EVALUATING THE EFFECTS OF BIOMASS HARVESTING ON SOIL NITROGEN AVAILABILITY, FOLIAR NUTRITION AND SEEDLING GROWTH IN THIRD-GROWTH BLACK SPRUCE PLANTATIONS IN NORTHWESTERN ONTARIO

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An Undergraduate Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Honors Bachelor of Science in Forestry

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ABSTRACT

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Keywords: Biomass Harvest, Black Spruce, Tree Growth, Soil Mineralizable N, Foliar Nutrition.

Residual forest biomass is a viable feedstock that can be used in the bioenergy stream. There remains, however, a concern that excessive removal of forest biomass may have negative impacts on forest biodiversity, stand regeneration, tree growth, soil nutrient availability, and foliar nutrition. This study examines the effects of different amounts of biomass removed from clear-cut harvested, 2nd growth black spruce (*Picea mariana*) plantations. The specific questions addressed in this study were: 1. How does the level of biomass retention influence seedling growth? 2. Are there measurable differences in soil N availability across a gradient of biomass removals? 3. Are any of the differences in soil N availability reflected in seedling foliar N concentrations or content?

The study was conducted on two black spruce plantations that were planted in 1962, and clearcut harvested in 2007. The sites represented contrasting soil types (i.e., clay versus loam). Six biomass retention treatments were applied in 15 x 15m treatments across 3 blocks at each site that represented a gradient of C (0 – 22 Mg ha^{-1}) and N (0 – 325 kg ha^{-1}) retention levels. PGPs (100 m^2) were established in each treatment plot, with tree measurements, foliar, and soil sampling done every 5 years up to year 15.

The results showed that biomass removal had little effect on the stand and soil condition in both sites out to 15 years since establishment. The most significant results were the differential responses across soil types, with the clay site having better growth, soil N availability, and foliar N concentrations. These results suggest that proper management and timing of the additional removal of biomass as bioenergy feedstock are unlikely to have significant negative effects on stand development and early growth.

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INTRODUCTION

Countries around the world have been setting goals and developing frameworks designed to enhance the use of renewable energy, which, in turn, has increased the amount of research and development of new methods and source options to support these energy streams (Gallagher 2013). To date, 118 countries have developed renewable energy targets, and 109 countries are developing policies that support the use, development, and research of renewable energy (Gallagher 2013). There are many options for renewable energy (e.g., solar power, wind power, and geothermal energy), including considerable interest in enhancing bioenergy production from forest biomass.

Bioenergy is a form of renewable energy generated from biomass that is sourced from trees, committed energy crops, agriculture waste, municipal wastes (potentially including wastewater treatment), and wood processing (Suttles et al. 2014). Broadly biomass refers to the mass of living organisms, however operationally, particularly in the context of bioenergy feedstock, it refers to plant material and sometimes includes materials derived from plants such as manure from animals (Perlack et al. 2005). In forestry contexts, biomass typically refers to saw and pulp mill "waste" (e.g., bark, sawdust) woody residuals or lower value trees or parts of trees harvested with an end goal of processing in a biomass boiler. Beyond processing in biomass boilers that are present across nearly all mills, accessing additional forest-derived feedstocks as an energy source can further provide energy for heating, transport fuel, and electricity generation as well as creating jobs, lowering greenhouse gas emissions, and creating a diverse energy supply (European Commission N.d).

In 2009, Europe met and exceeded its target of 20% for renewable energy by the year 2020, at 22%, followed by having renewable energy sources used for transportation fuel to be at 10% which includes the use of biofuel (Pedroli et al. 2012; Eurostat 2022). In Sweden, the use of biomass as a renewable energy source has more than doubled over the past 25 - 30 years resulting in close to one-fifth of used energy being sourced from forest biomass (Bjorheden 2003). The European Union, working under the framework of the EU Renewable Energy Directive (EU-RED), has improved steadily since the 1990s, using biomass and waste reaching nearly two-thirds of the desired renewable energy development by the year 2012 (Lindstad et al. 2015).

Ontario's transition to renewable energy is directed by the Crown Forest Sustainability Act (CFSA), the Forest Sector Strategy (FSS), and the more recent Forest Biomass Action Plan (FBAP). The CFSA came into effect in 1994, replacing the Crown Timber Act of 1951, and ensures that our forests will be managed with proper licensing, regulated independent forest audits, control over forest operations on crown land, and licensed scalers, that, in turn, ensures that our forest will stay healthy and continue to benefit present and future generations (Ontario 1994).

The overarching CFSA is supported by a series of legislation, forest management guidelines, and manuals that, collectively, govern forest health and sustainability of social, environmental, and economic values for the people of Ontario (Ontario 1994). Ontario's FSS strategy was put into effect in August 2020 to ensure that our forests will be managed sustainably, improve our partnerships in and outside Canada, promote innovation, and keep up with growing markets (Ontario 2020). The FBAP was released in March 2022 as a five-year plan that mapped out required actions to promote the use of forest biomass with the desired outcomes to be creating jobs, improving economic development, and promoting sustainability in Ontario's forests (Ontario 2022). Collectively, these pieces of legislation create opportunities for innovation for new products and materials created from wood such as personal protective equipment, 3D printing, cosmetics, food, green chemicals, new wood-based composites, and energy alternatives (Ontario 2020).

The goal of increased utilization of forest biomass as a renewable resource does have the potential for negative effects caused by excessive harvesting of biomass sources (Pedroli et al. 2012). In Scandinavia, intense biomass harvesting has led to a measurable loss of dead wood in managed forest areas and has resulted in negative impacts on plant species diversity due to the removal of logging residues, roots, and stumps (Pedroli et al. 2012). Over-harvesting biomass may also result in loss of soil nutrients which could, in turn, result in slower growth and development of forests after biomass harvesting, and lead to poor regeneration and lower quality forests (Garcia et al. 2018).

This study examines the effects of different amounts of biomass removed from clear-cut harvested, 2nd growth black spruce (Picea mariana) plantations.

The overall objective is to develop an understanding of how the subsequent regenerating stands will develop. With the strong potential of biomass being used more commonly as an alternative energy source, describing the level of positive or negative effects caused by increased biomass removals can inform forest management policies/guidelines that regulate the amount of biomass that can be removed to minimize any adverse effects of these practices. The specific questions for this study were:

1. How does the level of biomass retention influence seedling growth? Here we hypothesize that there will be a threshold level of retention required to maximize seedling growth, and this level may vary between sites with different soil types.

2. Are there measurable differences in soil N availability across a gradient of biomass removals? Here we hypothesize that only the complete biomass removal treatment will affect soil N availability.

3. Are any of the differences in soil N availability reflected in seedling foliar N concentrations or content? Here we anticipate strong correlations between soil N availability and foliar N content.

LITERATURE REVIEW

To support increased bioenergy feedstocks in the forestry sector, logging residues are more commonly diverted to energy production after harvesting operations (Luiro et al.. 2009). This promotes the use of harvesting methods like whole tree harvesting (WTH), which removes all biomass above ground instead of practices like stem-only harvesting or conventional stem harvesting, which leaves the foliage and branches behind at the harvest site (Vanguelova et al. 2010). Harvesting the whole tree removes nutrients from the area that would normally be reused by other trees after the tree has been harvested or died naturally (Woongsoon 2015).

Concerns regarding the effects of biomass removal have been voiced for decades due to its possible impacts on short and long-term forest health (Thiffault *et al.* 2010). The concept of "forest biomass" refers to the main residues produced during forest operations like clearcut harvesting, salvage logging, thinning, and final felling while secondary residues are created throughout industrial wood processes (Thiffault *et al.* 2011). Tertiary residues are residues that are derived from conventional firewood, construction, demolition, and packaging (Thiffault *et al.* 2011).

The overarching concern is that the depletion of nutrients in a stand will restrict the growth and development of trees that regenerate the site if significant amounts of nutrients are removed during WTH and are not replenished within the course of a normal cycle (Roxby 2012). Eliminating harvest residues from a site may also alter the microenvironment on the forest floor, which could affect the species of trees that successfully regenerate (Thiffault *et al.* 2010). In contrast to a site protected by layers of logging slash left behind the forest floor of a whole-tree harvested site may feature harsher conditions (Thiffault *et al.* 2011). There have been many reported good and negative effects of WTH on the growth of forests and the environment, but the possible long-term reduction in forest productivity due to the depletion of soil nutrients remains a concern (Walmsley *et al.* 2008). While tree residues have been observed to reduce weed growth, WTH has also been linked to increased competition from colonizing vegetation (Walmsley *et al.* 2008).

Soil management in a stand is a notable factor that can contribute to the maintenance of long-term site productivity. Soils are affected by how trees are harvested, including the level of biomass removed and factors such as soil disturbance and the equipment used to harvest the area (Thiffault et al. 2010). With the harvesting of whole trees and the associated levels of biomass removed, these removals can affect the condition of the stand in the future (Powers *et al.* 2005). These effects have been shown to reduce stand volumes by up to 8% and as much as 42% as a result of significant soil compaction and forest floor/topsoil removal (Powers *et al.* 2005).

The United States Forest Service, the Canadian Forest Service, the Ontario Ministry of Natural Resources and Forestry (OMNRF), forest industry partners, and several university institutions continue to collaborate on the Long-Term Soil Productivity (LTSP) study, a sizable scientific endeavor (Powers *et al.* 2005). The objective of the project was to create evidence-based guidelines for sustainable forest management and to evaluate the long-term impacts of logging and other land management methods on soil productivity (Powers *et al.* 2005). Many research sites were established across North America for the project, which started in the 1990s with nearly 100 installations that represent various forest types, soils, climate regimes, and management techniques (Powers *et al.* 2005). Each site's soil characteristics and forest productivity have been monitored for an extended period, often several decades (Powers *et al*. 2005). One of the major conclusions is that land management methods such as harvesting trees along with other land uses can affect soil productivity, however, the form and scope of these effects can vary greatly depending on the soil type, the climate, and management practices (Morris *et al.* 2020). For instance, certain types of harvesting, like clearcutting, might cause temporary drops in soil productivity, but other types, like partial cutting, can sustain or even increase soil productivity over time (Morris *et al.* 2020).

In LTSP trials done by Ponder *et al.* 2012, Morris *et al.* 2020, and Olsson *et al.* 2000, the ecosystem response to the removal of biomass can be related to the amount of nutrients in the soil with the soil textural properties being [NB1] a determining factor in how much nutrients it can retain. Coarse to medium sand textured soils, which tend to be more nutrient poor due to limited water and nutrient retention, did have a noticeable impact with biomass removed whereas there was no noticeable difference on certain finer-textured sites which can retain more water and nutrients (Morris *et al.* 2020). Harvest intensities can also cause changes in foliar nutrition such as causing imbalances between nitrogen and potassium if biomass is left after harvest, and alternatively, lower soil nitrogen levels in the upper soil layers under intensified biomass harvest, at least if the soil has poor nutrient retention (Olsson *et al.* 2000).

EFFECTS OF BIOMASS HARVESTING ON TREE REGENERATION AND GROWTH

The effect of growth and survivability in the early stages of tree development (regeneration stage) tends to be unaffected by the removal of biomass and is more related to the soil type (Egnell and Valinger 2003). This result could be due to the fact there are enough nutrients available for the seedlings and competition is low (Egnell and Valinger 2003). Seedling survival has been shown to increase where whole tree harvest was used compared to conventional (stem only) harvest plots (Walmsley et al. 2009). In this case, survival rates of 40-68 % were recorded on the WTH plots and had a 10% higher survival rate than the CH method (Walmsley *et al.* 2009). This increase in survival may indicate that tree seedling survival is occurring on sites with increased soil disturbance and lower harvest slash loadings (Morris & Miller

1994). Although over time when other plants become more competitive, the basal area has been shown to decrease between 15 to 25 years after establishment (Egnell and Valinger 2003, Walmsley *et al.* 2009).

After year 15, the effects from biomass removal do tend to show some evidence not seen in early measurement periods. Increased soil temperatures during the growing season, regulated near-surface air temperatures and vapor pressure imbalances, and a decrease in the frequency of overnight frost events throughout this period can all result from topsoil extraction from harvesting operations (Fleming *et al.* 2021). Morris *et al*. (2013) showed that seedling survival was not negatively affected by biomass removal and the patterns were comparable across soil types (sand, coarse loamy, wet mineral, peat). The biomass removal treatments also did not affect the growth of the planted trees from years 10-15 (Morris *et al.* 2013). There was some evidence that indicated increased stem volume in years 10 - 15 on the complete removal treatment, but only on the wetter (peatland) sites, likely the result of removing the ericaceous shrub layer and live sphagnum layer (Morris *et al.* 2013).

In a different study, whole tree harvest did appear to have had detrimental long-term consequences on the mineralization of C and N, which may partially account for the slower tree growth observed on the whole tree harvest plots (Tamminen *et al.* 2011). This study found that the changes in soil nitrogen were minimal with WTH (Tamminen *et al.* 2011). The levels of base cations, on the other hand, which in the majority of boreal highland forests are not growth-limiting nutrients like nitrogen, were found at lower levels in the organic layer following whole-tree pre-commercial thinnings (Tamminen *et al.* 2011).

EFFECTS OF BIOMASS HARVESTING ON SOIL CARBON AND NUTRIENTS

There has been a rising concern about harvesting biomass as biofuel and how it can impact soil carbon and nutrients in a forest (Vanguelova *et al.* 2010). By harvesting biomass, soil's biological, chemical, and physical properties can be affected, which, in turn, can influence nutrient availability and productivity (MCCS 2010). It has been noted that the short-term effects of logging methods used for harvesting biomass, such as whole tree harvesting, are difficult to detect and quantify given the very dynamic nature of nutrient fluxes (Nilsson *et al.* 2018).

The effects of harvesting, particularly WTH, on soil quality and site productivity have been the subject of much research and review (Johnson and Curtis 2001, Powers *et al.* 2005, Walmsley and Godbold 2010, Thiffault *et al.* 2011, Quideau *et al.* 2013). When negative effects have been observed, they generally have occurred on inherently nutrient-poor sites (O'Hehir and Nambiar 2010), where more intensive practices were employed (Egnell and Valinger

2003, Smith *et al.* 2000), or in colder climates (Morris and Miller 1994). The most sensitive sites to increased biomass removal have shallow soils (< 20 cm) or dry, coarse-textured outwash sands (Bhatti *et al.* 1998, Paré *et al.* 2002, Abbas *et al.* 2011, Roach 2012) due to their limited soil nutrient reserves, a relatively high proportion of ecosystem nutrients present in biomass (Green and Grigal 1980, Foster 1995, Morris 1997), low soil cation exchange capacity (Hazlett *et al*. 2014), and a high potential for available nutrients to be leached from the system (Evans and Perschel 2009, Wilhelm *et al.* 2013).

When looking into a review about if litter decomposition is affected by harvesting methods, Jerabkova *et al.* 2011 found that it did have a significant effect on boreal and temperate forests. These effects did vary depending on litter type, with the decomposition of conifer needles being generally slower within clear-cuts, whereas broad leaf litter decomposed more quickly, with cellulose decomposition exhibiting a similar, albeit but not significant, rate associated with the conifer litter (Jerabkova *et al.* 2011). Higher amounts of mineralizable N have been related to the increased forest floor decomposition after a clear-cut harvest due to the increase in moisture and temperature, although some studies have found uncut forest floor decomposition has a similar rate as well (Jerabkova *et al.* 2011). In another study, Achat *et al.* (2015), found that although their observations suggested that the decomposition rate increased after harvesting (i.e., clearcut harvesting), there was no significant impact on the organic carbon stock in the forest floor soil.

In another review (Thiffault *et al.* 2011), the impacts of biomass harvesting and its effects on soil productivity are examined. When compared to stem-only harvesting, WTH only retains a small amount of organic matter (i.e., logging debris) which has the potential to result in negative long-term effects on soil productivity and quality (Thiffault *et al*. 2011). These effects can include organic carbon content, base cation capacity, soil disturbance, and changes to soil microclimate (Thiffault *et al.* 2011). They concluded that the intensive removal of biomass may result in the reduction of the base cation concentrations in soils and foliage, but at large did not conclude that there were large effects on tree growth.

EFFECTS OF BIOMASS HARVESTING ON FOLIAR NUTRITION

There has been limited research on foliar nutrition and the effects of intensive biomass removal but what is known is that the nutrients in leaves, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), which are crucial for plant growth and development, can be diminished through intensive biomass harvesting (Thibodeau *et al.* 2000). This reduction is, in part, because these nutrients are in high concentrations in the foliage and other harvested above-ground plant components (Thibodeau et al. 2000). Hence, frequent and extensive biomass harvesting may result in a loss in foliar nutrition, which may, in turn, result in growth reductions (Thibodeau et al. 2000).

A study by Fleming *et al.* (2021), reported that foliar concentrations were higher on sites where the logging debris had not been removed, and showed signs of decrease over time compared to biomass-harvested sites. Foliar nutrients may be higher in some instances, generally linked to differences in soil type, where nutrient-poor soils (i.e., infertile sands) tend to retain fewer nutrients, most notably for N and P (Powers *et al.* 2005, Thiffault *et al.* 2010).

As a management option to minimize declines in foliar nutrient concentrations over longer time frames, thinning was found to increase foliar nutrients significantly (Thiffault *et al.* 2010). This increase (N, P, and K) was the case for both pre-commercial (i.e., thinned trees were left after thinning) and commercial thinning (i.e., thinned trees were removed) (Thiffault *et al.* 2010).

MATERIALS AND METHODS

STUDY SITE DESCRIPTIONS

This study includes two black spruce plantations that are located approximately 20 kilometers northeast of Nipigon, ON, CAN (Figure 1). These sites represent black spruce plantations established (planted in 1962) on contrasting soil types that vary (i.e., 1.5 m estimated at breast height age 50) in the site index (clay: 11.8 m, loam: 13.3 m). In 1962, the sites were planted with 1.5 + 1.5 black spruce bare root stock at a 5 x 6-foot spacing following mechanical site preparation (i.e., barrels and chains). In 2007, portions (1 ha blocks) of these plantations (45-year-old plantations at the time of harvest)) were clear-cut and planted at 2 m x 2 m spacing using over-wintered containerized stock grown from local seed sources. To improve survival and early growth, competing vegetation was controlled using one chemical (year 2) and two manual treatments (years 4 and 8).

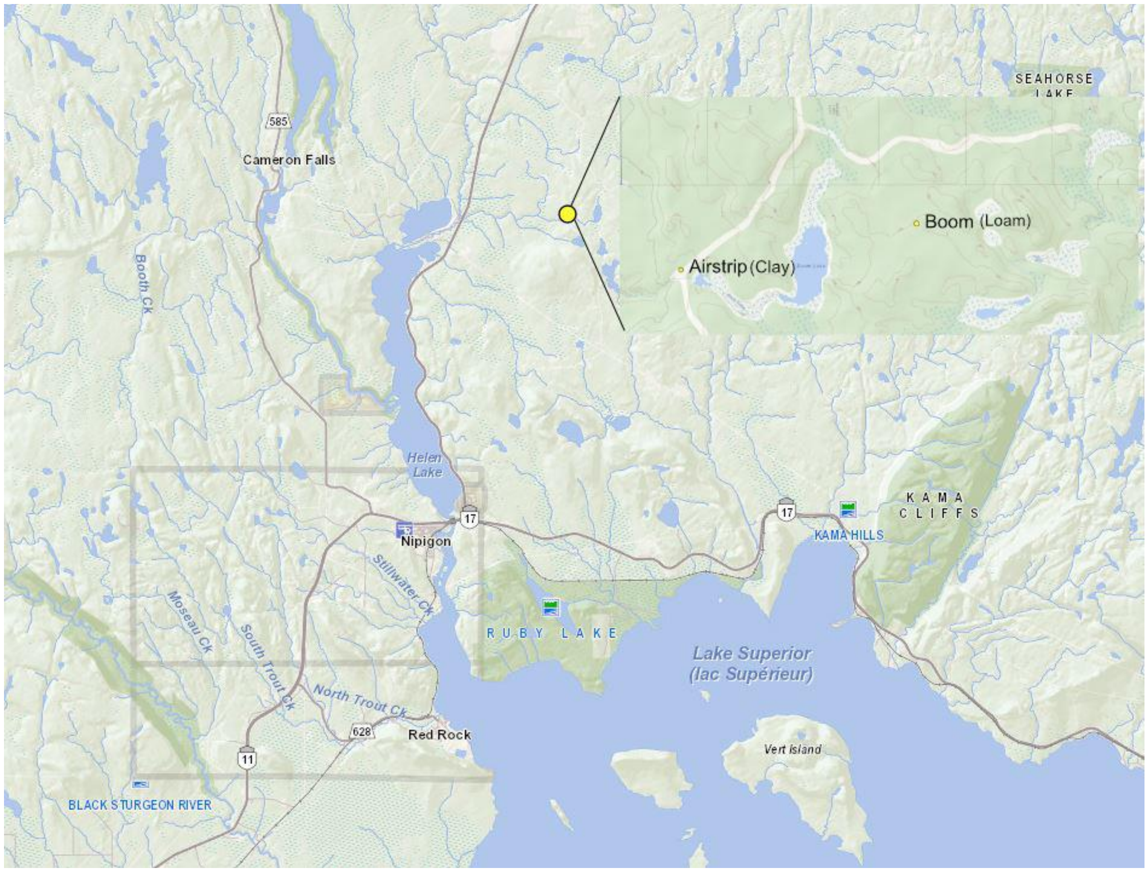

Figure 1. An overview map of the study site locations situated northeast of Nipigon, ON, CAN.

One of the plantations (Airstrip: 49°08'00.3"N 88°11'07.3" W) was established on a fine-textured, lacustrine clay (i.e., Orthic Gray Luvisol), and the other site (Boom Lake: 49°08'12.4"N 88°09'20.1" W) represented a deep, silty loam glaciofluvial deltaic overlay (>1 m) that overtops the underlying lacustrine plain (approximately 1 m), and is representative of a Humo-ferric podzol.

The study sites are located within the Black Sturgeon Ecodistrict (Wester et al 2018). The ecodistrict is populated with a variety of boreal tree species that include black and white spruce, jack pine, trembling aspen, paper birch, and balsam fir (Wester et al 2018). The Black Sturgeon Ecodistrict is dominated by thin to very thin layers of mineral soil (Wester et al 2018). This area includes significant areas of base-rich bedrock (Wester et al 2018).

Long-term macroclimate norms class the ecodistrict with a Humid Continental Mild Summer climate, and generally wet all year – a balance of year-round precipitation (Michael Pidwirny n.d.). The annual mean temperature for the Ecodistrict is 3.0 °C, with annual precipitation of 766 mm (Climate Data. N.d.). The mean frost-free days in the Nipigon area is 105 (Climate Atlas of Canada 2023). The mean growing degree days at a base 5^{O} were 1368 days from 1976 to 2005 and 1738 days from 2021 to 2050 (Climate Atlas of Canada 2023).

BIOMASS RETENTION TREATMENTS

In each of the black spruce plantations, three 1-ha clearcut harvests were done in 2007. Two types of slash were focused on for this study, coarse slash (During logging operations, bigger branches, stems, and other woody wastes are left on the ground. This material, which can have a diameter of several centimeters, is frequently left in windrows or heaps to degrade naturally over time) and fine slash (after logging operations, tiny twigs, leaves, and other small woody waste are dropped to the ground. This substance, which is normally only a few centimeters in diameter, is dispersed over the forest floor). Within these clear-cuts, there were 12 plots (15x 15 m), and 6 levels of biomass retention treatments were applied that included both fine slash (0 – 100% removed, 1 – 100% retained) and coarse logging slash (live branches/tops) that included three levels of retention: (2: full retention – equivalent to a stem only harvest, with all crown material retained, 1: half retention: one-half retention of a stem-only harvest, and 0: no retention). To ensure uniform distribution, the harvest slash was chipped with a portable chipper and applied to the treatment plots.

Figure 2. Establishment of the plots at the beginning of the study. Top-left image shows the chipper creating the fine slash. Top-right shows the spreading of the fine slash. Bottom-left shows the fine slash distributed on a plot. Bottom-right shows the fine slash distributed on a plot from another angle.

The applied treatment combinations resulted in a clear gradient of biomass retention for both C (Figure 3) and N (Figure 4). For C, treatments ranged from 0 Mg ha^{-1} (zero retention: 0 - fine slash removed,0 – no coarse slash retained) to approximately 22 Mg ha^{-1} (1 – fine slash retained, 2 – full retention equivalent to a stem-only harvest).

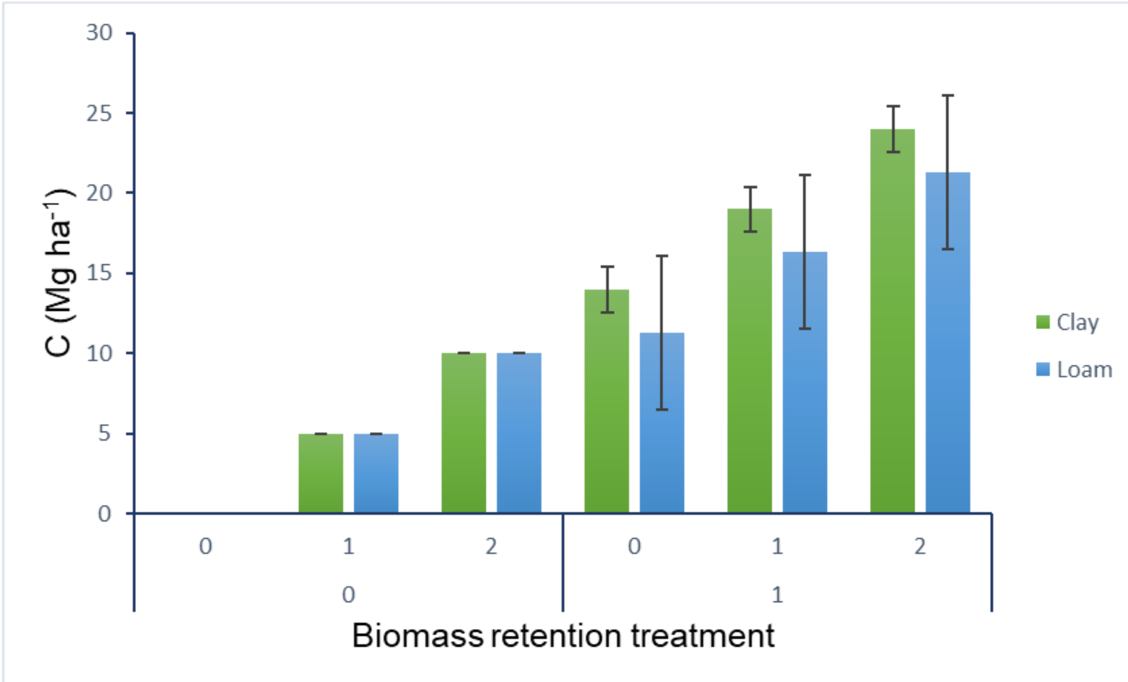

Figure 3. Differences in the levels of logging debris C pools across the gradient of biomass retention treatments for each soil type (clay versus loam). 0 at the bottom represents the coarse slash removed, and 1 coarse slash retained. The values above that are from 0 to 2 and represent the amount of fine slash (0- no retention, 1- half retention, 2- full retention)

A similar pattern occurred for total N (Figure 4), ranging from 0 kg ha^{-1} to 325 ka ha^{-1} for the full retention treatment. The clay site consistently had higher retention levels of the fine slash (1,0, 1,1, 1,2) compared to the loam site for both C and N loadings.

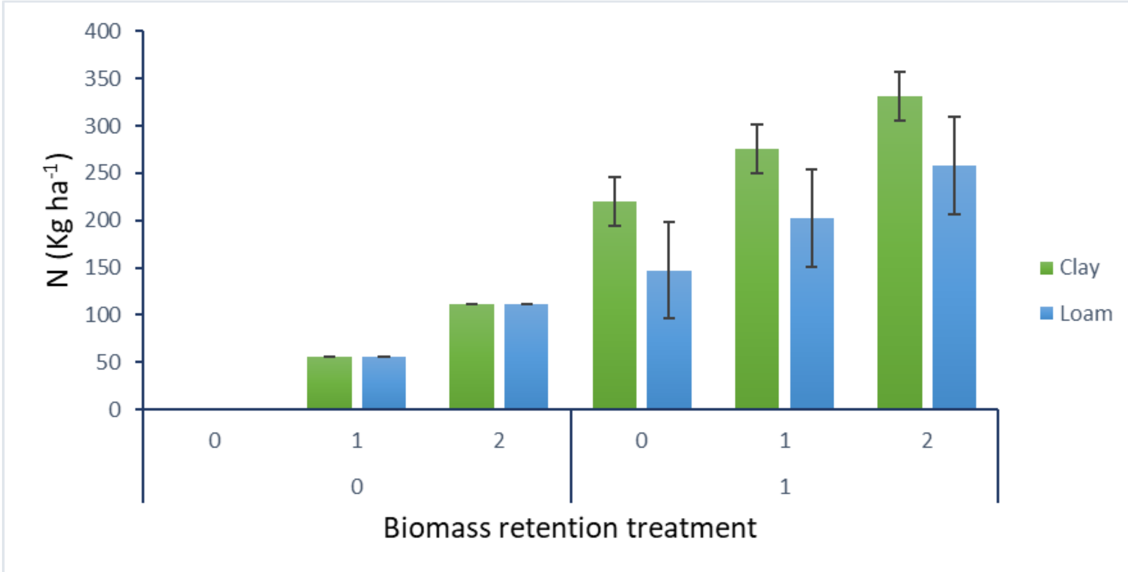

Figure 4. Differences in the levels of logging debris N pools across the gradient of biomass retention treatments for each soil type (clay versus loam). 0 at the bottom represents the coarse slash removed, and 1 coarse slash retained. The values above that are from 0 to 2 and represent the amount of fine slash (0- no retention, 1- half retention, 2- full retention)

MEASUREMENTS AND SAMPLING PROCEDURES:

TREE MEASUREMENTS

Seedling measurements were taken at 5-year intervals starting in 2012 and done in each plot within a 5.28 m circle from the plot center. In year 5 (2012), the height and root collar diameter of all planted black spruce trees were collected. At year 10 (2017), all live and dead trees (including ingressed spruce) in each plot had their heights and RCD measured. Any trees >1.3 m in height also had DBH recorded. At year 15 (2022), all live and dead tree heights and DBH were recorded within each PGP plot.

FOLIAR SAMPLING

At each sampling period, 5 planted trees per treatment plot were randomly selected that represented the average size and condition (i.e., no visual defects caused by insect or mechanical damage), based on the plot tallies, in each treatment plot. Foliar sampling was done in the upper ⅓ of the live crown, with laterals clipped to include both the current and previous year's foliage. At the plot level, foliar clippings from each tree were then composited (i.e., combined into one bag per foliage age). In the lab, samples were oven-dried at 50 °C until the final constant weight is achieved. After drying, 100 needles were counted from each bag, weighed, and the weight was recorded, to allow for a standardized calculation of nutrient content. The samples were then ground using a Wiley Mill (20 mesh) and put in sample vials for chemical analysis.

In the lab, the ground foliar samples were digested with sulphuric acid and selenium dioxide in Kjeldahl tubes placed inside Kjeldahl digestion blocks. The digestion was carried out at about 355 to 360 °C for 2.5 hours. The digested solution was then analyzed for total nitrogen by automated wet chemistry procedure using Traacs 800 auto analyzer. The dissolved cations were analyzed using Varian Liberty II ICP-AES sequential spectrometer.

SOIL SAMPLING

At each sampling period, three soil samples (F/H, 0-10 cm, and 11-20 cm) were collected at the base of each foliar tree, then bulked by layer at the treatment plot level. In the laboratory, pH (pH_{H2O}, pH_{CaCl}) was done on fresh subsamples using calibrated Oakton pH testr5 meters. The remaining sample was placed on plates and put into a drying room for air drying. Once dried, the organic F/H samples were ground to a homogeneous powder using a Whiley mill (20 mesh screen), and the mineral samples were ground with a mortar and pestle and passed through a 2 mm sieve. These samples were then bagged and labeled for further analysis.

Organic C was determined by dry combustion using a LECO C/N/S analyzer. Soil nitrogen (N) concentrations were determined by the semi-micro-Kjeldahl procedure, and exchangeable cations were determined by ICAP in an unbuffered 1 mol L^{-1} NH4Cl solution (Kalra and Maynard 1991). Extractable phosphorus (P) was determined by ICAP in Bray and Kurtz No. 1 extractant (Kalra and Maynard 1991).

Using the procedure outlined in Powers (1980), anaerobic incubations (i.e., an index of potentially available N) were conducted using 2 g (organic) and 10 g (mineral) of the air-dried samples placed in sealable vials. 50 mL of deionized water was added to each vial and placed in an incubator for 14 days at 30°C. After the incubation period, 50 mL of a 4M KCl solution was added to the samples (which yields a 2M extraction solution with the deionized water) and agitated for one hour at 180 rpm. The extracted solutions were filtered (Fisher Scientific Q2 filters) and analyzed for NH4+-N using the sodium nitroprusside method on a Technicon autoanalyzer IIC.

DATA SYNTHESIS AND ANALYSIS

The study's experimental design represented a 2-way Randomized Complete Block Design (RCBD), with soil type (clay versus loam) and biomass retention treatments (6 levels: 2 fine slash and 3 coarse levels as a factorial experiment) as main factors, with 3 ages (time since establishment: years 5, 10, 15). The individual trees within each treatment plot represented the sample unit and the individual plot was the experimental unit. ANOVAs were done using the GLM procedure in SAS/STAT (version 9.4), with the Student-Newman-Keuls (SNK) post-hoc means separation test used to examine significant differences ($p<0.05$) between levels within the main effects.

RESULTS

INDIVIDUAL TREE GROWTH RESPONSE

There was a clear and significant site/soil type difference ($p<0.05$ across all sampling years) in average height growth (planted plus ingressed naturals), with the seedlings growing on the clay soil consistently having greater heights compared to those growing on the loam soil (Figure 5). This difference has increased over time, with a difference of nearly 140 cm by Year 15 (clay: 418.6 cm versus loam: 279.8 cm, $P<0.0001$).

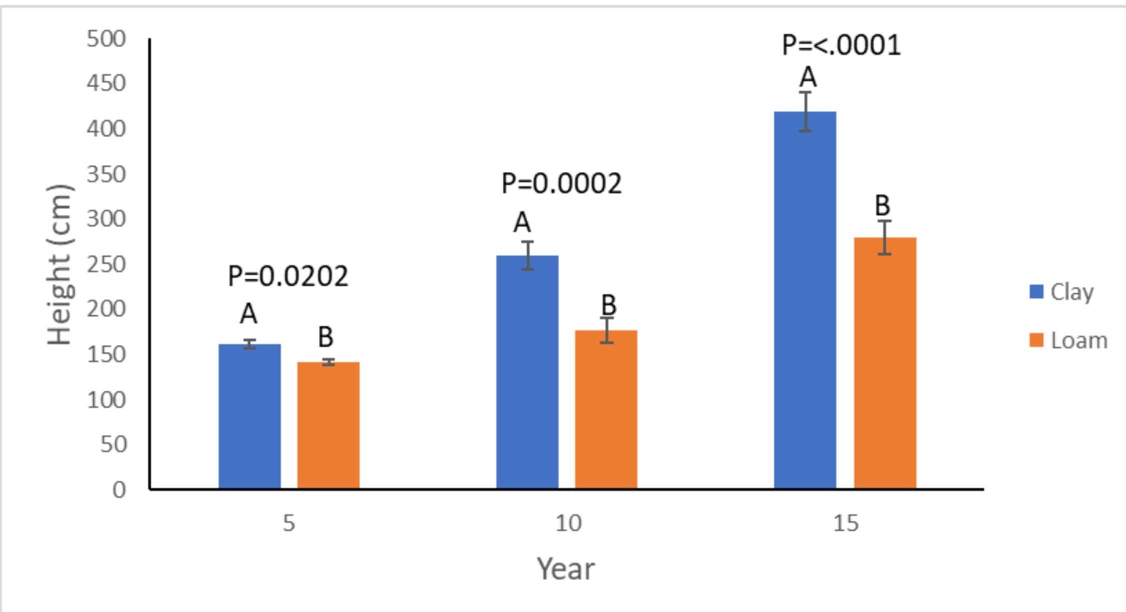

Figure 5. Temporal patterns in average height growth of black spruce seedlings as a function of soil type (clay versus loam). Vertical bars represent standard errors. Different uppercase letters represent significant differences ($p<0.05$) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

A similar pattern was seen for the average root collar diameter (RCD) (Figure 6). In this case, the difference in RCD by Year 15 was 2.5 cm (clay: 7.3 cm, loam: 4.8 cm, p<0.0001).

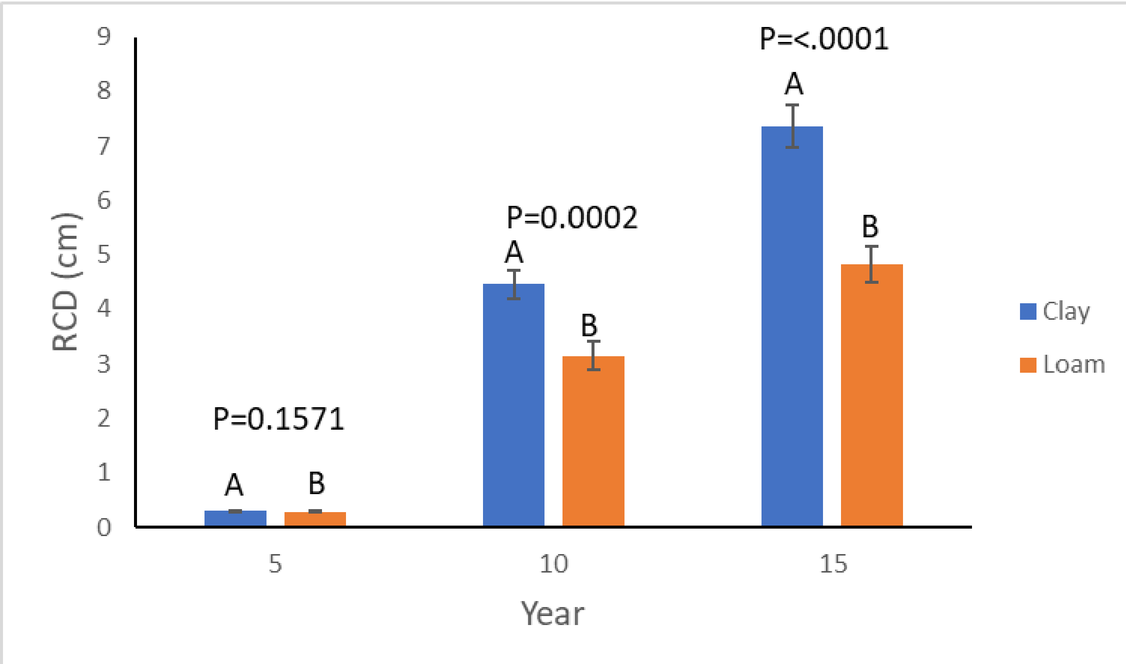

Figure 6. Temporal patterns in average RCD of black spruce seedlings as a function of soil type (clay versus loam). Vertical bars represent standard errors. Different uppercase letters represent significant differences (p<0.05) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

I also analyzed the "top" height and "top" RCD seedlings (i.e., only included the upper quartile (^25%) heights and RCDs) to provide a better representation of site/soil quality potential (Figures 7 and 8). In this case, the higher productivity measured at the clay site in years 5 and 10 was reversed by year 15 with the "top" height at the loam site (638 cm) being significantly greater (greater than 120 cm, p<0.0001) than the clay site (514.9 cm).

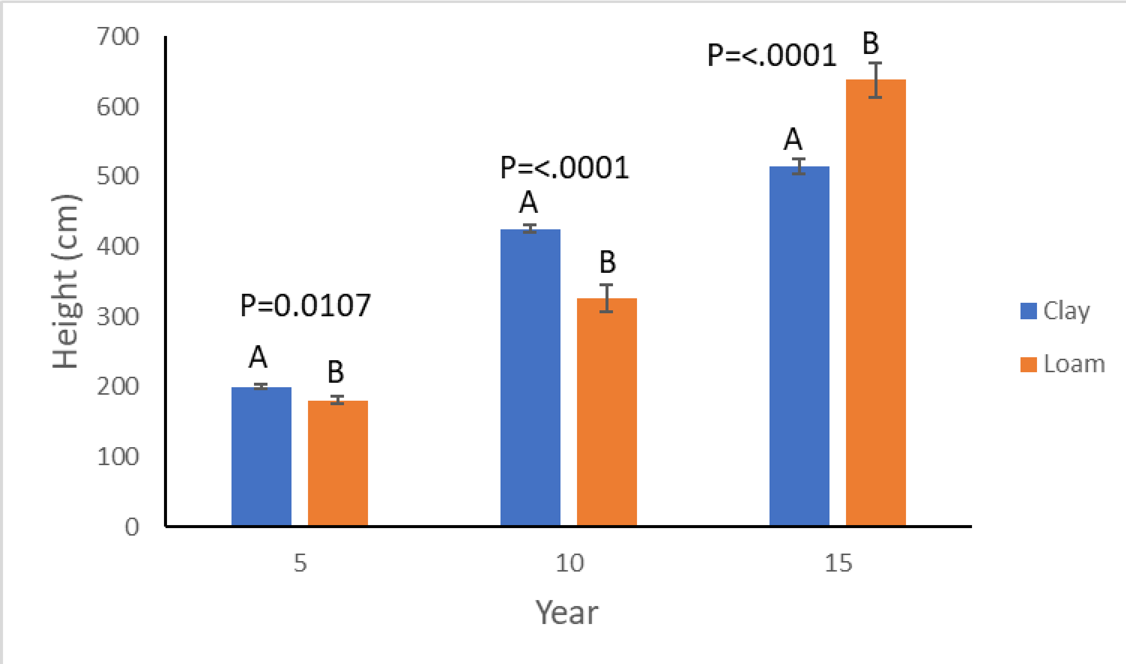

Figure 7. Temporal patterns in “top” (upper quartile) height growth of black spruce seedlings as a function of soil type (clay versus loam). Vertical bars represent standard errors. Different uppercase letters represent significant differences (p<0.05) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

There was, however, no reversal between soil types for “top” (upper quartile) RCD, with significantly higher “top” RCD on the clay site for all measurement years. By year 15, the “top” RCD was 11.13 cm on the clay site and 8.99 cm on the loam site.

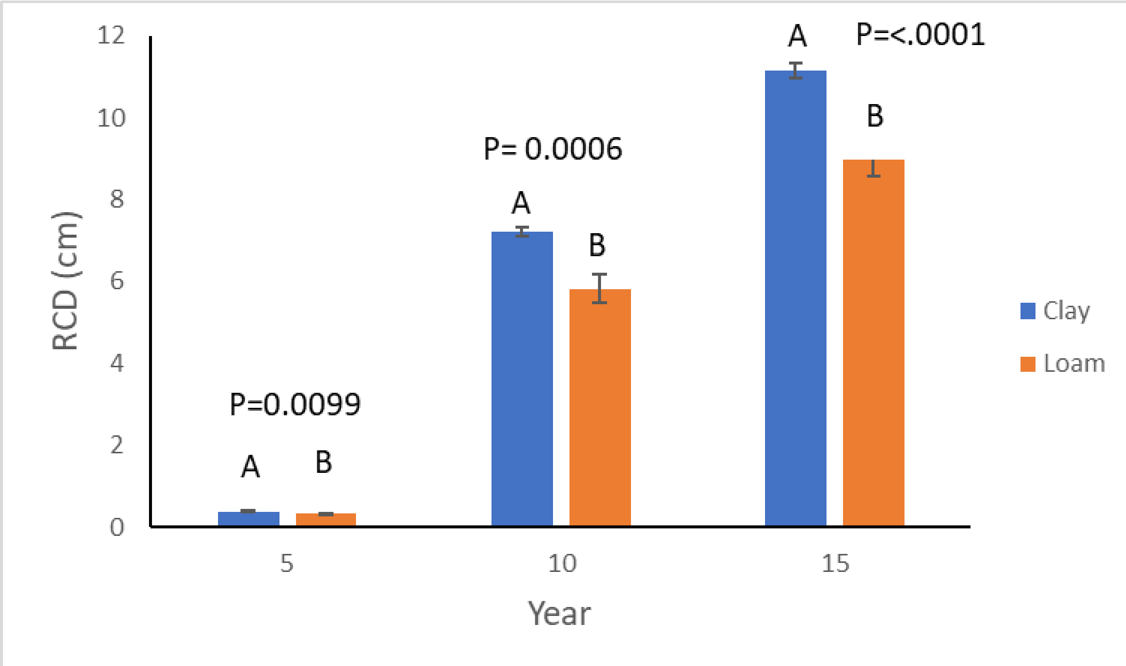

Figure 8. Temporal patterns in “top” (upper quartile trees) RCD of black spruce seedlings as a function of soil type (clay versus loam). Vertical bars represent standard errors. Different uppercase letters represent significant differences ($p<0.05$) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

There was a significant difference in year 10 when comparing the height of the trees across biomass retention treatments (Figure 9): fines removed/half slash, fines removed/no slash, and fines not removed/half slash (p-value=0.0060). On the clay site, the fines removed/no slash treatment had better height growth, followed by the fines removed/half slash and then the fines not removed/half slash treatment.

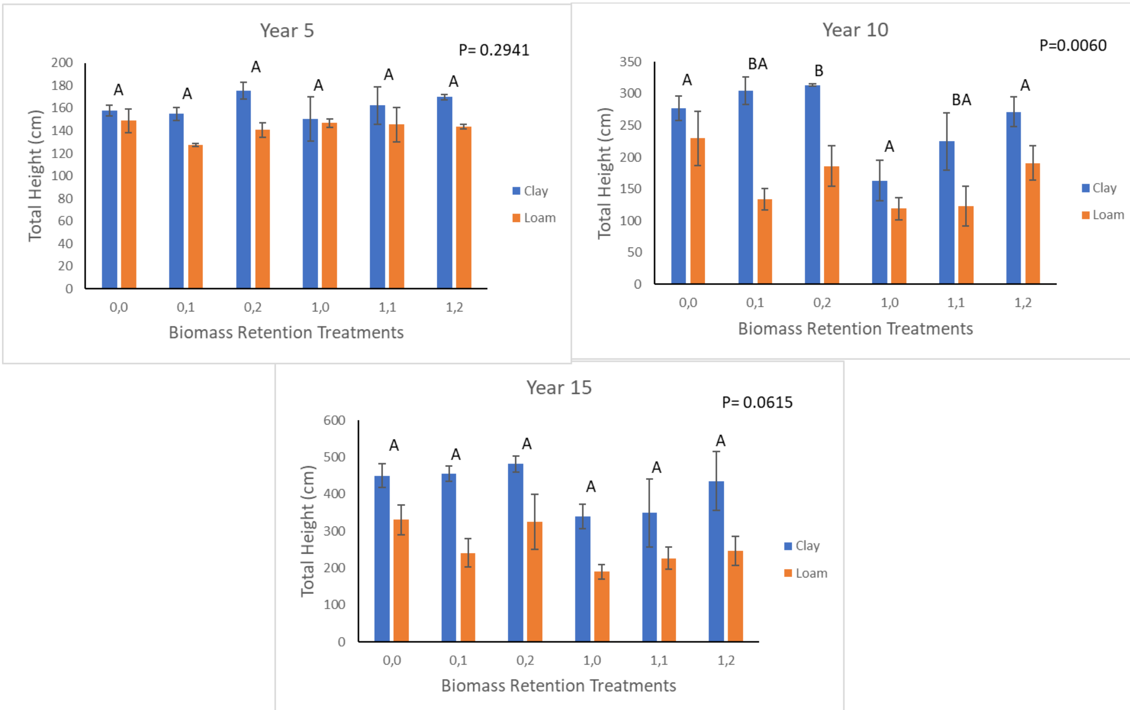

Figure 9. Differences in total height (cm) across the gradient of biomass retention treatments. Vertical bars represent standard errors. Different uppercase letters represent significant differences (p<0.05) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

Similar to the height responses, year 10 had a significant difference in RCD across biomass harvest retention treatments compared to years 5 and 15 (Figure 10), fines removed/half slash, fines removed/no slash, and fines not removed/half slash (p-value=0.0072). The clay site had a more significant difference in RCD for the biomass retention treatments with fines removed/half slash (0,1), while the treatment with fines removed/full slash (0,2) had the highest total RCD.

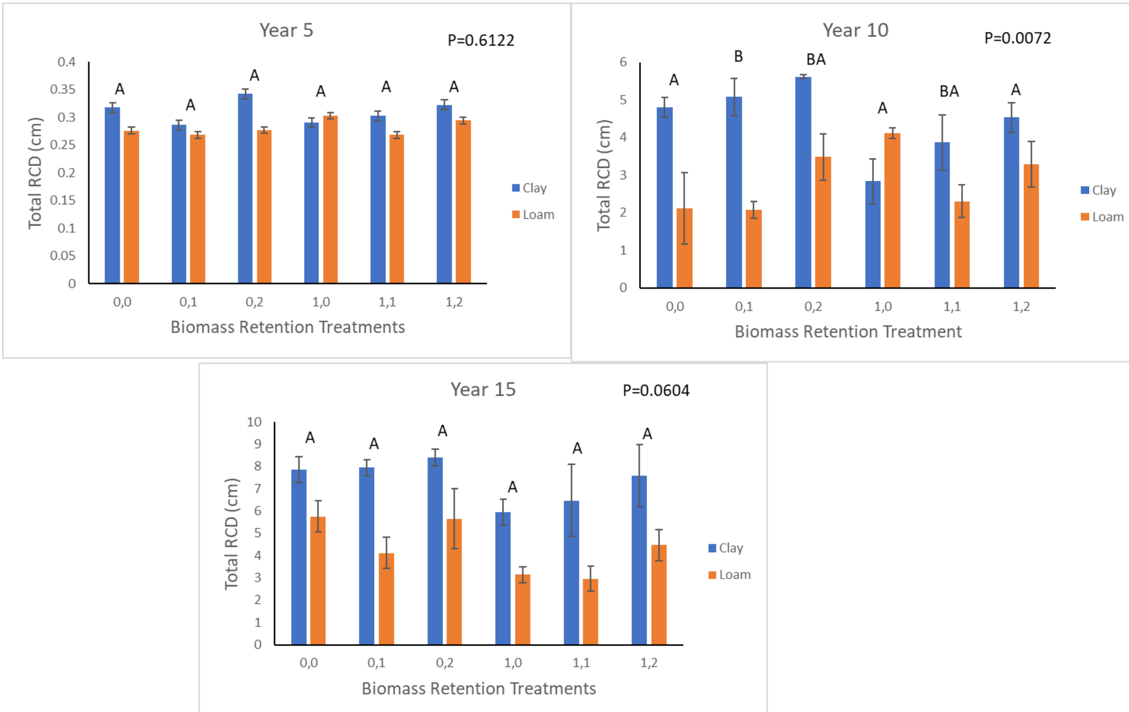

Figure 10. Differences in total RCD (cm) across the gradient of biomass retention treatments. Vertical bars represent standard errors. Different uppercase letters represent significant differences ($p<0.05$) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

There was no significant difference in "top" height (upper quartile) when compared across biomass retention treatments (Figure 11). Notable treatments were fines removed/half slash, fines removed/no slash, and fines not removed/half slash but differences with other treatment combinations were not significant (P=0.0837).

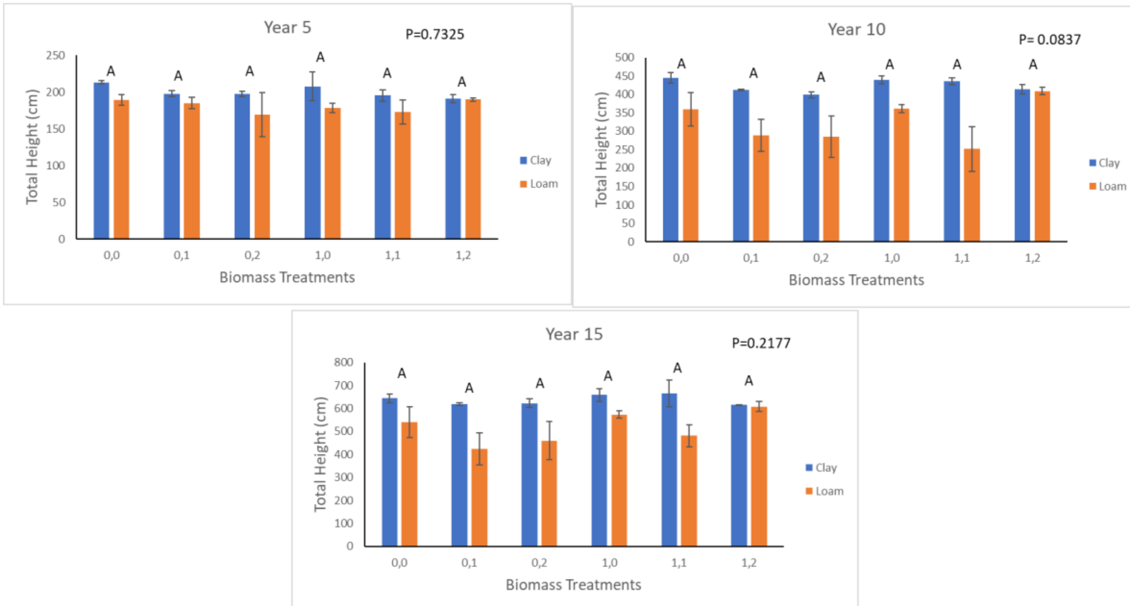

Figure 11. “Top” (upper quartile trees) height of black spruce seedlings in comparison to the gradient of biomass retention treatments. Vertical bars represent standard errors. Different uppercase letters represent significant differences (p<0.05) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

There also was no significant difference in “top” RCD (upper quartile) across biomass retention treatments (Figure 12). In this case, the clay soil site had some treatments with larger “top” RCDs, notably: fines removed/half slash, fines removed/no slash, and fines not removed/half slash but none were significantly different from the other treatment combinations (P=0.2524).

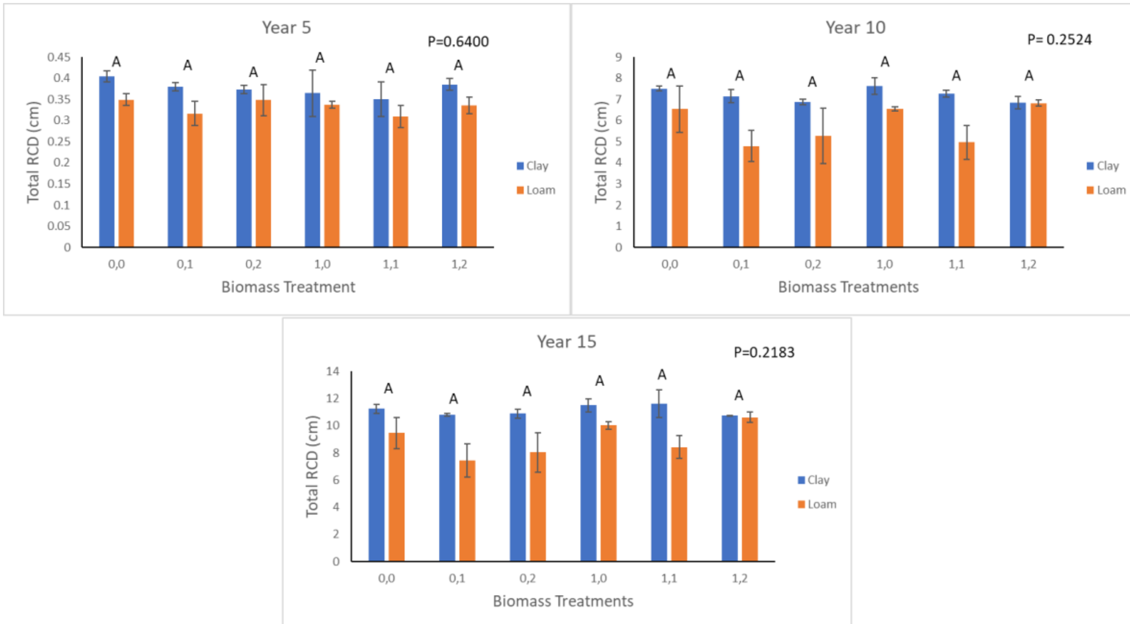

Figure 12. “Top” (upper quartile trees) RCD of black spruce seedlings in comparison to the gradient of biomass retention treatments. Vertical bars represent standard errors. Different uppercase letters represent significant differences ($p<0.05$) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

STAND-LEVEL GROWTH RESPONSE

Similar to the individual tree growth metrics, stand volume (m^3 ha^{-1}) was significantly higher on the clay soil compared to the loam (Figure 13). By year 15, the stand volume remained significantly higher ($p=0.0462$) on the clay soil (11.68 m^3 ha^{-1}) compared to the loam (9.2 m^3 ha^{-1}).

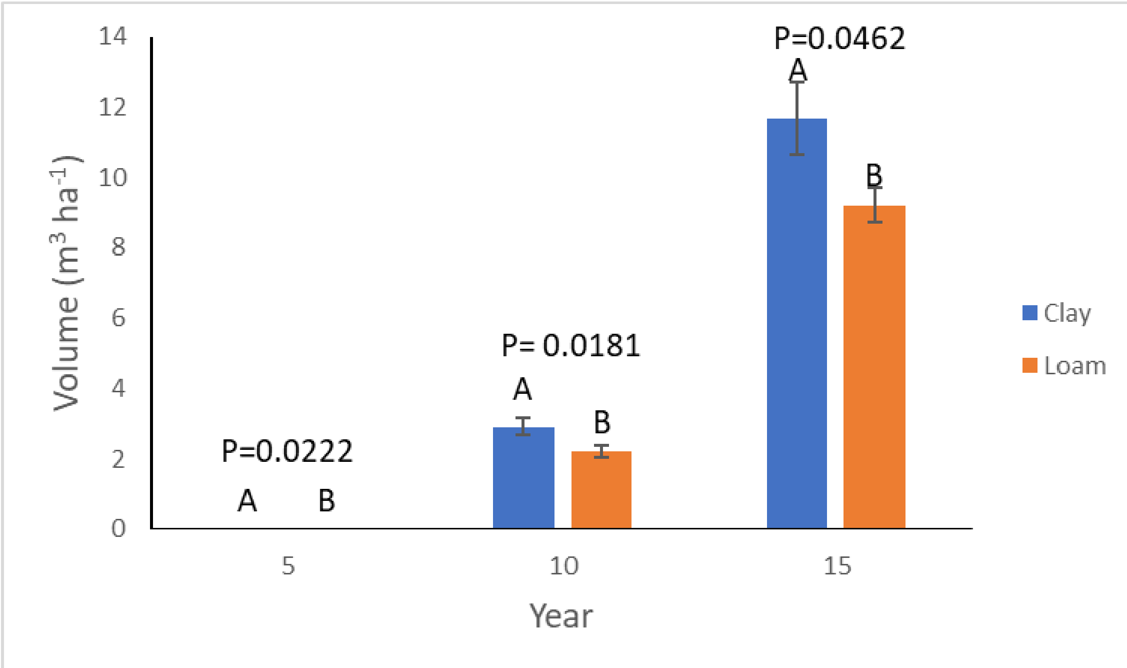

Figure 13. Temporal patterns in stand volume (m^3ha^{-1}) as a function of soil type (clay versus loam). Vertical bars represent standard errors. Different uppercase letters represent significant differences ($p<0.05$) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

There were no significant differences in stand volume when compared across the biomass retention treatments (Figure 14). The clay site was more productive in years 5 and 10, but by year 15 residual fines not removed/full slash and residual fines not removed/half slash on the loam soil type had the highest stand volumes.

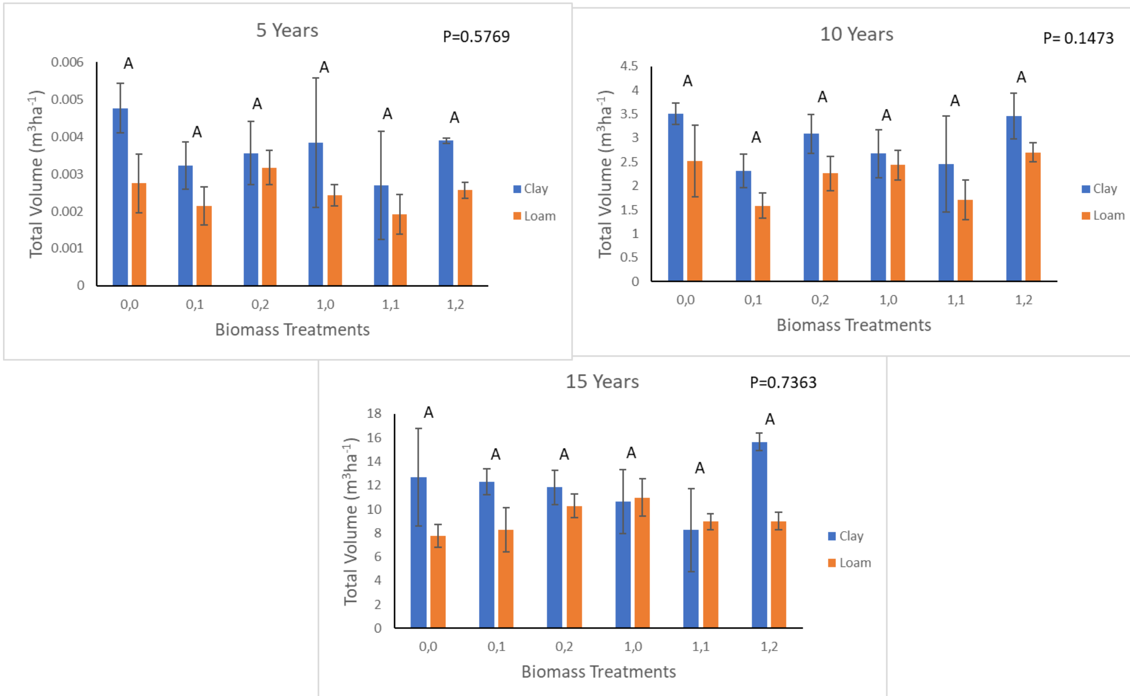

Figure 14. Stand volume (m^3ha^{-1}) comparison to the gradient of biomass retention treatments. Vertical bars represent standard errors. Different uppercase letters represent significant differences ($p<0.05$) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

SOIL CHEMISTRY

There were no significant differences in the pH of the organic (forest floor) or upper (0-20 cm) mineral soil layers between soil types (organic: p=0.543, mineral: p=0.191), biomass retention treatments (organic: p=0.643, mineral: p=0.921), and sampling period (organic: p=0.092, mineral: p=0.390) Although not significant, there was a slight increase in soil pH in both the forest floor (organic) and mineral soil layers between Year 10 and 15 (Figure 15). The clay site did have a slightly higher pH (5.8-5.9) compared to the loam site (<5.7) (Figure 16). There was no consistent pattern in soil pH associated with the biomass retention treatments, although the heaviest slash loadings (full slash) had the lowest pH values in the organic layer (approximately 5.6) compared to the other treatments (generally pH > 5.8) (Figure 17).

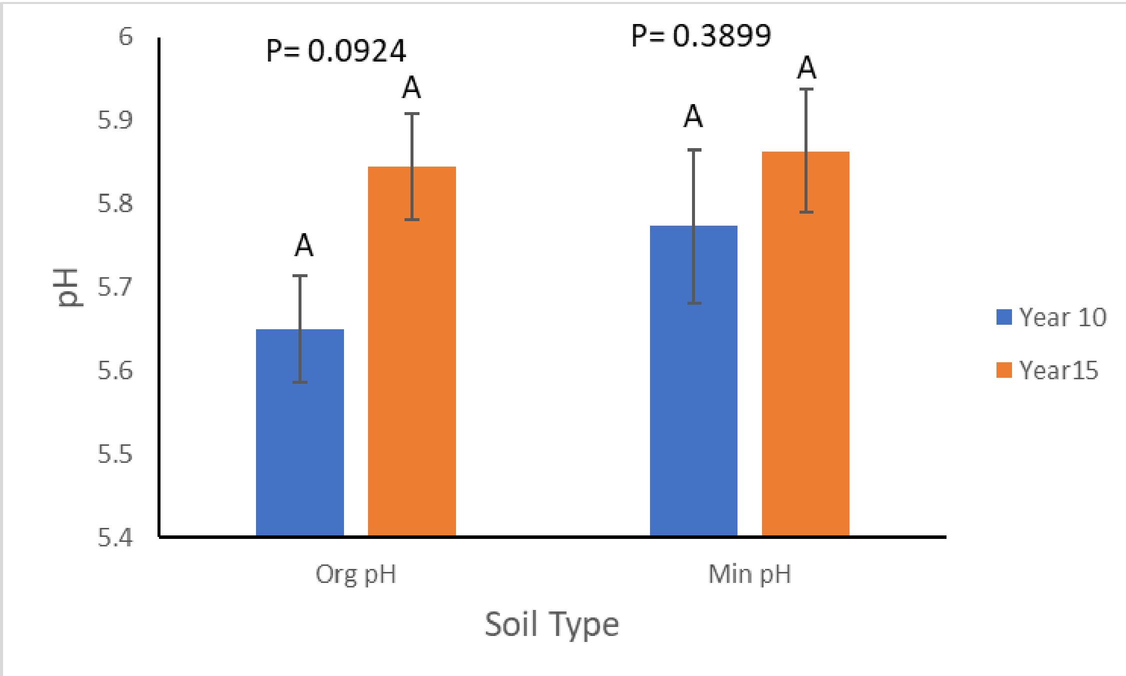

Figure 15. Changes in soil pH as a function of the sampling period (Year 10 versus Year 15). Vertical bars represent standard errors. Different uppercase letters represent significant differences (p<0.05) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

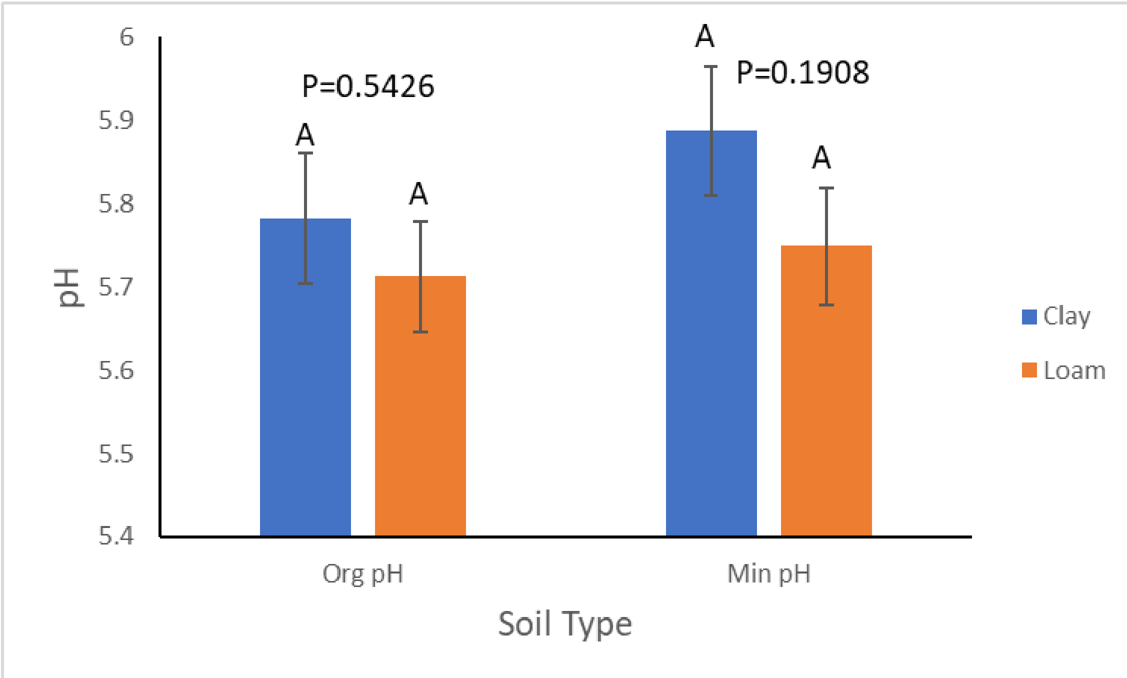

Figure 16. Changes in soil pH as a function of soil type (clay versus loam). Vertical bars represent standard errors. Different uppercase letters represent significant differences (p<0.05) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

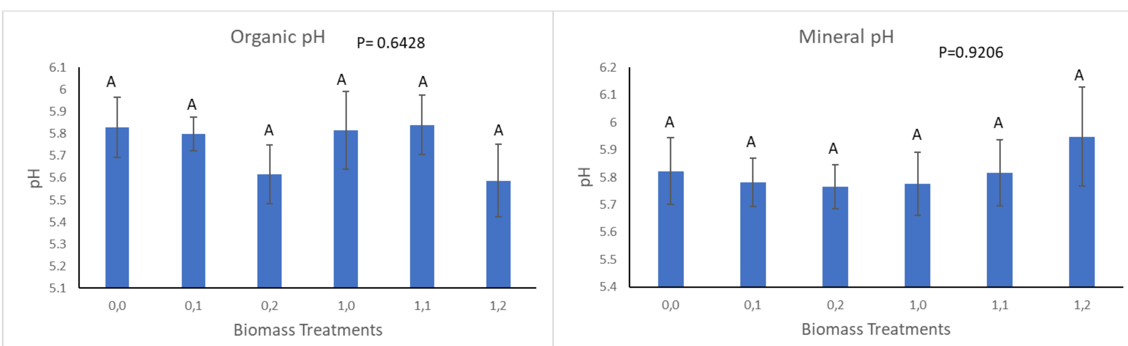

Figure 17. Differences in soil pH across the gradient of biomass retention treatments. Vertical bars represent standard errors. Different uppercase letters represent significant differences (p<0.05) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

There were, however, significant differences in the mineralizable N concentrations (mg L^{-1}) for both the organic and mineral soil layers. For the organic layer, there were significant differences between soil type ($p<0.0001$), sampling period ($p=0.0002$), and an age x soil type interaction ($p<0.0001$), but no significant differences across the biomass retention treatments ($p=0.3536$). In particular, there was a significant (2-fold) increase in mineralizable N from Year 10 to 15 for both the organic (1.5 mg L^{-1} to nearly 3 mg L^{-1}) and mineral (<1 mg L-1 to 2.2 mg L^{-1}) soil layers (Figure 20). There was also a notable difference between soil types for the organic layer, with higher values in the loam site (3.2 mg L^{-1}) compared to the clay site (1.1 mg L^{-1}) (Figure 19). There was, however, a significant age x soil type interaction for mineralizable N in the organic layers (Figure 18) with no difference between soil types in year 10, but the loam site (4.5 mg L^{-1}) was significantly higher than the clay site (0.6 mg L^{-1}) in year 15.

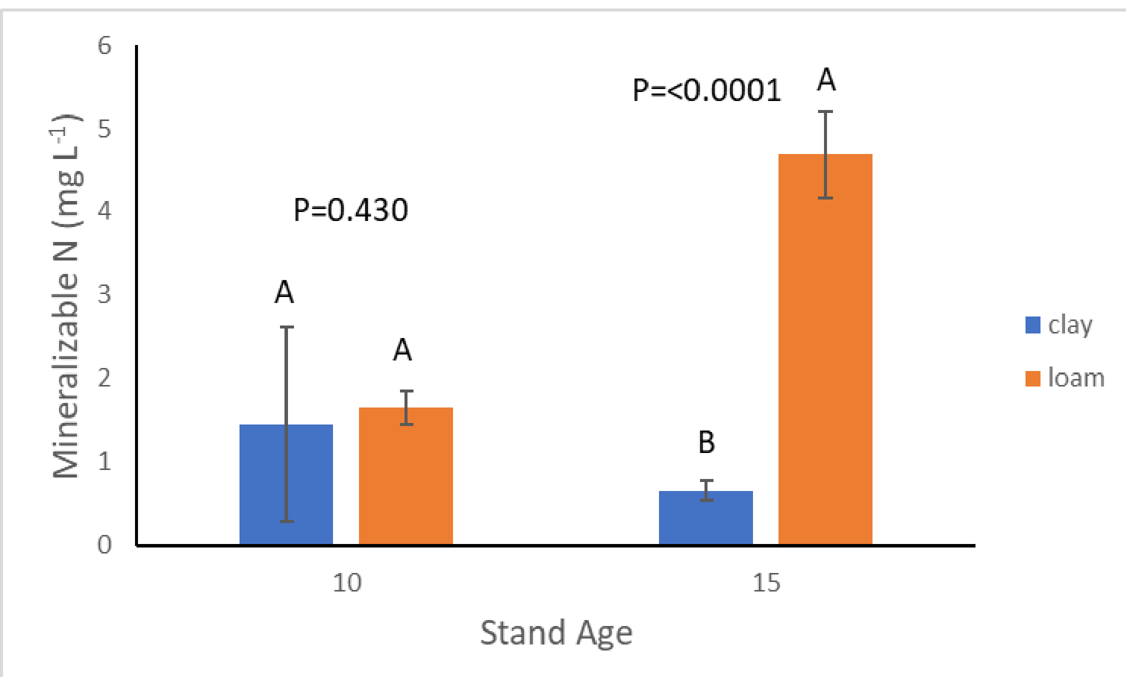

Figure 18. Differences in the organic layer for mineralizable N concentrations (mg L^{-1}) as a function of age X soil type. Vertical bars represent standard errors. Different uppercase letters represent significant differences (p<0.05) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

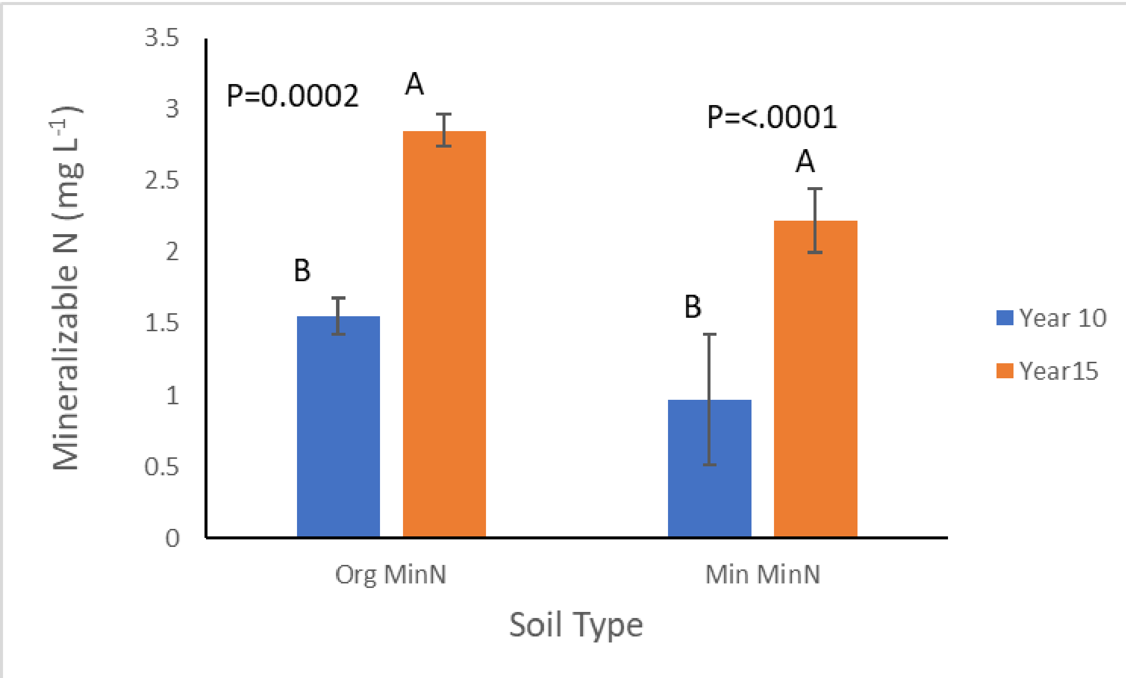

Figure 19. Differences in mineralizable N concentrations (mg L^{-1}) as a function of soil type (Year 10 versus Year 15). Vertical bars represent standard errors. Different uppercase letters represent significant differences (p<0.05) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

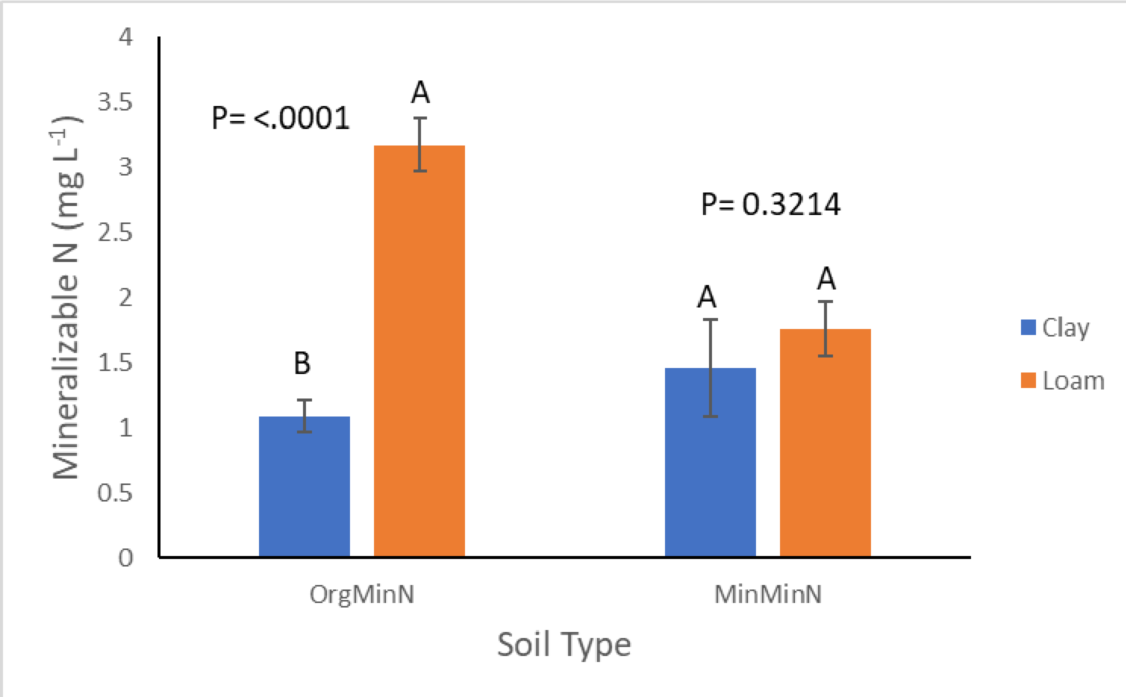

Figure 20. Differences in mineralizable N concentrations (mg L^{-1}) as a function of soil type (clay versus loam). Vertical bars represent standard errors. Different uppercase letters represent significant differences ($p<0.05$) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

Similar to the results for soil pH, there were no consistent patterns in mineralizable N across the gradient of biomass retention treatments. Generally, half and full slash-loaded treatments had higher mineralizable N values (organic: >2 mg L^{-1}, mineral: >1.5 mg L^{-1}), but this was not always the case (e.g., the 1,0 – fines retained, no slash applied had the highest mineralizable N value in the mineral soil layer at 1.7 mg L^{-1}) (Figure 21).

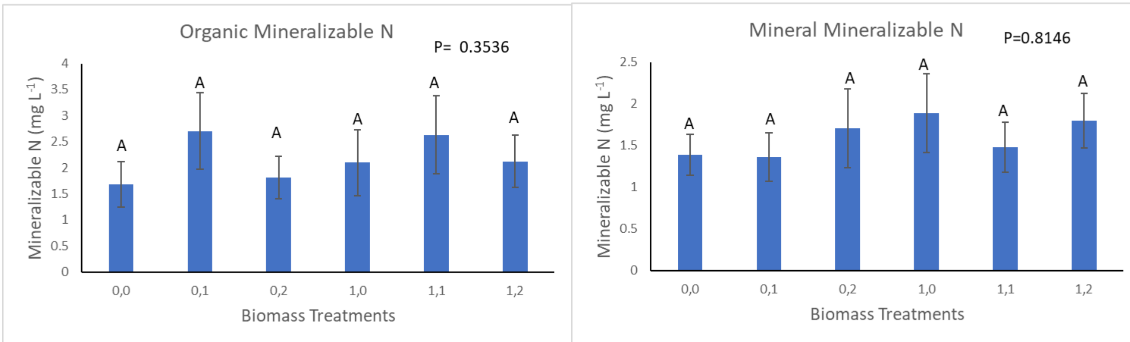

Figure 21. Differences in mineralizable N concentrations (mg L^{-1}) across the gradient of biomass retention treatments. Vertical bars represent standard errors. Different uppercase letters represent significant differences ($p<0.05$) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

FOLIAR NUTRITIONAL STATUS

There were significant differences in foliar nutrient concentrations between sampling years (Years 5 and 10) for all macronutrients, except for Mg (Figure 22), and differences between soil types (clay versus loam) for N, P, and K (Figure 23). There were not, however, any significant differences across the gradient of biomass retention treatments for any of the macronutrients (Figure 24). In the case of N, foliar concentrations increased between year 5 (9419 mg kg^{-1}) and year 10(10730 mg kg^{-1}). Similar increases occurred for K (4685 mg kg^{-1} to 6394 mg kg^{-1}) and Ca (2797 mg kg^{-1} to 3288 mg kg^{-1}). In contrast, P concentration decreased from 1246 mg kg^{-1} at year 5 to 1146 mg kg^{-1} by year 10. There were no significant differences in Mg concentration of magnesium between year and year 10 (ranging between 620 – 650 mg kg^{-1}).

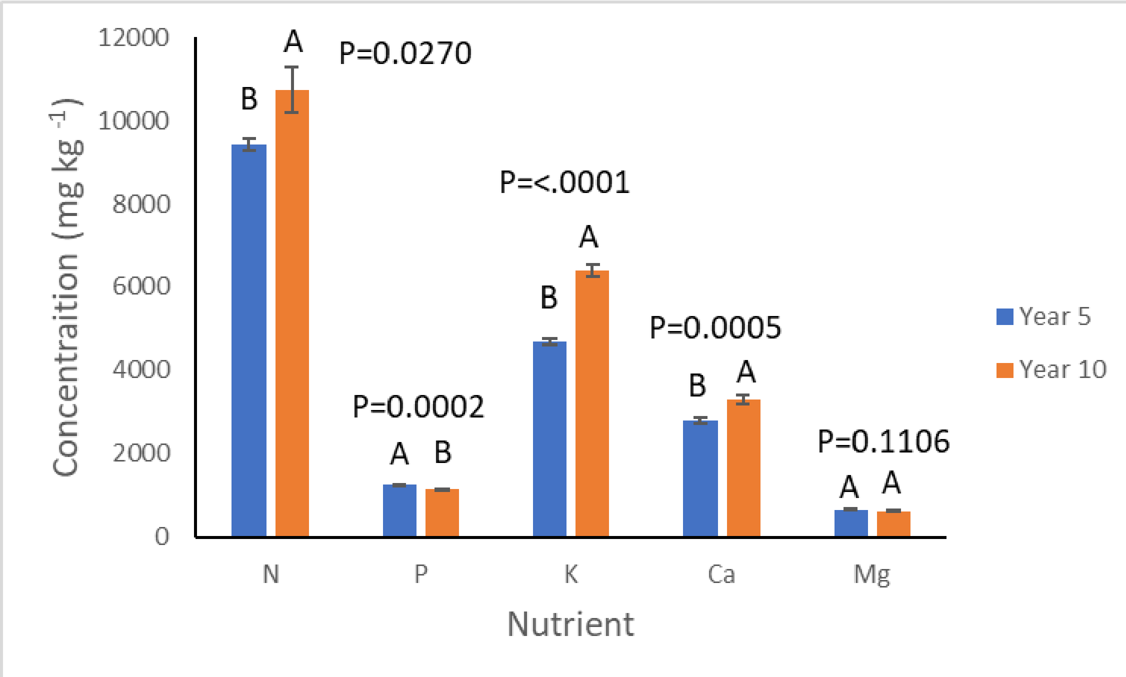

Figure 22. Differences in foliar macronutrient concentrations (mg kg^{-1}) as a function of the sampling period (Year 5 versus Year 10). Vertical bars represent standard errors. Different uppercase letters represent significant differences ($p<0.05$) between sample periods, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

When comparing the foliar concentration responses to the different soil types, N concentrations were higher on the loam (10663 mg kg^{-1}) compared to the clay site (9486 mg kg^{-1}) but had lower P concentrations (loam: 1171 mg kg^{-1}, clay: 1222 mg kg^{-1}). There were no differences between soil types for K, Ca, or Mg.

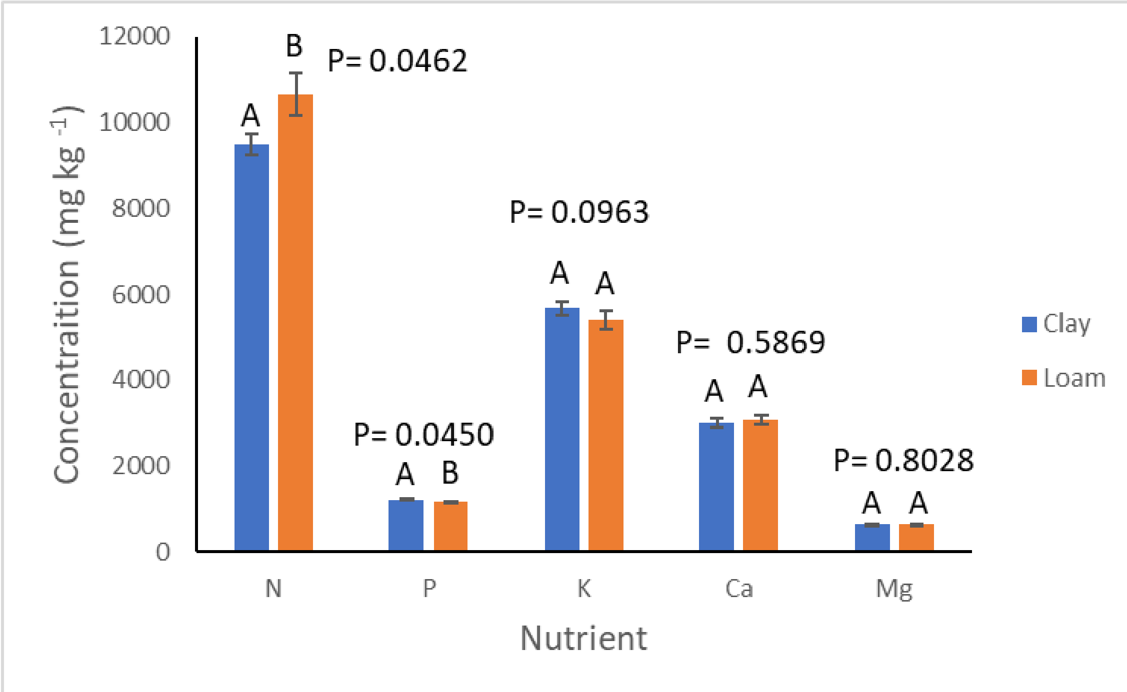

Figure 23. Differences in foliar macronutrient concentrations (mg kg^{-1}) as a function of soil type (clay versus loam). Vertical bars represent standard errors. Different uppercase letters represent significant differences ($p<0.05$) between soil types, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

As noted above, there were no consistent or discernable patterns in foliar macro-nutrient concentrations across the biomass retention gradient.

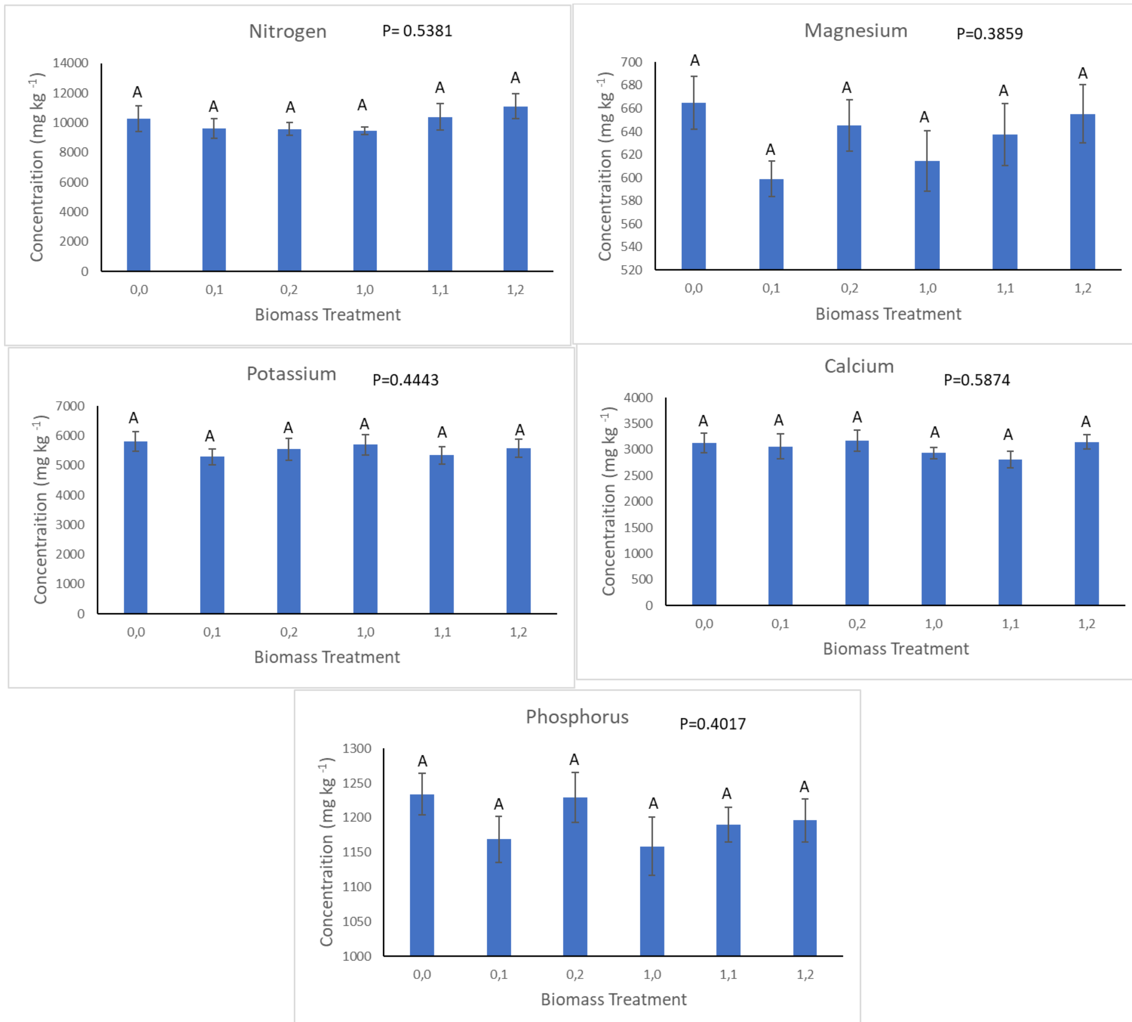

Figure 24. Differences in foliar macronutrient concentrations (mg kg^{-1}) across the gradient of biomass retention treatments. Vertical bars represent standard errors. Different uppercase letters represent significant differences ($p<0.05$) between biomass retention treatments, based on the post-hoc Student-Newman-Keuls (SNK) mean separation test.

DISCUSSION

Our results concerning stand regeneration and growth (i.e., height, RCD, stand volume) showed that there was no significant impact from the range of biomass retention treatments 15 years after trial establishment. We hypothesized that there would be a threshold level of retention required to maximize seedling growth and that this threshold may vary between sites with different soil types. Based on the 15th-year results, we reject this hypothesis. There was, however, a significant difference in tree growth response between the soil types, with the clay site having better growth metrics compared to the loam site. This difference was likely due to a combination of higher water and nutrient availability associated with the finer-textured (clay) site. Another factor likely influencing the “no response” to the biomass retention treatments was the aggressive vegetation control regiment (i.e., herbicide application in year 2, followed by 2 manual cleanings of hardwood brush) that would have reduced the stand-level demand for water and nutrients during this establishment period. Therefore, nutrient limitations created by the different levels of biomass retention may become apparent over time (i.e., during the crown closure phase of stand development where nutrient demand is maximal), requiring ongoing monitoring. Previous studies have also highlighted that longer-term assessments are required to evaluate the effects of biomass removals. For example, these longer-term studies have reported tree growth reductions of 3 to 20%, linked to the reduction of N availability and soil C storage (Bessaad *et al.* 2021, Egnell and Valinger 2003).

For soil chemical properties, we hypothesized that only the complete biomass removal treatment (0,0: fines removed, no coarse slash) will affect soil N availability. While there were no significant differences in the biomass removal treatments, there was a tendency to have higher amounts of mineralizable N in the half-slash and full-sash treatments. Overall, the results showed a significant difference when comparing years and soil types in the organic and mineral layer mineralizable N. Again, the strong signals were related to the sampling period and soil types, as opposed to the gradient of biomass retention treatments. These results are consistent with other studies that have noted that soil type, in particular, will influence the results of biomass removal trials, and time-since-establishment of the trials influences the results (e.g., little differences in the early reported results) (O'Hehir and Nambiar 2010, Powers *et al.* 2005).

With respect to foliar nutrition, we hypothesized that there would be a strong correlation between soil N availability and foliar N concentration. Foliar N was relatively similar for each biomass treatment regardless of the mineralizable N amount. With that result, it can be said in this study there was not a strong correlation between soil N availability and foliar N content. While there was no significant difference between the biomass treatments, there were differences in foliar nutrition from soil type and sampling period which has been a similar trend in this study.

CONCLUSION

In conclusion, the biomass retention treatments applied in our study did not have a significant effect on the growth of black spruce plantations from 5 to 15 years after establishment. The overarching growth and soil chemical property differences were between soil types, with differences emerging at different sampling periods. It will be important to continue this study into the future (i.e., through the crown closure stage of stand development). Based on the current results, biomass harvesting does not appear to result in significant negative effects on growth in black spruce plantations. However, growth predictions are dependent on soil type. Continued research is needed on this topic to better understand the longer-term effects of biomass removal in support of the development of forest policies to ensure sustainable harvest levels of these resources as biofibre feedstocks for renewable energy production.

LITERATURE CITED

Achat, D.L., M. Fortin, G. Landmann, B. Ringeval, and L. Augusto. 2015. Forest soil carbon is threatened by intensive biomass harvesting. Scientific Reports. 5:1-10 pp (online). DOI: 10.1038/srep15991.

Bessaad, A., I. Bilger, and N. Korboulewsky. 2021. Assessing Biomass Removal and Woody Debris in Whole-Tree Harvesting System: Are the Recommended Levels of Residues Ensured? MDPI. 12(6):1-15 (online). https://doi.org/10.3390/f12060807.

Climate Data. N.d. Nipigon Climate (Canada). Data And Graphs For Weather & Climate In Nipigon (online) https://en.climate-data.org/north-america/canada/ontario/nipigon-767939. (March 2023).

Climate Atlas of Canada. 2023. Climate Atlas of Canada. (online) https://climateatlas.ca/map/canada/dd5_2030_85#lat=50.18&lng=-88.47&z=8&grid=542

Egnell, G., and E. Valinger. 2003. Survival, growth, and growth allocation of planted Scot's pine trees after different levels of biomass removal in clear-felling. Forest Ecology and Management. 177:65-74 pp. (online). https://doi.org/10.1016/S0378-1127(02)00332-8.

European Commission. n.d. Biomass. European Commission. (online) https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/biomass_en/. (March 2023).

Eurostat. 2022. EU overachieves 2020 renewable energy target. European Commission. (online). https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20220119-1#:~:text=At%20EU%20level%2C%20the%20share,of%20energy%20from%20renewable%20sources. March 2023.

Fleming, R.L., D.M. Morris, and P.W. Hazlett. 2021. Elsevier. Assessing temporal response to biomass removal: A framework for investigating evolving constraints on boreal stand development. 497 (online). https://doi.org/10.1016/j.foreco.2021.119518.

Gallagher, K.S. 2013. Why & How Governments Support Renewable Energy. American Academy of Arts & Sciences, and The MIT Press. 142(1):59-77 pp (online). https://www.jstor.org/stable/43297301.

Garcia, W.D.O., T. Amann, J. Hartmann. 2018. Increasing biomass demand enlarges negative forest nutrient budget areas in wood export regions. Scientific Reports. 1-7 pp (online). https://doi.org/10.1038/s41598-018-22728-5

Government of Canada. 2013. Gray Luvisol (GL). Canadian System of Soil Classification, 3rd edition. (online). https://sis.agr.gc.ca/cansis/taxa/cssc3/LU/GL/index.html.

Huang, Z., Z. He, X. Wan, Z. Hu, S. Fan, Y. Yang. 2013. Harvest residue management effects on tree growth and ecosystem carbon in a

Chinese fir plantation in subtropical China. Springer Science and Business Media. 364(1/2):303-314 (online). https://www.jstor.org/stable/42953459

Jerabkova, L., C.E. Prescott, B.D. Titus, G.D. Hope, and M.B. Walters. 2011. A meta-analysis of the effects of clearcut and variable-retention harvesting on soil nitrogen fluxes in boreal and temperate forests. NRC Research Press. (41):1852–1870 (online). doi:10.1139/X11-087.

Johnson, D.W. and P.S. Curtis. 2001. Effects of forest management on soil C and N storage: meta-analysis. For. Ecol. Manage. 140: 227-238.

Kalra, Y.P, and D.G. Mynard.1991. Methods manual for forest soil and plant analysis. Forestry Canada. 1-116 pp (online). https://web.unbc.ca/~arocenaj/lab/kalra_maynard.pdf

Lindstad, B.H., T. Pistorius, F. Ferranti, G. Dominguez, E. Gorriz-Mifsud, M. Kurttila, V. Leban, P. Navarro, D.M. Peters, S. Pezdevsek Malovrh, I. Prokofieva, A. Schuck, B. Solberg, H. Viiri, L. Zadnik Stirn, and J. Krc. 2015. Forest-based bioenergy policies in five European countries: An explorative study of interactions with national and Eu policies. Biomass and Bioenergy and Elsevier Ltd. 80:102-113 pp (online). https://www.sciencedirect.com/science/article/abs/pii/S0961953415001695?via%3Dihub. P103-113

Luiro, J, M. Kukkola, A. Saarsalmi, P. Tamminen, H. Helmisaari. 2009. Logging residue removal after thinning in boreal forests: long-term impact on the nutrient status of Norway spruce and Scot's pine needles. Oxford University Press. 30:78-88 (online). doi:10.1093/treephys/tpp097

[MCCS] Manomet Center for Conservation Sciences. 2010. Biomass Sustainability and Carbon Policy Study: Chapter 4. Manomet Center for Conservation Sciences. 62-81 pp (online). https://www.mass.gov/doc/manometbiomassreportchapter4pdf/download

[MNRF] Ministry of Natural Resources and Forestry. 2021. Ministry of Natural Resources and Forestry. Ontario's Draft Forest Biomass Action Plan. (online) https://ero.ontario.ca/notice/019-3514

Morris, D. M., M. M. Kwiaton, and D. R. Duckert. 2013. Black spruce growth response to varying levels of biomass harvest intensity across a range of soil types: 15-year results. NRC Research Press. 44:313–325 pp (online). dx.doi.org/10.1139/cjfr-2013-0359.

Morris, D.M., R.E. Miller. 1994. Evidence for long-term productivity change as provided by field trials. In: Dyck, W.J., Cole, D.W., Comerford, N.B. (Eds.), Impacts of Forest Harvesting on Long-Term Site Productivity. Chapman and Hall, London, UK, 41–80 pp. (online)

Morris, D. M., R.L. Fleming, and P.W. Hazlett. 2020. Ontario, Canada's LTSP Experience: Forging Lasting Research Partnerships and the Adaptive Management Cycle in Action. Journal of Forestry. 337–351 pp (online). doi:10.1093/jofore/fvaa002

Michael Pidwirny. n.d. Physical Geography Lab Manual: The Atmosphere and Biosphere. (online) https://pressbooks.bccampus.ca/physgeoglabmanual1/back-matter/appendix-2-koppen-climate-classification-system/

Nilsson, D., B. Nilsson, T. Thörnqvist, and J. Bergh. 2018. Amount of nutrients extracted and left behind at a clear-felled area using the fresh-stacked and dried-stacked methods of logging residue extraction. Scandinavian Journal of Forest Research. 33(5):437-445. https://doi.org/10.1080/02827581.2018.1427786

O'Hehir, J.F., and E.K.S. Nambiar. 2010. Productivity of three successive rotations of *P. radiata* plantations in South Australia over a century. For. Ecol. Manage. 259: 1857-1869.

Olsson, B.A., H. Lundkvist, and H. Staaf. 2000. Nutrient status in needles of Norway spruce and Scots pine following harvesting of logging residues. Springer. 223(1/2)161-173 (online). https://www.jstor.org/stable/42950799.

Ontario. 1994. Crown Forest Sustainability Act. (online). Government of Ontario.

https://www.ontario.ca/laws/statute/94c25#:~:text=1%20The%20purposes%20of%20this,1994%2C%20c.

Ontario. 2020. Sustainable Growth: Ontario's Forest Sector Strategy. (online). Government of Ontario. https://www.ontario.ca/page/sustainable-growth-ontarios-forest-sector-strategy

Ontario. 2020. Forest Biomass Action Plan. (online). Government of Ontario. https://www.ontario.ca/page/forest-biomass-action-plan/

Ontario. 2022. Forest Management Policies. (online) Government of Ontario. https://www.ontario.ca/page/forest-management-policies

Pedroli, B., B. Elbersen, P. Frederiksen, U. Grandin, R. Heikkilä, P. H. Krogh, Z. Izakovičová, A. Johansen, L. Meiresonne, and J. Spijker. 2012. Is energy cropping in Europe compatible with biodiversity? - Opportunities and threats to biodiversity from land-based production of biomass for bioenergy purposes. Biomass and Bioenergy. 55:73-86 (online). https://www.sciencedirect.com/science/article/pii/S0961953412003947?via%3Dihub

Perlack, R.D., L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, and D.C. Erbach. 2005. Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply. U.S. Department of Energy. 1-59 pp (online).

https://www1.eere.energy.gov/bioenergy/pdfs/final_billionton_vision_report2.pdf.

Ponder, Jr. F., R.L. Fleming, S. Berch, M.D. B, J.D. Elioff, P.W. Hazlett, R.D. Kabzems, J.M. Kranabetter, D.M. Morris, D. Page-Dumroese, B.J. Palik, R.F. Powers, F.G. Sanchez, A.D. Scott, R. H. Stagg, D. M. Stone, D.H. Young, J. Zhang, K.H. Ludovici, D.W. McKenney, D.S. Mossa, P.T. Sanborn, and R.A. Voldseth. 2012. Effects of organic matter removal, soil compaction, and vegetation control on 10th-year biomass and foliar nutrition: LTSP continent-wide comparisons. Forest Ecology and Management. 278:35–54 pp (online). http://dx.doi.org/10.1016/j.foreco.2012.04.014

Powers, R.F., A.D. Scott, F.G. Sanchez, R.A. Voldseth, D. Page-Dumroese, J.D. Elioff, D.M. Stone. 2005. The North American long-term soil productivity experiment: Findings from the first decade of research. Forest Ecology and Management. 220:31–50 pp (online). doi:10.1016/j.foreco.2005.08.003

Quideau, S.A., M.J.B. Swallow, C.E. Prescott, S.J. Grayston, and S.-W. Oh. 2013. Comparing soil biogeochemical processes in novel and natural boreal forest ecosystems. Biogeosciences 10: 5651-5661.

Roxby, G.E. 2012. Effects of whole-tree harvesting on site productivity and species composition of a northern hardwood forest. University of New Hampshire Master's Theses and Capstones. 1-110 pp (online).

https://scholars.unh.edu/cgi/viewcontent.cgi?article=1713&context=thesis

Smith, C.T., A.T. Lowe, M.F. Skinner, P.N. Beets, S.H. Schoenholtz, and S. Fang. 2000. Response of radiate pine forests to residue management and fertilization across a fertility gradient in New Zealand. For. Ecol. Manage. 138: 203-223.

Suttles, S.A., W.E. Tyner, G. Shively, R.D. Sands, B. Sohngen. 2014. Economic effects of bioenergy policy in the United States and Europe: A general equilibrium approach focusing on forest biomass. Renewable Energy: An International Journal and Elsevier Ltd. 69:428-436 pp (online). http://dx.doi.org/10.1016/j.renene.2014.03.067

Tamminen, P., A. Saarsalmi, A. Smolander, M. Kukkola, and H. Helmisaari. 2011. Effects of logging residue harvest in thinnings on amounts of soil carbon and nutrients in Scots pine and Norway spruce stands. Forest Ecology and Management. 263:31–38 pp (online). doi:10.1016/j.foreco.2011.09.015

Thibodeau, L., P. Raymond, C. Camiré, and A.D. Munson. 2000. Impact of precommercial thinning in balsam fir stands on soil nitrogen dynamics, microbial biomass, decomposition, and foliar nutrition. Canadian Journal of Forest Research. 30(2):229-238 pp (online). DOI: 10.1139/cjfr-30-2-229

Thiffault, E., K.D. Hannam, D. Paré, B.D. Titus, P.W. Hazlett, D.G. Maynard, S. Brais. 2011. Effects of forest biomass harvesting on soil productivity in boreal and temperate forests — A review. Canadian Science Publishing. 19:278-309 (online). https://www.jstor.org/stable/10.2307/envirevi.19.278.

Thiffault, E., J. Barrette, D. Paré, B.D. Titus, K. Keys, D.M. Morris, G. Hope. 2014. Developing and validating indicators of site suitability for forest harvesting residue removal. Ecological Indicators. 43:1-18 pp (online). http://dx.doi.org/10.1016/j.ecolind.2014.02.005

Thiffault, E., D. Paré, S. Brais, and B.D. Titus. 2010. Intensive biomass removals and site productivity in Canada: A review of relevant issues. The Forestry Chronicle. 86(1):36-42 pp (online). https://doi.org/10.5558/tfc86036-1

Vanguelova, E., R. Pitman, J. Luiro, and H. Helmisaari. 2010. Long-term effects of whole-tree harvesting on soil carbon and nutrient sustainability in the UK. Biogeochemistry. 101:43-59 (online). DOI 10.1007/sl0533-010-9511-9

Walmsley, J.D., D.L. Jones, B. Reynolds, M.H. Price, J.R. Healey. 2008. Whole tree harvesting can reduce second-rotation forest productivity. Forest Ecology and Management. 257:(3)1104-1111 (online). https://doi.org/10.1016/j.foreco.2008.11.015

Walmsley, J.D., and D.L. Godbold. 2010. Stump harvesting for bioenergy – a review of the environmental impacts. Forestry 83: 17-38

Wester, M.C., B.L. Henson, W.J. Crins, P.W.C. Uhlig and P.A. Gray. 2018. The Ecosystems of Ontario, Part 2: Ecodistricts. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Technical Report TR-26. 1-504 pp (online). https://files.ontario.ca/ecosystems-ontario-part2-03262019.pdf

Wilhelm, R.C, E. Cardenas, K.R Maas, H. Leung, L. McNeil, S. Berch, W. Chapman, G. Hope, JM. Kranabetter, S. Dubé, M. Busse, R. Fleming, P. Hazlett, K.L. Webster, D. Morris, A.D. Scott, and W.W. Mohn. 2017. Biogeography and organic matter removal shape long-term effects of timber harvesting on forest soil microbial communities. The ISME Journal, and International Society for Microbial Ecology. 11:2552–2568 pp (online). doi:10.1038/ismej.2017.109.

Woongsoon, J. 2015. Consequences of Biomass Harvesting on Forest Condition and Productivity in the Northern Rocky Mountains. The Graduate Student Theses, Dissertations, & Professional Papers. 1-245 pp (online). https://scholarworks.umt.edu/etd/4597

APPENDIX I ANOVA TABLES

Top Height Year 5	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	5680.13192	516.37563	1.13	0.3814
Error	24	10955.75106	456.48963		
Correct Total	35	16635.88298			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	3498.229601	3498.229601	7.66	0.0107
Treatcode	5	1268.734223	253.746845	0.56	0.7325
stype*Treatcode	5	913.168096	182.633619	0.4	0.8439

Top RCD Year 5	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.02641121	0.00240102	1.1	0.4026
Error	24	0.05241293	0.00218387		
Correct Total	35	0.07882414			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	0.01713794	0.01713794	7.85	0.0099
Treatcode	5	0.00746965	0.00149393	0.68	0.64
stype*Treatcode	5	0.00180363	0.00036073	0.17	0.973

Top Growth Year 10	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	146142.6263	13285.6933	4.55	0.0009
Error	24	70151.0223	2922.9593		
Correct Total	35	216293.6486			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	87039.27227	87039.27227	29.78	<.0001
Treatcode	5	32655.32485	6531.06497	2.23	0.0837
stype*Treatcode	5	26448.02921	5289.60584	1.81	0.149

Top RCD Year 10	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	31.38310962	2.85300997	2.54	0.0272
Error	24	26.95505169	1.12312715		
Correct Total	35	58.33816131			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	17.48444639	17.48444639	15.57	0.0006
Treatcode	5	7.98271012	1.59654202	1.42	0.2524
stype*Treatcode	5	5.91595311	1.18319062	1.05	0.4101

Top Growth Year 15	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	218105.2857	19827.7532	3.22	0.0081
Error	24	147886.0146	6161.9173		
Correct Total	35	365991.3003			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	136447.2207	136447.2207	22.14	<.0001
Treatcode	5	47160.9089	9432.1818	1.53	0.2177
stype*Treatcode	5	34497.1561	6899.4312	1.12	0.3765

Top RCD Year 15	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	66.3863807	6.0351255	3.21	0.0082
Error	24	45.1155981	1.8798166		
Correct Total	35	111.5019788			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	41.51195865	41.51195865	22.08	<.0001
Treatcode	5	14.37080402	2.8741608	1.53	0.2183

stype*Treatcode	5	10.50361803	2.10072361	1.12	0.3776

Mean Height Year 5	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	4714.37759	428.57978	1.44	0.2179
Error	24	7130.77803	297.11575		
Correct Total	35	11845.15562			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	1837.883105	1837.883105	6.19	0.0202
Treatcode	5	1941.905482	388.381096	1.31	0.2941
stype*Treatcode	5	934.589001	186.9178	0.63	0.6793

Mean RCD Overall Year 5	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.01799327	0.00163575	0.87	0.582
Error	24	0.05241293	0.00188748		
Correct Total	35	0.06329288			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	0.00402555	0.00402555	2.13	0.1571

Treatcode	5	0.00683079	0.00136616	0.72	0.6122
stype*Treatcode	5	0.00713694	0.00142739	0.76	0.5899

Mean Height Year 10	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	128529.4298	11684.4936	4.84	0.0006
Error	24	57960.3516	2415.0147		
Correct Total	35	186489.7814			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	60266.23423	60266.23423	24.95	<.0001
Treatcode	5	52208.70875	10441.74175	4.32	0.006
stype*Treatcode	5	16054.48682	3210.89736	1.33	0.2855

Mean RCD Year 10	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	38.42434355	3.49312214	4.26	0.0015
Error	24	19.68276706	0.82011529		
Correct Total	35	58.10711061			

Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	15.52239614	15.52239614	18.93	0.0002
Treatcode	5	17.08985995	3.41797199	4.17	0.0072
stype*Treatcode	5	5.81208747	1.16241749	1.42	0.2538

Mean Height Year 15	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	279355.6257	25395.966	3.98	0.0023
Error	24	153237.693	6384.9039		
Correct Total	35	432593.3188			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	184454.9823	184454.9823	28.89	<.0001
Treatcode	5	78663.6607	15732.7321	2.46	0.0615
stype*Treatcode	5	16236.9826	3247.3965	0.51	0.7669

Mean Height Year 15	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	88.0312454	8.0028405	3.96	0.0023
Error	24	48.4921484	2.0205062		
Correct Total	35	136.5233938			

Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	58.04000411	58.04000411	28.73	<.0001
Treatcode	5	25.03716606	5.00743321	2.48	0.0604
stype*Treatcode	5	4.95407526	0.99081505	0.49	0.7801

Volume Overall Year 5	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.00002253	0.00000205	1	0.474
Error	24	0.00004914	0.00000205		
Correct Total	35	0.00007167			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	0.00001225	0.00001225	5.98	0.0222
Treatcode	5	0.00000794	0.00000159	0.78	0.5769
stype*Treatcode	5	0.00000235	0.00000047	0.23	0.9461

Volume Overall Year 10	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	11.69992756	1.06362978	1.47	0.2058
Error	24	17.3279664	0.7219986		

Correct Total	35	29.02789397			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	4.65063944	4.65063944	6.44	0.0181
Treatcode	5	6.56394353	1.31278871	1.82	0.1473
stype*Treatcode	5	0.48534459	0.09706892	0.13	0.9828

Volume Overall Year 15	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	152.0824147	13.8256741	1.1	0.4001
Error	24	300.7848443	12.5327018		
Correct Total	35	452.867259			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
stype	1	55.405358	55.405358	4.42	0.0462
Treatcode	5	34.5066662	6.90133324	0.55	0.7363
stype*Treatcode	5	62.17039051	12.4340781	0.99	0.4433

Foliar Results N	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	133969636	5824766.8	0.98	0.506
Error	48	285448141.9	5946836.3		

Correct Total	71	419417778			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
Age	1	30961402.58	30961402.58	5.21	0.027
Stype	1	24910815.68	24910815.68	4.19	0.0462
treatcode	5	24534300.62	4906860.12	0.83	0.5381
Age*Stype	1	14899196.91	14899196.91	2.51	0.12
Age*treatcode	5	22629700.13	4525940.03	0.76	0.5823
Stype*treatcode	5	4263409.4	852681.88	0.14	0.9811
Age*Stype*treatcode	5	11770810.7	2354162.14	0.4	0.8492

Foliar Results P	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	423323.038	18405.3495	1.7	0.061
Error	48	520165.2801	10836.7767		
Correct Total	71	943488.3181			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
Age	1	180807.1891	180807.1891	16.68	0.0002
Stype	1	45894.7746	45894.7746	4.24	0.045
treatcode	5	56688.5986	11337.7197	1.05	0.4017
Age*Stype	1	49627.3372	49627.3372	4.58	0.0375
Age*treatcode	5	32063.071	6412.6142	0.59	0.7063
Stype*treatcode	5	37749.1303	7549.8261	0.7	0.6285
Age*Stype*treatcode	5	20492.9373	4098.5875	0.38	0.8612

Foliar Results K	GLM				

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	60496530.91	2630283.95	5.3	<.0001
Error	48	23806121.73	495960.87		
Correct Total	71	84302652.64			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
Age	1	52626938.36	52626938.36	106.11	<.0001
Stype	1	1427240.53	1427240.53	2.88	0.0963
treatcode	5	2410742.99	482148.6	0.97	0.4443
Age*Stype	1	1211796.07	1211796.07	2.44	0.1246
Age*treatcode	5	719327.1	143865.42	0.29	0.9162
Stype*treatcode	5	1596102.25	319220.45	0.64	0.6676
Age*Stype*treatcode	5	504383.61	100876.72	0.2	0.9595

Foliar Results Ca	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	12179066.74	529524.64	1.69	0.063
Error	48	15050841.7	313559.2		
Correct Total	71	27229908.43			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
Age	1	4334623.357	4334623.357	13.82	0.0005
Stype	1	93824.845	93824.845	0.3	0.5869
treatcode	5	1181938.668	236387.734	0.75	0.5874
Age*Stype	1	680085.681	680085.681	2.17	0.1474
Age*treatcode	5	2105078.775	421015.755	1.34	0.2627
Stype*treatcode	5	2590029.673	518005.935	1.65	0.1645
Age*Stype*treatcode	5	1193485.737	238697.147	0.76	0.5822

Foliar Results Mg	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	139846.4593	6080.2808	0.87	0.6279
Error	48	333797.7866	6954.1206		
Correct Total	71	473644.246			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
Age	1	18378.60722	18378.60722	2.64	0.1106
Stype	1	438.35633	438.35633	0.06	0.8028
treatcode	5	37389.87175	7477.97435	1.08	0.3859
Age*Stype	1	31383.14135	31383.14135	4.51	0.0388
Age*treatcode	5	13965.98416	2793.19683	0.4	0.8453
Stype*treatcode	5	27126.01521	5425.20304	0.78	0.569
Age*Stype*treatcode	5	11164.48331	2232.89666	0.32	0.8979

Soil Results OrgH20	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	25	5.33008333	0.23174275	1	0.4789
Error	48	11.08146667	0.23086389		
Correct Total	71	16.41155			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
Age	1	0.68055556	0.68055556	2.95	0.0924
Stype	1	0.08680556	0.08680556	0.38	0.5426
treatcode	5	0.78168333	0.15633667	0.68	0.6428
Age*Stype	1	0.0032	0.0032	0.01	0.9068
Age*treatcode	5	0.95864444	0.19172889	0.83	0.5344

Stype*treatcode	5	0.65549444	0.13109889	0.57	0.7241
Age*Stype*Treatcode	5	2.1637	0.43274	1.87	0.1164

Soil Results MinH20	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	25	2.70439861	0.11758255	0.6	0.9049
Error	48	9.35346667	0.19486389		
Correct Total	71	12.05786528			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
Age	1	0.14670139	0.14670139	0.75	0.3899
Stype	1	0.34306806	0.34306806	1.76	0.1908
treatcode	5	0.27502361	0.05500472	0.28	0.9206
Age*Stype	1	0.09316806	0.09316806	0.48	0.4926
Age*treatcode	5	1.02219028	0.20443806	1.05	0.4001
Stype*treatcode	5	0.66022361	0.13204472	0.68	0.6425
Age*Stype*Treatcode	5	0.16402361	0.03280472	0.17	0.973

Soil Results OrgMinN	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	25	186.8352847	8.1232732	4.62	<.0001
Error	48	79.0807555	1.7573501		
Correct Total	68	265.9160402			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
Age	1	29.03976769	29.03976769	16.52	0.0002
Stype	1	70.38533601	70.38533601	40.05	<.0001
treatcode	5	10.01370934	2.00274187	1.14	0.3536

Age*Stype	1	62.93207606	62.93207606	35.81	<.0001
Age*treatcode	5	4.31249425	0.86249885	0.49	0.7814
Stype*treatcode	5	8.88644883	1.77728977	1.01	0.4222
Age*Stype*Treatcode	5	1.26545252	0.2530905	0.14	0.9808

Soil Results MinMinN	GLM				
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	40.0781455	1.7425281	1.25	0.252
Error	47	65.4237399	1.3919945		
Correct Total	70	105.5018854			
Source	DF	Type 1 SS	Mean Square	F Value	Pr > F
Age	1	28.07847178	28.07847178	20.17	<.0001
Stype	1	1.39824932	1.39824932	1	0.3214
treatcode	5	3.09789821	0.61957964	0.45	0.8146
Age*Stype	1	1.39322392	1.39322392	1	0.3222
Age*treatcode	5	3.31438037	0.66287607	0.48	0.7921
Stype*treatcode	5	1.49694777	0.29938955	0.22	0.9544
Age*Stype*Treatcode	5	1.29897409	0.25979482	0.19	0.9663