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Synthesis of Current AshNet Study Designs and Methods with Recommendations towards a Standardized Protocol

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Abstract

AshNet is a network of Canadian government, academic, and industry researchers, foresters and policy makers investigating the potential beneficial diversion of wood ash, a by-product of the growing bioenergy industry, from landfills across Canada to forest soils. AshNet currently consists of 14 wood ash application experiments established at sites representing varying forest stand and soil types, tree species, and stand ages. These trials include ash sources with different ash chemistries and application rates. The main objective of this report is to guide future Canadian ash amendment research by (1) synthesizing the current practices and experimental approaches across AshNet studies, and (2) identifying recommendations and considerations towards a standardized protocol and important areas of research. Key recommendations include the use of control plots, buffer zones, and randomized complete block design or other variations (e.g., split-plot, watershed or catena) based on the study objective and site characteristics. Monitoring of ash chemistry, available plant nutrient pools in soil, soil pH, tree growth, foliar nutrients, and the influence of wood ash addition on soil and hydrologically connected aquatic biota are also recommended. Additional considerations include wood ash quality, storage, pre-treatment, and application rates and methods. Building on the current ash application trials across Canada, future research should focus on gaining a better understanding of the key ash and site characteristics that result in beneficial and safe wood ash application to different forest soils and stand types, and to addressing the challenges of ash application at an operational scale.

1.0 Introduction

AshNet is a network of Canadian government, academic, and industry researchers, foresters and policy makers investigating the potential beneficial diversion of wood ash (also referred to as "ash" in this document), a by-product of the growing bioenergy industry, from landfills across Canada to forest soils (Hannam et al. 2017, Natural Resources Canada 2018a). The majority of ash produced in Canada is landfilled because it is often classified as a waste material and there are few viable alternatives that can be easily implemented (Hannam et al. 2018). However, ash has the potential to be utilized as a beneficial soil amendment with examples in agricultural (Gill et al. 2015) and forest settings (Huotari et al. 2015). The factors that influence the viability of ash amendment practices include economics (Hope et al. 2017), regulatory requirements (Hannam et al. 2016), ash quality, and forest stand and soil nutrient and liming requirements (Pitman 2006).

Ash amendment is generally a more accepted practice in agricultural settings, but in Europe, ash application to northern forest soils is common practice (Emilsson 2006, Hannam et al. 2016). The potential benefits of ash application to forest soils include counteracting the effects of acidification, contributing to forest stand productivity via the addition and or replacement of important macronutrients (Ca, Mg, K, P), and by potentially emulating wildfire as a natural disturbance (Hannam et al. 2018). However, the beneficial nature of ash application to forest soils has been shown to vary based on the chemical composition of the ash, soil type and tree species at the application site, and the time elapsed since ash application (Pitman 2006, Augusto et al. 2008, Reid and Watmough 2014, Brais et al. 2015). Although forest application of ash has the potential to divert this residual from landfills, while benefiting forest productivity (e.g. Domes et al. 2018), further research is required to ensure the avoidance of any adverse impacts on the environment, and to enhance the benefits of ash application on a site-by-site basis by considering varying ash characteristics and the nature of the receiving sites.

To explore the potential beneficial application of wood ash to forest soils in Canada, 14 experimental study sites within the AshNet network have been established across 5 provinces (BC, SK, MB, ON, QC). These field trials examine the implications of ash application across a variety of forest stand and soil types, tree species, stand ages, and ash chemistries and application rates. As a product of these research projects currently underway across Canada, a wealth of information on ash application protocols and methods exist. The main objective of this report is to guide future Canadian ash amendment research by (1) synthesizing the current practices and experimental approaches across AshNet studies, and (2) identifying recommendations and considerations towards a standardized protocol and important areas of research.

2.0 Current AshNet Study Sites and Methods

2.1 Overview of AshNet studies' site types

AshNet currently consists of 10 different research groups, with a total of 14 established sites located across 4 vegetation zones including the Cordilleran Subboreal Forest (Meidinger and Baldwin 2017), West-Central Boreal Forest (Baldwin et al. 2016a), Eastern Boreal Forest (Baldwin et al. 2016b), and Eastern Temperate Mixed Forest (Baldwin et al. 2018) (Figure 2.1.1). An additional site in the Eastern Temperate Mixed Forest (Porridge Lake) is also being planned for establishment in 2018 (Figure 2.1.1). Currently there are no established study sites in the Pacific Cool Temperate Forest vegetation zones to the west, or the Acadian Temperate Forest vegetation zone to the east. However, there have been ash amendment studies in each of these vegetation zones in the past with one on Vancouver Island (Prescott and Brown 1998), and one on Prince Edward Island (Mahendrappa et al. 2006) that are no longer being maintained (Figure 2.1.1).

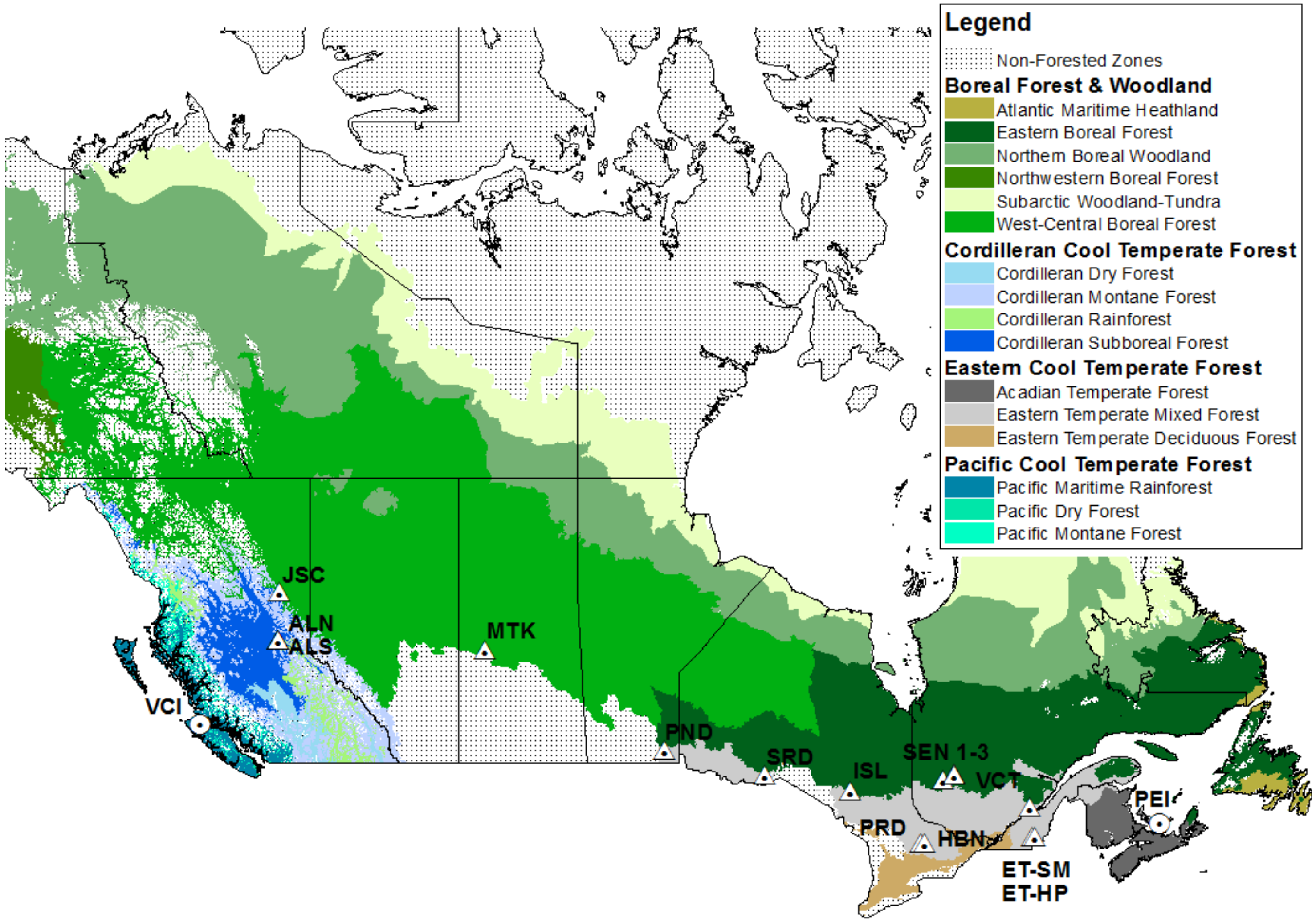

Figure 2.1.1 *Location of AshNet study sites (triangles), along with 2 historical ash amendment trials no longer being maintained (circles) across Canada in relation to the major forested Canadian National Vegetation Classification zones* (Canadian National Vegetation Classification [online] 2018). *Site short forms stand for Vancouver Island (VCI), Johnson Creek Site (JSC), Aleza Lake North & South (ALN & ALS), Mistik (MTK), Pineland (PND), 25th Sideroad (SRD), Island Lake (ISL), Porridge Lake (PRD), Haliburton (HBN), Senneterre 1-3 (SEN 1-3), Valcartier (VCT), Eastern Township Sugar Maple & Hybrid Poplar (ET-SM, ET-HP), and Prince Edward Island (PEI).*

4

AshNet trials have been established on different glacial deposits (glaciolacustrine – 3, glaciofluvial – 3, and morainal tills – 6) resulting in a range of soil textures (silty clay loams to sands) and soil orders. Soils from the Brunisolic order were the most common soil type studied, with a wide range in forest floor depths (0-15 cm) (Figure 2.1.2). Other soil orders under study include Luvisols, Gleysols, and Podzols with forest floor depths varying from moderate (5 - 10 cm), to deep (10 - 15cm) (Figure 2.1.2). There are no AshNet sites in forests with soils of the Organic order. In addition, fine textured soils, and soils with parent materials derived from Cumulose, Loess/Eolian sand, or Colluvium are unrepresented by the AshNet sites (See Appendix A for outline of individual study site characteristics).

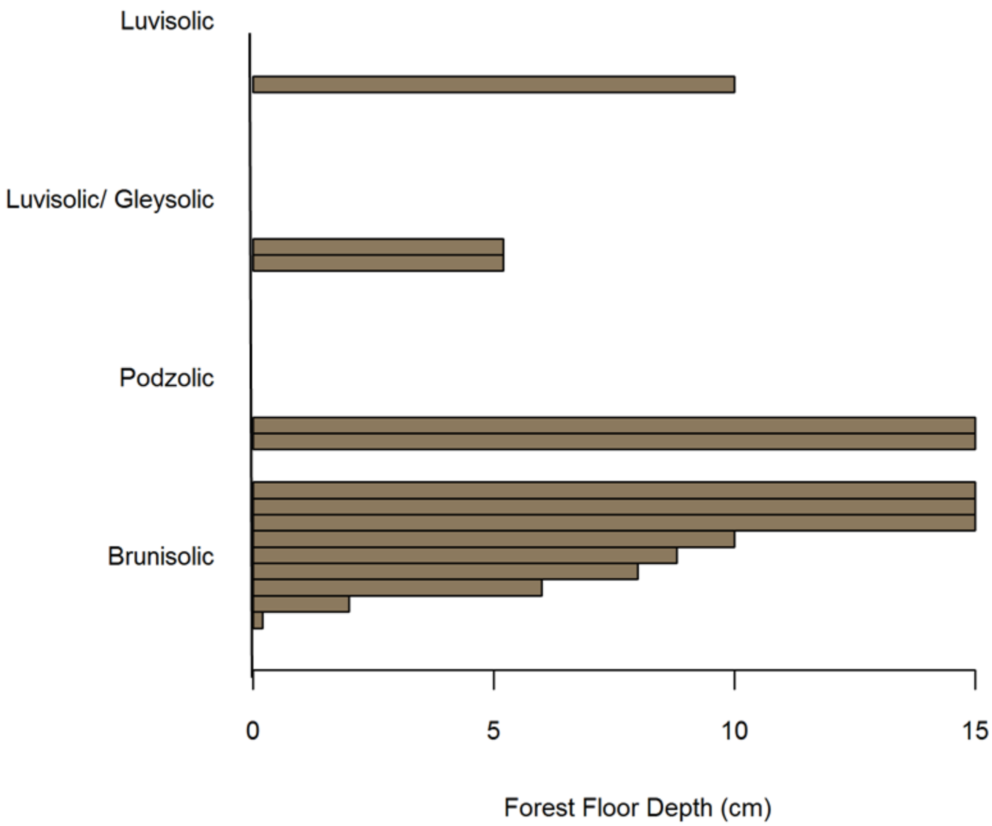

Figure 2.1.2 *AshNet study sites by soil order and forest floor depth. Each bar represents a unique study for each of the soil orders. The bar just above zero represents a Brunisolic soil with 0 cm of forest floor (25th Sideroad).*

A large number (10) of the sites were established in conifer-dominated stands, with only three sites established in mixed deciduous forests, and one in a hybrid poplar plantation. Jack pine (*Pinus banksiana*) represents the most common coniferous species, followed by spruce (white spruce (*Picea glauca)*, black spruce (*Picea mariana*), hybrid spruce (*Picea engelmannii* x *glauca*)), with age of stand at ash application varying from less than one year to fifty-three years (Figure 2.1.3). Across all AshNet study sites and tree species, half of the studies applied ash during seedling development (i.e. just before or after seedlings were planted, or before natural regeneration), and half of the sites applied ash to more mature stands that ranged in age from approximately 7-80 years (Figure 2.1.3). Not all of the AshNet stands under study were of even age at ash application reflecting the reality of uneven-aged stand forest management practices commonly used in Canada. For example, the Haliburton site is an uneven aged stand typical of single-tree-selection or shelterwood managed systems (See Appendix A for outline of individual study site characteristics). Future studies could further research the benefits of ash additions to uneven and even-aged stands that are in different stages of rotation (e.g., mid to late rotation).

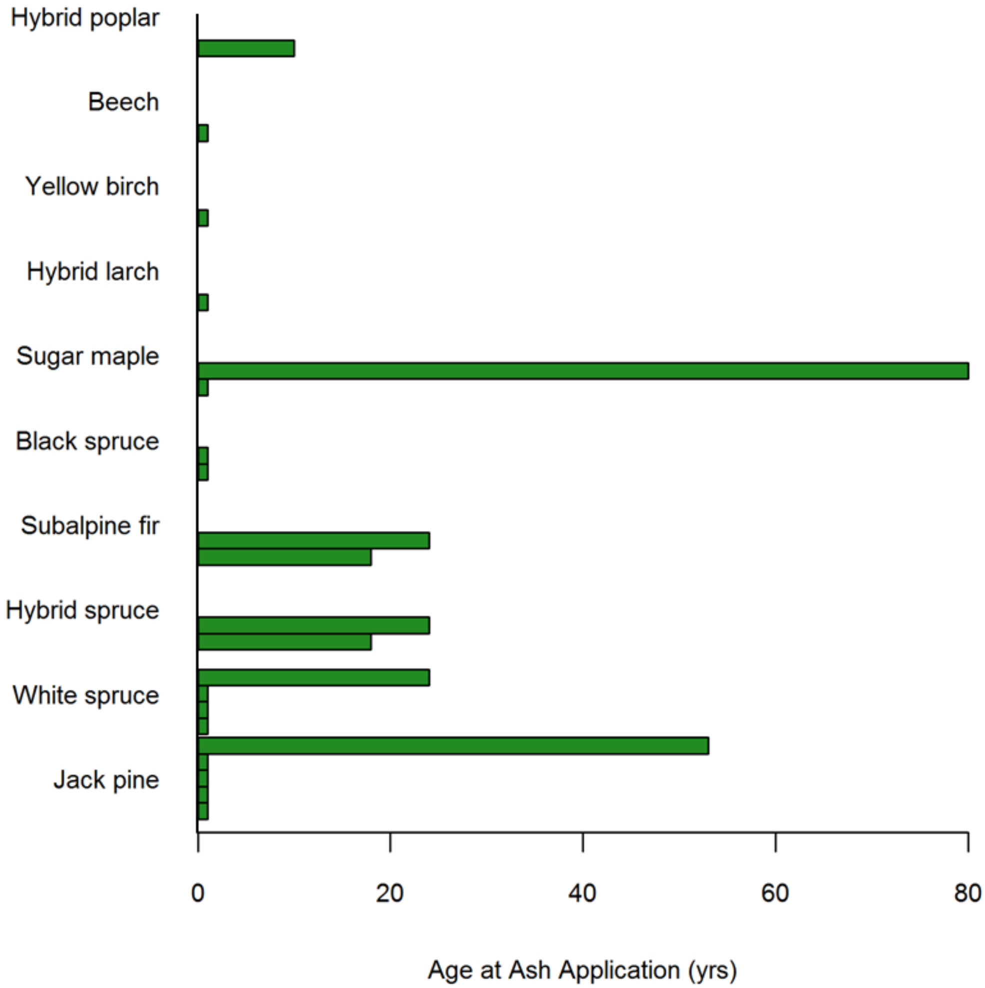

Figure 2.1.3 *AshNet study sites by main tree species and stand age at ash application. Each bar represents a unique study for each of the tree species. Bars just above zero represent newly planted (jack pine, white spruce, black spruce, hybrid larch) or regenerating stands (sugar maple, yellow birch, beech) less than one year old at ash application. Haliburton sugar maple, American beech, eastern hemlock, and yellow birch were not included due to a wide range in age at ash application attributed to management practices that maintain uneven-aged stands as part of harvest rotation.*

The focus of current AshNet studies is on the application of ash following harvest, with all but two studies (25th Sideroad old tree nursery – repeatedly tilled, and Johnson Creek – wildfire) having a history of clearcut, single tree selection cut, salvage cut or understory clearing (Figure 2.1.4). Additionally, some sites also have histories of fire prior to harvest (Senneterre 1-3), or were subjected to broadcast prescribed burn after harvest and prior to experimental set-up (Aleza Lake South). Across AshNet studies, the most common type of harvest was clearcut with ash being applied after different amounts of time had elapsed since clearcut (<1 year - 25 years) (Figure 2.1.4). Across all disturbance histories ash was applied immediately following (i.e. <1 year) disturbance at half of the sites, and between one and twenty-six years following disturbance at all other sites (See Appendix A for outline of individual study site characteristics). Given the potential for increased removal of nutrients following multiple harvest rotations, the potential for increased benefit of ash application to second and third rotation stands could be explored in future studies.

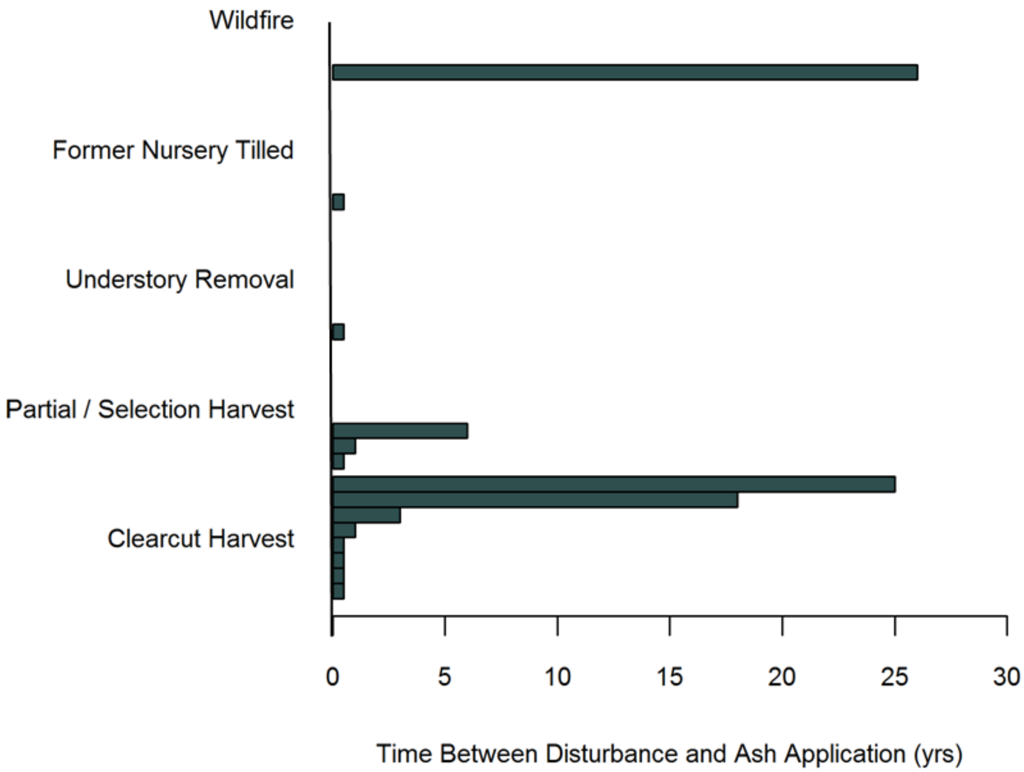

Figure 2.1.4 *AshNet study sites by disturbance history type and time between disturbance and ash application. Each bar represents a unique study for each of the different disturbance histories. Bars just above zero represent ash application less than one year following disturbance.*

2.2 Pre-ash-application measurements and experimental design

Pre-ash-application site characterization can provide a reference condition, along with quantitative evidence for soil and tree response when the same characteristics are collected post-ash-application. Almost all of the AshNet studies (n = 13 of 14) included some form of pre-ash-application measurements. Soil chemical properties, followed by forest stand characteristics were the most common types of data collected across AshNet study sites prior to ash application (Table 2.2.1), with the exception that forest stand characteristics were generally not collected prior to ash application at sites with harvest immediately prior to experiment establishment. Specifically, the most common pre-application site data collected included soil pH and stand basal area (Table 2.2.1). When soil chemical properties were determined, analyses tended to include total elements (92%), especially C and N and exchangeable or extractable nutrients and cations (85%), especially the exchangeable cations Ca, Mg, K, and Na. Less commonly, complete total elemental analysis (42%) and organic matter content (25%) were performed (Table 2.2.1). Five sites also collected soil physical properties and two sites collected information on the quantity and elemental content of downed woody debris (See Appendix B for site specific pre-application measurements).

Table 2.2.1 *Summary of pre-ash-application measurements taken across the 14 AshNet study sites.*

Measurement	AshNet studies with measurement	Range of measurements across studies	Most represented (% representation)
Forest stand	Studies with mature tree stands, or prior to harvest 64% - 9 of 14	Basal diameter, basal area, height, stem density, biomass of above ground wood + branch + bark + foliage of live and dead standing trees, species inventory	Basal area (56% - 5 of 9)
Downed woody debris	14% - 2 of 14	Above and below ground biomass, volume, decay class, and C,N,P, Ca, Mg and K contents (fine and coarse downed woody debris)	Above ground biomass (100% - 2 of 2)
Soil physical properties	36% - 5 of 14	Soil texture, forest floor thickness, particle size analysis, bulk density, coarse fragment content and texture	Bulk density (60% - 3 of 5)
Soil chemical properties	86% - 12 of 14	Soil pH, exchangeable acidity, electrical conductivity, cation exchange capacity, base saturation, total and plant available nutrients (N,P,S), inorganic N, total elements (Al, As, B, C, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Hg, Mo, Na, Ni, Se, Zn), organic matter (loss on ignition), organic and inorganic carbon, exchangeable base cations (Ca, Mg, K, Na), extractable elements/compounds (P, NH4, NO3, Fe, Al, Mn, Cu, Zn)	Soil pH (92% - 11 of 12)

Optimal ash application rates can be established by determining nutrient and alkalinity requirements of the receiving site in conjunction with a determination of the chemical-physical properties of the ash. Although ash characterization was conducted prior to the establishment of all field trials (e.g., to ensure acceptable concentrations of heavy metals), experimental application rates were not generally selected based on ash elemental concentrations of nutrients (i.e. Ca, K, Mg, P) or liming potential (i.e. $CaCO_3$ equivalent). Two exceptions were at the Island Lake site, where experimental ash was applied based on Ca application rates (kg/ha), and at Valcartier, where ash was applied based on the $CaCO_3$ equivalent. This is important to note because ash chemistries can vary widely depending on several factors, such as the type and source of feedstock (especially clean versus mixed fuels) and combustion conditions (Emilsson 2006). The type and source of feedstock used to generate ash for AshNet sites varied from effluent sludge to slash and from hardwood to softwood, but was most commonly made up of softwood species and included bark (Table 2.2.2). Additionally, ashes applied across studies were derived from different types of bioenergy facilities (most were industrial boilers, but one of the ashes used at the two Aleza Lake sites was from an updraft gasifier). As a result, different ashes applied at the same rate often had very different elemental application rates and liming potential. For example, Ca application rates varied from 84 to 970 kg/ha across study sites that applied ash at the same rate of 5 Mg/ha (Figure 2.2.1). Developing elemental application rates based on either the concentration of macronutrients in the ash or the capacity of ash to increase soil pH may be a good approach to account for these differences and optimize the desired benefit of application.

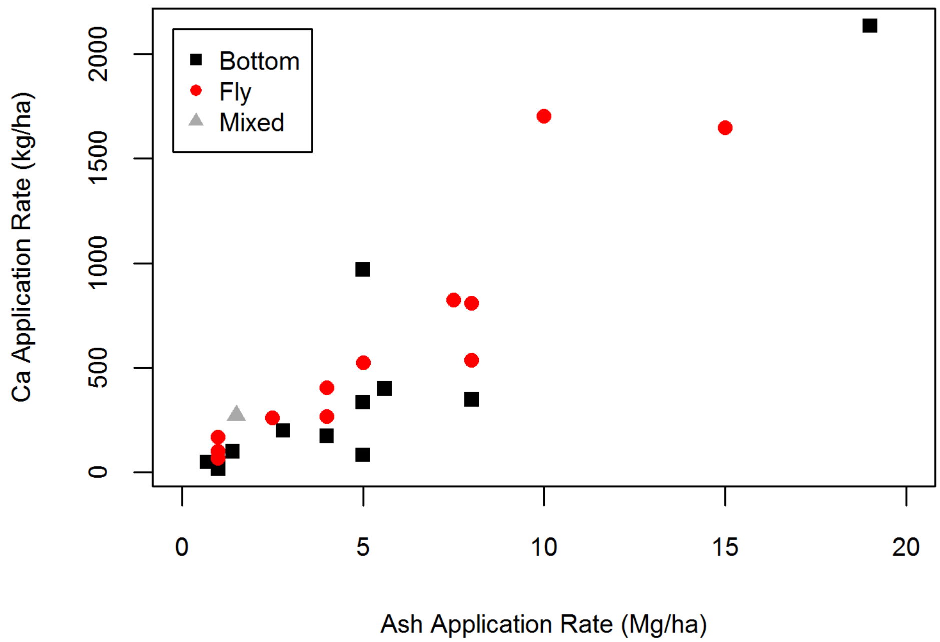

Figure 2.2.1 *Relationship between ash application rates (Mg/ha dry weight) and Ca application rates (kg/ha) across AshNet study sites. Black squares represent bottom ash, red circles fly ash, and the grey triangle a mix of fly and bottom ash.*

Other practical considerations have included the use of different ash sources (fly ash, bottom ash, or fly - bottom ash mixtures), as well as pre-treatment of the ash prior to application. Fly ash is made up of fine particles that are collected from the exhaust or flue gases following the combustion process, while bottom ash (sometimes called grate ash) is the ash that is collected under the boiler or gasifier (Emilsson 2006). In the AshNet studies 57 % applied bottom ash, 43 % fly ash, and one study applied a mix of fly and bottom ash (Table 2.2.2). In addition, one study (25th Sideroad) also applied a biochar-like ash. This treatment was defined as biochar-like due to its high carbon content and appearance that resembled true biochar, but that was produced in a low temperature boiler rather than by pyrolysis (Sevean 2014).

Both fly and bottom ash chemistries can vary greatly based on combustion temperature, airflow, and type of feedstock (Hannam et al. 2018); but in general, fly ash has the potential to accumulate greater concentrations of the more volatile elements (Emilsson 2006). A recent effort to catalogue and compare ash chemistries from different biomass boilers across Canada shows that fly ash can, although not always, have a more alkaline pH and contain greater concentrations of the elements K, Ca, S, Cd, Mo, Se, Ni, and Zn (Natural Resources Canada 2018b). The database also shows that there is variability in elemental concentrations from one boiler to the next when comparing fly and bottom ash (Natural Resources Canada 2018b).

Table 2.2.2 *Summary of experimental approaches across the 14 AshNet study sites including study design and ash application.*

Characteristic	Range of characteristics across studies	Most represented (% representation)
Study design	Randomized complete/incomplete block design, split plot design, complete random design	Randomized complete block design (57%)
Size of plots	0.0008 - 5 ha	< 0.05 ha (57%)
Replicate number	3-12 (plots)	3 (43%)
Additional treatments	Urea/fertilizer, deer exclosures, paper biosolids, herbicide weed control, lime, soil scarification	Urea/fertilizer (50%)
Ash pre-treatment	None, self-hardened & crushed	None (93%)
Ash feedstock	Chips, sawdust, bark, shavings, sawmill residues, de-watered paper sludge, effluent sludge, construction and demolition debris	Bark (86%)
Ash source	Softwood (unidentified mix, spruce-pine-fir, jack pine, black spruce, balsam fir), hardwood (unidentified mix, trembling aspen), softwood hardwood mix	Softwood (92%)
Ash type	Fly ash, bottom ash, fly ash-bottom ash mix, biochar-like ash (high carbon ash, produced at low temperatures & not via pyrolysis)	Bottom ash (57%)
Ash application rates	0.7 Mg/ha - 19 Mg/ha dry weight (20 Mg/ha fresh weight)	≤ 5 Mg/ha (43%)
Ash application methods	Hand-applied to surface (e.g., using shovel), hand-applied & raked into top 10 cm, mechanical spreader to surface	Hand-applied to surface (57%)

For the AshNet sites established to date, ash pre-treatment or stabilization has not been a common practice. Mistik is the only site where ash was pre-treated by crushing after ash had self-hardened during storage. Along with self-hardening and crushing, other forms of pre-treatment can include pelletization and granulation. Pre-treatment prior to application may be an important practical consideration when applying ash at operational scales (e.g., health concerns associated with airborne particles during transport and application, uniform distribution), along with the effectiveness of ash as an amendment (e.g., stable rate of elemental release, influence on soil physical characteristics such as moisture retention) (Steenari et al. 1999, Emilsson 2006, Hannam et al. 2016).

At the AshNet study sites, ash was applied either manually (e.g., by using buckets and shovels) or by mechanical spreaders to plots that varied in size from 0.0008 to 5 ha. In addition, one study (Eastern Township Hybrid Poplar) applied ash as a slurry by combining the ash with biosolids. Ash was almost always applied to the surface of the forest soil, with only one study mixing the ash into the top 10 cm of the forest floor following application (25^{th} Sideroad). Ash application rates have been moderate according to dosage recommendations in Europe (Hannam et al. 2016), most commonly being < 5 Mg/ha and not exceeding 19 Mg/ha in dry weight or 20 Mg/ha fresh weight (Table 2.2.2).

Randomized complete block designs have been the most common study design, being applied at more than half of the AshNet study sites to date. In these cases, multiple blocks contain all treatments applied at *a priori* locations across the experimental sites (e.g., accounting for within-site variations in slope, soil conditions, etc.). More complex split-plot designs have also been utilized to test additional factors (i.e. vegetation and herbivore control or tree species subplots). In some cases, incomplete randomized block designs or complete random designs have also been established. All studies included control plots (plots where no ash was applied) in their experimental design, and some studies included additional treatments to look at the influence of ash amendments when applied in combination with inorganic N fertilizer (an essential plant macronutrient found in low concentrations in ash) (See Appendix C for individual site experimental set-up details).

2.3 Post-ash-application measurements

Post-ash-application measurements of forest stand characteristics and soil chemical properties have been the focus of all AshNet studies. To date, established AshNet experiments are relatively young, with experiments having run for up to 11 years following ash application, except for Mistik that was established in 1995 and has been re-measured at 21 years following ash application.

Common across all sites, tree growth has been measured at the time of application (Time 0) and over time after ash application. Controls (no ash application) have also been re-measured. Seedling measurements typically included survival, height, and root collar diameter, while mature tree growth included diameter at breast height (Table 2.3.1). Foliar nutritional analysis has also been done in all but two of the study sites to assess the influence of ash application on tree nutrient uptake. Only one site (Johnson Creek) collected pre- and post-ash-application foliar nutrient measurements, while all other sites focused on the differences in foliar nutrient concentrations between control and treatment plots for the assessment of ash effects. This foliar elemental analysis focuses on total C and macronutrients N, P, Ca, Mg, S, and K, but other elements have also been included in some studies (eg., Al, B, Cu, Fe, Mn, Zn) (Table 2.3.1). Other vegetation characteristics measured have included root and shoot biomass and nutrients, along with characterization of understory vegetation percent cover, biomass, and composition, and percent cover and solar radiation measurements (Table 2.3.1).

The most common soil chemical properties collected following the ash applications included: alkalinity and pH, exchangeable cations, total C and N, and available P (Table 2.3.1). Other soil characteristics collected included total elemental analysis, exchangeable acidity, organic carbon, base saturation, cation exchange capacity, electrical conductivity, and bulk density. A few studies have also analyzed soil solution chemistry to examine nutrient and metal concentrations in soil water leachate (See Appendix D for site specific post-application measurements).

Table 2.3.1 *Summary of post-ash-application measurements taken across the 14 AshNet study sites.*

Measurement	AshNet studies with measurement	Range of measurements across studies	Most represented (% representation)
Forest stand	93% - 13 of 14	Survival, health, height, height increment, diameter (root collar diameter, basal, or diameter at breast height), biomass, foliar elements (C, N, P, S, Ca, Mg, K, Al, B, Cu, Fe, Mn, Zn), needle mass, root and shoot biomass, root and shoot nutrients, tree inventory	Diameter (100% - 13 of 13), foliar nutrients (92% - 12 of 13), height (69% - 9 of 13)
Understory	50% - 7 of 14	Species diversity, species composition, percent cover, stocking, biomass, root and shoot biomass of weeds, seedlings (counts, height, stem elongation), percent cover, light measurements	Species composition (57 % - 4of 7), percent cover (57% - 4 of 7)
Downed woody debris	14% - 2 of 14	Above and below ground biomass, volume, decay class, and C,N,P, Ca, Mg and K contents (fine and coarse downed woody debris)	Above ground biomass (100% - 2 of 2)
Carbon & nutrient stocks	29% - 4 of 14	C, N, P, Ca, Mg and K content of above or above and below ground including downed woody debris, coarse roots, forest floor, mineral soil, and tree stocks	NA
Soil chemical properties	100% - 14 of 14	Soil pH, exchangeable acidity, electrical conductivity, cation exchange capacity, base saturation, total and plant available nutrients (N,P,S), inorganic N, total elements (Al, As, B, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Hg, Mo, Na, Ni, Pb, Se, Zn), organic matter (loss on ignition), organic and inorganic carbon, exchangeable base cations (Ca, Mg, K, Na), extractable elements/compounds (P, NH4, NO3, Fe, Al, Mn, Cu, Zn)	Soil pH (93% - 13 of 14)
Soil solution chemistry	29% - 4 of 14	Nutrient and heavy metal concentrations, pH, C, (at 15, 30, 50, 60 or 100 cm) by lysimetry, or partially by PRS probes	Nutrients & heavy metals (75% - 3 of 4)
Soil biota	36% - 5 of 14	Soil microorganisms (biomass, respiration, enzyme assays, community composition, bacteria, fungi, protozoa), soil fauna (springtails, mites, round worms, red-backed salamanders), epigaeic fauna (ground beetles, spiders, rove beetles, millipedes, ants)	Soil microorganisms (80% - 4 of 5)

The potential influence of ash addition on soil biota (e.g., diversity, abundance, community structure) has also been investigated at five different AshNet study sites. The biota examined in these studies included soil microbial communities, soil fauna from mites to salamanders, and various epigaeic fauna (Table 2.3.1). There is also a joint project currently underway looking to examine the effect of ash applications on soil biodiversity, including soil invertebrates and fungi collected across different AshNet sites. These multi-taxa examinations will help improve our understanding of any potential negative effects of ash application to forest biota and ecosystem function. Opportunities also exist to evaluate the impacts of run-off and ground water leachate following ash applications on hydrologically-connected stream and lake water chemistry, and aquatic communities. It has been shown that increased nutrients and ions in run-off and ground water following forest fires can influence water quality and aquatic biota (Earl and Blinn 2003, Mast et al. 2016).

3.0 Considerations and Recommendations

3.1 Practical considerations

Wood ash production, storage, pre-treatment, application methods and application site location are important considerations for any ash application experiment, as these factors can influence the potentially detrimental and/or beneficial effects of ash amendments. Different feedstock sources (i.e. tree species, salt-laden wood) and type (e.g., bark, sawdust, shavings, clean versus containing other materials), along with combustion conditions (i.e. temperature, airflow), influence the quality of ash as an amendment product. Research seeking to understand which **feedstock and combustion conditions result in the highest quality ash** has been conducted in Europe (Emilsson 2006) and could be further explored to allow for greater consistency in the chemical properties of ash as a by-product of bioenergy production in Canada (Hannam et al. 2017).

Storage of ash prior to application is also an important consideration as highly concentrated leachate from large quantities of stored ash can present an environmental hazard and long-term storage can result in changes to ash quality by changing ash chemical (e.g., loss of plant micro and macronutrients via leaching and microbial processes) and physical (e.g., self-hardening into clumps) properties (Etiégni and Campbell 1991, Steenari et al. 1999). These changes in ash physical properties, in turn, can result in the need for additional treatments, like crushing of ash prior to application, to ensure adequate application and uniform release of plant nutrients from ash to forest soils. Other pre-treatment options that are utilized in Europe to improve soil physical (e.g., soil moisture retention) and chemical (e.g., slow plant nutrient release over time) properties following ash application include pelletization and granulation, and represent important areas for operationally-based application research in Canada (Emilsson 2006, Hannam et al. 2016).

The **location and scale of ash-application** remains an important consideration as ultimately the overall objective is to determine the viability of ash application at operational scales. Current experiments are not yet operational, but are located in stand and ecosystem types that are candidates for ash application in the future. Specifically, the study of ash application to stand and ecosystem types that are candidates for harvest, sensitive to nutrient depletion, can benefit from increased soil pH, and that are potentially located near facilities producing ash should be prioritized as these are the most economically viable and represent the most likely ash application sites for operational applications. Additionally, methods for application of ash at an operational scale also represent important considerations, as the majority of research studies and applications in Canada have only applied ash by hand (i.e. using buckets and shovels), or by mechanical spreader to ≤5 ha. Future research needs to build on the current operational scale methods being utilized (e.g. in Europe and in southern Quebec) to refine larger scale application methods for use across Canada. The potential of winter ash application is a topic raised by some land managers and should be explored.

Deciding on **ash application rates** has generally been based on heavy metal concentrations (i.e. to ensure safe metal loadings to receiving sites) and typical experimental doses (e.g., from the literature, other studies, or other jurisdictions, such as Europe), and less on actual ash plant-available nutrient concentrations (i.e. demand and supply of nutrients) or soil lime requirement. Future studies might consider quantifying the concentrations of plant macro- and micro-nutrients in ash along with soil lime requirement (i.e. $CaCO_3$ equivalent), to help select optimal application rates that will benefit tree growth and productivity via nutrient replacement or increased soil pH.

3.2 Experimental design and measurement recommendations

The experimental design for any specific ash-application study should be chosen based on the objectives of the experiment, as the objectives will dictate the appropriate scale of the experiment as well as the type and duration of pre-and post-ash-application monitoring. For example, different objectives for ash-application experiments might target different endpoints and fall broadly under assessing the ability of ash application to emulate natural disturbance (wildfire), or benefit tree-growth and productivity.

Preferably, to evaluate the effects of ash application, the use of **control plots within a randomized complete block design** are recommended because this design allows for control and treatment plots to be compared through time while accounting for *a priori* variations in site conditions (e.g., slope, topography, moisture, etc.). A buffer zone is also recommended to ensure that treatments from one plot do not overlap with the next plot. Additionally, increased replication will allow for increased ability to tease out difference between plots, by better accounting for variability in conditions within sites and across plots. Other more complex designs, such as split-plot or fractional factorial designs, can also be effective depending on the suite of questions being addressed. To more thoroughly assess aquatic impacts of ash application, watershed or catena level experiments should be considered. To date, the variables that best capture the potential beneficial influence of ash amendment through time relate to **plant nutrient availability** (e.g., soil exchangeable cations, total N, and available P), **soil pH, and tree growth**. In addition, **foliar elemental analysis** allows for tracking the beneficial effects by providing a rapid response measure of changes in tree foliar nutrient status following ash amendment.

Along with the beneficial effects of ash, the **potential detrimental effects of ash application** should be monitored by assessing **heavy metal concentrations,** along with dioxins and furans where applicable (found in ash derived from contaminated wood or wood exposed to seawater), in ash prior to application and by monitoring the influence of ash amendment on **soil biota**, **soil leachate**, **stream chemistry and aquatic biota**, and **tree growth**. Analyzing initial ash chemistry can also be informative with respect to identifying likely sources of heavy metal and plant nutrient concentrations (i.e. fly ash, bottom ash, or combined fly and bottom ash). Initial ash chemistry analyses should be based on replicate samples to properly capture any variability within the ash source.

Across the AshNet studies to date, effects of ash amendment on forest stands has been measured over a relatively short time frame, with most from less than one to eleven years and only one study up to twenty-one years. Observing the effects of ash application over longer time periods should be prioritized to assess how long-lasting the effects of ash amendment are, if these effects change over time, and if a re-application timeline can be identified. It should be noted that in order to achieve long-term monitoring, the size of plots must be large enough to keep the different treatments from overlapping as the trees grow. Additionally, building on the current ash application trials across Canada, future research should focus on gaining a better understanding of the key ash and site characteristics that optimize (capitalize on) the beneficial and safe application to different forest soils and stand types, as this determination is critical for the successful implementation of ash application at an operational scale through the development of provincial-level forest policies.

3.3 Key recommendations and considerations

- **Select study sites** in locations and ecosystem types that have a recognized potential for future wood ash application (e.g., site or ecosystem subject to harvest, sensitive to harvest removals such as nutrient poor sites or second or third harvest rotation sites, sites with high nutrient demands such as mid-rotation stands, sites with tree species that would benefit from increased soil pH such as sugar maple in mixed stands, and sites near to biomass boilers).

- **Design experiments** that include control plots in a randomized complete block design, split-plot design, watershed or catena studies or other variations based on core experimental questions and objectives (e.g., emulating natural disturbance, increasing tree growth) and individual site considerations.
- **Assess wood ash quality** for heavy metal concentrations and dioxins and furans where applicable (Hannam et al. 2016), but also plant nutrients, $CaCO_3$ equivalent, and pH to help determine optimal **ash elemental application rates** and type of ash to be applied (i.e. fly, bottom, or a mix of fly and bottom).
- **Investigate ash storage, pre-treatment, and application methods.** This is especially important as the application experiments increase in size and scope towards an operational scale.
- Evaluate the suitability of sampling techniques, frequency of sampling, and length of time since ash application to thoroughly determine the effects on **soil nutrients, soil pH, and forest stand productivity and health.**
- **Measure** the influence on **soil biota and at watershed scale on hydrologically connected aquatic biota** (e.g., microbial communities, invertebrates) to assess potential impacts on the ecosystem.

4.0 Individual Site Summaries

4.1 Johnson Creek Wood Ash Trial

Climate

(1981-2010 monthly climate point estimates, modelled as described at:
http://cfs.nrcan.gc.ca/projects/3/1)
Mean annual precipitation: 555 mm
Mean minimum temperature in January: -15.2 °C
Mean maximum temperature in July: 21.4 °C

Site Description

Prior to establishment of the experiment, the site supported a second growth white-spruce-dominated stand mixed with balsam poplar (*Populus balsamifera*), paper birch (*Betula papyrifera*), and lodgepole pine (*Pinus contorta*). The soils developed from glaciofluvial veneer deposits and have a silt loam over clay loam texture. The soils are Brunisolic Grey Luvisols with a forest floor thickness of 6 cm.

Ash Description

The ash used for the Johnson Creek Wood Ash Trial was collected from biomass burner multicones at the Chetwynd Forest Industries West Fraser co-generation plant in Chetwynd, BC. The ash feedstock was comprised of softwood bark, shavings and sawdust. The ash used for the experiment was predominantly fly ash and was not pre-treated prior to application.

Treatment Description

Prior to plot establishment, the Johnson Creek site experienced conifer rehabilitation in 1987 and wildfire in 1991. Planting with white spruce (and to a lesser extent lodgepole pine) occurred in 1993 at a density of 2400 trees ha^{-1}. Four different treatments were applied in June of 2017 including a control (no ash or urea), ash at a rate of 5.0 Mg ha^{-1}, urea at a rate of 100 kg N ha^{-1}, and ash at a rate of 5.0 Mg ha^{-1} + urea at a rate of 100 kg N ha^{-1}. Ash application rates were calculated on a dry weight basis and applied to the soil surface by hand. Treatment and control plots were replicated three times.

Status

Monitoring of treatment effects on trees and soil chemistry is ongoing.

Main Contact

Richard Kabzems, Research Silviculturist, BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development

4.2 Aleza Lake Research Forest Wood Ash Trial (N&S)

Climate

(1981-2010 monthly climate point estimates, modelled as described at: http://cfs.nrcan.gc.ca/projects/3/1).

Mean annual precipitation: 714 mm (north site); 719 mm (south site)
Mean minimum temperature in January: -12.2 °C
Mean maximum temperature in July: 23.1 °C (north site); 22.9 °C (south site)
[See note: 2005 ALRF management plan (p. 21) at http://alrf.unbc.ca/?page_id=17
Mean annual ppt 895 mm; mean min temp in January ~ -9C; mean max temp in July 32.2 C]

Site Description

The two sites (~2.5 km apart) are located in the Sub-Boreal Spruce (SBS) B.C. Biogeoclimatic Zone and wk1 Subzone. Prior to establishment of the experiment, each site was clearcut (south site: winter 1989/1990; north site: winter 1996/1997). The south site was subjected to an intense broadcast burn in September 1990. At the time of establishment, each site supported a planted 24-year-old (south site) or 18-year-old (north site) hybrid spruce plantation, plus naturally regenerated species (e.g., Douglas fir, lodgepole pine, western hemlock, trembling aspen, paper birch, cottonwood). The soils at both sites developed on glaciolacustrine deposits and have a silty clay loam to clay texture; they are predominantly Gray Luvisols with associated Luvic Gleysols with a ~5.2 cm forest floor layer.

Ash Description

Two ash types were used at the Aleza Lake Wood Ash Trial: (1) bottom ash produced in the Nexterra updraft gasifier at the UNBC bioenergy plant, or (2) bottom ash produced in a fixed bed boiler at one of Canfor Pulp Limited Partnership's (CPLP) facilities in Prince George, BC (PG Pulp Boiler #2). In both cases, the ash feedstock was clean softwood residues (wood chips, bark and/or sawdust). Only bottom ash was used for the experiment (the UNBC gasifier also produces fly ash) and the ash was not pre-treated prior to application. But, the UNBC gasifier ash was wetted in October 2014 and stored moist in a covered bin until it was used in May 2015.

Treatment Description

A randomized block design was employed at each of the two sites. At each site, there were three ash treatments (0 (control), 5 Mg UNBC gasifier ash ha^{-1} or 5 Mg CPLP boiler ash ha^{-1}) x 2 urea treatments (0 (control) or 100 kg urea-N ha^{-1}) x three blocks (replicates), for a total of six treatment combinations distributed over 18 individual plots. Circular plots (8.0 m radius) were staked out in the summer of 2014; ash and fertilizer treatments were implemented in late May 2015. Ash application and fertilizer were applied manually using a shovel; ash application rates were based on a dry ash basis.

Status

Monitoring of treatment effects on trees and soil chemistry is ongoing.

Main Contact

P. Michael Rutherford, Professor, University of Northern British Columbia

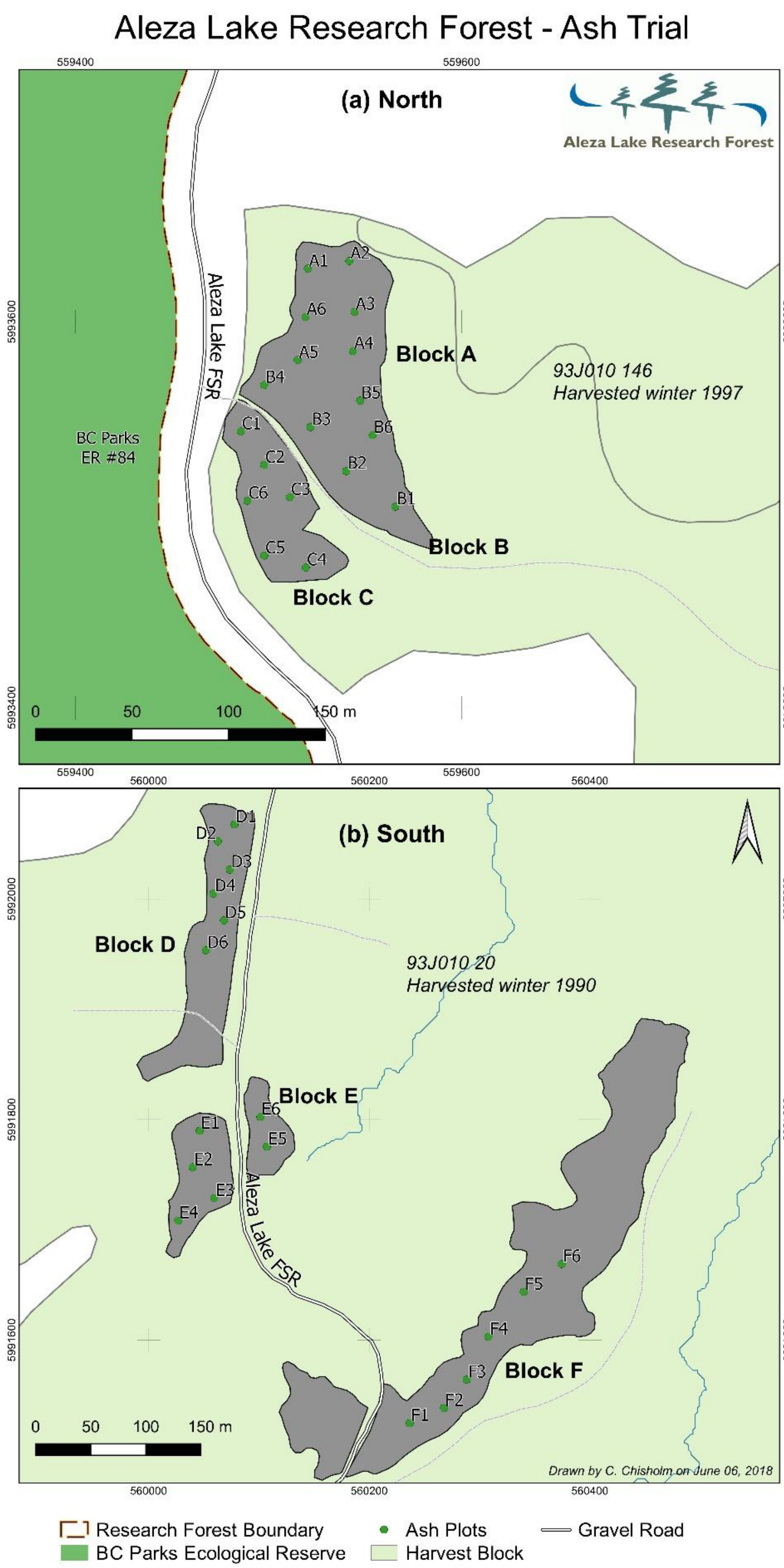

Figure 4.2.1 *Aleza Lake Research Forest North (a) and South (b) wood ash amendment experimental set-up.*

4.3 Mistik (Burness Rd) Wood Ash Trial

Climate

(1981-2010 monthly climate point estimates, modelled as described at: http://cfs.nrcan.gc.ca/projects/3/1)
Mean annual precipitation: 431 mm
Mean minimum temperature in January: -22.2 °C
Mean maximum temperature in July: 22.4 °C

Site Description

Prior to establishment of the experiment, the site supported a 60-69-year-old stand of trembling aspen (*Populus tremuloides*) and white spruce. Soils are Orthic Gray Luvisols that developed from ablation moraine. They have a clay loam texture with pockets of sandy loam, and are moderately to excessively stony.

Ash Description

The ash used in the Mistik (Burness Rd) Wood Ash Trial was produced in an olivine burner at the Millar Western Mill in Meadow Lake, SK. The ash feedstock was 85% trembling aspen bark and chips and 15% de-watered pulp sludge. Only bottom ash was used for this experiment. Because the ash had self-hardened during storage outdoors, it was crushed prior to application.

Treatment Description

The site was clearcut using full-tree harvesting in the winter of 1995 and disc-trenched in May 1995. In late June/early July of that year, white spruce seedlings were planted at a density of ~6944 stems ha^{-1}. After planting, ash was applied at three rates: 0 Mg ash ha^{-1} (control); 1 Mg ash ha^{-1}; or 5 Mg ash ha^{-1}. Application rates were calculated on a dry weight basis and ash was applied to the soil surface by hand. Treatments were replicated three times.

Status

This site is being monitored for long-term effects.

Main Contact

Ken Van Rees, Professor, Department of Soil Science, University of Saskatchewan

4.4 Pineland Wood Ash Trial

Climate

(1981-2010 monthly climate point estimates, modelled as described at: http://cfs.nrcan.gc.ca/projects/3/1)

Mean annual precipitation: 635 mm

Mean minimum temperature in January: -22.5 °C

Mean maximum temperature in July: 25.0 °C

Site Description

Prior to establishment of the experiment, the site supported a ~30-year-old jack pine stand. The soils developed from glaciofluvial deposits and have a sandy texture; they are predominantly brunisols with ~2 cm forest floor layer.

Ash Description

The ash used for the Pineland Wood Ash Trial was produced in a biomass burner at the Pineland Forest Nursery in Hadashville, MB. The ash feedstock was predominantly jack pine wood chips, with some bark. A mixture of fly and bottom ash was used for the experiment and the ash was not pre-treated prior to application.

Treatment Description

Prior to plot establishment, the Pineland Wood Ash Trial was clearcut using whole-tree harvesting. In May 2015, four ash + urea treatments were applied in a factorial design. Treatments included: 0 Mg ash ha^{-1} (control) or 1.5 Mg ash ha^{-1} and 0 kg urea ha^{-1} (control) or 70 kg urea ha^{-1}. Ash application rates were calculated on a dry weight basis and ash was applied to the soil surface by hand. Treatments were replicated five times. In May 2015, jack pine seedlings were planted at a density 2500 stems ha^{-1}.

Status

Monitoring of treatment effects on trees, understory vegetation and soil chemistry is ongoing.

Main Contact

John Markham, Professor, Department of Biological Science, University of Manitoba

4.5 25th Sideroad Nursery Wood Ash Trial

Climate

(1981-2010 monthly climate point estimates, modelled as described at: http://cfs.nrcan.gc.ca/projects/3/1)
Mean annual precipitation: 694 mm
Mean minimum temperature in January: -19.2 °C
Mean maximum temperature in July: 23.8 °C

Site Description

This site was established on a former tree nursery compartment. The soils developed on glaciofluvial outwash and have a sandy loam texture. The soils are Orthic Eutric Brunisols with no forest floor layer (because the site had been repeatedly tilled).

Ash Description

The ash used at the 25th Sideroad Nursery Wood Ash Trial was produced in a vibrating grate power boiler at the Resolute Forest Product's facility in Thunder Bay, ON. The ash feedstock was primarily softwood bark, sawdust and wood chips, with 8-14% secondary effluent sludge. Two ash-like materials were applied: (1) fine-textured, grey, low-carbon fly ash and (2) coarse-textured, black, high-carbon biochar-like fly ash. The biochar-like ash was produced at a lower temperature. Neither ash type was pre-treated prior to application, but the biochar-like ash had been stored outdoors for three years.

Treatment Description

In May 2012, nine ash + biochar treatments were applied in a factorial design, with five blocks. Nine treatments were included that represent paired combinations of: 0 Mg low-carbon ash ha^{-1} (control); 1 Mg low-carbon ash ha^{-1}; or 10 Mg low-carbon ash ha^{-1}; and 0 Mg biochar ha^{-1} (control); 1 Mg biochar ha^{-1}; or 10 Mg biochar ha^{-1}. Application rates were calculated on a dry weight basis; ash was applied by hand and raked into the soil surface. Immediately following treatment application, half of each plot (split plot) was planted with white spruce or black spruce; the border of each plot was planted with jack pine. Seedlings were planted at a density of 25 600 stems ha^{-1}.

Status

Monitoring of treatment effects on trees, understory vegetation, soil chemistry and soil microbes is ongoing.

Main Contact

Amanda Diochon, Associate Professor, Department of Geology, Lakehead University

4.6 Island Lake Biomass Harvest Experiment

Climate

(1981-2010 monthly climate point estimates, modelled as described at: http://cfs.nrcan.gc.ca/projects/3/1)

Mean annual precipitation: 927 mm

Mean minimum temperature in January: -20.6 °C

Mean maximum temperature in July: 23.1 °C

Site Description

Prior to establishment of the experiment, the site supported a second growth, ~40 year-old jack pine stand that had regenerated after a conventional clearcut. The soils developed from glaciofluvial deposits, and have a sandy to sandy loam texture. The soils are predominantly Eluviated Dystric Brunisols with a ~10 cm forest floor layer.

Ash Description

The ash used in the Island Lake Biomass Harvest Experiment was produced at the Tembec co-generation plant in Chapleau, ON. The ash feedstock was predominantly jack pine and black spruce bark, shavings and sawdust. Only bottom ash was used for the experiment, and the ash was not pre-treated prior to application.

Treatment Description

In December 2010/January 2011, the site was clearcut using full-tree harvesting with biomass removal. All harvesting residues were removed. In October 2011, ash was applied at five rates: 0 Mg ha^{-1} (control); 0.7 Mg ha^{-1}; 1.4 Mg ha^{-1}; 2.8 Mg ha^{-1} or 5.6 Mg ha^{-1}. Application rates were calculated on a dry weight basis; ash was applied to the soil surface by hand. Treatments were replicated four (ash-treated plots) or five (control plots) times. In May 2012, jack pine seedlings were planted at a density of 2645 stems ha^{-1}; the site was fill-planted in May 2013.

Status

Monitoring of treatment effects on trees and understory vegetation, soil and soil solution chemistry and soil biota is ongoing.

Main Contact(s)

Dave Morris, Research Scientist, Ontario Ministry of Natural Resources and Forestry

Paul Hazlett, Research Scientist, Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre

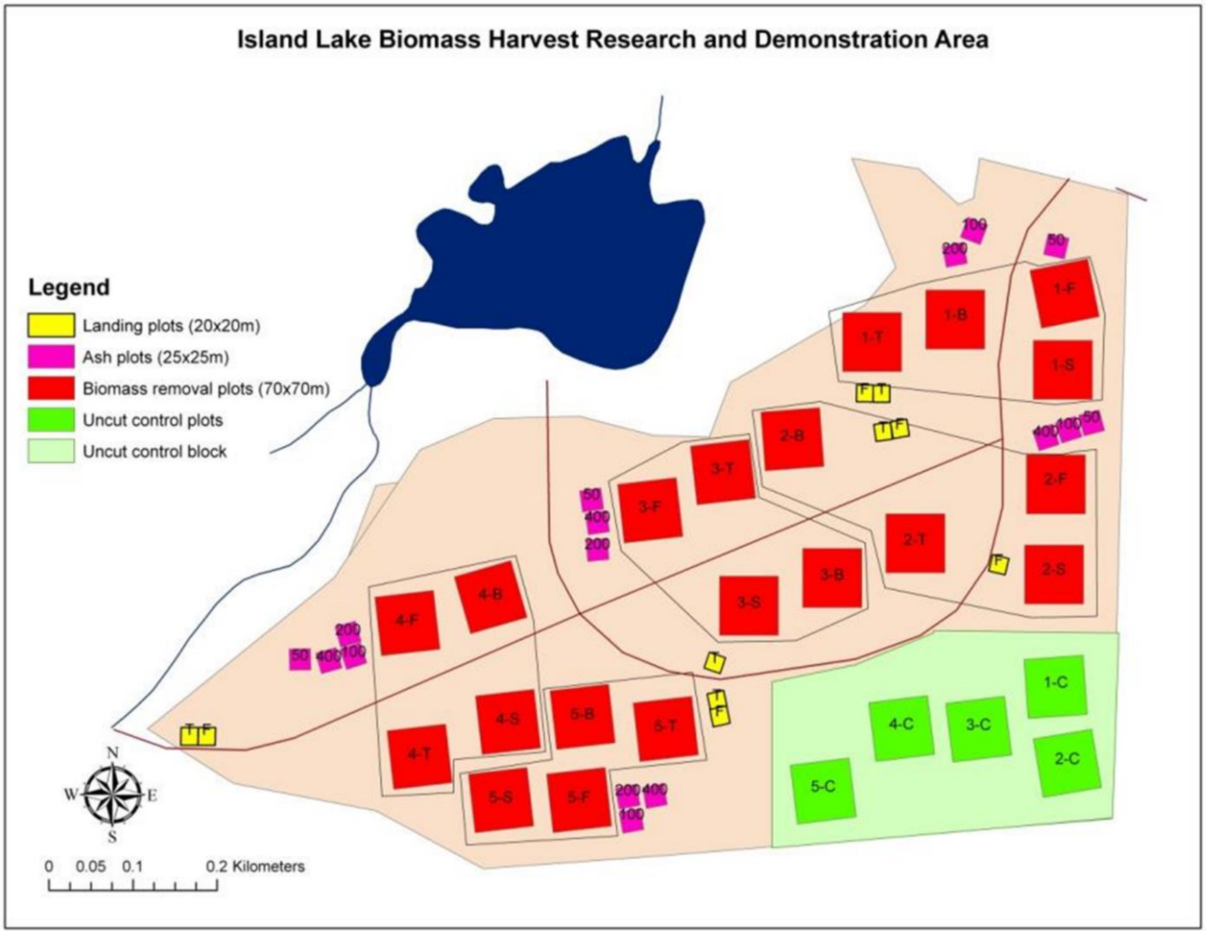

Figure 4.6.1 *Island Lake Biomass Harvest experimental set-up.*

4.7 Haliburton Wood Ash Trial

Climate

(1981-2010 monthly climate point estimates, modelled as described at: http://cfs.nrcan.gc.ca/projects/3/1)
Mean annual precipitation: 1074 mm
Mean minimum temperature in January: -17.0 °C
Mean maximum temperature in July: 24.7 °C

Site Description

Prior to establishment of the experiment, the site was managed using single-tree selection followed by salvage cutting of American beech (*Fagus grandifolia*), and supported an uneven-aged mixed deciduous stand of sugar maple (*Acer saccharum*), American beech, eastern hemlock (*Tsuga canadensis*) and yellow birch (*Betula alleghaniensis*). The soils have developed from poorly weathered granite or granitic gneiss deposits over Precambrian Shield, and have a sandy loam texture. The soils are Orthic or Eluviated Dystric Brunisols with a 5-8 cm forest floor layer.

Ash Description

The ash used at the Haliburton Wood Ash Trial was produced in a vibrating grate biomass boiler at a pulp and paper mill. The ash feedstock was spruce/pine/fir bark generated during the de-barking stage of the pulp production process. Bottom ash and fly ash were used for the experiment; neither ash type was pre-treated prior to application.

Treatment Description

Seven ash treatments were applied in August/September 2013. Treatments included: 0 Mg ash ha^{-1} (control); 1 Mg fly ash ha^{-1}; 4 Mg fly ash ha^{-1}; 8 Mg fly ash ha^{-1}; 1 Mg bottom ash ha^{-1}; 4 Mg bottom ash ha^{-1}; and 8 Mg bottom ash ha^{-1}. Application rates were calculated on a dry weight basis; ash was applied to the soil surface by hand. Treatments were replicated four times.

Status

Monitoring of treatment effects on trees, soil and soil solution chemistry and soil biota is ongoing.

Main Contact(s)

Nathan Basiliko, Professor, Department of Biology and the Vale Living with Lakes Centre, Laurentian University

Trevor Jones, Research Scientist, Ontario Ministry of Natural Resources and Forestry, Forest Research and Monitoring Section

4.8 Senneterre 1 Wood Ash Trial

Climate

(1981-2010 monthly climate point estimates, modelled as described at: http://cfs.nrcan.gc.ca/projects/3/1)
Mean annual precipitation: 992 mm
Mean minimum temperature in January: -24.1 °C
Mean maximum temperature in July: 22.5 °C

Site Description

Prior to establishment of the experiment, the site supported a ~53-year-old jack pine stand that had regenerated after wildfire; the stand had been commercially thinned in 1999. The soils developed from glacial till material, and have a sandy to loamy sand texture. The soils are Eluviated Dystric Brunisols with a 10-15 cm forest floor layer that consists primarily of feathermoss.

Ash Description

The ash used in the Senneterre 1 Wood Ash Trial was produced at the Boralex plant in Senneterre, QC. The ash feedstock was predominantly softwood bark and shavings. Only fly ash was used for the experiment and the ash was not pre-treated prior to application.

Treatment Description

In the autumn of 2005, ten ash + urea treatments were applied in a factorial design. Treatments included: (1) 0 Mg ash ha^{-1} (control); 1 Mg ash ha^{-1}; 2 Mg ash ha^{-1}; 4 Mg ash ha^{-1} or 8 Mg ash ha^{-1}, and (2) 0 kg urea ha^{-1} or 280 kg urea ha^{-1}. Application rates were calculated on a dry weight basis; ash was applied to the soil surface using a mechanical spreader. Treatments were replicated four times.

Status

This trial is no longer operational because the stand has been harvested.

Main Contact

Nicolas Bélanger, Professor, Department of Science and Technology, Université TÉLUQ
Suzanne Brais, Retired Professor, Université du Québec en Abitibi-Témiscamingue

4.9 Senneterre 2 Wood Ash Trial

Climate

(1981-2010 monthly climate point estimates, modelled as described at: http://cfs.nrcan.gc.ca/projects/3/1)
Mean annual precipitation: 934 mm and 920 mm
Mean minimum temperature in January: -23.3 °C and -23.6 °C
Mean maximum temperature in July: 23.6 °C and 23.5 °C

Site Description

Prior to establishment of the experiment, the site supported a jack pine stand that had regenerated after wildfire. The soils developed from glaciolacustrine deposits and have a loamy to loamy sand texture. The soils are predominantly Eluviated Dystric Brunisols with a 10-15 cm forest floor layer that consists primarily of feathermoss.

Ash Description

The ash used in the Senneterre 2 Wood Ash Trial was produced at the Boralex plant in Senneterre, QC. The ash feedstock was predominantly softwood bark and shavings. Only fly ash was used for the experiment and the ash was not pre-treated prior to application.

Treatment Description

In 2005, the site was clearcut. In the autumn of 2006, ash treatments were applied at three rates: 0 Mg ash ha^{-1} (control); 2.5 Mg ash ha^{-1}; or 5 Mg ash ha^{-1}. Application rates were calculated on a dry weight basis and varied by block, depending on the lime requirements of the soil. Ash was applied to the soil surface using a mechanical spreader. Following ash application, the sites were disc trenched. Treatments were replicated in three blocks. In May 2007, white spruce, jack pine and hybrid larch (*Larix marschlinsii*) seedlings were planted at a density of 2500 stems ha^{-1}.

Status

Monitoring of treatment effects on trees and soil chemistry is ongoing.

Main Contact

Nicolas Bélanger, Professor, Department of Science and Technology, Université TÉLUQ
Suzanne Brais, Retired Professor, Université du Québec en Abitibi-Témiscamingue

4.10 Senneterre 3 Wood Ash Trial

Climate

(1981-2010 monthly climate point estimates, modelled as described at: http://cfs.nrcan.gc.ca/projects/3/1)
Mean annual precipitation: 969 mm and 979 mm
Mean minimum temperature in January: -23.9 °C and -24.0 °C
Mean maximum temperature in July: 23.0 °C and 22.8 °C

Site Description

Prior to establishment of the experiment, the site supported a jack pine and black spruce stand that had regenerated after wildfire. The soils developed from coarse till material and have a loamy sand texture. The soils are predominantly Eluviated Dystric Brunisols with a 10-15 cm forest floor layer that consists primarily of feathermoss.

Ash Description

The ash used in the Senneterre 3 Wood Ash Trial was produced at the Boralex plant in Senneterre, QC. The ash feedstock was predominantly softwood bark and shavings. Only fly ash was used for the experiment and the ash was not pre-treated prior to application.

Treatment Description

In the summer of 2007, the site was clearcut. In the autumn of 2007, ash treatments were applied at three rates: 0 Mg ash ha^{-1} (control); 7.5 Mg ash ha^{-1}; or 15 Mg ash ha^{-1}. Application rates were calculated on a dry weight basis and ash was applied to the soil surface using a mechanical spreader. Following ash applications, the sites were disc trenched. Treatments were replicated three times. In June 2008, black spruce and jack pine seedlings were planted at a density of 2500 stems ha^{-1}. The seedlings in half of the plots were spot-fertilized with 26-21-0-4.6 (NPKS).

Status

Monitoring of treatment effects on trees and soil chemistry is ongoing.

Main Contact

Nicolas Bélanger, Professor, Department of Science and Technology, Université TÉLUQ
Suzanne Brais, Retired Professor, Université du Québec en Abitibi-Témiscamingue

4.11 Valcartier Wood Ash Trial

Climate

(1981-2010 monthly climate point estimates, modelled as described at: http://cfs.nrcan.gc.ca/projects/3/1)

Mean annual precipitation: 1373 mm

Mean minimum temperature in January: -18.9 °C

Mean maximum temperature in July: 23.7 °C

Site Description

The trial is established in a mature ~70-year-old sugar maple, yellow birch, American beech stand. The soils developed from till material. Assessment of soil type and texture is planned, but has not yet been completed.

Ash Description

The ash used in the Valcartier trial was produced at the Resolute Forest Products biomass boiler in Château-Richer near Québec City, QC. The ash feedstock was predominantly black spruce, balsam fir (*Abies balsamea*) and jack pine bark. Only bottom ash was used for the experiment and the ash was not pre-treated prior to application.

Treatment Description

In September/October 2017, the understory cover (mainly beech saplings) was cleared at each location where the plots were established. All residues were removed. In May 2018, ash was applied at a rate of 0 Mg ha^{-1} (control) and 19 Mg ha^{-1} (5 Mg ha^{-1} $CaCO_3$ equivalent). Other treatments include light soil scarification, lime addition and fertilizer addition (NH4NO3). Application rates were calculated on a dry weight basis; ash was applied to the soil surface by hand. Treatments are replicated in 12 blocks within the stand.

Status:

Monitoring of treatment effects on trees and soil chemistry is ongoing.

Main Contact

Jérôme Laganière, Research Scientist, Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre

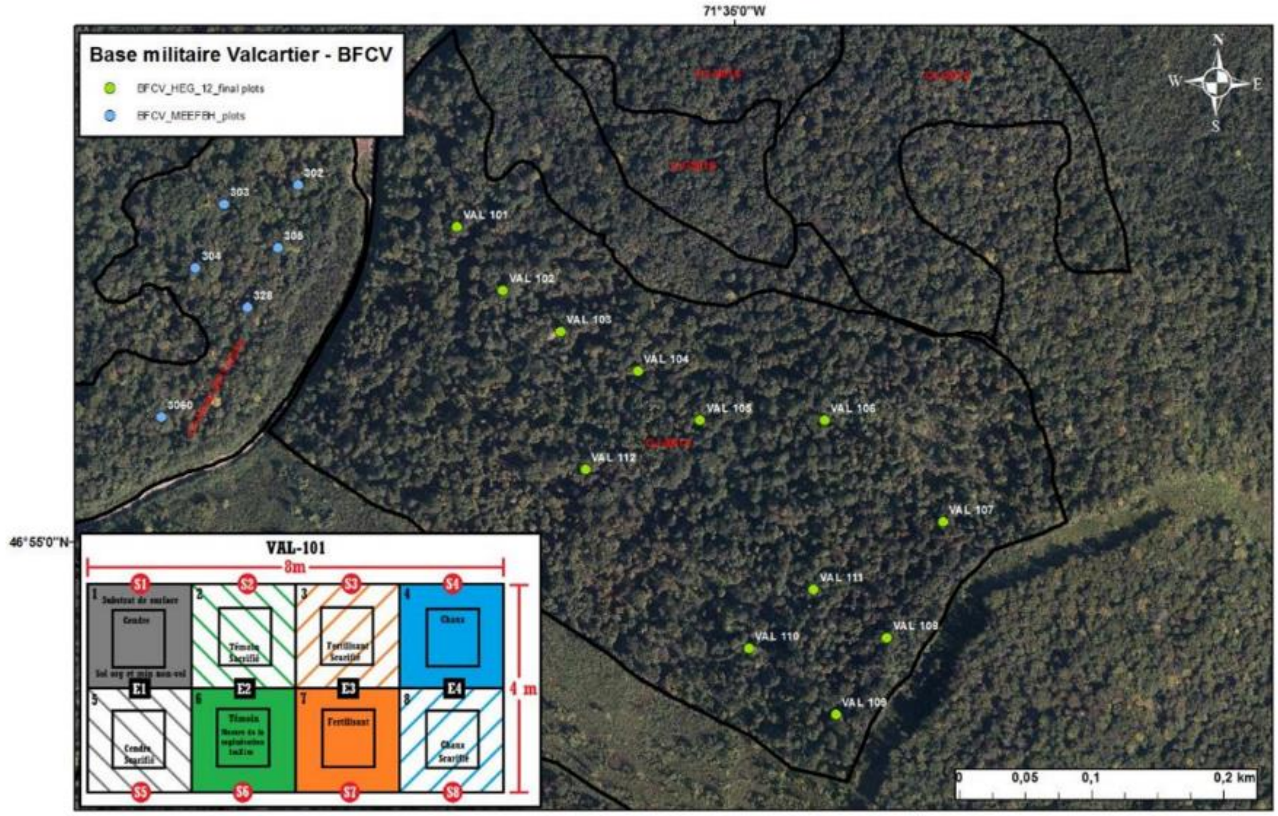

Figure 4.11.1 *Valcartier wood ash amendment experimental set-up.*

4.12 Eastern Townships Wood Ash Trial – Sugar Maple Stands

Climate

(1981-2010 monthly climate point estimates, modelled as described at: http://cfs.nrcan.gc.ca/projects/3/1)
Mean annual precipitation: 1264 mm
Mean minimum temperature in January: -16.6 °C
Mean maximum temperature in July: 23.7 °C

Site Description

Prior to establishment of the experiment, each of the 15 study sites supported a 60 to 80-year-old mixed deciduous stand dominated by sugar maple with some American basswood (*Tilia americana*), American beech, white ash (*Fraxinus americana*) and/or butternut (*Juglans cinerea*). All of the stands had previously been clearcut or selection cut. The soils have developed on tills with gentle to moderate slopes and have a sandy to loamy sand to sandy loam texture. The soils are typically Orthic Humo-Ferric or Ferro-Humic Podzols with a 10-15 cm forest floor layer consisting primarily of leaves and twigs.

Ash Description

The ash used for this trial was produced at the Domtar mill in Windsor, QC. The ash feedstock consisted of 80% hardwood and softwood bark and 20% construction and demolition debris. Only bottom ash was used for the experiment and the ash was not pre-treated prior to application.

Treatment Description

Prior to plot establishment, each site was selection cut (2012-2014). In the summer to early autumn of 2015, one treated plot and one control plot was established at each of the 15 sites. Treatments included: 0 Mg ash ha^{-1} (control) or 20 Mg ash ha^{-1}. Application rates were calculated on a fresh weight basis and ash was applied to the soil surface using a mechanical spreader. Small deer exclosures were also installed in each plot to examine the influence of deer browsing.

Status:

Monitoring of treatment effects on trees and soil chemistry is ongoing.

Main Contact

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4.13 Eastern Townships Wood Ash Trial– Hybrid Poplar Stands

Climate

(1981-2010 monthly climate point estimates, modelled as described at: http://cfs.nrcan.gc.ca/projects/3/1)
Mean annual precipitation: 1204 mm
Mean minimum temperature in January: -16.5 °C
Mean maximum temperature in July: 24.2 °C

Site Description

Prior to establishment of the experiment, each of the three study sites supported 60 to 80 year-old mixed deciduous stands dominated by sugar maple with some American basswood, American beech, white ash and butternut. All of the stands had previously been clearcut or selection cut. The soils have developed on tills with gentle to moderate slopes and have a sandy to loamy sand to sandy loam texture. The soils are typically Orthic Humo-Ferric or Ferro-Humic Podzols with a 10-15 cm forest floor layer consisting primarily of leaves and twigs.

Ash Description

The ash used for this trial was produced at the Domtar mill in Windsor, QC. The ash feedstock consisted of hardwood and softwood bark and shavings. Only bottom ash was used for the experiment and the ash was not pre-treated prior to application.

Treatment Description

Prior to plot establishment, all three sites were clearcut (2009-2012). Each site then received 120 Mg ha^{-1} of paper biosolids + 10 Mg ha^{-1} of lime mud prior to being planted to poplar at a density of 1111 stems ha^{-1}. In the summer of 2015, four treatments were applied in a factorial design. Treatments included: (1) no additional soil amendments, (2) an application of 100 Mg ha^{-1} of paper biosolids + 15 Mg ha^{-1} of wood ash, (3) no weed control, and (4) weed control using herbicide. Ash application rates were calculated on a fresh weight basis; soil amendments were applied to the soil surface using a mechanical spreader. Treatments were replicated in two blocks at each of the three sites.

Status

Monitoring of treatment effects on trees and soil chemistry is ongoing.

Main Contact

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5.0 Literature Cited

Augusto, L.; Bakker, M.R.; Meredieu, C. 2008. Wood ash applications to temperate forest ecosystems - potential benefits and drawbacks. Plant Soil 306(1–2):181–198. doi:10.1007/s11104-008-9570-z.

Baldwin, K.; Downing, D.; Meidinger, D.; Chapman, K. 2016a. West-Central North American Boreal Forest [online]. Sault Ste. Marie, Ontario, Canada: Canadian National Vegetation Classification. May 2016; generated September-15-2016; cited 2018-01-30. Macrogroup(M496): 1–11. Available from http://cnvc-cnvc.ca.

Baldwin, K.; Saucier, J.-P.; Meades, B.; Chapman, K. 2016b. Eastern North American Boreal Forest [online]. Sault Ste. Marie, Ontario, Canada: Canadian National Vegetation Classification. May 2016; generated 15-September-2016; cited 2018-01-30. Macrogroup (M495): 1–12. Available from http://cnvc-cnvc.ca.

Baldwin, K.; Saucier, J.-P.; Uhlig, P. 2018. Eastern Temperate Mixed Forest [online]. Sault Ste. Marie, Ontario, Canada: Canadian National Vegetation Classification. Draft; cited 2018-01-30. Macrogroup (CM014): 1–12. Available from http://cnvc-cnvc.ca.

Brais, S.; Bélanger, N.; Guillemette, T. 2015. Wood ash and N fertilization in the Canadian boreal forest: Soil properties and response of jack pine and black spruce. For. Ecol. Manage. 348: 1–14. doi:10.1016/j.foreco.2015.03.021.

Canadian National Vegetation Classification [online]. 2018. Sault Ste. Marie, ON, Canada. Available from http://cnvc-cnvc.ca/page.cfm?page=2306 [accessed 21 June 2018].

Earl, S.R.; Blinn, D.W. 2003. Effects of wildfire ash on water chemistry and biota in South-Western U.S.A. streams. Freshw. Biol. 48(6): 1015–1030. doi:10.1046/j.1365-2427.2003.01066.x.

Emilsson, S. 2006. International Handboook. From Extraction of Forest Fuels to Ash Recycling. Swedish Forest Agency. 48 p.

Etiégni, L.; Campbell, A.G. 1991. Physical and chemical characteristics of wood ash. Bioresour. Technol. 37(2): 173–178. doi:10.1016/0960-8524(91)90207-Z.

Gill, K.S.; Malhi, S.S.; Lupwayi, N.Z. 2015. Wood ash improved soil properties and crop yield for nine years and saved fertilizer. J. Agric. Sci. 7(12): 72–83. doi:10.5539/jas.v7n12p72.

Hannam, K.D.; Deschamps, C.; Kwiaton, M.; Venier, L.; Hazlett, P.W. 2016. Regulations and Guidelines for use of wood ash as soil amendment in Canadian forests. Information report GLC-X-17. Available from http://www.cfs.nrcan.gc.ca/pubwarehouse/pdfs/37781.pdf.

Hannam, K.D.; Venier, L.; Allen, D.; Deschamps, C.; Hope, E.; Jull, M.; Kwiaton, M.; McKenney, D.; Rutherford, P.M.; Hazlett, P.W. 2018. Wood ash as a soil amendment in Canadian forests: what are the barriers to utilization? Can. J. For. Res. 48(4): 442–450. doi:10.1139/cjfr-2017-0351.

Hannam, K.D.; Venier, L.; Hope, E.; McKenney, D.; Allen, D.; Hazlett, P.W. 2017. AshNet: Facilitating the use of wood ash as a forest soil amendment in Canada. For. Chron. 93(1): 17–20. doi:10.5558/tfc2017-006.

Hope, E.S.; McKenney, D.W.; Allen, D.J.; Pedlar, J.H. 2017. A cost analysis of bioenergy-generated ash disposal options in Canada. Can. J. For. Res. 47(9): 1222–1231. doi:10.1139/cjfr-2016-0524.

Huotari, N.; Tillman-Sutela, E.; Moilanen, M.; Laiho, R. 2015. Recycling of ash - For the good of the environment? For. Ecol. Manage. 348: 226–240. doi:10.1016/j.foreco.2015.03.008.

Mahendrappa, M.K.; Pitt, C.M.; Kingston, D.G.O.; Morehouse, T. 2006. Environmental impacts of harvesting white spruce on Prince Edward Island. Biomass and Bioenergy 30(4): 363–369. doi:10.1016/j.biombioe.2005.07.016.

Mast, M.A.; Murphy, S.F.; Clow, D.W.; Penn, C.A.; Sexstone, G.A. 2016. Water-quality response to a high-elevation wildfire in the Colorado Front Range. Hydrol. Process. 30: 1811–1823. doi:10.1002/hyp.10755.

Meidinger, D.; Baldwin, K. 2017. Rocky Mountain Intermontane Subboreal Forest [online]. Sault Ste. Marie, Ontario, Canada: Canadian National Vegetation Classification. July, 2017; generated 31-December-2017; cited 2018-01-30. Macrogroup(M890): 1–9. Available from http://cnvc-cnvc.ca/.

Natural Resources Canada. 2018a. AshNet Research Project. Available from http://www.nrcan.gc.ca/forests/research-centres/glfc/ashnet/20279.

Natural Resources Canada. 2018b. Canadian Wood Ash Chemistry Database. Available from http://www.nrcan.gc.ca/forests/research-centres/glfc/ashnet/20288.

Pitman, R.M. 2006. Wood ash use in forestry - a review of the environmental impacts. Forestry 79(5): 563–588. doi:10.1093/forestry/cpl041.

Prescott, C.E.; Brown, S.M. 1998. Five-year growth response of western red cedar, western hemlock, and amabilis fir to chemical and organic fertilizers. Can. J. For. Res. 28: 1328–1334. doi:10.1139/x98-109.

Reid, C.; Watmough, S.A. 2014. Evaluating the effects of liming and wood-ash treatment on forest ecosystems through systematic meta-analysis. Can. J. For. Res. 44(8): 867–885. doi:10.1139/cjfr2013-0488.

Sevean, R. 2014. Impact of biochar and industrial ash amendments on soil properties, growth and nutrition of black and white spruce seedlings in a sandy loam soil (M.Sc. Thesis). Lakehead University.

Steenari, B-M.; Karlsson, L.G.; Lindqvist, O. 1999. Evaluation of the leaching characteristics of wood ash and the influence of ash agglomeration. Biomass and Bioenergy 16(2): 119–136.

Appendices

Appendix A - Soil and stand characteristics for each of the AshNet study sites.

Site	Soil order	Mode of deposition	Soil texture	Forest floor thickness (cm)	Stand type	Dominant Tree species	Stand age at ash app. (years)	Pre-treatment disturbance type (year)	Time since latest disturbance at ash app. (years)
Johnson Creek	Brunisolic Grey Luvisol	Glaciofluvial veneer	Silt loam over clay loam	6	Second growth white spruce 81%,balsam poplar 8%, paper birch 7%, and lodgepole pine 4%	White spruce 81%,balsam poplar 8%, paper birch 7%, and lodgepole pine 4%	24	Conifer rehabilitation (1987); wildfire (1991)	26
Aleza Lake N	Luvisolic/ Gleysolic	Glaciolacustrine	Silty clay loam to clay (< 50% sand)	~5.2	18-year-old hybrid spruce plantation	Hybrid spruce, subalpine fir	18	Clearcut (1996/97)	18
Aleza Lake S	Luvisolic/ Gleysolic	Glaciolacustrine	Silty clay loam to clay (<50% sand)	~5.2	24-year-old hybrid spruce plantation	Hybrid spruce, subalpine fir	24	Clearcut (1989/90); broadcast burn (1990)	25
Mistik	Luvisolic	Ablation moraine till	Clay loam, with pockets of sandy loam; moderately to excessively stony (> 50% sand)	5 to 10	White spruce planted	White spruce	<1	Clearcut full tree + disc trenched (1995)	0
Pineland	Brunisolic	Glaciofluvial	Sandy (> 50% sand)	2	Jack pine	Jack pine	<1	Clearcut whole tree 2015)	0
25th Sideroad	Brunisolic	Fluvial outwash	Sandy loam (> 50% sand)	0	Black and white spruce	Black and white spruce	<1	Former nursery; tilled	0
Island Lake	Brunisolic	Glaciofluvial	Sandy to sandy loam (> 50% sand)	~10	Jack pine	Jack pine	<1	Clearcut full tree (2010/11)	0
Haliburton	Brunisolic	Glacial till	Sandy loam (> 50% sand)	5-8	Mixed deciduous	Sugar maple, American beech, eastern hemlock, yellow birch	Uneven stand age	Single tree selection (2003); beech salvage (2013)	0
Senneterre 1	Brunisolic	Glacial till	Loamy sand to sand (> 50% sand)	10-15	Jack pine	Jack pine	53	Commercially harvested & thinned (1999)	6
Senneterre 2	Brunisolic	Glaciolacustrine sands	Loamy to loamy sand (> 50% sand)	10-15	White spruce, jack pine, hybrid larch	White spruce, jack pine, hybrid larch	<1	Clearcut (2005)	1
Senneterre 3	Brunisolic	Coarse till	Loamy sand (> 50 % sand)	10-15	Jack pine, black spruce	Jack pine & black spruce	<1	Clearcut (2007)	0
Valcartier	Brunisolic	Glacial till	TBD	8.8	Sugar maple, yellow birch, beech forest	Sugar maple, yellow birch, beech	<1	Understory removal (2017)	0
Eastern Township Sugar Maple	Podzolic	Glacial till	Sandy to loamy sand to sandy loam (> 50% sand)	10-15	Mixed deciduous	Sugar maple, American basswood, American beech, white ash, butternut	~60-80	Selection cut (2012-14)	1
Eastern Township Hybrid Poplar	Podzolic	Glacial till	Sandy to loamy sand to sandy loam (> 50% sand)	10-15	Hybrid poplar	Hybrid poplar	~7-10	Clearcut (2009-2012)	3

*Appendix B - Pre-ash-application measurements taken at each of the Ashnet study sites. *EC = electrical conductivity, CEC = cation exchange capacity.*

Site	Forest stand	Downed woody debris	Soil physical properties	Soil chemical properties
Johnson Creek	Species, stem density, diameter of live standing trees, foliar nutrients of spruce	NA	Soil profile description	Forest floor and upper 10 cm mineral soil sampling for pH, total C and N, inorganic C (mineral soil only), total S, ammonium-N and nitrate-N, saturated paste EC, effective CEC and cations; total As, B, Ca, Cd, Co, Cr, Cu, K, Mg, Pb, Hg, Mo, Na, Ni, P, Se and Zn
Aleza Lake N	Species, diameter, height by species for each individual tree	-	Texture	Forest Floor and upper 10 cm mineral soil for pH, EC, total C,N,S (EA); total via ICP As, B, Ca, Cd, Co, Cr, Cu, K, Mg, Hg, Mn, Mo, Na, Ni, P, Pb, Se, Zn; inorganic C, effective CEC + exchangeable cations; Mehlich III extractable nutrients
Aleza Lake S	Species, diameter, height by species for each individual tree	-	Texture	Forest Floor and upper 10 cm mineral soil for pH, EC, total C,N,S (EA); total via ICP As, B, Ca, Cd, Co, Cr, Cu, K, Mg, Mn, Hg, Mo, Na, Ni, P, Pb, Se, Zn; inorganic C, effective CEC + exchangeable cations; Mehlich III extractable nutrients
Mistik	NA	-	-	-
Pineland	NA	-	-	Inorganic N, extractable phosphate, organic carbon (loss on ignition)
25th Sideroad	NA	NA (no debris)	Bulk density, texture	Organic matter, pH, EC; available Ca, K, Mg, Na, ; total C, N, S; extractable ammonium-N and nitrate-N , P, Fe, Mn, Cu, Zn ; total Al, B, Cu, Fe, Mn, Ni, P, Zn in the top 0-10 cm of soil
Island Lake	Species, stem density, basal area, mean height and diameter of live and standing dead trees; above ground wood, branch, bark and foliar biomass of live and standing dead trees;	Above- and below ground biomass, volume, decay class and C, N, P, Ca, Mg and K contents of fine and coarse downed woody debris	Horizon depths, bulk density, coarse fragment content and texture	pH, extractable Fe and Al concentrations, total C, N; extractable P; exchangeable Ca, Mg, K
Haliburton	Basal area, canopy openness, large tree diameters (individually recorded), seedling and sampling counts (in sub-plots)	-	-	Soil pH, total and plant available nutrients (exchangeable cations, available P, N mineralization), metals, and other elements
Senneterre 1	Tree inventory, basal area	-	-	-
Senneterre 2	NA	-	-	pH (water), pH(buffer), P, K , Al, CEC, OM
Senneterre 3	NA	-	-	Total C, N; exchangeable Ca, Mg, K, Na, available P, pH (water), pH (buffer), lime requirement
Valcartier	Inventory of large trees, small trees, regeneration (species, diameter, status)	NA (debris removed)	Horizon depths, bulk density, coarse fragment content and texture	pH, extractable Fe and Al concentrations, C, N (total + inorganic), P, Ca, Mg, K
Eastern Township Sugar Maple	Tree inventory, basal area	Around insect traps	-	pH, total C, N, exchangeable cations, exchangeable acidity, base saturation, CEC
Eastern Township Hybrid Poplar	Tree inventory, basal area	-	-	Soil pH, total C and N, exchangeable cations, exchangeable acidity, base saturation, CEC (in controls and first fertilization plots)

Appendix C - Experimental approaches including study design and ash amendment details for each of the AshNet study sites.

Site	Study Design	Size of plots (ha)	Number of replicate plots	Additional treatments	Ash pre-treatment	Ash feedstock & source	Ash type	Ash application rates	Ash application methods
Johnson Creek	Randomized, complete block	0.02011	3	Urea @ 100 kg/ha actual N	-	Softwood bark, shavings and dust-Chetwynd Forest Industries (West Fraser) co-generation plant	Fly	0, 5 Mg/ha dry weight	Hand-applied to surface
Aleza Lake N	Randomized, complete block	0.0201	3	0, 100 kg urea-N/ha	-	*CPLP* = softwood chips, bark & sawdust (boiler- high C ash); *UNBC*=softwood sawmill residues (gasifier- low C ash) - Clean hog fuel	Bottom	0, 5 Mg/ha dry ash	Broadcast by hand (shovel-applied) to surface
Aleza Lake S	Randomized, complete block	0.0201	3	0, 100 kg urea-N/ha	-	*CPLP* = softwood chips, bark & sawdust (boiler- high C ash); *UNBC*=softwood sawmill residues (gasifier- low C ash) - Clean hog fuel	Bottom	0, 5 Mg/ha dry ash	Broadcast by hand (shovel-applied) to surface
Mistik	Randomized, complete block	0.003	3	-	Crushed	85% trembling aspen bark & chips + 15% de-watered pulp sludge(Olivine burner Millar Western Mill)	Bottom	1,5 Mg/ ha dry ash	Hand-applied to surface 1 m^2 around seedling
Pineland	Split plot design	0.0225	5	70 kg urea/ha	-	Jack pine wood chips + some bark (biomass burner @ Pineland Forest Nursery)	Fly & bottom	0, 1.5 Mg/ha dry ash	Hand-applied to surface
25th Sideroad	Randomized, complete block	0.00165	5	Biochar	-	Softwood bark, sawdust & wood chips, with 8-14% effluent sludge (vibrating grate power boiler @ Resolute Forest Product)	Fly	0, 1 , 10 Mg/ha dry ash	Hand-applied & raked into top 10cm
Island Lake	Randomized, incomplete block	Control=0.49, Treatment=0. 0625	5 control, 4 treatment	-	-	Softwood (Pj&Sb) bark, shavings and sawdust (Tembec co-generation plant)	bottom	0 , 0.7 ,1.4 , 2.8 ,5.6 Mg/ha dry ash	Hand-applied to surface
Haliburton	Randomized, incomplete block	0.0009 and 0.04	4	-	-	SPF bark(Vibrating grate biomass boiler-P&P mill-Detroit Rotostoker)	Fly & bottom	0 , 1 , 4 , 8 Mg/ha dry ash	Hand-applied to surface
Senneterre 1	Complete random design	1	4	280 kg urea/ha	-	Softwood bark & shavings (Boralex plant-QC)	Fly	0 , 1 , 4 , 8 Mg/ha dry ash	Mechanical spreader to surface
Senneterre 2	Randomized, complete block	~2	3	-	-	Softwood bark & shavings (Boralex plant-QC)	Fly	0 , 2.5 , 5 Mg/ha dry ash	Mechanical spreader to surface
Senneterre 3	Randomized, complete block	2-4	3	Spot-fertilizer 26-21-0-4.6(NPKS)	-	Softwood bark & shavings (Boralex plant)	Fly	0 , 7.5 , 15 Mg/ha dry ash	Mechanical spreader, then disc trenched
Valcartier	Complete block design	0.0008	12	Lime, fertilizer, soil scarification	-	Softwood bark (Resolute biomass boiler at Château Richer)	Bottom	0 , 19 Mg/ha dry ash	Hand-applied to surface
Eastern Township Sugar Maple	Split plot	3	5	Small deer exclosures	-	80% hardwood & softwood bark, 20% construction and demolition debris (Domtar Mill)	Bottom	0 , 20 Mg/ha fresh weight	Mechanical spreader to surface
Eastern Township Hybrid Poplar	Complete random design	0.25-5	6	100 Mg/ha paper biosolids, herbicide weed control	-	Hardwood and softwood bark and shavings	Bottom	0 Mg/ha, 15 Mg/ha fresh weight	Mechanical spreader to surface

*Appendix D - Post-ash-application measurements taken at each of the Ashnet study sites. *EC = electrical conductivity, CEC = cation exchange capacity.*

Site	Forest stand	Understory	Downed woody debris	Carbon & nutrient stocks	Soil chemical properties	Soil solution chemistry	Soil biota
Johnson Creek	Foliar nutrients five years post application; diameter 5 years post	-	-	Ash, forest floor, and mineral soil content of total N, C, ammonium N, nitrate N, available P, K and heavy metals, pH	Forest floor and upper 10 cm mineral soil sampling for pH, Total C and N, inorganic C (mineral soil only), total S, ammonium N and nitrate-N, saturated paste EC, effective CEC and cations; total As, B, Ca, Cd, Co, Cr, Cu, K, Mg, Pb, Hg, Mo, Na, Ni, P, Se and Zn	-	-
Aleza Lake N	Species, diameter, height, foliar nutrient content: total C, N, S, Al, B, Ca, Cu, Fe, Mg, Mn, P, K, S, Zn, needle mass	Species diversity and composition	-	-	Forest Floor and upper 10 cm mineral soil for pH, EC, total C, N, As, B, Ca, Cd, Co, Cr, Cu, K, Mg, Hg, Mo, Na, Ni, P, S, Se, Zn; exchangeable cations	-	-
Aleza Lake S	Species, diameter, height, foliar nutrient content: total C, N, S, Al, B, Ca, Cu, Fe, Mg, Mn, P, K, S, Zn, needle mass	Species diversity and composition	-	-	Forest Floor and upper 10 cm mineral soil for pH, EC, total C, N, As, B, Ca, Cd, Co, Cr, Cu, K, Mg, Hg, Mo, Na, Ni, P, S, Se, Zn; exchangeable cations	-	-
Mistik	Survival; seedling height, diameter; root and shoot biomass; root and shoot nutrients	-	-	-	pH, EC; extractable P, exchangeable cations; mineral N	Solution nutrient and heavy metal concentrations at 15 and 60 cm	-
Pineland	Height, diameter, biomass, foliar nutrients	Cover, biomass	-	-	Inorganic N, extractable phosphate, organic carbon	-	-
25th Sideroad	Mortality, height, height increment, diameter, and foliar nutrients	Percent cover; root and shoot biomass of weeds	-	-	Organic matter, pH, EC; available Ca, K, Mg, Na; total C, N, S; mineral N, P, Fe, Mn, Cu, Zn, total Al, B, Cu, Fe, Mn, Ni, P, Zn	-	Microbial biomass and respiration

Appendix D (cont.) - Post-ash-application measurements taken at each of the Ashnet study sites. **EC = electrical conductivity, CEC = cation exchange capacity.*

Site	Forest stand	Understory	Downed woody debris	Carbon & nutrient stocks	Soil chemical properties	Soil solution chemistry	Soil biota
Island Lake	Survival and health; tree height, diameter and foliar nutrients	Species composition and percent cover	Above ground biomass; biomass, volume and decay class of fine and coarse DWD; total C, N, P, Ca, Mg and K contents of DWD	C, N, P, Ca, Mg and K content of above- & below ground dead woody debris, harvesting slash, stumps & coarse roots, forest floor & mineral soil	pH, total C, N, cations; exchangeable cations; N mineralization	Solution pH, C, nutrient and heavy metals at 30 cm, 50 cm and 100 cm depths	Soil fauna (springtails, mites and roundworms), epigaeic fauna (ground beetles, spiders, rove beetles and millipedes), soil microbes (microbial respiration, substrate-induced respiration, enzyme assays, microbial biomass, microbial community composition)
Haliburton	Large tree diameter, tissue chemistry	Seedling counts, height, stem elongation	-	-	pH, total C, N, cations; exchangeable cations; N mineralization	Solution pH, C, nutrient and heavy metals at 30 cm, 50 cm and 100 cm depths	Soil fauna (red-backed salamanders), soil microbes (bacteria, fungi, protozoa)
Senneterre 1	Tree inventory, diameter, foliar nutrients (N, P, Ca, Mg, K)	-	-	-	pH, total C, N; available P, exchangeable cations, exchangeable acidity	-	-
Senneterre 2	Survival and health; height, root collar diameter and foliar nutrients (C, N, P, Ca, Mg, K and traces)	-	-	-	pH, total C, N; available P, exchangeable cations, exchangeable acidity, manganese speciation	-	-
Senneterre 3	Survival and health; tree height, diameter and foliar nutrients (C, N, P, Ca, Mg, K and traces)	-	-	-	pH, total C, total N; available P, exchangable cations, exchangeable acidity	-	-
Valcartier	-	Species composition, stocking, biomass and percent cover, light measurements	-	-	pH, total C, N, cations; exchangeable cations	Resin bags	Soil microbiome (bacteria and fungi)
Eastern Township Sugar Maple	Tree inventory, diameter, foliar nutrients (N, P, Ca, Mg, K, Al, Mn, Fe)	-	Around insect traps	Possible via allometry (e.g., Maliondo et al. 1995); dendrometry of 10 trees per site (5 with ash, 5 without ash)	pH, total C, N;available P, exchangeable cations, exchangeable acidity, CEC, base saturation	-	Epigaeic fauna (ants, beetles, spiders)
Eastern Township Hybrid Poplar	Height, diameter, foliar nutrients (N, P, Ca, Mg, K, Al, Mn, Fe)	-	-	Possible via allometry (Brazeau & Camiré, 1998)	pH, total C, N;, available P, exchangeable cations, exchangeable acidity, CEC, base saturation	Partially, via PRS-probes	-