	25	104.0
39	213	28	1350	11	140	12	64.1
40	248	28	1960	10	181	17	67.0
41	263	31	1990	11	187	15	74.8
42	221	31	1650	12	173	14	69.8
43	190	27	1610	11	144	16	61.6
44	236	29	1770	12	186	14	69.2
45	260	29	1480	12	176	15	72.5

Plot	eCa (mg kg-1)	eCu (mg kg-1)	eFe (mg kg-1)	eK (mg kg-1)	eMg (mg kg-1)	eMn (mg kg-1)	eNa (mg kg-1)	eP (mg kg-1)	eZn (mg kg-1)
1	2160	2.069	332.77	153	224	112.01	9	315	13.05
2	2110	1.673	297.16	161	286	95.177	12	267	3.23
3	1320	1.786	327.31	67	185	67.89	10	255	2.88
4	2100	1.669	287.22	215	198	91.712	11	259	9.64
5	1140	1.65	310.23	73	170	63.517	19	203	1.69
6	1880	2.033	245.15	121	165	91.327	10	234	13.5
7	1030	1.44	318.65	66	128	63.729	4	181	1.33
8	1190	1.538	284.14	67	134	56.587	12	178	2.37
9	1470	1.51	291.44	105	146	77.958	7	188	3.42
10	1610	1.663	286.17	148	151	69.04	8	167	6.56
11	1000	1.783	365.19	101	131	80.211	6	152	1.7
12	1000	1.658	354.34	76	137	61.569	5	279	1.58
13	1090	1.458	280.13	75	135	55.365	10	110	2.01
14	946	1.52	253.69	108	147	45.913	4	201	1.13
15	1500	1.763	359.4	221	154	75.216	8	377	8.4
16	1310	1.465	256.05	135	145	79.799	8	112	3.78
17	1060	1.743	328.81	105	136	65.76	5	271	1.78
18	1570	2.221	440.37	170	141	98.485	8	444	11.26
19	1370	1.626	357.34	98	179	74.928	7	324	2.59
20	1400	1.743	376.77	90	200	70.006	24	415	2.76
21	1550	1.678	379.1	208	165	84.252	7	401	6.71
22	1210	1.701	378.97	81	174	65.015	5	355	2.12
23	1130	2.179	469.78	101	161	65.406	5	481	3
24	1630	2.427	508.52	148	168	92.202	13	506	8.07
25	1350	2.388	493.8	110	173	94.051	5	461	3.67
26	2000	2.154	380.26	189	195	89.995	12	453	10.31
27	1430	2.014	408.27	83	177	60.078	6	338	2.71
28	1690	2.593	453.68	185	155	84.614	13	471	12.31
29	1300	2.112	473.88	139	157	87.077	11	414	2.88
30	1890	2.142	378.68	244	179	94.401	15	432	13.11
31	1310	2.249	491.61	80	178	52.015	5	417	1.84
32	1380	1.899	440.15	77	172	53.946	7	375	1.7
33	1190	1.701	350.57	86	156	49.108	10	312	1.56
34	1260	2.27	499.6	92	162	57.409	8	414	1.96
35	1670	2.068	364.5	153	144	72.974	10	356	7.39
36	1060	1.786	364.73	82	127	38.081	7	282	1.96
37	1610	1.809	417.01	172	130	80.868	12	453	9.73
38	1940	2.026	413.31	175	153	98.168	13	480	15.2
39	1030	1.548	379.06	93	119	51.233	3	332	2.23
40	1620	1.675	433.8	150	196	74.051	8	496	3.38
41	1080	1.68	477.76	87	144	68.08	4	465	2.16
42	1290	1.741	383.94	88	148	59.527	4	343	3.36
43	1460	1.888	434.8	138	150	79.97	6	427	2.97
44	1210	1.631	416.51	74	151	47.744	8	362	2.79
45	1460	1.956	410.23	126	124	91.229	8	388	11.6

Plot	100 needle weight	Foliar Al	Foliar B	Foliar Ba	Foliar Ca	Foliar Cr
	(g)	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})
1	0.1894	2.17	3.26	8.92	863.68	0.03
2	0.1968	1.95	1.98	13.96	897.25	0.02
3	0.1844	1.43	2.51	14.63	951.74	0.02
4	0.2012	2.29	2.48	9.43	842.12	0.03
5	0.166	1.44	1.84	9.55	611.91	0.05
6	0.1933	1.45	2.97	11.72	894.73	0.05
7	0.1834	2.31	1.78	14.18	914.01	0.08
8	0.1512	1.98	1.76	9.86	696.29	0.04
9	0.1572	1.76	1.64	8.12	551.22	0.03
10	0.1856	1.58	2.46	12.95	887.08	0.05
11	0.1865	2.48	2.15	11.70	674.12	0.04
12	0.216	2.79	1.66	15.23	968.28	0.05
13	0.166	-	1.41	11.96	710.05	0.05
14	0.2361	3.91	2.44	18.95	1064.72	0.23
15	0.167	1.07	1.77	9.65	749.73	0.03
16	0.2047	1.17	2.26	11.99	865.45	0.02
17	0.1858	2.58	1.69	13.79	752.45	0.07
18	0.1976	1.96	2.14	7.61	677.93	0.04
19	0.1584	1.19	1.50	8.91	658.83	0.04
20	0.1532	1.24	2.18	8.03	636.42	0.03
21	0.1607	1.60	1.77	7.91	636.37	0.03
22	0.1899	1.51	2.04	11.17	768.20	0.05
23	0.1775	1.35	1.66	9.96	724.15	0.03
24	0.1709	1.19	1.46	8.50	730.96	0.04
25	0.1608	1.56	2.07	7.95	735.52	0.03
26	0.1676	1.28	1.99	10.09	714.80	0.05
27	0.2023	1.74	2.56	13.25	806.25	0.05
28	0.1739	1.43	1.76	11.79	865.64	0.04
29	0.1943	1.35	2.19	13.39	864.25	0.03
30	0.1842	0.90	1.85	10.05	750.01	0.03
31	0.1623	2.36	1.66	10.89	830.23	0.10
32	0.1702	1.21	2.24	10.35	580.08	0.04
33	0.177	1.41	1.80	10.94	666.51	0.04
34	0.1918	1.76	2.06	10.07	687.16	0.04
35	0.1614	1.23	2.39	9.46	670.46	0.14
36	0.179	1.39	1.60	10.77	755.34	0.04
37	0.2006	1.58	2.54	7.19	806.55	0.04
38	0.194	1.52	2.16	12.19	973.34	0.04
39	0.1896	1.36	1.65	11.31	752.94	0.06
40	0.2341	2.20	1.72	17.22	1486.84	0.04
41	0.1822	1.71	1.42	11.12	801.92	0.05
42	0.1543	1.17	1.27	13.65	746.60	0.03
43	0.165	1.19	1.58	10.39	715.29	0.04
44	0.1675	1.46	1.39	11.16	674.42	0.04
45	0.1582	1.25	1.82	8.13	696.29	0.04

Plot	Foliar Cu (µg 100 needles^{-1})	Foliar Fe (µg 100 needles^{-1})	Foliar K (µg 100 needles^{-1})	Foliar Mg (µg 100 needles^{-1})	Foliar Mn (µg 100 needles^{-1})	Foliar N (µg 100 needles^{-1})	Foliar Na (µg 100 needles^{-1})
1	0.50	7.36	1094.73	211.49	46.15	2.56	1.69
2	0.49	6.72	1115.34	230.77	62.18	2.56	0.81
3	0.47	5.32	1065.54	196.82	68.59	2.66	0.70
4	0.48	8.09	1214.81	181.85	47.62	2.62	0.68
5	0.43	5.06	998.95	151.11	54.36	2.36	0.51
6	0.53	6.48	1292.52	210.06	44.56	2.51	0.58
7	0.56	7.08	1271.40	189.12	99.19	2.46	0.48
8	0.43	5.31	964.19	166.45	85.94	1.91	0.35
9	0.41	5.63	1143.24	169.24	41.29	1.85	0.46
10	0.46	6.04	1356.40	199.62	39.12	2.12	0.50
11	0.46	6.43	1340.04	193.68	84.33	2.33	0.43
12	0.65	8.97	1535.82	258.18	107.62	2.79	0.54
13	0.40	4.79	1029.65	179.40	54.22	2.04	0.27
14	0.55	12.19	1554.77	261.51	110.98	3.12	0.68
15	0.44	5.58	1184.20	158.53	30.09	2.05	0.25
16	0.54	5.62	1412.92	210.12	53.22	2.68	0.33
17	0.44	7.08	1211.36	182.44	73.79	2.21	0.46
18	0.55	6.67	1531.64	196.57	50.83	2.51	0.41
19	0.39	4.72	956.32	197.65	38.44	1.79	0.49
20	0.43	4.74	964.35	178.17	39.03	1.81	0.51
21	0.40	6.10	983.69	173.33	34.21	1.96	0.61
22	0.48	5.63	1170.92	226.38	61.00	2.35	0.49
23	0.44	5.35	1146.21	231.67	53.18	2.17	0.34
24	0.49	5.76	1228.94	182.06	34.88	2.12	0.44
25	0.51	5.53	1151.02	231.06	52.44	2.06	0.51
26	0.55	6.27	1143.45	202.90	31.88	2.33	0.52
27	0.60	7.47	1430.06	227.73	56.43	2.75	0.45
28	0.56	7.17	1326.27	190.62	41.25	2.45	0.38
29	0.50	6.18	1281.29	202.23	42.44	2.43	0.31
30	0.49	5.40	1156.44	192.62	30.65	2.28	0.18
31	0.64	12.43	951.74	201.04	47.47	2.09	0.62
32	0.42	4.66	1109.23	206.20	40.39	2.18	0.24
33	0.46	5.19	966.97	237.16	51.94	2.18	0.19
34	0.67	7.31	1245.76	208.19	46.00	2.61	0.35
35	0.65	6.33	1008.94	161.33	35.11	2.15	0.45
36	0.58	5.54	1098.09	201.67	53.48	2.47	0.50
37	0.50	6.34	1328.73	205.70	60.69	2.39	0.32
38	0.61	5.71	1429.82	214.24	65.56	2.31	0.25
39	0.52	5.18	1113.35	197.20	62.43	2.37	0.15
40	0.60	6.60	1102.56	219.98	61.46	3.07	-
41	0.55	6.22	900.14	197.85	63.27	2.31	0.36
42	0.51	4.70	936.59	172.49	53.13	2.01	0.20
43	0.51	4.82	956.36	172.96	52.12	2.41	0.13
44	0.51	5.47	1076.14	172.11	63.24	2.13	0.13
45	0.48	4.91	1046.81	155.02	51.26	2.02	-

Plot	Foliar Ni (µg 100 needles^{-1})	Foliar P (µg 100 needles^{-1})	Foliar S (µg 100 needles^{-1})	Foliar Si (µg 100 needles^{-1})	Foliar Sr (µg 100 needles^{-1})	Foliar Zn (µg 100 needles^{-1})
1	0.18	373.06	219.72	30.57	4.64	9.46
2	0.36	377.17	178.91	34.54	5.80	9.37
3	0.35	329.67	176.78	26.87	5.80	10.87
4	0.21	359.50	211.18	22.41	4.44	9.29
5	0.48	279.44	149.78	18.26	3.48	7.00
6	4.03	386.31	205.25	25.98	6.17	10.78
7	1.04	419.62	195.83	29.20	4.93	8.86
8	0.70	357.10	158.43	21.56	3.91	7.27
9	0.51	282.96	143.95	17.54	2.88	6.77
10	0.50	375.00	193.49	22.09	4.77	10.03
11	0.61	364.98	148.27	22.16	2.91	7.96
12	0.86	485.03	214.25	31.64	4.65	12.72
13	0.51	307.42	156.80	19.69	4.28	8.99
14	0.62	517.22	222.08	25.92	5.48	11.60
15	0.43	353.41	184.52	13.98	4.60	9.48
16	0.51	424.75	189.55	20.45	2.82	10.64
17	0.80	361.66	162.67	19.38	4.65	7.40
18	0.44	379.53	211.57	16.16	4.81	9.17
19	0.41	287.59	139.82	15.00	4.80	7.38
20	0.62	300.47	142.28	14.52	4.16	8.26
21	0.20	296.68	185.13	15.65	5.87	8.91
22	0.50	350.97	167.32	22.66	5.16	9.22
23	0.32	373.51	163.32	16.47	5.43	8.93
24	0.30	336.59	183.22	14.07	4.48	9.47
25	43.19	348.50	164.87	21.92	4.08	8.88
26	0.52	346.19	197.20	13.61	6.22	11.63
27	1.94	447.97	191.68	19.20	6.27	9.90
28	24.17	385.88	204.40	7.86	6.90	10.79
29	2.61	365.42	181.46	17.31	7.15	11.35
30	0.33	320.29	173.85	14.90	6.29	10.05
31	0.38	305.09	156.75	17.27	5.95	8.60
32	0.40	351.80	144.65	19.64	5.30	7.41
33	0.41	330.78	160.03	18.14	4.23	8.74
34	15.61	388.16	193.49	16.38	4.42	9.93
35	0.75	325.00	194.83	13.12	4.59	10.00
36	0.72	414.37	188.85	18.17	3.63	8.86
37	0.56	339.44	192.52	21.36	4.36	8.67
38	0.68	418.30	211.77	18.35	7.12	11.92
39	0.66	360.81	160.78	18.58	4.13	7.80
40	0.87	438.80	165.60	65.95	11.69	13.50
41	0.55	335.16	173.89	15.10	6.00	9.11
42	0.62	299.94	151.31	11.74	5.60	7.72
43	0.95	332.99	144.52	12.99	4.66	7.48
44	1.31	324.36	151.22	13.08	4.65	7.35
45	0.44	290.41	161.02	17.32	3.83	7.02

Appendix B

2019 Soil and Foliar Data from Sub-Plots Containing Black Spruce

Plot	Block	Treatment	Bulk Density	Field Moisture	Conductivity	pH	total N	total C	C:N
		(LC/HC)	(g/cm^3)	(g H2O / g soil)	(µS cm-1)		(g kg^{-1})	(g kg^{-1})	
1	1	10/0	0.8	15.2	349.0	7.1	1.2	20.6	17.2
2	1	0/10	0.8	15.4	98.9	7.1	1.2	22.3	18.6
3	1	1/0	0.8	14.5	75.9	6.3	1.2	20.0	16.7
4	1	10/10	0.8	16.2	371.0	7.1	1.3	26.0	20.0
5	1	0/0	0.8	14.2	44.8	6.1	1.2	18.1	15.1
6	1	10/1	0.8	16.4	234.0	6.9	1.3	23.7	18.2
7	1	0/1	0.9	13.1	45.3	6.0	1.1	16.2	14.7
8	1	1/1	0.9	13.8	48.6	6.0	1.0	16.9	16.9
9	1	1/10	0.8	17.0	102.1	6.5	1.3	21.8	16.8
10	2	10/0	0.8	16.9	289.0	6.9	1.4	25.5	18.2
11	2	1/1	0.8	15.1	53.9	6.3	1.3	20.5	15.8
12	2	0/1	0.8	14.9	37.1	6.2	1.1	18.9	17.2
13	2	1/0	0.8	12.7	69.6	5.9	1.1	17.0	15.5
14	2	0/0	0.9	14.5	35.5	6.0	1.1	17.1	15.5
15	2	10/1	0.8	16.7	149.5	6.8	1.3	21.5	16.5
16	2	1/10	0.9	15.8	94.4	6.9	1.1	21.5	19.5
17	2	0/10	0.8	16.0	73.5	6.7	1.1	19.9	18.1
18	2	10/10	0.8	20.9	301.0	7.1	1.3	24.3	18.7
19	3	0/10	1.0	17.3	105.0	6.9	1.2	22.7	18.9
20	3	1/1	0.9	16.7	56.1	6.3	1.2	19.0	15.8
21	3	10/10	1.0	17.6	300.0	7.3	1.0	20.9	20.9
22	3	0/1	1.0	16.3	40.5	6.3	1.1	19.4	17.6
23	3	0/0	1.0	17.4	42.7	6.1	1.3	21.4	16.5
24	3	10/1	1.0	18.4	232.0	6.7	1.3	23.5	18.1
25	3	1/10	0.9	19.4	128.9	6.7	1.2	24.1	20.1
26	3	10/0	1.0	19.2	195.5	6.9	1.3	24.2	18.6
27	3	1/0	1.0	17.3	45.9	6.4	1.2	20.7	17.3
28	4	10/1	1.0	15.1	228.0	7.0	0.8	15.1	18.9
29	4	1/10	0.9	16.1	100.6	6.9	1.0	17.8	17.8
30	4	10/10	0.9	19.0	249.0	7.3	1.0	23.9	23.9
31	4	0/1	0.7	15.4	40.3	5.8	1.1	18.1	16.5
32	4	0/10	0.7	18.7	75.0	6.6	1.2	24.0	20.0
33	4	0/0	0.6	14.7	44.7	5.8	1.2	19.9	16.6
34	4	1/0	0.7	15.6	45.2	6.0	1.1	18.1	16.5
35	4	10/0	0.6	17.2	221.0	7.0	1.2	20.4	17.0
36	4	1/1	0.7	14.6	54.4	6.0	1.1	17.0	15.5
37	5	10/0	0.6	17.5	368.0	6.9	1.1	19.4	17.6
38	5	10/10	0.7	17.5	259.0	7.1	1.1	22.2	20.2
39	5	1/0	0.8	14.4	37.2	5.9	1.1	16.5	15.0
40	5	1/10	0.6	19.5	292.0	6.9	1.1	23.1	21.0
41	5	0/1	0.7	16.4	30.4	6.1	1.1	18.7	17.0
42	5	1/1	0.7	16.0	72.3	6.1	1.3	19.0	14.6
43	5	0/10	0.6	15.2	53.2	6.3	1.1	19.5	17.7
44	5	0/0	0.6	15.9	40.3	5.8	1.2	20.2	16.8
45	5	10/1	0.8	15.3	153.9	6.5	1.0	17.8	17.8

Plot	Al (mg kg-1)	As (mg kg-1)	Ca (mg kg-1)	Co (mg kg-1)	Cr (mg kg-1)	Cu (mg kg-1)	Fe (mg kg-1)	K (mg kg-1)	Mn (mg kg-1)	Mn (mg kg-1)
1	15300	5.1	4840	18	50.7	20.6	59000	1370	4560	900
2	17000	6.2	4290	19	53.5	20.1	58400	1460	4800	1010
3	14100	5.8	2880	16	42	18.8	47400	900	3940	875
4	14200	6.7	4520	19	44.9	19.2	52200	1430	4520	897
5	15900	5.2	3230	18	49.6	20.1	60500	1190	4590	917
6	13800	3.7	4120	18	44	19	47400	1180	3830	881
7	14400	6.3	2770	18	51.3	20.5	61200	980	4830	898
8	14100	4.8	2890	18	46.5	17.9	52800	970	3740	776
9	15200	5.8	3350	17	47.2	18.4	52000	1250	4000	847
10	14800	4.9	4440	16	43.7	19.3	47700	1300	4120	912
11	12300	5.9	2290	16	39.5	17.2	43100	850	3370	714
12	13700	6.7	2560	15	40.4	18.5	45200	910	3770	757
13	13300	4.9	2530	15	42.9	18	45500	870	3680	728
14	15300	7.3	2670	15	51.7	19	52400	1070	4450	797
15	14000	5.9	3660	15	39.7	19.5	48100	1260	3640	793
16	14200	4.7	3060	16	45.2	21	53400	1110	4740	883
17	14000	3.7	3050	16	42.1	16.8	45300	1050	4010	745
18	14000	3.8	4650	15	45.6	19.4	51000	1230	3950	836
19	14100	4.9	3300	14	40.4	18	42700	1150	4310	748
20	14800	-	3480	14	40.3	17.7	42100	1230	4010	628
21	13400	3.2	4200	12	40.9	20.2	46900	1240	4100	706
22	13500	7	2830	14	39	17.6	44900	920	3820	605
23	15400	-	3520	14	45.8	18.9	46200	1200	4190	699
24	13900	2.9	3920	13	39.8	19.1	44400	1090	4020	705
25	14100	3.2	3630	15	41.5	17.5	45700	1080	4130	734
26	15000	8.4	4360	14	46.6	21.2	50600	1280	4420	792
27	15700	3.3	3860	15	44.6	22	46000	1290	4170	735
28	12100	-	3510	11	31.4	16.8	36100	1000	3400	553
29	12900	4.5	3230	11	35.1	17	36600	1020	3820	549
30	15000	3.4	4870	12	37.3	17	38400	1620	3890	629
31	15300	8.2	3540	13	41.5	18.1	42600	1320	4100	642
32	15600	8.4	4490	14	40.5	18.8	46100	1520	4910	727
33	15800	8.5	3350	13	38.1	18.1	41200	1480	4420	755
34	16000	8.1	3540	14	43.2	19.5	44900	1560	4420	679
35	13800	5.5	4570	13	38.5	20	44100	1370	3880	690
36	16000	9.9	3220	15	46.8	22.8	56200	1410	5000	813
37	16900	8.2	5210	13	41.7	20.6	42400	1670	4510	734
38	15700	7.2	4690	13	39.1	18.7	41500	1530	4010	696
39	16000	8.1	3380	13	40.9	19.9	45500	1520	4280	618
40	15900	7.5	4410	13	37.2	17.4	38800	1680	4100	666
41	15300	6.9	3200	12	37.2	16.5	38300	1350	4110	604
42	14800	8.5	3320	12	40.5	17.9	40200	1260	4270	628
43	15500	7.7	3360	12	39.6	18.1	46300	1580	4360	694
44	14900	8.4	3030	13	41	17.5	40700	1100	4230	663
45	14400	7.8	3520	14	40.3	20.3	48500	1130	4200	822

Plot	Na	Ni	P	Pb	S	Sr	Zn
	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})
1	187	39	1760	15	226	19	94.6
2	166	37	1820	18	176	15	85.1
3	93	33	1570	14	165	9	76.1
4	194	38	1430	16	172	16	151
5	160	36	1580	16	149	12	82.1
6	173	35	1390	12	197	13	100
7	122	36	1490	15	124	9	75.5
8	159	35	1370	14	147	10	78.1
9	166	32	1400	15	152	13	78.9
10	160	32	1470	16	247	15	88.4
11	88	31	1180	14	143	7	69.2
12	98	31	1610	14	135	9	74.3
13	111	32	1090	10	138	8	71.1
14	134	34	1450	12	128	10	75.1
15	145	30	1800	14	181	13	81.3
16	122	37	1220	13	131	10	74.2
17	139	33	1360	15	121	11	72
18	174	32	1760	15	190	15	90.8
19	135	33	1570	12	138	11	69.7
20	201	32	1700	9	148	13	70.8
21	137	29	1820	10	169	14	78
22	148	32	1670	15	142	11	67.8
23	170	33	1870	11	167	13	71.4
24	135	30	1830	11	194	13	77.1
25	164	33	1670	12	147	13	72.9
26	169	32	1880	13	201	15	83.2
27	217	32	1680	10	163	14	73.4
28	173	26	1370	10	130	12	63.2
29	147	26	1490	10	125	12	57.2
30	282	27	1530	9	164	17	74.7
31	235	30	1600	14	159	14	65.9
32	264	33	1700	11	156	17	69.3
33	237	29	1550	12	182	13	66.1
34	251	31	1620	12	176	14	69.3
35	234	29	1570	12	177	17	82.6
36	155	33	1610	16	156	14	74.1
37	281	32	2000	11	333	20	92.4
38	261	29	1910	13	201	18	84.5
39	258	29	1560	13	158	13	69.9
40	285	28	1900	13	172	16	71.5
41	233	29	1640	11	146	13	67.8
42	215	30	1440	12	140	12	66.7
43	211	30	1810	12	138	14	68.2
44	156	31	1740	14	176	12	67.6
45	167	32	1610	15	184	13	77.3

Plot	eCa	eCu	eFe	eK	eMg	eMn	eNa	eP	eZn
	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})
1	1820	1.5	177	184	194	110	19	57.03	10.5
2	1460	1.2	164	155	213	86.3	13	56.76	2.77
3	1250	1.2	163	78	168	81.1	10	50.63	3.06
4	1930	1.4	170	299	192	104	21	46.81	10.8
5	1120	1.2	150	87	157	71	12	44.07	2.08
6	1790	1.6	155	190	174	92.1	19	50.8	12.4
7	1070	1.3	174	80	140	71	8	45.06	1.9
8	1060	1.2	159	80	126	56.7	9	45.06	2.32
9	1360	1.2	170	132	153	75	14	47.67	2.91
10	1940	1.8	201	172	163	152	20	45.81	14.1
11	1080	1.3	176	104	138	107	12	37.22	2.39
12	1100	1.3	181	95	148	82.6	11	46.28	2.1
13	1040	1.1	154	106	134	69.7	9	36.03	2.04
14	922	1.2	153	109	143	58.3	10	39.83	1.67
15	1590	1.4	207	215	176	92.2	18	63.31	7.12
16	1280	1.3	223	127	148	-	15	45.74	2.34
17	1250	1.4	252	137	154	-	14	73.01	3.23
18	1910	1.6	238	228	162	-	25	92.12	12.8
19	1400	1.2	235	145	190	-	16	84.26	2.25
20	1230	1.2	226	112	177	-	12	92.23	2.25
21	1830	1.5	237	260	165	-	20	98.54	11.3
22	1090	1.2	228	85	161	-	11	90.6	2.06
23	1230	1.5	238	113	183	-	12	85.9	8.52
24	1810	1.6	243	175	198	-	21	100.64	9.49
25	1490	1.3	232	166	198	-	14	96.46	3.08
26	1910	1.7	238	195	201	-	25	103.75	11.2
27	1400	1.5	217	113	176	-	16	87.72	4.1
28	1500	1.3	243	199	150	-	20	80.74	7.89
29	1260	1.1	233	168	160	-	16	81.63	2.47
30	1930	1.5	214	273	165	-	23	104.17	11.2
31	1240	1.2	229	175	100	46	7	84.36	1.87
32	1500	1.3	227	181	153	68.2	14	95.55	2.55
33	1140	1.3	199	150	86	49.2	7	79.11	1.78
34	1230	1.4	229	159	140	41.6	15	73.57	3.06
35	1790	1.7	215	158	255	88.8	8	67.89	12.3
36	1150	1.3	190	139	85	56	6	58.84	2.32
37	1830	1.8	263	155	192	102	17	68.6	13
38	1660	1.7	239	146	222	90.1	9	96.93	9.63
39	1040	1.4	205	128	94	50.2	22	84.51	2.16
40	1540	1.3	240	175	212	86.7	19	92.84	4.72
41	1080	1.3	251	138	79	62.8	8	89.04	2.14
42	1190	2.1	227	146	106	80.7	14	76.45	2.96
43	1200	1.5	248	149	121	71.1	6	83.04	2.42
44	1090	2.2	216	138	92	78	9	80.37	7.72
45	1450	1.3	225	138	150	60.9	8	73.64	2.07

Plot	100 needle weight	Foliar Al	Foliar B	Foliar Ba	Foliar Ca	Foliar Cr
	(g)	(μg 100 needles^{-1})	(μg 100 needles^{-1})	(μg 100 needles^{-1})	(μg 100 needles^{-1})	(μg 100 needles^{-1})
1	0.13	2.06	1.11	17.50	1375.55	0.06
2	0.14	3.15	1.14	26.30	1759.35	0.07
3	0.16	2.45	1.21	24.46	1840.77	0.08
4	0.15	3.13	1.44	22.22	1741.44	0.07
5	0.14	2.84	1.50	26.12	1881.08	0.05
6	0.15	1.97	2.16	34.76	1695.83	0.05
7	0.12	2.58	0.69	21.46	1278.16	0.04
8	0.11	2.01	1.72	21.47	1139.98	0.03
9	0.12	1.65	0.91	27.30	1501.63	-
10	0.17	1.94	1.53	34.14	2313.33	0.05
11	0.19	5.12	2.29	31.69	2082.00	0.06
12	0.14	2.96	1.08	25.09	1514.74	0.05
13	0.13	3.51	1.45	32.33	1823.96	0.04
14	0.13	2.82	1.06	25.54	1775.89	0.04
15	0.12	2.39	1.51	16.95	1738.60	0.04
16	0.13	2.42	1.71	19.32	1428.91	0.04
17	0.14	3.86	1.85	33.92	2172.27	0.04
18	0.13	2.10	1.66	18.75	1563.45	-
19	0.14	2.29	1.50	16.02	1426.60	0.04
20	0.11	2.25	1.64	12.43	1320.57	-
21	0.13	2.53	1.43	12.43	1189.03	0.06
22	0.13	2.37	1.04	13.31	1385.28	0.10
23	0.12	1.81	0.83	12.11	1160.28	-
24	0.13	3.07	1.24	16.18	1542.14	0.06
25	0.15	2.94	1.22	13.78	1469.34	0.05
26	0.13	1.98	1.25	16.47	1268.47	-
27	0.17	4.41	1.91	18.99	1557.94	0.08
28	0.12	2.88	1.27	12.92	1470.53	0.06
29	0.15	1.64	1.75	25.84	1848.51	0.05
30	0.16	3.15	2.06	16.91	1746.05	0.08
31	0.16	2.78	1.29	16.68	1597.70	0.08
32	0.14	1.94	1.89	27.13	1655.28	0.07
33	0.13	2.33	1.14	17.22	1237.64	0.06
34	0.15	3.00	1.51	20.53	1734.60	0.07
35	0.12	1.62	1.48	16.01	1274.85	0.04
36	0.15	3.21	1.25	20.57	1774.86	0.05
37	0.13	2.28	1.91	19.31	2003.04	0.06
38	0.16	3.52	1.99	23.64	2388.12	0.05
39	0.14	3.15	1.89	20.62	1570.79	0.05
40	0.15	1.94	1.37	22.39	1814.92	-
41	0.14	2.96	1.31	23.09	1869.49	0.07
42	0.16	3.10	1.55	33.35	2166.12	0.13
43	0.15	2.34	1.50	21.54	1797.73	0.07
44	0.17	3.24	1.67	32.42	2280.70	-
45	0.17	3.54	2.29	21.39	2062.28	0.05

Plot	Foliar Cu	Foliar Fe	Foliar K	Foliar Mg	Foliar Mn	Foliar N	Foliar Na
	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})
1	1.03	10.71	2347.49	329.47	52.30	1.69	2.06
2	0.91	13.83	2607.28	358.22	64.16	1.66	0.91
3	1.13	12.10	2773.76	390.85	91.03	2.16	1.01
4	1.15	16.48	3177.10	367.88	82.17	1.88	0.72
5	1.08	13.06	2657.79	334.52	92.56	1.90	0.69
6	1.03	13.86	3029.95	371.11	53.79	1.78	0.47
7	0.78	9.50	2430.98	301.97	98.95	1.50	0.57
8	0.63	8.18	1908.48	291.38	91.85	1.40	0.51
9	0.85	10.43	1886.52	329.90	54.60	1.62	0.57
10	1.09	12.56	3550.56	406.95	67.46	2.05	0.82
11	1.16	18.36	3494.69	464.97	187.47	2.50	96.55
12	0.93	12.66	2758.18	363.99	121.40	1.85	-
13	0.81	10.92	2611.78	366.08	141.29	1.69	-
14	0.80	11.06	2332.99	339.89	124.09	1.75	-
15	0.89	12.62	2661.12	333.13	47.31	1.75	0.59
16	0.93	12.53	2781.39	356.70	67.94	1.76	-
17	0.90	11.23	3189.89	354.93	141.07	1.98	-
18	0.77	9.78	2955.68	352.64	73.79	1.71	-
19	0.74	11.04	2597.76	342.04	68.19	1.62	-
20	0.72	10.63	2017.79	279.25	49.18	1.46	-
21	0.75	12.21	2635.15	334.21	62.56	1.69	-
22	0.83	12.06	2392.00	326.56	69.26	1.72	-
23	0.69	10.99	2179.01	277.50	52.89	1.59	-
24	0.94	13.11	2703.36	366.59	55.50	1.84	0.61
25	0.93	13.08	2966.72	415.81	85.03	1.84	-
26	0.80	11.33	2574.00	343.89	40.98	1.70	-
27	1.12	17.31	3852.96	429.97	83.76	2.13	-
28	0.87	14.71	2563.49	284.17	57.63	1.75	-
29	0.89	11.04	2818.56	411.04	63.89	1.78	0.47
30	1.01	14.89	2952.14	375.96	63.08	1.97	0.76
31	0.94	14.92	2780.80	399.42	77.36	2.02	0.76
32	0.91	11.86	2804.40	446.88	78.43	1.95	-
33	0.99	10.33	2147.14	330.17	70.09	1.51	-
34	1.06	16.28	2643.20	354.00	81.42	1.87	0.71
35	0.80	10.10	2496.34	316.33	43.26	1.60	0.76
36	0.93	12.44	2774.72	409.03	98.79	1.90	0.48
37	0.80	11.09	2752.90	361.57	115.25	1.57	0.62
38	1.00	14.71	3152.64	370.44	142.92	2.12	-
39	0.83	10.89	2210.23	368.37	136.92	1.78	-
40	0.86	11.90	2519.42	368.58	71.85	1.91	-
41	0.83	12.33	2264.02	376.59	117.68	1.71	-
42	1.02	15.23	2678.11	425.35	139.16	2.18	-
43	0.98	11.47	2715.33	376.87	94.57	1.90	0.70
44	1.22	14.96	3159.17	379.65	163.50	2.32	-
45	1.10	14.53	3565.12	400.39	115.46	2.30	-

Plot	Foliar Ni	Foliar P	Foliar S	Foliar Si	Foliar Sr	Foliar Zn
	(μg 100 needles^{-1})	(μg 100 needles^{-1})	(μg 100 needles^{-1})	(μg 100 needles^{-1})	(μg 100 needles^{-1})	(μg 100 needles^{-1})
1	-	658.94	457.14	16.27	9.88	17.32
2	0.68	766.31	331.01	23.13	12.70	16.73
3	0.50	852.30	428.67	20.42	9.83	19.04
4	-	850.41	523.15	25.56	9.56	19.73
5	0.92	756.10	364.30	21.08	8.48	17.57
6	0.47	970.05	450.97	23.25	11.74	17.73
7	0.76	674.22	294.38	19.94	6.65	13.48
8	0.85	618.55	269.23	20.11	5.96	12.13
9	0.38	595.34	307.15	15.17	6.07	16.34
10	0.55	920.41	562.63	22.94	11.74	28.40
11	1.18	1083.95	453.12	35.84	7.70	22.36
12	1.13	974.40	323.29	28.94	5.88	20.03
13	0.64	837.05	329.68	29.11	7.28	18.43
14	1.01	758.22	331.85	26.55	5.63	14.52
15	-	747.08	490.83	15.97	8.67	22.87
16	1.06	745.24	354.57	22.51	7.22	17.13
17	1.12	887.33	393.12	28.53	8.99	21.77
18	-	693.06	458.64	20.38	8.36	22.42
19	0.65	781.49	335.54	22.30	9.09	15.07
20	0.36	619.75	290.06	19.46	6.13	14.81
21	-	664.14	550.60	24.85	8.78	16.97
22	0.62	715.52	334.88	28.70	6.03	14.68
23	-	702.12	271.91	10.99	5.96	17.25
24	-	794.62	475.14	26.21	8.81	21.30
25	-	838.62	383.10	26.16	7.01	18.36
26	-	656.88	442.73	15.03	9.27	20.30
27	0.56	1047.00	432.76	24.85	8.93	18.68
28	-	735.26	449.11	13.91	7.15	19.34
29	0.47	770.41	389.90	17.85	14.33	20.08
30	0.50	860.41	560.15	25.23	11.61	18.90
31	0.51	879.74	404.48	23.76	10.87	15.45
32	0.68	934.80	355.68	21.20	13.91	18.06
33	0.61	694.78	295.74	19.24	8.30	16.37
34	0.71	840.16	410.64	20.53	9.44	19.09
35	-	665.05	426.85	16.39	8.19	19.44
36	0.96	973.54	447.30	23.68	9.33	17.39
37	0.62	749.86	447.86	18.49	11.50	16.56
38	0.53	914.27	570.10	25.75	14.19	22.36
39	0.93	725.16	342.89	20.16	11.35	15.11
40	-	844.47	382.58	17.03	13.76	18.80
41	0.67	871.98	325.03	19.50	13.23	17.28
42	0.53	911.08	427.97	23.11	14.70	18.22
43	1.17	854.39	360.48	20.83	9.36	16.22
44	1.39	950.52	435.08	23.83	12.75	19.87
45	0.55	976.29	540.25	28.80	9.60	19.75

Appendix C

2020 Soil and Foliar Data from Sub-Plots Containing White Spruce

Plot	Block	Treatment	Bulk Density	Field Moisture	Conductivity	pH	Total N	Total C	C:N
		(LC/HC)	(g/cm3)	(g H2O / g soil)	(µS cm-1)		(g kg^{-1})	(g kg^{-1})	
1	1	10/0	0.8	14.9	192.5	6.4	1.3	21.3	16.4
2	1	0/10	1.0	14.6	133.5	6.2	1.2	22.5	18.8
3	1	1/0	1.0	15.2	86.0	5.8	1.3	22.5	17.3
4	1	10/10	0.8	20.9	331.0	6.4	1.1	25.2	22.9
5	1	0/0	0.9	16.2	102.2	5.6	1.3	18.8	14.5
6	1	10/1	0.8	21.4	215.0	6.3	1.4	26.5	18.9
7	1	0/1	0.9	14.4	71.4	5.5	1.0	17.0	17.0
8	1	1/1	0.9	17.5	100.2	5.5	1.3	21.1	16.2
9	1	1/10	0.9	19.8	134.0	5.9	1.1	22.0	20.0
10	2	10/0	0.8	25.8	350.0	6.5	1.4	26.6	19.0
11	2	1/1	1.0	20.6	81.4	5.7	1.3	23.2	17.8
12	2	0/1	0.9	22.1	87.3	5.6	1.2	20.2	16.8
13	2	1/0	1.0	19.4	71.4	5.7	1.2	18.4	15.3
14	2	0/0	0.9	20.5	83.4	5.5	1.1	18.2	16.5
15	2	10/1	1.0	22.7	284.0	6.4	1.3	23.6	18.2
16	2	1/10	0.8	27.0	92.1	6.2	1.2	20.9	17.4
17	2	0/10	0.9	25.9	100.1	5.8	1.2	22.5	18.8
18	2	10/10	0.9	28.4	432.0	6.9	1.7	42.5	25.0
19	3	0/10	0.7	22.2	134.2	6.1	1.3	23.4	18.0
20	3	1/1	1.0	17.2	78.2	5.9	1.1	19.0	17.3
21	3	10/10	0.7	30.5	357.0	6.6	1.3	27.3	21.0
22	3	0/1	1.0	16.1	88.8	5.7	1.2	19.6	16.3
23	3	0/0	1.0	14.7	93.0	5.8	1.4	22.8	16.3
24	3	10/1	0.9	23.2	153.5	6.0	1.5	29.0	19.3
25	3	1/10	0.9	21.1	143.0	6.1	1.3	23.8	18.3
26	3	10/0	1.0	21.3	171.0	6.3	1.4	25.4	18.1
27	3	1/0	0.9	18.5	90.5	5.8	1.2	20.5	17.1
28	4	10/1	0.9	16.2	177.2	6.4	1.3	25.1	19.3
29	4	1/10	0.9	15.6	102.0	6.1	1.2	23.2	19.3
30	4	10/10	0.7	25.3	453.0	6.7	1.3	32.1	24.7
31	4	0/1	1.0	20.1	85.5	5.7	1.3	21.3	16.4
32	4	0/10	0.7	23.6	142.9	6.1	1.4	28.1	20.1
33	4	0/0	1.0	15.9	65.5	5.6	1.2	19.5	16.3
34	4	1/0	1.0	19.1	82.1	5.7	1.3	23.0	17.7
35	4	10/0	0.9	19.6	187.0	6.3	1.3	25.0	19.2
36	4	1/1	0.9	16.4	85.8	5.6	1.1	17.1	15.5
37	5	10/0	1.0	15.2	223.0	6.3	1.1	21.1	19.2
38	5	10/10	0.9	17.3	466.0	6.6	1.3	25.5	19.6
39	5	1/0	1.0	12.7	75.9	5.7	1.0	17.4	17.4
40	5	1/10	0.7	25.3	120.4	5.9	1.3	26.1	20.1
41	5	0/1	0.9	18.2	81.1	5.7	1.3	21.5	16.5
42	5	1/1	1.0	15.9	71.7	5.7	1.3	23.3	17.9
43	5	0/10	0.8	20.6	105.0	5.8	1.4	27.5	19.6
44	5	0/0	0.9	15.4	70.4	5.5	1.3	21.6	16.6
45	5	10/1	0.9	22.1	256.0	6.4	1.3	25.1	19.3

Plot	Al (mg kg^{-1})	As (mg kg^{-1})	Ca (mg kg^{-1})	Co (mg kg^{-1})	Cr (mg kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	K (mg kg^{-1})	Mg (mg kg^{-1})	Mn (mg kg^{-1})
1	17800	8.9	4750	20	74	22.6	71900	1890	5880	911
2	16600	10.8	4130	20	53.3	21.9	66900	1660	5210	866
3	15400	9.2	3380	19	49.9	20.5	65100	1260	4080	878
4	14100	8.5	4280	20	45.4	19.7	63000	1440	3980	908
5	15900	8.6	3770	24	49.1	19.7	67000	1280	4330	1260
6	15100	9.6	4270	18	48	20.6	63700	1470	4140	844
7	15900	6.8	2930	19	51	21	63200	1480	4300	837
8	16400	9.9	3630	21	51.1	19.8	66600	1310	4320	952
9	14800	8.6	3290	17	49	18.7	57300	1220	3870	779
10	15700	6.1	5400	20	48	20.4	56900	1500	4070	991
11	15200	7.2	3180	20	47.7	17.8	56600	1220	4020	837
12	16400	9.9	3400	18	46.1	21.8	63300	1370	4670	838
13	16400	11.4	2920	18	54.4	21.3	69800	1350	4880	872
14	16100	11.2	2540	17	53.2	22.9	77500	1290	4240	883
15	14900	9.6	3990	16	45.5	21.7	67600	1470	3790	855
16	16000	10.1	3310	18	49	17.7	53000	1360	5180	708
17	14900	9.2	3030	17	46.6	19.6	58600	1330	4290	790
18	11300	6.1	4340	14	35	17.5	43600	1220	3200	708
19	16500	8.6	3960	18	48.5	21.3	60600	1590	4290	805
20	15900	7.5	3720	17	46	18.6	51300	1420	5040	719
21	11400	5.7	3880	12	31	14.6	38400	1210	3140	555
22	16200	11.6	3150	17	45.2	22.4	56000	1320	4760	737
23	15900	8.5	3610	17	46.4	20.1	57400	1290	4110	730
24	15400	6.3	3980	16	41.6	19.2	50600	1490	4030	784
25	15900	9	3660	17	47.3	20.1	62400	1350	4330	766
26	14000	5.3	4080	15	38.8	18.1	45500	1220	3350	685
27	8790	5.1	2020	9	23.1	10.7	24700	710	2030	425
28	8140	5.2	2440	9	22.5	10.4	25800	750	1980	407
29	12300	8.8	3190	12	31.9	15.8	37400	1200	3900	509
30	6300	2	2530	6	23.6	9.1	19200	700	1640	325
31	9650	6.1	1870	9	24.7	12.7	31000	820	2590	406
32	10700	6.7	2560	10	36.7	17	45400	930	3390	557
33	8880	5.9	1510	8	24.3	10.1	27700	760	2680	366
34	7700	4.8	1550	8	22.2	11.2	27600	740	2490	384
35	8450	6.5	2010	8	22.1	11.5	29000	910	2350	405
36	8740	6.4	1820	8	22.8	11.3	32500	760	2470	399
37	8160	4.3	2260	7	21.2	10	23900	750	2250	361
38	9040	4.9	2680	8	23.2	12.4	30300	910	2480	435
39	7250	4.9	1270	7	18.3	8.7	21800	600	2130	309
40	7830	3.5	1750	7	19.2	9	20400	750	2060	326
41	7750	5	1640	7	19	8.8	21700	620	2130	325
42	10200	4.8	1820	10	30.2	11.8	33500	830	2730	427
43	7200	4.2	1420	6	18.6	7.9	27100	670	1920	335
44	9750	7.2	1840	10	27.2	12.3	33500	810	2770	481
45	11500	5.4	2850	11	31.3	14.7	41500	1080	3360	545

Plot	Na (mg kg^{-1})	Ni (mg kg^{-1})	P (mg kg^{-1})	Pb (mg kg^{-1})	S (mg kg^{-1})	Sr (mg kg^{-1})	Zn (mg kg^{-1})
1	247	43	1740	14	194	19	93.6
2	231	40	1660	13	198	16	89.8
3	171	37	1620	15	182	12	86.6
4	242	38	1520	13	182	17	90.3
5	179	37	1870	13	158	14	78.8
6	225	38	1560	15	198	16	92.9
7	213	39	1450	13	140	12	79.5
8	217	42	1500	15	171	15	89.9
9	202	34	1310	11	149	13	74.7
10	312	38	1410	14	234	20	115
11	213	38	1320	15	172	12	87.2
12	178	36	2030	13	178	13	87.1
13	204	36	1370	15	160	11	79.3
14	173	36	1680	16	153	10	92.5
15	194	32	2000	15	174	15	94.1
16	235	37	1020	11	158	12	74.6
17	209	36	1460	15	135	12	76.5
18	217	28	1400	9	141	16	82.4
19	253	37	1870	14	169	16	84.7
20	227	33	1820	12	155	15	75.7
21	204	24	1340	9	150	14	63.3
22	178	34	1820	12	180	14	75.7
23	217	35	1810	12	175	13	81.5
24	217	33	1880	14	196	16	82.5
25	204	35	1850	15	185	14	79.5
26	223	32	1650	11	212	15	74
27	134	19	915	6	119	8	42.1
28	146	19	955	5	110	9	44.5
29	181	25	1400	7	134	12	56.6
30	124	12	877	4	102	10	37
31	113	21	1010	6	116	7	39.3
32	141	24	1410	9	121	10	50.7
33	100	18	832	6	87	6	39.9
34	92	16	820	7	75	7	35.3
35	145	17	839	7	85	8	38.1
36	104	17	997	8	90	7	39
37	131	16	960	5	94	9	43.4
38	145	18	1070	6	117	11	51
39	88	15	704	6	67	5	32.3
40	104	15	998	5	87	8	35.4
41	98	15	852	7	87	7	34
42	130	22	1010	7	99	8	50.7
43	92	13	874	6	71	6	33.7
44	113	21	1010	9	104	7	46.2
45	158	22	1160	10	131	11	57

Plot	eCa (mg kg^{-1})	eCu (mg kg^{-1})	eFe (mg kg^{-1})	eK (mg kg^{-1})	eMg (mg kg^{-1})	eMn (mg kg^{-1})	eNa (mg kg^{-1})	eP (mg kg^{-1})	eZn (mg kg^{-1})
1	1800	2.171	390.92	157	193	115.636	10	350	12.62
2	1470	1.476	241.27	114	215	66.142	3	220	2.8
3	1440	1.73	310.94	67	188	62.717	6	244	4.83
4	1870	2.247	358.98	202	163	123.811	12	330	14.65
5	1180	1.378	276.02	57	181	51.902	4	185	2
6	2040	2.419	375.63	161	165	116.808	13	315	16.49
7	1050	1.535	355.37	54	120	51.086	9	194	1.42
8	1050	1.382	267	62	120	55.958	7	164	2.39
9	1380	1.621	322.79	61	138	74.511	12	173	3.06
10	1970	2.376	435	153	160	141.22	11	233	13.57
11	1050	2.009	356.9	77	142	68.12	7	158	2.79
12	1070	1.711	374.3	64	151	54.418	4	330	1.66
13	966	1.53	288.11	88	125	45.778	4	117	1.11
14	894	1.74	306.29	76	143	62.471	4	180	1.32
15	1810	2.172	369.25	145	154	107.998	11	425	14.76
16	1150	1.453	269.97	112	140	52.047	10	113	1.76
17	1040	1.445	274.18	88	137	54.924	10	174	1.41
18	2490	2.945	420.99	312	192	167.733	9	495	28.92
19	1450	1.685	412.31	104	180	73.348	8	365	2.47
20	1190	1.697	438.01	69	164	65.293	7	400	2.2
21	2190	1.894	383.75	238	188	122.813	16	424	12.99
22	1070	1.858	466.08	63	151	62.91	5	412	1.46
23	736	2.523	526.74	37	100	92.196	4	517	3.87
24	1590	2.416	496.08	152	158	91.463	8	532	12.06
25	946	2.387	498.09	75	109	107.72	6	466	5.55
26	1820	2.32	427.26	130	180	91.011	9	487	9.13
27	1380	1.947	417.22	92	165	65.595	7	324	2.98
28	1920	1.47	333.88	183	176	52.071	17	303	5.09
29	1420	1.793	498.64	104	171	76.217	15	447	2.61
30	1930	2.425	433.63	211	125	137.499	11	506	21.89
31	1230	2.325	514.51	76	155	62.523	3	408	1.98
32	1700	1.682	415.76	132	224	68.311	6	386	2.33
33	1240	1.599	371.42	68	180	38.094	5	354	0.9
34	1240	2.216	464.96	94	158	52.422	5	353	1.88
35	1500	2.183	440.44	134	138	71.907	10	437	7.24
36	925	2.377	452.84	57	107	57.013	4	377	1.89
37	1730	1.661	391.37	169	139	70.37	10	440	8.78
38	1900	2.324	466.91	169	147	109.031	9	541	17.45
39	1260	1.8	427.69	64	150	60.163	5	383	1.86
40	970	2.461	596.81	66	109	113.391	4	695	4.98
41	1250	1.566	418.9	66	156	50.464	2	392	1.62
42	1090	1.677	374.78	72	128	52.589	6	351	2.79
43	1440	1.346	343.51	137	174	58.593	7	358	1.88
44	706	2.08	500.06	47	80	59.538	2	425	2.19
45	1310	2.614	415.09	109	104	100.152	8	426	15.49

Plot	100 needle weight	Foliar Al	Foliar B	Foliar Ba	Foliar Ca	Foliar Cr
	(g)	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})
1	0.29	2.38	1.95	24.56	1654.62	0.12
2	0.19	1.63	1.66	10.58	794.77	0.06
3	0.27	2.42	1.46	22.17	1540.31	0.07
4	0.31	3.59	1.95	29.48	2311.33	0.12
5	0.23	3.36	1.26	28.07	1665.46	0.09
6	0.26	3.28	1.66	19.08	1520.13	0.07
7	0.28	4.10	1.78	31.24	1723.52	0.08
8	0.27	3.02	1.69	26.45	1742.19	0.05
9	0.29	4.44	1.60	28.08	1692.98	0.11
10	0.28	2.29	1.68	19.86	1421.78	0.03
11	0.27	2.84	1.86	24.87	1348.15	0.11
12	0.28	2.15	0.78	17.10	1056.09	0.02
13	0.27	3.64	1.10	24.90	1525.80	0.10
14	0.20	2.39	0.97	24.01	1189.87	0.03
15	0.45	4.43	2.17	27.28	1995.18	0.06
16	0.25	2.11	1.17	18.63	1404.19	0.04
17	0.30	2.13	1.38	25.61	1417.95	0.04
18	0.29	1.88	2.00	22.72	1633.62	0.05
19	0.27	2.66	2.19	18.54	1257.72	0.03
20	0.27	2.41	1.35	16.55	1530.78	0.05
21	0.28	1.65	1.22	13.83	1165.24	0.04
22	0.27	2.46	1.66	19.60	1480.17	0.05
23	0.18	2.10	0.91	9.19	984.71	0.05
24	0.29	1.98	1.73	18.90	1450.97	0.05
25	0.37	3.69	2.12	22.55	1798.49	0.09
26	0.29	2.35	1.15	16.14	1551.68	0.07
27	0.27	2.48	1.29	15.22	1358.36	0.06
28	0.31	2.31	1.46	18.48	1339.13	0.04
29	0.32	2.41	1.45	19.01	1441.38	0.06
30	0.25	1.82	0.91	14.09	1243.53	0.05
31	0.32	3.26	1.68	18.84	1706.00	0.09
32	0.36	3.14	1.28	23.27	1928.15	0.08
33	0.31	2.53	1.71	16.65	1611.31	0.07
34	0.32	2.88	1.75	21.44	1431.12	0.11
35	0.31	2.36	2.26	22.63	1415.98	0.09
36	0.30	3.21	2.30	26.03	1820.85	0.08
37	0.29	2.64	2.47	17.52	1915.26	0.08
38	0.32	2.96	1.56	21.88	2081.52	0.06
39	0.29	2.56	1.24	24.64	1679.33	0.06
40	0.19	1.35	1.33	9.23	761.12	0.07
41	0.32	3.84	1.72	19.44	1623.59	0.12
42	0.27	2.82	1.55	20.04	1544.35	0.07
43	0.24	2.36	1.26	16.11	1489.47	0.06
44	0.33	4.71	2.28	35.60	2389.23	0.08
45	0.28	2.33	2.13	35.18	2044.79	0.10

Plot	Foliar Cu (µg 100 needles^{-1})	Foliar Fe (µg 100 needles^{-1})	Foliar K (µg 100 needles^{-1})	Foliar Mg (µg 100 needles^{-1})	Foliar Mn (µg 100 needles^{-1})	Foliar N (µg 100 needles^{-1})	Foliar Na (µg 100 needles^{-1})
1	1.09	9.78	1509.86	260.17	35.79	3.42	0.34
2	0.67	8.00	1125.37	197.82	48.27	2.49	0.39
3	0.97	9.39	1304.71	310.29	55.61	3.63	-
4	0.97	12.25	2234.06	312.49	71.35	4.63	6.61
5	0.59	8.93	1283.86	267.94	81.36	3.16	0.53
6	0.65	9.25	1694.55	242.30	75.12	3.78	-
7	0.91	11.40	1425.48	310.23	118.14	3.85	0.50
8	0.81	8.39	1395.73	324.64	78.19	4.19	0.29
9	0.63	11.73	1791.00	341.20	141.85	3.83	0.50
10	0.68	7.73	2015.29	292.76	62.33	3.96	0.22
11	0.98	9.25	1693.30	287.91	67.70	3.91	0.27
12	0.86	8.51	1273.37	301.91	68.12	3.76	-
13	1.04	10.37	1422.31	267.81	76.49	2.77	0.19
14	0.62	6.61	952.31	240.18	63.34	2.60	-
15	0.97	12.87	3262.41	512.96	97.72	5.82	-
16	0.69	7.86	1475.62	304.36	51.67	3.55	0.17
17	0.77	9.56	1656.22	292.74	67.55	3.86	-
18	0.51	7.23	1653.26	264.87	46.84	4.53	-
19	0.66	9.54	1549.87	274.96	68.21	3.59	0.35
20	0.97	9.19	1776.87	291.93	50.42	3.18	0.52
21	0.51	7.71	1578.30	258.21	28.82	3.51	0.42
22	0.64	8.75	1602.41	276.97	52.24	4.12	0.54
23	0.53	8.31	1042.93	161.17	35.47	2.32	0.33
24	0.59	8.42	1740.20	255.72	41.77	3.20	0.29
25	0.73	11.08	2250.99	371.59	69.57	4.62	0.26
26	0.61	9.40	1752.59	249.72	47.49	3.46	0.35
27	0.61	11.40	1606.32	231.54	52.37	3.45	0.16
28	0.59	10.11	1758.48	279.00	41.98	4.04	0.37
29	0.69	10.20	1569.39	278.92	50.09	3.79	0.19
30	0.47	7.16	1490.40	195.77	30.78	3.25	0.43
31	0.80	10.67	2342.66	336.38	56.67	4.28	0.19
32	0.86	12.19	2469.20	426.39	72.09	4.72	0.43
33	0.63	9.90	1593.39	314.11	61.23	3.94	-
34	0.80	12.60	1765.85	283.54	47.83	3.66	0.38
35	0.65	9.71	1915.14	316.89	37.03	4.30	0.68
36	0.70	11.78	1806.40	321.92	77.51	4.08	0.42
37	0.69	9.89	1604.16	249.10	57.76	3.39	0.14
38	0.65	9.99	1738.90	364.73	71.94	4.36	0.22
39	0.62	7.75	1718.59	281.12	79.99	4.10	1.15
40	0.41	6.12	930.13	203.64	51.17	2.19	0.22
41	0.68	11.30	1560.62	382.78	80.65	3.90	0.54
42	0.76	10.68	1394.49	285.82	65.96	3.75	0.29
43	0.50	6.92	1260.33	272.43	55.57	3.33	0.15
44	0.82	11.80	1972.05	364.54	93.38	4.49	0.26
45	0.75	8.63	1785.84	327.30	67.87	4.68	0.25

Plot	Foliar Ni (µg 100 needles^{-1})	Foliar P (µg 100 needles^{-1})	Foliar S (µg 100 needles^{-1})	Foliar Si (µg 100 needles^{-1})	Foliar Sr (µg 100 needles^{-1})	Foliar Zn (µg 100 needles^{-1})
1	5.59	556.06	215.29	79.72	11.55	16.73
2	27.26	345.59	178.87	15.56	5.43	9.23
3	3.82	529.96	235.78	72.14	11.14	15.68
4	15.02	729.65	298.46	117.96	11.74	18.61
5	0.82	532.92	213.11	81.86	11.91	14.70
6	0.83	556.11	218.45	75.53	7.74	16.87
7	5.93	617.52	235.63	76.15	10.09	14.64
8	1.96	557.24	226.73	75.00	8.68	15.50
9	0.78	624.50	233.55	85.06	10.53	15.57
10	1.15	589.33	228.62	58.12	7.06	15.84
11	1.72	652.73	212.76	47.88	6.16	14.97
12	2.50	541.40	191.27	59.80	8.04	12.38
13	5.81	461.93	204.21	62.53	7.03	14.21
14	1.17	386.48	142.28	47.22	7.17	11.39
15	1.26	913.71	331.73	93.93	13.85	24.14
16	1.15	539.42	182.58	71.53	5.45	14.02
17	1.70	599.52	228.29	82.73	7.70	13.55
18	0.67	556.03	161.73	61.12	9.39	13.13
19	2.30	597.06	185.28	68.92	8.93	14.49
20	6.73	590.65	202.91	76.75	8.89	18.15
21	0.51	597.87	204.48	78.06	8.66	15.13
22	1.68	600.10	218.35	67.14	11.09	16.76
23	0.84	341.98	158.14	40.71	5.15	10.53
24	1.02	582.76	192.10	71.95	10.67	13.47
25	1.04	738.67	255.37	113.15	9.13	19.85
26	0.58	608.10	215.85	64.94	9.40	16.97
27	0.66	602.09	208.96	68.82	7.21	13.30
28	1.54	555.62	189.14	81.18	10.89	14.74
29	0.95	630.32	231.56	72.74	11.61	14.55
30	0.30	547.15	177.80	54.88	7.94	12.70
31	1.45	784.68	263.99	104.33	10.64	18.81
32	2.17	768.50	275.98	102.35	12.57	21.57
33	0.74	589.03	236.98	71.91	7.33	16.92
34	1.04	648.18	263.84	80.41	9.26	16.03
35	1.07	662.20	240.49	59.49	10.87	15.32
36	1.08	708.63	281.92	75.64	11.25	19.10
37	0.68	531.16	245.81	69.47	10.34	18.67
38	0.89	638.08	238.05	79.37	14.04	20.54
39	0.86	551.92	217.19	71.73	11.17	16.24
40	1.31	334.78	149.94	18.70	5.20	8.13
41	1.09	658.31	234.89	76.53	13.00	21.12
42	0.75	574.59	254.27	51.62	10.49	17.68
43	1.44	515.03	196.23	66.68	8.77	14.34
44	3.67	684.59	297.78	87.61	14.66	23.15
45	1.02	598.28	241.50	69.26	16.08	17.61

Appendix D

2019 Soil and Foliar Data from Sub-Plots Containing White Spruce

Plot	Block	Treatment	Bulk Density	Field Moisture	Conductivity	pH	total N	total C	C:N
		(LC/HC)	(g/cm^3)	(g H2O / g soil)	(µS cm-1)		($g\ kg^{-1}$)	($g\ kg^{-1}$)	
1	1	10/0	0.8	14.5	270.0	7.3	1.3	20.2	15.5
2	1	0/10	0.8	15.4	81.0	6.9	1.3	21.7	16.7
3	1	1/0	0.9	14.8	39.9	6.3	1.3	21.2	16.3
4	1	10/10	0.9	15.6	175.3	7.3	1.2	21.2	17.7
5	1	0/0	0.9	14.2	23.6	6.2	1.3	19.4	14.9
6	1	10/1	0.9	15.4	181.6	6.8	1.2	21.0	17.5
7	1	0/1	0.9	13.0	32.7	6.1	1.1	15.9	14.5
8	1	1/1	0.9	13.9	43.0	6.2	1.1	17.8	16.2
9	1	1/10	0.8	15.6	70.7	6.6	1.0	20.0	20.0
10	2	10/0	0.7	15.3	290.0	6.7	1.3	23.3	17.9
11	2	1/1	0.8	13.5	45.5	6.2	1.2	16.9	14.1
12	2	0/1	0.8	15.4	35.5	6.2	1.2	19.4	16.2
13	2	1/0	0.9	13.6	38.6	6.1	1.1	16.2	14.7
14	2	0/0	0.9	13.4	34.1	5.9	1.2	17.7	14.8
15	2	10/1	0.8	15.8	183.3	6.6	1.1	20.3	18.5
16	2	1/10	1.0	15.6	101.1	6.6	1.1	20.4	18.5
17	2	0/10	0.8	17.0	67.7	6.7	1.2	21.5	17.9
18	2	10/10	0.8	18.9	326.0	7.1	1.2	24.3	20.3
19	3	0/10	0.9	17.1	61.9	6.8	1.0	20.2	20.2
20	3	1/1	0.9	17.1	55.7	6.4	1.0	17.9	17.9
21	3	10/10	0.8	20.7	316.0	7.2	1.1	22.7	20.6
22	3	0/1	1.0	16.1	43.9	6.2	1.3	20.2	15.5
23	3	0/0	0.9	17.0	42.9	6.1	1.3	23.0	17.7
24	3	10/1	1.0	19.2	199.4	6.9	1.2	20.3	16.9
25	3	1/10	0.8	18.4	114.3	6.8	1.2	23.2	19.3
26	3	10/0	0.8	19.7	150.1	6.9	1.2	22.3	18.6
27	3	1/0	1.0	16.8	48.7	6.2	1.2	20.6	17.2
28	4	10/1	0.9	16.1	273.0	6.9	1.0	19.1	19.1
29	4	1/10	1.0	16.8	79.6	6.6	1.1	20.2	18.4
30	4	10/10	1.0	17.9	290.0	7.2	1.1	21.3	19.4
31	4	0/1	0.7	16.4	51.8	6.0	1.2	19.4	16.2
32	4	0/10	0.7	16.6	84.9	6.6	1.2	21.9	18.3
33	4	0/0	0.6	15.3	50.3	5.9	1.2	19.4	16.2
34	4	1/0	0.7	15.4	40.7	6.0	1.2	19.3	16.1
35	4	10/0	0.7	16.8	138.6	6.7	1.1	19.9	18.1
36	4	1/1	0.7	15.0	64.7	6.3	1.2	18.4	15.3
37	5	10/0	0.6	16.4	165.1	6.7	0.9	17.4	19.3
38	5	10/10	0.7	19.6	208.0	7.2	1.1	20.5	18.6
39	5	1/0	0.7	14.8	46.4	6.1	1.0	16.8	16.8
40	5	1/10	0.6	16.4	80.5	6.4	1.1	21.8	19.8
41	5	0/1	0.6	15.7	44.2	6.1	1.2	20.2	16.8
42	5	1/1	0.8	15.8	52.2	6.0	1.0	18.3	18.3
43	5	0/10	0.5	16.6	53.1	6.5	1.2	21.5	17.9
44	5	0/0	0.7	15.3	39.7	5.7	1.1	18.7	17.0
45	5	10/1	0.6	20.2	224.0	7.1	1.1	19.7	17.9

Plot	Al (mg kg^{-1})	As (mg kg^{-1})	Ca (mg kg^{-1})	Co (mg kg^{-1})	Cr (mg kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	K (mg kg^{-1})	Mn (mg kg^{-1})	Mn (mg kg^{-1})
1	14900	7.7	4390	18	50.6	22.2	59500	1360	4410	918
2	14900	6.4	3630	18	46	17.7	57400	1230	4130	847
3	17400	8.2	3760	19	50.2	20.8	60200	1460	4930	1130
4	15800	7	4640	18	50.2	20.7	56700	1670	4570	841
5	16700	6	3500	20	51.5	19.2	56500	1470	4600	848
6	15900	8.8	3930	19	55.5	18.6	56000	1410	4380	857
7	15800	3.5	3210	19	48	19.5	59700	1360	4250	845
8	16800	6	3460	18	46.8	19.4	53500	1390	5300	916
9	15000	5.6	3570	18	46.8	17.2	52600	1250	3870	812
10	16700	6.3	4350	17	48.2	19.6	48700	1820	4240	841
11	17300	6	3070	17	49.9	19.4	52100	1580	4500	820
12	16300	6.7	3360	17	44.9	18	47100	1510	4200	772
13	15600	5.5	2830	18	46.4	18	50400	1290	4130	826
14	14900	7.9	2460	16	44.6	18.7	46800	1090	4070	730
15	15100	6.6	3860	15	44.5	19.2	45000	1370	4160	765
16	14400	4.8	3330	15	41.3	18.4	47900	1150	4240	740
17	16100	3.8	3500	17	43.7	19.9	47400	1600	4410	790
18	17900	4.3	5610	17	49.9	20.5	52700	1970	4830	936
19	16200	5.5	3930	15	41.6	17.7	47100	1680	4470	705
20	15600	3.5	3540	14	42.4	18.9	43700	1330	4270	654
21	15700	3.3	4970	13	42.3	20.5	48600	1870	4150	676
22	18000	8.3	3740	17	53.5	20.2	54700	1690	5430	897
23	15000	9.9	3250	15	41.4	18.8	46500	1170	4070	726
24	15200	6.7	4630	13	40.8	18.3	42400	1560	4040	693
25	18200	5.8	4430	17	47.4	18.9	51300	1810	5400	751
26	16600	3.3	5040	16	45.2	19.8	48000	1740	4130	766
27	17000	4.1	3850	16	45.9	20.5	49700	1470	4480	747
28	14500	4.5	4160	13	38.1	17.7	40500	1490	3860	616
29	13700	4.3	3610	13	34.4	16.8	36200	1120	3860	584
30	13000	3.7	4160	12	35	18.2	39800	1240	3950	630
31	13300	10	3090	13	36.1	18.2	41000	910	3810	679
32	14100	7.8	3470	13	42.2	18.8	45100	1110	4200	702
33	13400	6.9	2890	12	35.3	17.8	39000	920	3840	603
34	16200	10.9	3510	15	46.1	23.6	52500	1320	4600	776
35	12200	7.8	3580	12	36.7	17.9	37600	1060	3880	673
36	13600	7.2	3020	15	37.6	19.8	43400	910	4050	737
37	12400	6.1	3420	11	32.1	16.2	33700	990	3280	585
38	14200	7.8	4660	12	37.6	19.3	40200	1300	3990	724
39	14000	6.9	2800	13	38	18.4	39800	920	3980	688
40	14600	9.9	3530	13	39.9	17.8	41100	1090	3920	738
41	14100	8.3	3020	12	37.1	17.2	39000	890	4160	664
42	13100	7.6	2920	12	36.8	18.7	38900	870	3990	660
43	14300	8.1	3220	13	39.5	17.5	42700	1100	4040	681
44	16300	10.5	4680	15	42.8	23.1	46800	1310	4750	790
45	11900	6.8	2200	11	31.2	14.7	39000	830	3240	552

Plot	Na	Ni	P	Pb	S	Sr	Zn
	(mg kg-1)	(mg kg-1)	(mg kg-1)	(mg kg-1)	(mg kg-1)	(mg kg-1)	(mg kg-1)
1	186	38	1630	15	217	15	96.2
2	166	37	1620	21	152	13	83
3	172	37	1770	16	211	13	90.9
4	247	37	1560	13	204	17	90.9
5	226	40	1500	14	174	13	87.5
6	218	38	1410	15	178	15	98.1
7	223	37	1420	15	138	14	82
8	204	35	1460	17	152	13	82.8
9	211	36	1400	16	152	13	80.6
10	250	35	1430	14	253	16	95.7
11	212	36	1360	17	159	12	85.9
12	204	33	1630	15	163	13	80.3
13	182	37	1170	15	145	10	79.7
14	125	32	1350	12	142	9	75
15	181	31	1770	14	195	14	86.5
16	152	33	1090	14	147	11	73.4
17	225	34	1530	13	146	14	79
18	285	35	1910	16	250	21	93.5
19	274	31	1550	15	124	16	70.9
20	205	32	1770	12	151	13	70.4
21	237	29	1990	11	188	18	80.8
22	222	39	1920	17	157	16	73.9
23	159	33	1770	10	163	12	72.1
24	252	32	1750	10	181	19	74
25	284	35	1750	14	154	20	82.2
26	285	32	1840	13	183	18	83.8
27	229	34	1760	13	175	16	76.2
28	279	29	1570	11	157	15	73.5
29	201	28	1610	12	153	13	60.1
30	164	26	1640	14	156	14	73.6
31	143	29	1720	12	169	11	61.8
32	175	30	1780	13	170	14	65.5
33	141	28	1520	12	156	10	61.4
34	195	33	1790	12	170	13	75
35	137	28	1370	11	154	12	68.8
36	151	31	1550	11	440	10	69.1
37	168	25	1610	10	262	12	70.8
38	191	29	1820	10	280	17	79.4
39	141	29	1420	15	239	9	66
40	156	29	2070	13	216	13	68.2
41	126	29	1680	12	166	11	65.2
42	104	29	1700	12	196	10	62
43	164	29	1830	13	168	13	66.3
44	179	36	1740	14	204	16	87.5
45	107	23	1310	11	136	8	56

Plot	eCa	eCu	eFe	eK	eMg	eMn	eNa	eP	eZn
	(mg kg-1)	(mg kg-1)	(mg kg-1)	(mg kg-1)	(mg kg-1)	(mg kg-1)	(mg kg-1)	(mg kg-1)	(mg kg-1)
1	1890	1.5	170	198	189	129	20	51.31	11.7
2	1340	1.2	167	103	190	102	8	53.81	2.69
3	1320	1.2	148	78	180	96.1	8	45.89	3.42
4	1740	1.5	193	208	165	132	19	54.7	10.3
5	1180	1.2	149	66	179	92.5	7	45.62	2.21
6	1520	1.4	164	127	145	119	14	46.42	6.77
7	952	1.2	181	61	116	105	8	40.99	1.88
8	1120	1.2	173	68	131	95.8	10	41.84	2.7
9	1360	1.2	184	92	145	98.3	11	48.35	2.57
10	1670	1.6	200	166	157	119	19	49.8	9.5
11	963	1.2	160	103	140	76.2	14	40.84	2.17
12	1120	1.2	173	99	162	78.5	7	56.58	2.12
13	978	1.2	156	101	128	66.4	8	34.45	2.09
14	866	1.2	149	91	144	67.7	9	38.88	1.64
15	1510	1.5	212	196	158	93.8	17	67.29	7.52
16	1260	1.2	163	125	148	-	16	45.45	2.57
17	1260	1.2	186	119	163	-	20	74.61	2.47
18	1980	1.7	214	212	165	-	24	95.05	12
19	1260	1.3	218	99	166	-	15	83.5	2.28
20	1270	1.3	244	83	177	-	15	84.59	3.4
21	1780	1.5	239	303	167	-	24	99.05	10.1
22	1190	1.4	216	94	167	-	14	82.02	2.3
23	1290	1.4	228	77	185	-	12	81.67	2.17
24	1770	1.5	243	173	182	-	19	104.37	9.05
25	1460	1.4	237	135	189	-	16	88.48	3.11
26	1820	1.7	227	150	188	-	18	95.62	8.98
27	1360	1.5	215	92	172	-	13	84.49	2.82
28	1550	1.4	255	175	162	-	19	96.23	8.32
29	1410	1.3	254	134	186	-	14	93.77	2.88
30	1830	1.6	239	267	149	-	24	95.62	12.1
31	1270	1.5	270	162	84	69.6	5	79.84	2.42
32	1460	1.4	258	197	138	82.7	13	85.34	2.54
33	1180	1.3	206	167	75	59.1	7	72.08	1.89
34	1300	1.4	228	169	86	59.8	9	68.81	2.24
35	1720	1.7	209	151	164	93	10	67.02	10.1
36	1150	1.4	209	136	73	80.3	8	68.66	2.3
37	1400	1.4	244	121	126	98.6	16	80.89	8.6
38	1880	1.7	255	156	218	121	12	81.02	10.7
39	1100	1.5	194	133	74	79.4	13	64.98	2.92
40	1310	1.4	262	149	110	103	19	90.64	3.16
41	1250	1.4	221	150	69	83	14	77.48	2.59
42	1100	1.9	222	145	83	82.8	12	70.26	2.94
43	1280	1.4	249	150	111	88	7	84.79	2.53
44	1040	1.3	214	124	78	75.3	7	72.19	2
45	1860	1.9	211	139	142	107	16	69.94	12.1

Plot	100 needle weight	Foliar Al	Foliar B	Foliar Ba	Foliar Ca	Foliar Cr
	(g)	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})
1	0.20	4.70	1.66	40.90	3045.03	0.19
2	0.22	4.70	2.01	34.44	2514.88	0.07
3	0.23	4.32	1.47	49.35	3955.39	3.59
4	0.22	5.30	1.56	46.57	3804.06	0.21
5	0.24	4.70	1.47	61.04	3965.76	0.08
6	0.22	4.55	1.49	37.18	2933.07	0.14
7	0.23	6.58	1.60	47.72	3295.99	0.07
8	0.21	5.35	2.00	55.15	3368.45	0.10
9	0.17	4.28	0.73	32.52	2236.08	0.16
10	0.21	5.15	1.43	47.19	3047.37	0.07
11	0.21	5.32	1.49	42.60	2952.35	-
12	0.24	4.80	0.96	29.50	2624.99	0.11
13	0.20	6.34	1.14	51.40	3216.67	-
14	0.20	5.05	1.32	40.87	2798.64	-
15	0.23	6.28	1.35	32.69	3581.45	0.07
16	0.20	7.24	1.12	43.65	2707.70	-
17	0.16	3.11	0.65	31.83	2456.56	0.05
18	0.21	3.66	1.72	36.59	3226.78	-
19	0.19	4.01	1.76	33.54	2621.13	0.09
20	0.21	4.86	1.72	33.88	3353.95	0.07
21	0.18	3.34	1.55	20.12	2150.70	0.09
22	0.21	4.57	2.11	41.74	3240.39	0.10
23	0.17	4.32	1.53	21.89	2518.64	0.05
24	0.20	4.26	1.56	30.95	3044.70	0.09
25	0.20	4.12	1.66	27.81	2725.58	-
26	0.19	3.38	1.35	28.19	2567.91	0.09
27	0.22	5.86	1.64	30.54	3106.01	0.10
28	0.23	5.52	1.80	32.82	3449.88	0.11
29	0.21	3.88	1.53	34.37	3216.84	0.14
30	0.22	5.24	1.93	33.48	3810.91	0.11
31	0.22	6.54	1.70	31.09	3380.89	0.11
32	0.22	5.83	1.74	31.76	3280.22	0.10
33	0.24	6.00	2.01	30.77	2930.96	0.15
34	0.24	5.18	1.84	33.89	2707.49	0.11
35	0.23	4.27	1.98	51.97	3860.48	0.19
36	0.22	4.83	1.85	36.22	2714.84	0.10
37	0.18	3.51	1.58	21.89	2806.40	0.06
38	0.24	5.24	2.06	36.49	4541.47	0.12
39	0.22	5.33	1.53	46.96	3707.76	0.11
40	0.20	4.52	1.92	40.00	4261.92	0.07
41	0.25	7.43	2.04	31.14	3357.27	0.12
42	0.20	5.21	1.52	37.40	3260.74	0.10
43	0.20	4.21	1.35	26.14	2677.25	0.06
44	0.23	7.18	1.98	64.27	4998.67	0.11
45	0.26	6.25	2.12	46.16	4248.19	0.16

Plot	Foliar Cu (µg 100 needles^{-1})	Foliar Fe (µg 100 needles^{-1})	Foliar K (µg 100 needles^{-1})	Foliar Mg (µg 100 needles^{-1})	Foliar Mn (µg 100 needles^{-1})	Foliar N (µg 100 needles^{-1})	Foliar Na (µg 100 needles^{-1})
1	1.44	21.73	3418.86	517.62	63.26	2.38	3.51
2	1.84	23.31	3353.18	490.45	70.26	3.17	4.17
3	2.03	37.74	3599.77	656.81	86.37	3.97	1.09
4	1.67	27.38	3910.72	551.06	88.52	3.64	1.07
5	1.87	22.55	3705.26	598.75	111.20	3.91	-
6	1.74	21.20	3857.47	469.15	88.27	2.95	1.39
7	1.89	22.57	3488.35	510.49	134.28	3.47	1.48
8	1.85	21.80	3335.42	568.01	113.93	3.18	1.32
9	1.11	18.97	2469.17	371.32	79.69	2.51	1.36
10	1.50	18.94	3655.52	561.62	114.98	3.78	-
11	1.42	17.50	3962.88	452.43	116.57	3.20	-
12	2.00	24.21	3820.22	559.80	101.75	4.28	-
13	1.86	27.44	3279.74	476.19	136.55	3.19	-
14	1.53	19.97	3276.00	424.32	93.91	3.10	-
15	1.86	27.12	5052.67	631.58	137.83	3.78	-
16	1.61	17.40	3479.52	563.05	162.90	2.65	0.95
17	1.29	14.67	2809.63	385.39	70.61	2.27	-
18	1.32	24.39	3955.20	491.10	92.62	2.60	-
19	1.27	15.84	3571.44	434.78	70.81	2.93	1.55
20	1.44	18.14	3969.98	540.74	100.28	2.82	2.74
21	1.11	16.72	3173.63	436.37	54.12	2.62	-
22	1.64	21.03	3384.99	611.27	93.01	3.55	-
23	1.32	16.75	2999.66	445.90	66.48	3.09	-
24	1.52	22.42	3884.83	451.65	71.06	3.20	-
25	1.34	16.03	3501.04	490.80	76.89	2.74	-
26	1.42	17.04	3841.02	495.62	60.40	3.31	-
27	1.32	21.86	4199.18	548.32	115.56	3.38	-
28	1.79	26.85	3647.55	589.28	83.92	4.17	-
29	1.41	17.87	3677.38	512.08	83.86	3.03	0.69
30	1.64	23.15	3882.14	519.99	92.25	3.56	0.71
31	1.84	28.26	4698.62	494.59	87.97	3.71	0.71
32	1.88	25.82	3873.46	593.23	102.25	3.62	1.05
33	1.92	25.00	4000.26	623.12	107.31	3.94	-
34	1.68	23.23	3922.24	571.20	77.30	3.67	-
35	1.78	22.64	4565.76	668.16	83.89	3.20	1.11
36	1.66	20.35	3829.06	551.94	101.42	2.85	1.03
37	1.26	17.68	2862.53	378.86	79.98	2.37	0.84
38	1.90	25.62	3769.03	624.94	149.44	3.59	1.55
39	1.77	20.13	3499.42	547.34	150.08	2.65	1.06
40	1.70	19.34	3239.06	524.54	131.79	3.73	0.66
41	1.88	23.15	3920.14	722.55	146.11	3.94	-
42	1.57	22.06	3113.68	553.05	110.61	3.04	0.64
43	1.47	17.85	3346.56	541.82	92.11	2.85	0.96
44	1.99	25.93	3908.74	601.34	169.13	3.83	0.75
45	1.96	26.96	4125.65	665.82	148.28	3.75	1.23

Plot	Foliar Ni	Foliar P	Foliar S	Foliar Si	Foliar Sr	Foliar Zn
	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})	(µg 100 needles^{-1})
1	1.28	1236.54	415.38	41.86	22.37	37.70
2	1.04	1318.31	542.63	48.00	15.30	29.57
3	3.27	1495.07	642.30	45.36	23.22	40.64
4	1.07	1574.95	583.05	50.13	17.78	33.63
5	1.56	1508.54	540.43	55.21	22.16	34.10
6	1.04	1556.89	514.33	38.57	16.33	29.43
7	1.85	1416.79	569.68	46.61	15.91	26.45
8	1.98	1489.38	505.27	42.60	17.50	32.17
9	2.17	894.43	273.75	32.80	8.94	28.46
10	1.33	1492.12	505.13	44.86	11.96	37.55
11	1.32	1608.27	482.15	44.58	10.57	36.99
12	1.13	1668.04	571.14	50.31	12.10	35.33
13	1.58	1381.28	485.65	42.57	15.45	36.58
14	1.25	1344.72	471.12	40.56	13.10	33.70
15	1.11	1783.30	746.76	47.93	15.98	43.47
16	0.95	1398.13	464.99	40.81	15.50	30.40
17	1.24	1034.34	360.53	34.56	12.68	25.36
18	0.99	1410.69	418.59	44.50	16.48	34.61
19	2.48	1378.89	416.15	49.38	17.39	28.14
20	1.37	1447.68	441.49	37.30	18.82	47.23
21	0.85	1204.28	493.05	27.77	14.45	27.26
22	1.31	1603.76	578.41	42.07	19.72	39.11
23	0.81	1162.03	440.49	46.48	12.16	30.54
24	0.95	1386.54	559.04	102.96	19.58	31.52
25	1.64	1269.54	438.45	83.44	12.76	31.97
26	0.62	1480.65	526.59	101.60	17.35	37.17
27	1.39	1520.04	555.26	98.21	14.23	36.44
28	1.49	1432.17	637.76	137.25	22.00	40.65
29	1.03	1398.78	532.70	126.13	20.96	33.20
30	1.07	1492.31	715.88	129.64	20.66	40.96
31	1.06	1950.11	674.76	126.83	18.02	36.74
32	1.05	1587.77	547.87	114.11	20.59	40.13
33	1.92	1665.49	611.58	130.78	15.00	37.69
34	1.52	1633.63	575.01	114.24	15.61	32.75
35	1.11	1633.28	567.94	67.56	28.21	41.95
36	1.72	1659.26	555.39	75.89	16.21	31.25
37	1.12	1105.72	420.96	65.67	15.44	29.75
38	1.55	1412.90	613.29	121.88	26.01	45.80
39	2.12	1405.42	522.62	100.99	21.19	33.69
40	1.31	1301.52	534.38	107.20	28.85	39.67
41	2.00	1784.42	602.79	103.79	19.96	46.31
42	1.28	1397.00	537.06	71.61	17.90	31.10
43	0.96	1319.50	500.39	71.71	15.62	32.19
44	1.50	1601.08	650.20	84.19	27.06	44.72
45	1.23	1670.68	698.50	95.99	23.28	38.40

Appendix E

Black Spruce Height and Volume Growth Data

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
1	1	5	0	10	16	157	173	0.024	0.059
1	2	6	10	0	1	167	196	0.045	0.082
1	2	6	10	0	5	174	191	0.073	0.097
1	1	5	0	10	2	187	205	0.078	0.168
1	1	5	0	10	14	204	211	0.103	0.173
1	7	3	1	0	10	202	222	0.122	0.268
1	9	8	10	1	7	215	231	0.359	0.278
1	1	5	0	10	8	221	246	0.133	0.296
1	1	5	0	10	10	230	248	0.216	0.298
1	7	3	1	0	6	232	253	0.218	0.304
1	1	5	0	10	12	202	227	0.143	0.307
1	8	4	1	1	8	228	248	0.214	0.334
1	2	6	10	0	3	197	229	0.140	0.345
1	7	3	1	0	2	231	242	0.278	0.364
1	4	9	10	10	15	215	245	0.129	0.368
1	8	4	1	1	6	219	238	0.234	0.396
1	5	1	0	0	1	240	251	0.256	0.417
1	2	6	10	0	13	231	261	0.217	0.433
1	7	3	1	0	4	241	275	0.257	0.456
1	4	9	10	10	13	225	250	0.211	0.458
1	8	4	1	1	10	235	251	0.283	0.460
1	1	5	0	10	4	235	259	0.220	0.474
1	7	3	1	0	16	233	242	0.315	0.488
1	9	8	10	1	15	240	254	0.324	0.511
1	5	1	0	0	9	230	255	0.246	0.513
1	8	4	1	1	16	232	255	0.349	0.513
1	7	3	1	0	12	225	251	0.304	0.552
1	4	9	10	10	9	251	276	0.267	0.553
1	8	4	1	1	5	240	260	0.324	0.571
1	9	8	10	1	3	234	266	0.316	0.584
1	7	3	1	0	8	243	269	0.365	0.590
1	6	7	1	10	6	243	271	0.292	0.594
1	4	9	10	10	8	249	272	0.414	0.649
1	8	4	1	1	2	255	273	0.306	0.651
1	2	6	10	0	9	256	275	0.384	0.656
1	9	8	10	1	1	270	276	0.448	0.658
1	3	2	0	1	14	239	257	0.398	0.667

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
1	3	2	0	1	8	245	258	0.408	0.670
1	6	7	1	10	10	260	295	0.571	0.702
1	5	1	0	0	5	257	281	0.385	0.727
1	4	9	10	10	6	259	284	0.430	0.734
1	5	1	0	0	7	268	286	0.490	0.739
1	3	2	0	1	2	219	247	0.443	0.749
1	3	2	0	1	10	277	300	0.459	0.774
1	3	2	0	1	6	249	261	0.457	0.790
1	5	1	0	0	11	261	287	0.433	0.802
1	8	4	1	1	4	266	293	0.441	0.818
1	2	6	10	0	15	253	273	0.421	0.824
1	5	1	0	0	3	273	298	0.499	0.831
1	4	9	10	10	12	267	288	0.443	0.868
1	1	5	0	10	6	286	293	0.522	0.882
1	3	2	0	1	16	268	294	0.538	0.885
1	8	4	1	1	13	276	296	0.504	0.891
1	5	1	0	0	13	270	297	0.448	0.894
1	3	2	0	1	4	279	307	0.462	0.922
1	9	8	10	1	9	288	310	0.525	0.931
1	7	3	1	0	14	312	339	0.803	0.940
1	6	7	1	10	8	297	328	0.649	0.983
1	3	2	0	1	12	281	304	0.513	0.983
1	4	9	10	10	4	260	285	0.522	0.991
1	5	1	0	0	15	284	305	0.734	1.058
1	6	7	1	10	14	291	317	0.636	1.097
1	6	7	1	10	4	269	299	0.642	1.111
1	9	8	10	1	13	299	313	0.711	1.160
1	6	7	1	10	12	292	315	0.638	1.167
1	6	7	1	10	2	294	323	0.588	1.195
1	2	6	10	0	7	304	340	0.847	1.340
1	9	8	10	1	11	331	347	0.850	1.366
1	2	6	10	0	11	296	326	0.764	1.459
1	4	9	10	10	2	305	345	0.786	1.540
1	6	7	1	10	16	367	409	1.535	2.398
1	9	8	10	1	5	347	378	1.644	2.467
2	14	1	0	0	9	139	149	0.009	0.016
2	16	8	10	1	10	142	155	0.010	0.032
2	16	8	10	1	16	151	171	0.023	0.058
2	13	2	0	1	9	177	188	0.048	0.095
2	14	1	0	0	15	167	187	0.057	0.113
2	18	9	10	10	13	174	190	0.059	0.115
2	15	7	1	10	8	168	191	0.045	0.135
2	16	8	10	1	14	193	206	0.081	0.146
2	10	5	0	10	4	192	211	0.116	0.149
2	15	7	1	10	16	180	197	0.076	0.162
2	14	1	0	0	3	171	199	0.058	0.163
2	11	4	1	1	9	191	209	0.180	0.224

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
1	3	2	0	1	8	245	258	0.408	0.670
1	6	7	1	10	10	260	295	0.571	0.702
1	5	1	0	0	5	257	281	0.385	0.727
1	4	9	10	10	6	259	284	0.430	0.734
1	5	1	0	0	7	268	286	0.490	0.739
1	3	2	0	1	2	219	247	0.443	0.749
1	3	2	0	1	10	277	300	0.459	0.774
1	3	2	0	1	6	249	261	0.457	0.790
1	5	1	0	0	11	261	287	0.433	0.802
1	8	4	1	1	4	266	293	0.441	0.818
1	2	6	10	0	15	253	273	0.421	0.824
1	5	1	0	0	3	273	298	0.499	0.831
1	4	9	10	10	12	267	288	0.443	0.868
1	1	5	0	10	6	286	293	0.522	0.882
1	3	2	0	1	16	268	294	0.538	0.885
1	8	4	1	1	13	276	296	0.504	0.891
1	5	1	0	0	13	270	297	0.448	0.894
1	3	2	0	1	4	279	307	0.462	0.922
1	9	8	10	1	9	288	310	0.525	0.931
1	7	3	1	0	14	312	339	0.803	0.940
1	6	7	1	10	8	297	328	0.649	0.983
1	3	2	0	1	12	281	304	0.513	0.983
1	4	9	10	10	4	260	285	0.522	0.991
1	5	1	0	0	15	284	305	0.734	1.058
1	6	7	1	10	14	291	317	0.636	1.097
1	6	7	1	10	4	269	299	0.642	1.111
1	9	8	10	1	13	299	313	0.711	1.160
1	6	7	1	10	12	292	315	0.638	1.167
1	6	7	1	10	2	294	323	0.588	1.195
1	2	6	10	0	7	304	340	0.847	1.340
1	9	8	10	1	11	331	347	0.850	1.366
1	2	6	10	0	11	296	326	0.764	1.459
1	4	9	10	10	2	305	345	0.786	1.540
1	6	7	1	10	16	367	409	1.535	2.398
1	9	8	10	1	5	347	378	1.644	2.467
2	14	1	0	0	9	139	149	0.009	0.016
2	16	8	10	1	10	142	155	0.010	0.032
2	16	8	10	1	16	151	171	0.023	0.058
2	13	2	0	1	9	177	188	0.048	0.095
2	14	1	0	0	15	167	187	0.057	0.113
2	18	9	10	10	13	174	190	0.059	0.115
2	15	7	1	10	8	168	191	0.045	0.135
2	16	8	10	1	14	193	206	0.081	0.146
2	10	5	0	10	4	192	211	0.116	0.149
2	15	7	1	10	16	180	197	0.076	0.162
2	14	1	0	0	3	171	199	0.058	0.163
2	11	4	1	1	9	191	209	0.180	0.224

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
2	17	6	10	0	4	195	217	0.118	0.232
2	17	6	10	0	16	225	249	0.184	0.233
2	15	7	1	10	2	206	219	0.104	0.234
2	18	9	10	10	5	190	213	0.115	0.257
2	17	6	10	0	12	220	239	0.132	0.288
2	15	7	1	10	10	195	217	0.099	0.294
2	14	1	0	0	7	199	223	0.368	0.302
2	12	3	1	0	1	219	229	0.206	0.309
2	15	7	1	10	6	183	206	0.093	0.311
2	16	8	10	1	5	213	233	0.150	0.315
2	15	7	1	10	14	220	244	0.235	0.329
2	18	9	10	10	16	212	244	0.199	0.367
2	16	8	10	1	11	229	245	0.215	0.408
2	17	6	10	0	2	200	225	0.302	0.414
2	14	1	0	0	5	233	254	0.281	0.422
2	17	6	10	0	10	192	218	0.206	0.441
2	18	9	10	10	1	224	247	0.270	0.453
2	12	3	1	0	3	235	259	0.283	0.474
2	11	4	1	1	13	233	256	0.315	0.515
2	13	2	0	1	11	262	289	0.314	0.527
2	18	9	10	10	3	232	265	0.248	0.532
2	10	5	0	10	8	269	287	0.361	0.574
2	18	9	10	10	2	257	273	0.385	0.598
2	10	5	0	10	6	259	301	0.275	0.601
2	12	3	1	0	11	240	263	0.361	0.629
2	16	8	10	1	3	259	281	0.430	0.670
2	10	5	0	10	2	267	291	0.400	0.693
2	14	1	0	0	11	250	269	0.416	0.697
2	17	6	10	0	6	239	269	0.322	0.697
2	12	3	1	0	7	242	270	0.488	0.699
2	12	3	1	0	15	263	295	0.354	0.702
2	11	4	1	1	1	241	274	0.325	0.709
2	12	3	1	0	9	252	274	0.507	0.709
2	11	4	1	1	15	262	288	0.435	0.744
2	18	9	10	10	11	264	291	0.483	0.751
2	13	2	0	1	15	272	292	0.545	0.754
2	13	2	0	1	7	240	270	0.484	0.756
2	13	2	0	1	1	264	281	0.483	0.786
2	15	7	1	10	12	248	285	0.413	0.797
2	10	5	0	10	12	243	311	0.535	0.801
2	11	4	1	1	7	251	269	0.505	0.813
2	14	1	0	0	1	275	310	0.502	0.863
2	13	2	0	1	5	290	312	0.528	0.869
2	16	8	10	1	8	274	300	0.501	0.902
2	17	6	10	0	8	278	301	0.460	0.905
2	17	6	10	0	14	271	301	0.495	0.905
2	16	8	10	1	2	280	307	0.464	0.922

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
2	11	4	1	1	3	288	312	0.630	0.937
2	15	7	1	10	4	286	325	0.626	0.974
2	13	2	0	1	3	275	304	0.502	0.983
2	14	1	0	0	13	275	307	0.502	0.992
2	10	5	0	10	16	291	322	0.876	1.114
2	11	4	1	1	5	295	318	0.888	1.178
2	12	3	1	0	13	302	333	0.718	1.314
2	13	2	0	1	13	298	340	0.769	1.428
2	12	3	1	0	5	306	349	0.788	1.464
2	18	9	10	10	10	302	318	0.977	1.603
2	10	5	0	10	14	312	348	1.157	1.746
2	10	5	0	10	10	341	370	1.096	1.851
2	11	4	1	1	11	346	372	1.363	2.310
3	21	9	10	10	5	102	116	0.087	0.147
3	21	9	10	10	13	98	108	0.074	0.102
3	20	4	1	1	16	140	155	0.147	0.006
3	23	1	0	0	7	115	136	0.120	0.188
3	23	1	0	0	13	147	174	0.022	0.047
3	23	1	0	0	9	148	162	0.022	0.055
3	26	5	0	10	12	146	163	0.030	0.056
3	21	9	10	10	15	162	174	0.044	0.073
3	22	3	1	0	12	160	178	0.017	0.075
3	26	5	0	10	10	154	182	0.010	0.076
3	24	7	1	10	15	165	185	0.025	0.078
3	20	4	1	1	5	178	193	0.027	0.081
3	21	9	10	10	1	173	201	0.026	0.084
3	26	5	0	10	4	163	181	0.017	0.092
3	20	4	1	1	14	173	201	0.026	0.102
3	22	3	1	0	5	160	201	0.017	0.102
3	26	5	0	10	16	189	215	0.051	0.109
3	19	6	10	0	1	172	180	0.035	0.109
3	21	9	10	10	10	181	203	0.109	0.144
3	21	9	10	10	11	186	217	0.078	0.178
3	25	8	10	1	2	214	233	0.089	0.190
3	19	6	10	0	9	205.5	226	0.104	0.212
3	24	7	1	10	8	198	220	0.100	0.235
3	23	1	0	0	3	190	203	0.096	0.246
3	19	6	10	0	2	194	213	0.098	0.257
3	24	7	1	10	4	199	228	0.101	0.275
3	27	2	0	1	13	206	228	0.124	0.275
3	26	5	0	10	6	218	236	0.154	0.284
3	27	2	0	1	1	208	237	0.196	0.285
3	20	4	1	1	8	216	238	0.130	0.286
3	26	5	0	10	8	202	229	0.102	0.309
3	23	1	0	0	1	208	237	0.125	0.320
3	22	3	1	0	7	220	242	0.180	0.326
3	23	1	0	0	15	204	218	0.144	0.329

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
3	21	9	10	10	9	198	223	0.083	0.336
3	24	7	1	10	9	200	226	0.142	0.340
3	26	5	0	10	2	222	255	0.157	0.343
3	25	8	10	1	15	221	243	0.156	0.365
3	23	1	0	0	5	227	244	0.242	0.367
3	27	2	0	1	3	212	244	0.199	0.406
3	19	6	10	0	5	202	221	0.102	0.407
3	22	3	1	0	16	227	246	0.160	0.409
3	19	6	10	0	7	228	252	0.186	0.419
3	21	9	10	10	7	244	268	0.199	0.444
3	25	8	10	1	11	234	247	0.219	0.453
3	20	4	1	1	10	258	286	0.241	0.473
3	20	4	1	1	12	234	261	0.219	0.478
3	19	6	10	0	15	245	264	0.200	0.483
3	23	1	0	0	11	248	268	0.298	0.490
3	19	6	10	0	13	240	272	0.196	0.497
3	19	6	10	0	11	239	269	0.255	0.540
3	21	9	10	10	4	228	252	0.214	0.554
3	26	5	0	10	13	219	256	0.132	0.562
3	25	8	10	1	5	236	259	0.284	0.569
3	25	8	10	1	13	255	271	0.271	0.647
3	24	7	1	10	6	250	275	0.375	0.656
3	27	2	0	1	5	263	283	0.436	0.674
3	20	4	1	1	6	234	266	0.219	0.689
3	27	2	0	1	11	255	281	0.424	0.727
3	25	8	10	1	4	279	305	0.417	0.786
3	27	2	0	1	7	280	306	0.464	0.788
3	22	3	1	0	1	260	287	0.522	0.865
3	27	2	0	1	8	279	313	0.509	0.871
3	24	7	1	10	13	254	274	0.465	0.890
3	25	8	10	1	9	279	299	0.509	0.900
3	24	7	1	10	11	263	297	0.577	1.031
3	22	3	1	0	14	283	328	0.619	1.057
3	20	4	1	1	2	287	311	0.628	1.077
3	22	3	1	0	3	258	291	0.670	1.082
3	22	3	1	0	10	263	295	0.577	1.096
3	27	2	0	1	15	308	335	0.671	1.156
3	24	7	1	10	2	308	338	0.858	1.510
3	25	8	10	1	8	331	359	1.480	2.120
4	28	7	1	10	9	80	90	0.068	-
4	33	1	0	0	10	115	128	0.133	0.193
4	35	5	0	10	10	130	140	0.248	0.005
4	35	5	0	10	4	130	147	0.009	0.016
4	28	7	1	10	7	142	160	0.010	0.024
4	35	5	0	10	12	157	174	0.024	0.059
4	30	9	10	10	13	164	187	0.025	0.078
4	31	3	1	0	8	172	187	0.046	0.095

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
4	31	3	1	0	14	168	191	0.025	0.097
4	29	8	10	1	9	169	181	0.071	0.109
4	34	2	0	1	10	168	181	0.025	0.109
4	34	2	0	1	11	185	219	0.050	0.111
4	31	3	1	0	10	169	187	0.046	0.113
4	28	7	1	10	4	158	173	0.033	0.123
4	32	6	10	0	2	197	211	0.298	0.127
4	35	5	0	10	2	161	188	0.024	0.133
4	30	9	10	10	6	167	191	0.034	0.135
4	35	5	0	10	6	175	205	0.036	0.145
4	33	1	0	0	8	187	199	0.078	0.163
4	34	2	0	1	16	185	200	0.078	0.164
4	36	4	1	1	7	189	207	0.079	0.170
4	33	1	0	0	14	197	211	0.100	0.173
4	33	1	0	0	6	194	216	0.081	0.177
4	29	8	10	1	5	168	191	0.071	0.180
4	33	1	0	0	2	189	211	0.096	0.199
4	36	4	1	1	5	210	224	0.126	0.210
4	32	6	10	0	5	218	236	0.154	0.221
4	33	1	0	0	16	194	207	0.098	0.222
4	31	3	1	0	4	211	230	0.107	0.246
4	36	4	1	1	13	229	246	0.161	0.262
4	36	4	1	1	11	221	234	0.156	0.282
4	34	2	0	1	7	183	214	0.062	0.290
4	30	9	10	10	10	227	242	0.213	0.291
4	28	7	1	10	1	226	247	0.185	0.333
4	31	3	1	0	2	204	222	0.192	0.335
4	35	5	0	10	16	226	251	0.136	0.338
4	29	8	10	1	7	206	233	0.221	0.351
4	29	8	10	1	1	194	224	0.183	0.374
4	36	4	1	1	3	225	253	0.240	0.380
4	36	4	1	1	9	239	257	0.224	0.385
4	34	2	0	1	2	240	262	0.196	0.392
4	28	7	1	10	5	209	241	0.197	0.401
4	34	2	0	1	14	224	250	0.210	0.416
4	31	3	1	0	16	216	228	0.292	0.419
4	31	3	1	0	12	245	270	0.330	0.448
4	34	2	0	1	5	240	264	0.225	0.483
4	29	8	10	1	3	212	241	0.227	0.486
4	30	9	10	10	3	198	220	0.140	0.486
4	32	6	10	0	8	255	273	0.343	0.499
4	32	6	10	0	13	236	254	0.319	0.511
4	36	4	1	1	15	254	270	0.422	0.542
4	35	5	0	10	14	225	247	0.304	0.543
4	36	4	1	1	1	253	276	0.341	0.553
4	30	9	10	10	1	257	269	0.427	0.590
4	35	5	0	10	8	221	248	0.369	0.594

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
4	28	7	1	10	15	241	275	0.290	0.602
4	33	1	0	0	4	244	261	0.406	0.624
4	30	9	10	10	15	233	262	0.428	0.626
4	29	8	10	1	14	225	253	0.497	0.657
4	30	9	10	10	8	253	276	0.421	0.658
4	28	7	1	10	10	250	278	0.375	0.663
4	32	6	10	0	16	259	283	0.388	0.674
4	30	9	10	10	12	263	282	0.354	0.729
4	33	1	0	0	12	271	294	0.449	0.759
4	34	2	0	1	4	294	329	0.438	0.779
4	28	7	1	10	13	290	315	0.479	0.811
4	29	8	10	1	13	240	270	0.400	0.816
4	32	6	10	0	10	276	315	0.457	0.877
4	32	6	10	0	11	285	308	0.570	0.925
4	32	6	10	0	3	296	321	0.591	0.963
4	29	8	10	1	15	232	260	-	1.037
4	31	3	1	0	6	288	305	0.744	1.058
5	37	5	0	10	2	140	153	0.100	0.016
5	44	1	0	0	14	150	157	0.010	0.024
5	43	6	10	0	10	186	208	0.050	0.125
5	40	8	10	1	2	196	209	0.067	0.126
5	38	9	10	10	8	180	195	0.092	0.138
5	41	3	1	0	4	192	204	0.116	0.167
5	41	3	1	0	16	185	204	0.078	0.167
5	42	4	1	1	1	190	202	0.135	0.190
5	43	6	10	0	8	207	212	0.125	0.199
5	40	8	10	1	10	210	217	0.317	0.204
5	40	8	10	1	6	197	220	0.083	0.207
5	41	3	1	0	2	202	228	0.122	0.214
5	44	1	0	0	10	203	240	0.122	0.225
5	37	5	0	10	4	192	217	0.136	0.232
5	40	8	10	1	12	198	217	0.083	0.232
5	45	7	1	10	2	204	225	0.192	0.240
5	41	3	1	0	10	201	226	0.165	0.273
5	42	4	1	1	11	210	232	0.126	0.279
5	43	6	10	0	2	213	232	0.128	0.279
5	43	6	10	0	6	219	240	0.155	0.289
5	37	5	0	10	8	195	201	0.118	0.304
5	43	6	10	0	14	230	249	0.216	0.335
5	38	9	10	10	2	212	223	0.199	0.336
5	39	2	0	1	4	219	238	0.234	0.358
5	45	7	1	10	16	233	252	0.249	0.378
5	43	6	10	0	4	222	228	0.209	0.380
5	40	8	10	1	16	239	255	0.322	0.382
5	44	1	0	0	16	220	232	0.266	0.387
5	38	9	10	10	16	234	244	0.282	0.406
5	38	9	10	10	4	229	254	0.309	0.422

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
5	42	4	1	1	3	214	240	0.229	0.441
5	37	5	0	10	15	217	232	0.131	0.468
5	37	5	0	10	10	238	258	0.286	0.472
5	44	1	0	0	2	236	258	0.319	0.472
5	39	2	0	1	8	237	260	0.356	0.476
5	39	2	0	1	7	227	243	0.307	0.489
5	45	7	1	10	6	236	257	0.284	0.517
5	37	5	0	10	12	235	263	0.317	0.528
5	45	7	1	10	12	209	241	0.253	0.531
5	37	5	0	10	16	234	256	0.352	0.562
5	41	3	1	0	14	234	263	0.250	0.577
5	45	7	1	10	14	228	263	0.275	0.577
5	41	3	1	0	6	252	269	0.339	0.590
5	45	7	1	10	8	266	283	0.319	0.619
5	44	1	0	0	4	235	260	0.317	0.622
5	44	1	0	0	8	249	276	0.335	0.658
5	39	2	0	1	16	256	272	0.425	0.704
5	38	9	10	10	10	274	299	0.600	0.711
5	37	5	0	10	14	246	275	0.409	0.712
5	40	8	10	1	14	263	276	0.436	0.714
5	38	9	10	10	6	265	284	0.440	0.734
5	44	1	0	0	12	250	269	0.416	0.754
5	39	2	0	1	12	272	303	0.451	0.781
5	39	2	0	1	5	277	312	0.414	0.803
5	43	6	10	0	12	253	271	0.464	0.819
5	40	8	10	1	8	277	296	0.555	0.826
5	40	8	10	1	4	248	280	0.499	0.845
5	41	3	1	0	8	264	283	0.530	0.853
5	45	7	1	10	4	265	301	0.440	0.905
5	38	9	10	10	12	287	310	0.574	0.931
5	44	1	0	0	6	275	291	0.551	0.943
5	45	7	1	10	10	263	293	0.528	0.949
5	42	4	1	1	7	302	323	0.779	0.968
5	38	9	10	10	14	294	329	0.699	1.060
5	41	3	1	0	12	290	312	0.749	1.081
5	39	2	0	1	11	269	295	0.540	1.096
5	37	5	0	10	6	293	322	0.640	1.114
5	42	4	1	1	8	285	300	0.737	1.114
5	42	4	1	1	13	304	328	0.914	1.133
5	42	4	1	1	15	285	308	0.797	1.142
5	43	6	10	0	16	324	336	0.900	1.325
5	42	4	1	1	5	294	311	0.885	1.481
5	39	2	0	1	14	297	347	1.255	1.946

Appendix F

White Spruce Height and Volume Growth Data

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
1	1	5	0	10	1	55	51	0.024	0.026
1	2	6	10	0	7	127	151	0.176	0.016
1	1	5	0	10	5	135	153	0.005	0.016
1	2	6	10	0	10	135	141	0.020	0.029
1	3	2	0	1	6	138	171	0.009	0.034
1	1	5	0	10	15	127	141	0.133	0.037
1	3	2	0	1	4	174	208	0.103	0.144
1	9	8	10	1	6	182	202	0.075	0.162
1	3	2	0	1	16	185	209	0.076	0.168
1	9	8	10	1	16	177	205	0.088	0.215
1	2	6	10	0	14	180	211	0.089	0.221
1	9	8	10	1	10	194	218	0.179	0.228
1	8	4	1	1	11	177	195	0.164	0.231
1	7	3	1	0	1	192	205	0.154	0.242
1	8	4	1	1	7	196	219	0.181	0.259
1	2	6	10	0	1	193	222	0.134	0.262
1	1	5	0	10	7	202	237	0.119	0.279
1	7	3	1	0	11	184	204	0.148	0.334
1	2	6	10	0	9	187	211	0.173	0.345
1	7	3	1	0	15	210	239	0.168	0.351
1	7	3	1	0	13	219	238	0.259	0.388
1	8	4	1	1	3	205	235	0.303	0.464
1	6	7	1	10	2	234	270	0.215	0.483
1	1	5	0	10	11	208	246	0.191	0.485
1	9	8	10	1	8	212	246	0.347	0.485
1	8	4	1	1	9	216	238	0.226	0.513
1	6	7	1	10	15	215	239	0.317	0.515
1	6	7	1	10	4	210	241	0.220	0.519
1	4	9	10	10	4	244	269	0.397	0.528
1	8	4	1	1	13	227	253	0.237	0.544
1	2	6	10	0	4	221	255	0.203	0.548
1	7	3	1	0	5	241	255	0.354	0.548
1	5	1	0	0	8	229	262	0.681	0.563
1	5	1	0	0	15	223	251	0.263	0.588
1	7	3	1	0	3	241	276	0.284	0.592
1	2	6	10	0	6	205	234	0.242	0.596

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
1	2	6	10	0	13	226	267	-	0.624
1	7	3	1	0	9	227	247	0.334	0.628
1	4	9	10	10	2	257	275	0.506	0.642
1	3	2	0	1	14	224	261	0.330	0.663
1	6	7	1	10	6	235	268	0.346	0.680
1	5	1	0	0	6	232	269	0.242	0.682
1	8	4	1	1	15	243	273	0.357	0.692
1	5	1	0	0	4	232	280	0.273	0.709
1	4	9	10	10	10	260	294	0.342	0.743
1	1	5	0	10	3	237	283	0.386	0.775
1	3	2	0	1	8	246	281	0.401	0.830
1	3	2	0	1	2	255	288	0.415	0.850
1	9	8	10	1	14	260	288	0.511	0.850
1	8	4	1	1	1	255	274	0.502	0.871
1	4	9	10	10	8	247	275	0.487	0.938
1	6	7	1	10	12	236	279	1.047	0.951
1	6	7	1	10	16	287	293	0.669	0.997
1	7	3	1	0	7	270	300	0.483	1.020
1	5	1	0	0	12	242	290	0.435	1.056
1	5	1	0	0	14	272	303	0.534	1.102
1	6	7	1	10	13	261	286	0.611	1.113
1	6	7	1	10	10	253	271	0.695	1.126
1	5	1	0	0	2	256	297	0.703	1.154
1	9	8	10	1	4	272	305	0.746	1.184
1	5	1	0	0	16	277	296	0.647	1.225
1	1	5	0	10	9	285	318	0.559	1.232
1	4	9	10	10	6	268	328	0.735	1.269
1	3	2	0	1	12	276	293	0.592	1.291
1	4	9	10	10	12	245	293	0.623	1.291
1	3	2	0	1	10	267	296	0.733	1.383
1	8	4	1	1	5	274	316	0.751	1.388
1	6	7	1	10	8	273	301	0.807	1.406
1	9	8	10	1	2	281	304	0.770	1.504
1	4	9	10	10	16	311	334	0.915	1.553
1	9	8	10	1	12	266	310	0.908	1.621
1	1	5	0	10	13	309	339	0.978	1.766
1	4	9	10	10	14	376	410	1.843	2.881
2	17	6	10	0	16	146	156	0.010	0.041
2	16	8	10	1	10	140	166	0.014	0.068
2	16	8	10	1	6	152	171	0.023	0.070
2	16	8	10	1	16	148	175	0.010	0.072
2	12	3	1	0	3	153	172	0.040	0.086
2	17	6	10	0	10	160	180	0.032	0.089
2	16	8	10	1	8	142	166	0.015	0.098
2	16	8	10	1	14	135	155	0.009	0.108
2	12	3	1	0	7	174	188	0.103	0.130
2	18	9	10	10	7	181	196	0.107	0.136

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
2	16	8	10	1	12	177	198	0.105	0.159
2	18	9	10	10	9	187	200	0.077	0.161
2	15	7	1	10	1	159	177	0.024	0.164
2	14	1	0	0	1	173	188	0.160	0.174
2	11	4	1	1	13	185	206	0.092	0.190
2	11	4	1	1	15	177	200	0.088	0.210
2	18	9	10	10	11	182	203	0.075	0.213
2	15	7	1	10	9	176	204	0.163	0.214
2	16	8	10	1	2	188	209	0.130	0.219
2	15	7	1	10	7	188	213	0.151	0.223
2	10	5	0	10	14	174	194	0.103	0.230
2	17	6	10	0	14	173	198	0.160	0.234
2	12	3	1	0	9	192	216	0.133	0.255
2	13	2	0	1	9	191	215	0.132	0.317
2	18	9	10	10	1	200	217	0.184	0.320
2	12	3	1	0	14	197	211	0.207	0.345
2	18	9	10	10	15	216	236	0.255	0.347
2	15	7	1	10	13	191	225	0.038	0.367
2	14	1	0	0	15	200	237	0.184	0.386
2	17	6	10	0	12	212	241	0.195	0.393
2	15	7	1	10	5	203	225	0.332	0.405
2	13	2	0	1	5	196	227	0.181	0.408
2	18	9	10	10	3	216	250	0.199	0.448
2	13	2	0	1	1	233	255	0.308	0.457
2	13	2	0	1	11	226	255	0.236	0.457
2	16	8	10	1	4	207	241	0.245	0.519
2	12	3	1	0	1	231	269	0.377	0.528
2	17	6	10	0	2	211	250	0.221	0.538
2	10	5	0	10	12	250	276	0.330	0.542
2	10	5	0	10	6	229	263	0.270	0.565
2	14	1	0	0	5	215	243	0.254	0.570
2	17	6	10	0	4	221	246	0.292	0.577
2	14	1	0	0	3	232	278	0.307	0.649
2	14	1	0	0	13	225	258	0.298	0.655
2	14	1	0	0	9	220	261	0.260	0.663
2	14	1	0	0	11	232	262	0.378	0.719
2	15	7	1	10	15	255	288	0.300	0.729
2	15	7	1	10	11	232	272	0.378	0.746
2	14	1	0	0	7	239	274	0.389	0.751
2	10	5	0	10	2	253	275	0.498	0.754
2	11	4	1	1	5	258	287	0.378	0.785
2	18	9	10	10	5	260	295	0.559	0.870
2	12	3	1	0	15	251	274	0.450	0.871
2	17	6	10	0	6	264	298	0.567	0.878
2	12	3	1	0	4	250	286	0.586	0.908
2	13	2	0	1	15	236	257	0.601	0.940
2	11	4	1	1	1	257	283	0.506	0.964

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
2	12	3	1	0	12	268	316	0.793	1.072
2	13	2	0	1	3	246	266	0.677	1.106
2	11	4	1	1	7	241	285	0.664	1.109
2	18	9	10	10	13	270	296	0.579	1.150
2	13	2	0	1	7	265	294	0.727	1.218
2	13	2	0	1	13	274	300	0.694	1.241
2	17	6	10	0	8	275	303	0.697	1.253
2	15	7	1	10	3	258	293	0.764	1.291
2	11	4	1	1	4	283	319	0.660	1.317
2	10	5	0	10	4	280	313	0.709	1.460
2	10	5	0	10	16	308	331	0.906	1.632
2	10	5	0	10	8	298	343	0.878	1.688
2	11	4	1	1	11	316	361	0.999	1.773
2	11	4	1	1	9	295	332	1.909	1.829
2	10	5	0	10	10	312	354	1.289	2.051
3	20	4	1	1	13	68	75	0.040	0.057
3	24	7	1	10	1	100	124	0.105	0.187
3	24	7	1	10	7	104	123	0.109	0.201
3	21	9	10	10	7	123	135	0.104	0.141
3	20	4	1	1	15	127	144	0.133	0.236
3	21	9	10	10	15	124	144	0.172	0.255
3	23	1	0	0	8	138	155	0.014	0.031
3	20	4	1	1	1	151	156	0.010	0.052
3	27	2	0	1	6	156	171	0.093	0.119
3	19	6	10	0	2	154	187	0.091	0.130
3	21	9	10	10	11	152	186	0.181	0.150
3	19	6	10	0	6	177	196	0.073	0.157
3	27	2	0	1	12	164	182	0.055	0.168
3	23	1	0	0	16	188	214	0.093	0.197
3	26	5	0	10	8	170	197	0.070	0.207
3	19	6	10	0	4	175	198	0.087	0.208
3	24	7	1	10	5	183	208	0.127	0.218
3	19	6	10	0	12	162	184	0.131	0.218
3	23	1	0	0	5	172	211	0.057	0.221
3	21	9	10	10	13	167	193	0.083	0.229
3	24	7	1	10	15	174	197	0.072	0.233
3	24	7	1	10	9	209	221	0.103	0.261
3	20	4	1	1	11	184	222	0.170	0.262
3	26	5	0	10	16	156	178	0.052	0.264
3	21	9	10	10	5	186	202	0.110	0.268
3	25	8	10	1	3	202	223	0.140	0.295
3	21	9	10	10	1	193	214	0.134	0.316
3	27	2	0	1	2	195	218	0.135	0.322
3	24	7	1	10	3	197	223	0.136	0.402
3	26	5	0	10	6	217	255	0.174	0.415
3	22	3	1	0	12	198	233	0.182	0.419
3	22	3	1	0	4	201	223	0.185	0.441

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
3	26	5	0	10	10	208	229	0.123	0.452
3	20	4	1	1	5	200	230	0.210	0.454
3	24	7	1	10	13	188	222	0.197	0.480
3	22	3	1	0	2	221	256	0.203	0.504
3	22	3	1	0	8	226	257	0.208	0.506
3	27	2	0	1	8	226	260	0.112	0.511
3	22	3	1	0	16	206	238	0.216	0.513
3	25	8	10	1	1	234	267	0.244	0.525
3	25	8	10	1	13	228	255	0.209	0.548
3	27	2	0	1	14	226	257	0.112	0.553
3	26	5	0	10	12	215	238	0.225	0.559
3	20	4	1	1	3	228	250	0.269	0.586
3	25	8	10	1	11	219	258	0.229	0.604
3	26	5	0	10	4	236	258	0.312	0.604
3	19	6	10	0	10	228	240	0.209	0.611
3	19	6	10	0	14	228	265	0.238	0.620
3	25	8	10	1	7	215	247	0.285	0.628
3	25	8	10	1	5	246	271	0.256	0.633
3	21	9	10	10	9	225	250	0.265	0.636
3	22	3	1	0	10	247	273	0.290	0.638
3	19	6	10	0	8	236	254	0.347	0.645
3	25	8	10	1	9	228	254	0.238	0.645
3	27	2	0	1	4	231	254	0.377	0.645
3	20	4	1	1	9	240	272	0.353	0.690
3	21	9	10	10	3	210	237	0.278	0.704
3	23	1	0	0	3	224	246	0.296	0.730
3	27	2	0	1	10	244	272	0.359	0.746
3	26	5	0	10	2	236	264	0.312	0.781
3	22	3	1	0	6	255	292	0.300	0.799
3	22	3	1	0	14	245	284	0.360	0.838
3	25	8	10	1	15	254	289	0.455	0.853
3	19	6	10	0	16	251	284	0.369	0.902
3	26	5	0	10	14	246	285	0.401	0.905
3	24	7	1	10	11	218	264	0.356	0.965
3	23	1	0	0	2	248	294	0.404	1.070
3	23	1	0	0	11	259	303	0.464	1.102
3	20	4	1	1	7	255	276	0.648	1.293
3	23	1	0	0	13	265	300	0.569	1.401
3	27	2	0	1	16	279	306	0.764	1.514
3	23	1	0	0	10	288	336	0.850	1.655
4	31	3	1	0	10	108	127	0.150	-
4	32	6	10	0	7	112	128	0.155	0.209
4	36	4	1	1	3	120	141	0.126	0.021
4	29	8	10	1	8	142	171	0.015	0.025
4	28	7	1	10	5	130	162	0.009	0.067
4	30	9	10	10	3	142	166	0.015	0.068
4	30	9	10	10	11	157	174	0.016	0.072

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
4	30	9	10	10	9	161	178	0.032	0.073
4	30	9	10	10	15	158	173	0.065	0.086
4	28	7	1	10	1	156	175	0.064	0.087
4	34	2	0	1	14	161	183	0.066	0.091
4	36	4	1	1	1	170	193	0.070	0.096
4	28	7	1	10	7	154	184	0.016	0.109
4	32	6	10	0	1	159	177	0.032	0.123
4	35	5	0	10	8	160	196	0.042	0.136
4	35	5	0	10	12	160	183	0.080	0.147
4	34	2	0	1	16	169	195	0.069	0.157
4	33	1	0	0	10	185	208	0.076	0.167
4	36	4	1	1	9	187	200	0.110	0.184
4	34	2	0	1	2	180	201	0.074	0.185
4	35	5	0	10	4	171	201	0.070	0.185
4	36	4	1	1	5	192	210	0.154	0.193
4	33	1	0	0	8	176	204	0.059	0.214
4	35	5	0	10	9	182	213	0.168	0.223
4	32	6	10	0	9	171	192	0.085	0.227
4	30	9	10	10	13	180	221	0.166	0.231
4	29	8	10	1	16	213	228	0.196	0.238
4	28	7	1	10	9	175	202	0.072	0.239
4	34	2	0	1	10	174	202	0.087	0.239
4	28	7	1	10	11	171	197	0.070	0.261
4	29	8	10	1	10	237	255	0.217	0.300
4	29	8	10	1	11	210	227	0.193	0.300
4	30	9	10	10	5	203	231	0.213	0.305
4	36	4	1	1	11	196	232	0.080	0.307
4	29	8	10	1	4	207	222	0.085	0.327
4	32	6	10	0	4	201	224	0.185	0.330
4	36	4	1	1	7	211	225	0.194	0.332
4	33	1	0	0	2	216	238	0.199	0.350
4	35	5	0	10	10	210	246	0.220	0.361
4	31	3	1	0	2	195	222	0.259	0.363
4	34	2	0	1	4	228	227	0.238	0.371
4	33	1	0	0	16	212	231	0.222	0.377
4	34	2	0	1	5	207	231	0.306	0.377
4	35	5	0	10	6	202	237	0.186	0.386
4	28	7	1	10	3	196	223	0.181	0.402
4	30	9	10	10	1	225	250	0.332	0.407
4	36	4	1	1	13	205	240	0.189	0.431
4	35	5	0	10	14	225	247	0.235	0.443
4	31	3	1	0	9	232	276	0.242	0.448
4	32	6	10	0	15	215	241	0.254	0.475
4	34	2	0	1	12	201	221	0.185	0.477
4	34	2	0	1	8	221	249	0.231	0.490
4	31	3	1	0	13	211	229	0.249	0.494
4	32	6	10	0	3	227	257	0.208	0.506

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
4	30	9	10	10	7	227	258	0.300	0.507
4	31	3	1	0	8	214	239	0.197	0.515
4	33	1	0	0	4	235	268	0.245	0.526
4	36	4	1	1	15	218	248	0.289	0.534
4	33	1	0	0	12	211	239	0.221	0.609
4	28	7	1	10	4	213	243	0.252	0.618
4	35	5	0	10	2	222	253	0.294	0.643
4	31	3	1	0	5	231	255	0.377	0.648
4	28	7	1	10	15	232	269	0.378	0.682
4	29	8	10	1	6	230	259	0.375	0.711
4	33	1	0	0	6	219	261	0.290	0.717
4	29	8	10	1	2	246	267	0.442	0.733
4	32	6	10	0	11	232	265	0.342	0.784
4	31	3	1	0	14	270	319	0.438	0.869
4	32	6	10	0	13	251	280	0.408	0.954
4	29	8	10	1	12	258	290	0.655	0.987
4	33	1	0	0	14	250	277	0.797	1.455
4	31	3	1	0	3	289	343	0.853	1.688
5	41	3	1	0	16	90	98	0.060	0.074
5	40	8	10	1	15	120	144	0.283	0.021
5	42	4	1	1	4	147	164	0.015	0.043
5	37	5	0	10	13	140	156	0.021	0.052
5	37	5	0	10	12	150	157	0.022	0.065
5	37	5	0	10	6	152	174	0.051	0.072
5	44	1	0	0	8	178	197	0.073	0.136
5	43	6	10	0	6	169	196	0.225	0.157
5	41	3	1	0	8	187	191	0.093	0.176
5	38	9	10	10	14	173	196	0.046	0.181
5	37	5	0	10	2	187	205	0.077	0.189
5	40	8	10	1	13	177	205	0.026	0.189
5	40	8	10	1	10	181	206	0.074	0.190
5	43	6	10	0	8	170	207	0.101	0.191
5	45	7	1	10	14	174	196	0.161	0.206
5	39	2	0	1	1	207	229	0.143	0.210
5	42	4	1	1	16	182	202	0.075	0.212
5	42	4	1	1	12	183	204	0.192	0.214
5	40	8	10	1	8	189	188	0.038	0.223
5	40	8	10	1	12	177	209	0.088	0.247
5	37	5	0	10	9	203	212	0.083	0.251
5	41	3	1	0	10	201	219	0.139	0.259
5	45	7	1	10	4	189	222	0.112	0.262
5	39	2	0	1	7	186	213	0.129	0.282
5	37	5	0	10	4	200	216	0.082	0.286
5	44	1	0	0	4	196	223	0.136	0.295
5	38	9	10	10	8	198	216	0.182	0.319
5	42	4	1	1	14	191	223	0.254	0.329
5	41	3	1	0	14	196	224	0.181	0.330

Block	Plot	Treatment	High C	Low C	Tree ID	2019 Height	2020 Height	2019 Volume	2020 Volume
			('000 kg ha^{-1})	('000 kg ha^{-1})		(cm)	(cm)	(dm^3)	(dm^3)
5	38	9	10	10	10	189	208	0.174	0.340
5	38	9	10	10	12	185	209	0.076	0.342
5	37	5	0	10	15	216	236	0.199	0.347
5	38	9	10	10	2	208	238	0.191	0.350
5	42	4	1	1	2	206	228	0.216	0.372
5	44	1	0	0	16	212	236	0.195	0.385
5	40	8	10	1	4	218	246	0.228	0.401
5	43	6	10	0	2	204	235	0.214	0.422
5	45	7	1	10	10	218	254	0.289	0.455
5	38	9	10	10	4	209	233	0.192	0.460
5	39	2	0	1	2	244	265	0.322	0.474
5	44	1	0	0	6	214	243	0.283	0.479
5	40	8	10	1	2	225	249	0.235	0.490
5	45	7	1	10	2	223	253	0.263	0.544
5	44	1	0	0	10	200	234	0.237	0.549
5	41	3	1	0	4	225	257	0.235	0.553
5	42	4	1	1	8	209	236	0.247	0.554
5	39	2	0	1	13	231	258	0.456	0.555
5	41	3	1	0	6	216	246	0.199	0.577
5	39	2	0	1	11	242	272	0.319	0.584
5	45	7	1	10	12	212	238	0.251	0.606
5	41	3	1	0	12	221	260	0.261	0.608
5	40	8	10	1	6	212	239	0.281	0.609
5	43	6	10	0	16	232	264	0.307	0.617
5	37	5	0	10	10	251	286	0.230	0.667
5	39	2	0	1	9	242	263	0.394	0.668
5	43	6	10	0	12	217	270	0.287	0.685
5	42	4	1	1	6	235	276	0.310	0.699
5	44	1	0	0	14	251	278	0.408	0.704
5	38	9	10	10	16	239	257	0.429	0.761
5	39	2	0	1	5	236	257	0.424	0.761
5	45	7	1	10	6	228	262	0.336	0.776
5	42	4	1	1	10	247	281	0.487	0.830
5	41	3	1	0	2	239	269	0.429	0.856
5	37	5	0	10	8	265	284	0.672	0.967
5	43	6	10	0	14	259	294	0.557	1.000
5	43	6	10	0	10	283	302	0.458	1.026
5	43	6	10	0	4	275	303	0.540	1.029
5	45	7	1	10	8	245	282	0.623	1.098
5	39	2	0	1	15	255	287	0.648	1.116
5	38	9	10	10	6	273	312	0.692	1.371
5	45	7	1	10	16	285	317	0.721	1.477
5	44	1	0	0	12	290	334	0.920	1.839
5	44	1	0	0	2	324	352	1.175	2.040