THE IMPACT OF AMENDING FOREST SOILS WITH WOOD ASH ON SOIL ORGANIC MATTER ATTRIBUTES AND ASSOCIATED PROPERTIES

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Abstract

Wood ash, the byproduct of bioenergy production from biomass, is typically discarded into landfills as waste. Adding ash back to soil may supply nutrients to soil that are lost through biomass harvesting, increase soil pH, and improve site productivity, but the effects on soil organic carbon are not well known. In Canada, there are eight wood ash experiments across the country investigating the effects of ash addition on site productivity. In this study we measured soil carbon concentrations and estimated stores of total soil organic carbon, sand fraction carbon, microbial biomass carbon, hot water extractable carbon and mineralizable carbon in soils collected from these experiments. Analyses of variance (ANOVA) were conducted to determine the significant effect of different rates of wood ash application on each fraction. The difference between ash application rates was analyzed using Tukeys post-hoc test. Following ANOVA, a multivariate analysis was conducted using principal component analysis (PCA) to capture the variables significantly contributing to the total variation in the study. Results revealed that labile fractions were more responsive than the total carbon, but none of the measured attributes showed consistent change across the sites with ash addition. Carbon attributes that varied significantly ($p<0.05$) with wood ash addition varied across the sites and between the forest floor and mineral soil layers. Wood ash addition had the greatest effect on microbial biomass carbon, hot water extractable carbon and sand sized fraction carbon. There was no detrimental effect of wood ash addition on carbon storage at any site. The effect of ash addition was also dependent on soil texture, soil layers and the application rate. Fractions of soil organic carbon were typically more responsive to ash addition than total carbon and may be included as indicators of soil quality.

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1. Introduction

Rising atmospheric concentrations of greenhouse gases in the atmosphere have been linked to fossil fuel combustion since the Industrial Revolution. Higher concentrations of greenhouse gases in the atmosphere have led to an enhanced greenhouse effect in the atmosphere that is causing concerning changes in climate (US Environmental Protection Agency, 2015). To mitigate rising atmospheric greenhouse gas concentrations, renewable energy sources are being explored and integrated into the energy grid (Natural Resources Canada (NRCan), 2013).

Renewable energy may decrease our reliance on fossil fuel based energy production and assist in mitigating atmospheric greenhouse gas concentrations. Canada is a leader in renewable energy production owing to our large river systems that generate hydroelectricity (National Energy Board (NEB), 2017). Biomass is the second most abundant renewable energy resource and accounts for 23% of renewable energy production in Canada. Electricity generation from biomass burning grew by 54% from 2005 to 2015 (NEB, 2017). The contribution of forest biomass to bioenergy production in Canada increased from 3.5% in the 1970s to 5.5% today ((NRCan), 2013).

The forest industry has been producing bioenergy through the combustion of residual materials from their operations for decades (Hannam et al., 2017), with bioenergy production nearly doubling from 2005 to 2015 (Hannam et al., 2019). The growing shift towards bioenergy production has intensified the demand for biomass (NRCan, 2013 & 2017) and has created debate around harvesting slash generally left on site after cutting and/or salvage logging after a stand has been compromised by insect infestation or fire to increase bioenergy production. This debate has been focused on nutrient removals that may compromise site productivity and biodiversity, among others (e.g. Thiffault et al., 2011).

Forest harvesting/biomass removal on an industrial scale can contribute to the degradation of the productivity potential of a site over successive rotations (Van Bich et al., 2018). Removal of vegetation through clear cutting might alter the soil's thermal environment creating conditions for increased decomposition of organic matter (Hannam et al., 2017) exposes the forest floor to erosion leading to the removal and or depletion of the organic matter and nutrient leaching (Mayer et al., 2020). Whole-tree harvesting can contribute to the removal of base cations, especially calcium from the topsoil (Reid and Watmough, 2014). Increased soil acidity is often reported with forest harvesting, which may negatively impact biodiversity (Jacobson et al., 2014; Reid and Watmough, 2014). Generally, the impact on nutrient removal and ecosystem function is proportional to the intensity of harvesting and the degree of biomass utilization (McFee and Kelly, 1995). Therefore, increases in whole tree harvesting with increasing demand for forest bioenergy resources has been an area of concern because of the potential for increased export of nutrients and soil acidification (Thiffault et al., 2011).

In addition to the concern and debate around the intensification of harvesting/biomass removal for bioenergy is the issue of the wood ash produced as a byproduct of the combustion reaction. Combustion of biomass creates ash, which is generally disposed of in a landfill. Landfill disposal of wood ash creates an economic burden on the bioenergy industry, is not sustainable because we are running out of available land nor is it environmentally responsible to concentrate heavy metals that may be leached into the environment (Staples and Van Rees, 2001; Maresca et al., 2017). The properties of wood ash are highly variable and depend on the furnace, feedstock, temperature of combustion, and how the ash is stored (Larsson and Westling, 1998; Demeyer et al., 2001). Solubility, nutrient concentrations and trace metal contents all vary widely in wood ash but despite the variability in ash chemistry, wood ash has been shown to have beneficial uses, for example it can be incorporated into cement (Cherian and Siddiqua, 2019), be used as a soil conditioner (Hannam et al., 2017), therefore it can be streamed out of the landfill system for the benefit of society.

Ash is alkaline with a pH ranging from 8 to 13 and contains micro and macro nutrients essential for plant growth (Pitman, 2006). Applying wood ash to forest soils can replace nutrients removed during timber harvesting (e.g. P, Ca, Mg, K) and decrease the acidity of the soil. In Europe application of wood ash to the soil is actually encouraged, particularly on nutrient poor soils, to mitigate nutrient deficiencies created by biomass harvesting (e.g. Karltun et al., 2008). Though ash application is well studied in Europe there have been relatively fewer studies in North America. Applying wood ash to forest soils in Canada presents an opportunity to gain value from forest biomass while enhancing the environmental sustainability of harvesting operations (Hannam et al., 2017).

The application of wood ash affects the biological, chemical and physical properties of soil, which can in turn affect soil quality/soil health (Demeyer et al., 2001). Maintaining and improving soil quality is critical to maintaining productivity and environmental sustainability. Chemically, wood ash has been used to increases the pH of the soil and can correct nutrient deficiencies (Reid and Watmough, 2014). Wood ash can also stimulate microbial activity and mineralization of carbon and nitrogen (Fritze et al., 1994; Saarsalmi et al., 2012), which are biological attributes of the soil. It can affect soil texture, aeration, water holding capacity because it is so fine grained (Demeyer et al., 2001), which are physical attributes of the soil. Wood ash application has been associated with increase in plant growth and yield in agricultural systems (Demeyer et al., 2001) and peatland soils (e.g. Moilanen et al., 2012) but in forested systems, the outcome has been variable. The variability has been attributed to factors such as site fertility, characteristics of the ash itself, the rate of ash application and the time since the ash was applied (Aronsson and Ekelund, 2004). The greatest effects of ash application were observed when the ash was loose and applied at rates greater than 5 Mg/ha (Aronsson and Ekelund, 2004).

When ash is applied to forested mineral soils, there is often no change or a negative effect on tree growth (e.g. Prescott and Brown, 1998; Staples and Van Rees, 2001; Aronsson and Ekelund, 2004). In their 2014 meta-analysis Reid and Watmough reported that the initial pH, species and time since trial establishment had the strongest effects on tree growth in mineral soils when wood ash was applied. The tree growth response in softwood species was greatest when soils were more acidic (pH 4.5-6). In addition to decreases in tree growth, studies have reported an increase in ruderal (i.e. weedy) understory species and a decline in bryophytes when wood ash is applied on infertile sites (C:N>30) (Jacobson, 2003; Saarsalmi et al., 2004; Bieser and Thomas, 2019). When wood ash is applied on fertile sites (i.e. C:N<30) an increase in tree growth was observed (Jacboson, 2003). The threshold of C:N in the forest floor has been related to rates of N mineralization. If the ratio is <30 then increases in net N mineralization may occur after liming whereas if the ratio is >30 then rates of N mineralization are decreased. Jacobson (2003) reported a negative relationship between C to N ratio and the relative growth rate of Scots Pine (*Pinus sylvestris* L.) and Norway Spruce (*Picea abies* (L.) Karst.).

The observed effects on biological functioning in the system are related most directly to the change in pH induced by the addition of the ash (Bååth et al., 1995; Pitman, 2006). Raising the pH in forest soils often makes nutrients more available for plant uptake and stimulates microbial activity, thereby increasing transformations of C and N (e.g. Zimmermann and Frey, 2002; Perkiomake et al., 2004; Perkiomaki and Fritze, 2005). However application of wood ash to boreal soils had variable effects. Increases in pH are thought to increase microbial activity but only three of 26 studies in Reid's and Watmough's (2014) meta-analysis showed an increase in microbial biomass carbon. Rosenberg et al. (2010) reported increase in soil respiration, while Ernfors et al. (2010) detected no effect. Both Klemedtsson et al. (2010) and Royer-Tardiff et al. (2019) reported declines in CO_2 emissions from soils amended with wood ash.

Wood ash is generally surface applied so the greatest effects are observed at the surface. After application the ash gradually dissolves and nutrients become available for plant growth. In their meta-analysis, Reid and Watmough (2014) showed a greater pH effect in the forest floor because this is where the ash is applied and that it takes time to leach down. The thickness of the forest floor can also play a role. Hansen et al. (2016) reported increases in the biodegradability of soil organic matter (SOM) in the forest floor that were related to an increase in pH but that these effects were not evident in the surface mineral soil. Gomoryova et al. (2016) also reported differences in pH, microbial activity and diversity only in the forest floor (no effect in mineral soil) and further stratification of effects between layers of the forest floor. They also reported shifts in the structure of the microbial community that reflected changes in pH, with higher functional diversity in the wood ash amended soils.

Though our understanding of the effects of wood ash addition on soil pH, base cations, tree growth and understory vegetation is increasing, there is comparatively less known about the effects of wood ash addition on carbon and nitrogen dynamics (Reid and Watmough, 2014). In a recent meta-analysis comparing wildfire and ash amendments on soil properties, Hannam et al. (2019) reported declines in the carbon and nitrogen concentrations in both the forest floor and mineral soil with ash application. Several studies have reported no effect on soil C or N (e.g. Gomoryova et al., 2016; Ventura et al., 2019). The lower number of studies examining carbon and nitrogen concentrations in the soil is surprising considering that these attributes are measurements of the total soil organic matter inventory (Gregorich et al., 1994).

Soil organic matter is a key attribute of soil quality/soil health because it influences the physical, chemical and biological properties and processes in the soil (Larson and Pierce, 1991; Doran and Parkin, 1994; Haynes, 2005). The capacity of a soil to function within its ecosystem boundaries in a way that sustains productivity, maintains environmental quality, and promotes the health of plants and animals defines a soil's quality/health (Karlen et al., 1997; Doran and Parkin, 1994; Karlen et al., 2019). Changes in soil quality/health in response to management have been gaining increasing attention because of concerns around soil degradation and sustainability (Haynes, 2005). Assessing changes requires the measurement of indicators that represent a critical soil function(s) which often include nutrient availability, soil structure and biological activity (Gregorich et al., 1994; Reeves, 1997; Cardoso et al., 2013). In agricultural studies, soil organic carbon is the most often reported attribute in long term studies examining the effects of management and it is chosen because of its influence on physical, chemical and biological indicators of soil quality (Reeves, 1997).

Characterizing a soil's health involves identifying indicators or parameters that represent the capacity of an attribute to function in a desired manner (Doran and Parkin, 1994). To assess how soil quality has been affected by management, indicators must be sensitive to changes in inputs or disturbance and must be easily measured and reproducible. Changes are comparative and made relative to some baseline like a control treatment. Though total soil organic matter is a master variable in determining site productivity and sustainability, changes in carbon and nitrogen are slow and often do not reveal short term changes. Fractions of soil organic matter that represent small but dynamic carbon pools that are sensitive to management may reveal changes not apparent in measurements of total carbon and nitrogen alone. Identifying a small subset of attributes or indicators to monitor soil quality has been recommended and established in the literature for some time (e.g. Larson and Pierce, 1991; Gregorich et al., 1994; Reeves, 1997) but has primarily focused on agricultural systems. A minimum dataset is a tool that frames or provides a picture of soil quality/health.

A minimum data set may include total carbon (TC) and nitrogen, the ratio of carbon to nitrogen, mineralizable carbon, particulate organic carbon, microbial biomass carbon (MBC), and carbohydrate carbon (Gregorich et al., 1994; Haynes, 2005). Changes in these fractions in soils amended with wood ash relative to the un-amended control may reflect the effect of wood ash addition on key soil functions and overall soil quality. Total soil carbon and nitrogen and the ratio of carbon to nitrogen can influence the responsiveness of a soil to disturbance, management and/or changes in inputs. The ratio of carbon to nitrogen is an indicator that reflects the capacity of the soil to store and recycle nutrients and energy (Gregorich et al., 1994). If there is a deficiency of available nitrogen for decomposition then turnover of organic matter may be delayed. Mineralizable carbon is an indicator of the metabolic activity of the decomposer community and affects nutrient dynamics (Gregorich et al., 1994). Particulate organic matter is a readily available pool of plant residues, animals and microbes in various stages of decomposition. It is an early indicator of change because this small pool is sensitive to changes in the rates of input of plant residues to the soil and their persistence (Gregorich et al., 1994). If wood ash alters the rate of residue return and/or the cycling of organic matter then we would expect to detect a change in this fraction relative to an unamended control. Microbial biomass is an indicator of the soil's ability or capacity to store and recycle nutrients and energy, and responds quickly to changes in the environment. Microbial biomass is often expressed relative to total carbon or the amount of carbon mineralized to indicate microbial efficiency (microbial quotient) (Pankhurst et al., 1997). Carbohydrate carbon influences the formation and stabilization of soil structure. These attributes influence soil structure, nutrient availability and turnover, and soil biological activity. Through concurrent measurements of these attributes we may better understand the effects of amending forest soils with wood ash on soil quality/health, which plays a key role in determining site productivity and environmental sustainability.

The goal of this investigation is to identify sensitive indicators of changes in soil quality/health that may be used across the country to assess the effect of wood ash addition on Canadian forest soils. Using a minimum data set approach, the primary objective of this investigation is to determine the effect of wood ash amendment on concentrations of carbon, nitrogen, CN ratio, microbial biomass carbon, particulate organic carbon and nitrogen, mineralizable carbon, microbial quotient (MBC:TC), and metabolic quotient (mineralizable C:MBC) (Pankhurst et al., 1997). Secondary objectives include determining the effects of wood ash addition on soil pH, carbon and nitrogen complexed with mineral particles, and normalized fractions from the minimum data set which may reveal changes in soil quality.

2. Materials and Methods

2.1 Sample collection

Soil samples were collected from eight wood ash experiments across Canada in 2017 (June 7-July 25) using PVC pipe that was 5 cm in diameter and 20 cm in length for a complementary meta-barcoding study. Soils were immediately frozen and shipped to the Great Lakes Forestry Centre in Sault Ste. Marie. Upon arrival, soil cores were separated by forest floor layer and mineral soil layer and remained frozen until further analysis. Study sites included forested areas in Aleza Lake North and South (British Columbia), Mistik (Saskatchewan), Pineland (Manitoba), 25th Side Road, Island Lake, and Haliburton (Ontario) and Eastern Township (Quebec). The ash application rate for each site was applied based on the calcium content and dry weight of the ash.

2.2 Site Description and Study Design

2.2.1 Aleza Lake North and South

Wood ash experiments were established on an 18 year and a 24 year old hybrid spruce *(Picea engelmannii* x *glauca* Parry*)* plantation located to the North and South of Aleza Lake, in Aleza Lake Research Forest area of British Columbia (54.08˚N, 122.08˚W) in May 2015. Both the northern and southern sites were classified as the Montane Forest Region of the Montane Cordillera Ecozone in Central British Columbia, dominated by hybrid spruce (*Picea engelmannii* x *glauca)* and subalpine fir (*Abies lasiocarpa* Hook.). The North site is at an elevation of 655 m where the mean minimum and maximum temperatures are -12.2 and 23.1°C with a mean annual precipitation of 714 mm. The South site is at an elevation of 670 m where the mean minimum and maximum temperatures are -12.2 and 22.9 °C with a mean annual precipitation of 719 mm. The Gray Luvisol soil type at both sites has a silty clay loam to clay loam texture and developed on glaciolacustrine deposits with a forest floor layer (LFH: litter-fibric-humic) thickness of approximately 5 cm. The mature stand at Aleza Lake North was clearcut and replanted in 1997. Aleza Lake South site was replanted in 1990 following clearcut harvesting and broadcast burning (NRCan, 2018).

Wood ash from two different sources: 1) University of Northern British Columbia (UNBC) and 2) Canfor Pulp Limited Partnership (CPLP) were used for this experiment. The treatment plots are circular with an 8 m radius and are 0.0201 ha in size. At both sites three ash treatments at 0 Mg/ha (Control), 5 Mg/ha of gasifier ash (UNBC) and 5 Mg/ha of boiler ash (CPLP) were applied to the soil. Each treatment was replicated three times and samples were collected from each plot The feedstock for the UNBC gasifier was sawmill residues of softwood species which produced bottom ash with a low carbon content. Ash produced from the gasifier was collected, wetted and stored moist in a covered bin for a year before application. The CPLP boiler feedstock was chips and sawdust, and the bottom ash produced was high in carbon content. Ash collected from the boiler was stored in a covered bin for a year before application. Wood ash was broadcast by hand to the sites (NRCan, 2018).

2.2.2 Mistik (Burness)

This wood ash experiment was initiated in 1995 on a replanted white spruce *(Picea glauca* Moench*)* plantation located at Mistik (Burness) in Saskatchewan (53.7 ˚N, 108.2 ˚W). The 60-69 year old stand of trembling aspen (*Populus tremuloides* Michx.) and white spruce was clearcut with full tree harvesting and disc-trenched prior to replanting. The site is at an elevation of 691 m where the mean minimum and maximum temperatures are -22.2 and 22.4 ^{o}C with a mean annual precipitation of 431 mm. The site was classified as the Boreal Forest Region of the Boreal Plains Ecozone in northwest Saskatchewan. The Orthic Grey Luvisol soil has a clay loam texture with pockets of sandy loam and is moderately to excessively stony. The soil developed on an ablation moraine and there is an approximately 5-10 cm thick forest floor layer (LFH) (NRCan, 2018).

Wood ash used for this experiment was a bottom ash produced from an olivine burner at Miller Western Mill in Saskatchewan. The experimental design was a complete randomized block design with three ash application rates at 0 Mg/ha (Control), 1 Mg/ha and 5 Mg/ha. The treatment plots are 0.003 ha in size. Three replicate soil samples were collected randomly from each block. The feedstock for the burner was 85% trembling aspen bark + chips and 15% de-watered pulp sludge. Ash from the burner was stored outdoors. Since the ash self-hardened due to exposed storage, it was crushed before application. Wood ash was broadcast by hand to the site in July 1995 (NRCan, 2018).

2.2.3 Pineland

The wood ash experiment in Pineland Manitoba (49.5˚N, 96.1˚W) was established in May 2015 on a planted jack pine *(Pinus banksiana* Lamb*.)* stand. The site was a 30 year old jack pine stand, which was clearcut using whole tree harvesting prior to replanting in May 2015. The site is at an elevation of 320 m where the mean minimum and maximum temperatures are -22.5 and 25 ^{o}C with a mean annual precipitation of 635 mm. The site was classified as the Great Lakes St. Lawrence Forest Region of the Boreal Shield Ecozone in southeastern Manitoba. The soil at the site is a Brunisol with a sandy texture that developed on glaciofluvial deposits. There is an approximately 2 cm thick forest floor layer (LFH) (NRCan, 2018).

The experiment uses a split plot design with two ash application rates at 0 Mg/ha (Control) and 1.5 Mg/ha. The treatment plots are 0.0225 ha in size. Five replicate soil samples were collected from each plot. The feedstock for the ash produced from biomass burner at

Pineland Forest Nursery contained jack pine chips and some barks. Ash used for treatment was a mixture of fly and bottom ash which was not pretreated before application. Wood ash was broadcast by hand to the site (NRCan, 2018).

2.2.4 25th Side Road (Lakehead)

Locally a wood ash experiment was established in 2012 on a former tree nursery located at 25th Side Road, Thunder Bay, Ontario (48.4˚N, 89.4˚W). The site is at an elevation of 215 m where the mean minimum and maximum temperatures are -19.2 and 23.8 °C with a mean annual precipitation of 694 mm. The site is classified as the Great Lakes St. Lawrence Forest Region of the Boreal Shield Ecozone in northwestern Ontario. The soil at the site is an Orthic Eutric Brunisol with a sandy loam texture that developed on fluvial outwash. There is no to a very limited forest floor layer (LFH) due to repeated tillage (NRCan, 2018).

The experimental design is an incomplete block design with three ash application rates at 0 Mg/ha (Control), 1 Mg/ha and 10 Mg/ha. The treatment plots are 0.00165 ha in size. Five replicate samples were randomly collected from each plot. Following the ash application, each treatment plot was planted with white spruce (*Picea glauca* (Moench) Voss) seedling on one half and black spruce (*Picea mariana* (Mill.) BSP) seedling on the other half in May 2012. Jack pine seedlings were planted as buffer around each plot to prevent deer browsing. The low carbon, fine textured fly ash used for the treatment was produced in a vibrating grate power boiler at Resolute Forest Products. The feedstock for the ash contained softwood bark, sawdust, and wood chips, with 8 to 14% secondary effluent sludge waste from pulp and paper production. Wood ash was broadcast by hand and raked into the soil (NRCan, 2018).

2.2.5 Island Lake

The Island Lake wood ash experiment was established in a 40 year old jack pine stand in May 2012 located at the Island Lake Biomass Harvest Experiment site, Ontario (47.7˚N, 83.6˚W). The site was clearcut using full tree harvesting in December 2010 and January 2011 and replanted in May 2012. The site is at an elevation of 455 m where the mean minimum and maximum temperatures are -20.6 and 23.1 ºC with a mean annual precipitation of 927 mm. The site is classified as the Boreal Forest Region of the Boreal Shield Ecozone in central northeastern Ontario. The soil at the site is an Eluviated Dystric Brunisol with a sandy to sandy loam texture that developed on glaciofluvial deposits. The forest floor layer (LFH) is approximately 10 cm thick (NRCan, 2018).

The experiment uses an incomplete block design with five ash application rates at 0 Mg/ha (Control), 0.7 Mg/ha, 1.4 Mg/ha, 2.8 Mg/ha and 5.6 Mg/ha. The control plots were 0.49 ha and the treatment plots were 0.0625 ha in size. Four replicate soil samples from treatment plots and five replicates from the control plots were randomly collected. Wood ash was broadcast by hand without any treatment to the soil surface. Following the ash application, jack pine seedlings were planted on the site in May 2012. The bottom ash used for the treatment was produced from Tembec cogeneration plant. The feedstock for the ash contained bark, sawdust, and shavings of mainly jack pine and black spruce (NRCan, 2018).

2.2.6 Haliburton

A wood ash experiment was established at Haliburton, Ontario (45.3˚N, 78.6˚W) in August and September 2013 on an uneven aged mixed deciduous stand. The dominant species include, sugar maple (*Acer saccharum* Marsh.), American beech (*Fagus grandifolia* Ehrh.), eastern hemlock (*Tsuga canadensis* (L.) Carrière), and yellow birch (*Betula* *alleghaniensis* Britt.). The site was managed using single tree selection harvesting in 2013. The site is at an elevation of 375 m where the mean minimum and maximum temperatures are -17 and 24.7 ^oC with a mean annual precipitation of 1074 mm. The site is classified as the Great Lakes St. Lawrence Forest Region of the Boreal Shield Ecozone in southern Ontario. The soil at the site is an Orthic or Eluviated Dystric Brunisol with a sandy loam texture that developed from poorly weathered granite or granitic gneiss deposits. The forest floor layer (LFH) at the site is approximately 5-8 cm thick (NRCan, 2018).

The experiment uses an incomplete block design with seven ash application rates at 0 Mg/ha (Control), 1 Mg/ha (fly ash), 4 Mg/ha (fly ash), 8 Mg/ha (fly ash), 1 Mg/ha (bottom ash), 4 Mg/ha (bottom ash) and 8 Mg/ha (bottom ash). The control plots are 0.49 ha and the treatment plots are 0.0625 ha in size. Four replicate soil samples were randomly collected from each plot. Wood ash was broadcast by hand without pretreatment to the soil surface. The ash used for the treatment was produced in a vibrating grate biomass boiler at Pulp and Paper Mill – Detroit Rotostoker. The feedstock for the ash contained bark of spruce, pine and fir from the debarking in pulp production (NRCan, 2018).

2.2.7 Eastern Township

A wood ash experiment was established on a 60-80 year old mixed deciduous stand located at Eastern Township, Quebec (45.57˚N, 71.25˚W). The dominant species in the stand includes sugar maple, American basswood (*Tilia americana* L.), American beech (*Fagus grandifolia* Ehrh.), white ash (*Fraxinus americana* L.), and/or Bbutternut (*Juglans cinerea* L.). The stand was managed using clearcut or selection harvesting before the experiment plots were established in 2015. The elevation of the site ranges from 270 - 400 m with a mean minimum and maximum temperature of -17 and 24.7 ^oC and a mean annual precipitation of 1264 mm. The site was classified as the Great Lakes St. Lawrence Forest Region of the Mixedwood Plains in southern Quebec. The soil at the site is an Orthic Humo-Ferric/Ferro-Humic Podzols with a sandy to loamy sand to sandy loam texture that developed on tills with gentle to moderate slopes. The forest floor layer (LFH) is approximately 10-15 cm thick (NRCan, 2018).

The experimental design is a split plot design with two ash application rates at 0 Mg/ha (Control) and 20 Mg/ha. The size of each treatment plot is 3 ha. Five replicate soil samples were collected from each plot. Wood ash was applied using a mechanical spreader without pretreatment to the soil surface in 2015. The bottom ash used for the treatment was produced in a biomass boiler at the Domtar Mill. The feedstock for the ash contained 80% hardwood and softwood bark and 20% wooden construction and demolition debris (NRCan, 2018).

2.3 Laboratory analyses

Samples were received frozen and a subsample of the frozen sample was air dried and sieved to 2 mm for the mineral layer and 4 mm for the forest floor (organic) layers to homogenize the samples. The remaining samples were kept frozen until further analysis. Moisture contents were determined on the field moist and air dried samples by drying to a constant weight at 105 ^{o}C (Appendix 1).

2.3.1 Total carbon and nitrogen

A representative fraction of air dried sample was ground in a SPEX 8000M Mixer/Mill to pass through a 53 mm sieve to further homogenize the sample. The concentrations of total carbon and nitrogen in the ground samples were determined using flash combustion in an elemental analyzer, (vario EL cube, Elementar, Langenselbold, Germany) (Appendix 1). Combustion of soil samples in the Elementar at 1150 ^{o}C in the presence of oxygen converted all the carbon present to CO_2. The CO_2 produced was then measured using a thermal conductivity detector. Measurement of total nitrogen (N) was also obtained from the Elementar in order to determine the CN ratio of the samples.

2.3.2 Sand fraction carbon

Physical fractionation on the basis of size was carried out to determine the carbon associated with the sand sized fraction. Organic matter associated with sand sized fraction contains remains of plants, animals and microorganisms at different stages of decomposition (Carter & Gregorich, 2008). This organic matter fraction has been used to assess the impact of land use, management and other disturbance on carbon turnover and storage (Carter & Gregorich, 2008).

Approximately 25 g of air dried and sieved mineral sample, 125 mL of distilled water and 30 borosilicate glass beads of 5 mm diameter were added to a 250 mL centrifuge bottle. Bottles were shaken on a mechanical shaker for 16.5 hours to disperse soil aggregates. Samples were then wet sieved using 53µm sieve which separated the sand sized and silt and clay particles. The silt and clay fraction was washed through the 53µm and collected in a 4 L graduated bucket using a minimum of 1L of distilled water and until the wash was clear. Particles retained on the sieve after the rinse are classified as the sand sized particles and the particles washed down through the sieve that was collected into the jar were the silt and clay sized particles. The sand sized particles retained in the sieve were then transferred to a pre-weighed container and oven dried at 60°C. Approximately 10 ml of 1 M $CaCl_2$ solution was added to the silt and clay fraction for better coagulation and settling of particles. Once settled, the supernatant was carefully removed by siphoning off the water and the silt and clay sized particles were rinsed into a pre-weighed container. The retained particles were then oven dried at 60 °C. The oven dried fractions of sand and silt and clay were weighed and transferred to scintillating vials. These fractions were then ground to powder in the high-energy ball mill. Carbon and nitrogen associated with sand fraction and silt and clay fractions were then determined using flash combustion.

Calculations:

Sand fraction C (g of C/g of soil) = $\%C_{sand}/100$

Silt and clay fraction C (g of C/g of soil) = $\%C_{silt+clay}/100$

Where, $\%C_{sand}$ - total carbon in sand fraction (percentage)

$\%C_{silt+clay}$ - total carbon in silt and clay fraction (percentage)

Mass, carbon and nitrogen recovered in the sand and silt+clay fractions were determined by adding the mass of carbon and nitrogen recovered in each fraction and dividing it by the initial mass of carbon and nitrogen concentration present in the whole soil (Appendix 2A). The contribution of sand fraction and silt and clay fraction to TC and TN were also computed (Appendix 2B, Appendix 2C).

2.3.3 Hot water extractable carbon

Water extractable organic matter in the soil is that fraction which can be extracted in solution and can pass through 0.45µ filter (Carter & Gregorich, 2008). Extraction of this labile pool of soil carbon in hot water is the hot water extractable carbon (HWEC) (Carter & Gregorich, 2008). Carbohydrate carbon represents about 40-50% of this fraction (Ghani et al., 2003). Since it is labile and easily extractable, it is the most active fraction of soil organic matter and has been used as a sensitive indicator to measure the impact of management on the carbon pool.

Approximately 20 g of mineral and 5 g of organic sieved and air dried samples were used to determine hot water extractable carbon (Carter & Gregorich, 2008). A 0.05 M $CaCl_2$ solution was added to each sample at a soil to solution ratio of 1:2 for minerals and 1:10 for organic samples. The mixture was kept in a hot water bath at 80 ^{o}C for 16 hours. Samples were then removed from the bath and extracted using a microfiltration unit consisting of a Buchner cup and funnel attached to an Erlenmeyer flask. A filter with 0.45µm pore size was used in the Buchner funnel for filtration. The extraction was assisted by a vacuum pump. The extracts were then transferred to a centrifuge tube and dissolved organic carbon concentrations were determined using continuous flow analysis (Carter & Gregorich, 2008) (SKALAR San++ Automated Wet Chemistry Analyzer, equipped with UV detector and DOC chemistry module, Skalar).

Calculation:

HWEC (mg of C/g of soil) = Corrected C con.*Volume of $CaCl_2$ / Weight of sample

Where, Corrected C con. – Corrected Dissolved Organic Carbon (DOC) concentration in mg/L

Volume of $CaCl_2$ – Volume of $CaCl_2$ added to each sample in L

Weight of sample – Weight of each soil sample in g

2.3.4 Mineralizable carbon

Carbon mineralization is the conversion of organic carbon to inorganic compounds as a result of decomposition by microorganisms (Carter & Gregorich, 2008). During decomposition, carbon dioxide is released as a metabolic byproduct (Carter & Gregorich, 2008). The common method used to determine carbon mineralization is an incubation of soil (Carter & Gregorich, 2008). Laboratory incubation under specific conditions measures the combined respiration rate of all active organisms present in the soil sample (Carter & Gregorich, 2008). The carbon dioxide-carbon (CO_2-C) released over a period of time can be used to estimate the readily mineralizable carbon fraction in the soil (Carter & Gregorich, 2008).

Frozen soil samples were thawed and weighed into a Buchner funnel seated with a 0.45 um membrane filter. Approximately 15 g of organic and 30 g of mineral sample was saturated with distilled water to adjust the moisture content. Moisture content was adjusted to 60% water holding capacity by applying vacuum pressure at -60 kPa, as it is within the optimum range of moisture content for mineralization (Papendick and Campbell, 2015). The disturbance of sample preparation typically results in a flush of microbial respiration (Hopkins, 2008) Therefore to allow equilibration so that we are not measuring artifacts associated with sample preparation, samples were pre-incubated for 5 days in an incubator maintained at 24 ^{o}C. After pre-incubation, the Buchner funnels containing the samples were transferred to a closed chamber incubation vessel. The vessel consisted of a 1 L mason jar and a lid fitted with a septum. After the samples were transferred into the sealed jar, the CO_2 concentration in the headspace of the jar was determined by extracting approximately 30 mL of gas from the headspace using a syringe, and CO_2 concentration was measured by gas chromatography using a flame ionization detector (SRI 310 gas chromatograph, SRI Instruments, Torrance, CA). The day and time of sample removal was recorded to calculate the incubation time. Closed chambers with blank replicates were also incubated similarly and used to correct for the background CO_2 concentration. The chromatograph was calibrated using air, and CO_2 standards (0.01%, 0.1% and 1%) every day the instrument was used for analysis. The samples in the sealed jars were incubated for 7 days, after which the measurement of CO_2 concentration in the headspace was repeated. The difference in the quantity of C-CO_2 measured between day 0 and day 7, along with the dry mass of soil, and the incubation time were used to determine the rate of carbon mineralization. The total microbial respiration obtained from 7 days incubation was used to determine the respiration rate per day (Appendix 3).

Calculation:

The moles (n) of CO_2 produced was determined using the ideal gas law equation,

$PV = nRT$

Where P = atmospheric pressure of the incubation chamber 101.325 kPa

R = universal gas constant 8.314 J/K

T = room temperature 298 K

V = volume of gas evolved in m^3

The number of moles of CO_2 multiplied by the atomic weight of carbon (12.0 g/mol) gives the mass of carbon produced.

Headspace volume (L) = Jar volume (L) - (volume occupied by soil + funnel volume + volume of soil moisture)

Volume of CO_2 produced (m^3) V = headspace volume*corrected CO_2 (ppm)/10^6

Moles of CO_2-C n= 101.3*V/(8.314*298)

Mass of C produced (mg of C-CO_2)= V/12000

Mineralizable carbon (mg of C- CO_2/g of soil) = Mass of C produced/Total carbon in the soil

2.3.5 Microbial biomass carbon

Microbial biomass carbon (MBC) represents the living component of soil organic matter (Carter & Gregorich, 2008). With a short turn over time, MBC rapidly responds to stress on the ecosystem (Carter & Gregorich, 2008). The fumigation-extraction method was used for estimating MBC on the incubated samples (Carter & Gregorich, 2008).

Incubated samples were equally divided and weighed into thick walled glass bottles for extraction. A 0.25 M K_2SO_4 solution was added to one half of the incubated sample at a soil to solution ratio of 1:3 to 1:5 for mineral and organic samples respectively. The mixture was shaken on the mechanical shaker for an hour. After shaking, the extract was filtered using Whatman filter paper (Cat No 1001-150) into centrifuge tubes. The other halves of the incubated samples were fumigated under a fume hood. The samples in the glass bottles were kept open in a thick-walled glass vacuum desiccator. The bottom of the desiccator was lined with moistened paper towels. A beaker containing 50 ml of $CHCl_3$ and some boiling chips was placed in the desiccator. The desiccator chamber was evacuated until the $CHCl_3$ boiled vigorously for 2 minutes. The desiccator was then sealed under vacuum and kept in the fume hood in the dark for 24 hours. After fumigation, the vacuum seal was released and the chloroform beaker and the paper towel were removed from the desiccator. The vacuum was then applied to the desiccator to evacuate any leftover chloroform vapors. A 0.25 M K_2SO_4 solution was added to the fumigated samples at the same ratio as previously discussed and shaken for an hour. Shaken samples were extracted using Whatman filter paper into a centrifuge tube. The dissolved organic carbon concentration in the fumigated and non-fumigated extracts was determined using continuous flow analysis. The difference in the carbon concentration between the fumigated and non-fumigated extracts was used to determine the MBC.

Calculation:

CO_2-C evolved from non-fumigated (incubated samples) = Corrected C con. of non-fumigated samples*Vnf/Dry weight of extracted soil (non-fumigated) -------------- A

CO_2-C evolved from fumigated (incubated samples) = Corrected C con. of fumigated samples*Vf/Dry weight of extracted soil (fumigated)---------------------- B

Where, Corrected C con. – Corrected Dissolved Organic Carbon (DOC) concentration in mg/L

Vnf = volume of solution in the non-fumigated extracted soil (L)

Vf = volume of solution in the fumigated extracted soil (L)

Soil microbial biomass carbon (mg of C/g of soil) = (A-B)/k

Where, k = efficiency of extraction of microbial biomass (0.45) (Carter & Gregorich, 2008).

2.3.6 Normalized Fractions, Storage and soil pH

Fractions were also normalized to total carbon to examine differences in carbon quality. The total carbon and nitrogen storage at each site and in each layer were also calculated using particle and bulk density estimated from the soil cores at the time of collection.

The pH of the soil samples was measured in 0.01 M $CaCl_2$ at a soil to solution ratio of 1:2 for mineral samples and 1:4 for organic samples.

2.4 Statistical analysis

For each site, a one-way ANOVA (Analysis of Variance) was conducted to test for the effect of wood ash treatment on total carbon (TOC), sand fraction C, microbial biomass C (MBC), carbohydrate C and mineralizable C for each layer (Quinn and Keough, 2002). ANOVAs were also conducted on the normalized fractions which were, HWEC/TC, MBC/TC (microbial quotient), mineralizable C/TC (soil respiration rate), and mineralizable C/MBC (metabolic quotient); the silt and clay fraction in the mineral soil; the total carbon and nitrogen storage at each site; and the soil pH measured for each layer. Treatment effects on the C to N ratio in the whole soil and mineral layers were also analyzed using ANOVA (Quinn and Keough, 2002). The normality of residuals was tested using Anderson-Darling test and the homogeneity of variance was verified by Leven's Test ($p>0.05$) (Quinn and Keough, 2002). Tukey's Honest Significant Difference was performed as post hoc following significance for an α of 0.05 to assess the difference between means of carbon concentrations with each treatment. For the sites with an unbalanced design, analysis was conducted with Type II error and the sum of squares obtained was compared to those of the analysis carried out assuming a balanced design ANOVA (Quinn and Keough, 2002). Results from both approaches showed similar levels of significance and results from the balanced analysis are presented because they have a higher power. If the distribution in the observations were non-normal, the data were logged transformed using log function in R to meet the assumptions of the ANOVA model. ANOVAs were performed on log-transformed values where the transformation satisfied the normality assumption of ANOVA. Non-parametric analyses using the Kruskal-Wallis test were conducted when transformation did not normalize the data (Quinn and Keough, 2002). The results obtained from the Kruskal-Wallis test were similar to that of balanced ANOVA. Thus parametric one-ANOVA was preferred over the Kruskal-Wallis test to maintain the power. All analyses were conducted using R software, version 3.1.2.

Multivariate analysis was conducted using Principal Component Analysis (PCA) to explain the factors contributing to the variability in the carbon fractions, normalized fractions and carbon and nitrogen stores (Kooch et al., 2008). The factors included site, rate of ash application and soil layer. The PCA was used to summarize and simplify data by reducing the dimensionality of dataset (Lê et al., 2008). In this analysis, the correlation coefficient between the variables and the coordinates of individual soil samples on the principle component axes are calculated to identify the factors explaining the observed variability in the data set. Each dimension is then described using these factors (Lê et al., 2008).

FactoMineR package from R was used for multivariate analysis. Missing values in the dataset were handled using the missMDA package in R. The PCA was used to cluster the 251 soil samples based on the rate of wood ash applied at eight different sites across Canada. To determine the contribution of site, treatment and layer (qualitative variables) to the distribution of carbon fractions, normalized fractions and carbon and nitrogen stores (quantitative variables) Factorial Analysis for Mixed Data (FAMD) was also conducted using FactoMineR package. FAMD is the PCA of mixed data (Lê et al., 2008).

3. Results

The effect of wood ash amendment on total carbon and the carbon fractions varied among the sites, rate of ash application and soil layers, but was not always significant ($p<0.05$) (Table 1, Table 2). The carbon concentrations were higher in the forest floor layers (LM: litter-moss, FH: fibric-humic and LFH: litter-fibric-humic) than in the mineral layers (MIN). The general trend observed with ash addition was a significant decline in the carbon concentration in the forest floor layers and a significant increase in the mineral soil layers. Soils under mature hardwood stands had a stronger response to ash amendment than the conifers but these sites also had the highest rate of ash (20 Mg/ha) application.

3.1 Effects of ash application on total carbon and labile carbon fractions

The total carbon concentrations ranged from 0.2 to 0.4 g/g of soil in the forest floor layers and 0.01 to 0.09 g/g of soil in the mineral layers across the studied sites (Table 2). A significant effect of wood ash application on total carbon (TC) concentration was only observed at two sites. Wood ash application significantly decreased the total carbon in the litter moss layer at the Island Lake site, whereas total carbon significantly increased in the mineral layer at the Pineland site (Table 1, Table 2). Compared to control (no ash), total carbon content decreased by 52.4% at Island Lake when ash was applied at 1.4 Mg/ha. At Pineland, the total carbon in the mineral layer was 45% higher than the control at an ash application rate of 1.5 Mg/ha.

The CN ratio ranged from 16.7 to 41.2 in the forest floor layers and from 13.3 to 23.6 in the mineral layers across the studied sites (Table 2). A significant decline of C:N by 12% was observed in the litter-moss layer at the Eastern Township site at an ash application rate of 20 Mg/ha relative to the control (Table 1, Table 2).

The HWEC concentration ranged between 2 and 23 mg/g of soil in the forest floor layers and 0.2 and 1.2 mg/g of soil in the mineral layers across the studied sites (Table 2).The effect of wood ash amendment on hot water extractable carbon (HWEC) showed a similar trend to that of the total carbon. The HWEC fraction decreased significantly (23%) in the litter-moss layer at the Eastern Township site relative to the control at an ash application rate of 20 Mg/ha (Table 1, Table 2). Compared to the control, a significant increase of 90% was observed in the mineral layer of the Pineland site at an ash application rate of 1.5 Mg/ha (Table 1, Table 2).

The microbial biomass carbon concentration ranged between 1 and 6 mg/g of soil in the forest floor layers and 0.2 and 0.7 mg/g of soil in the mineral layers across the studied sites (Table 2). A significant increase was observed in the microbial biomass carbon (MBC) concentration with the highest rate of wood ash application. The microbial biomass carbon increased by 70.3% in the litter-moss layer at the Eastern Township site when wood ash was applied at the rate of 20 Mg/ha (Table 1, Table 2).

The mineralizable carbon concentrations ranged between 0.3 and 1.4 mg CO_2-C/g of soil in the forest floor layers and 0.04 and 0.3 mg CO_2-C/g of soil in the mineral layers across the studied sites (Table 2). The application of wood ash significantly increased the mineralizable carbon content in the mineral layer at the Mistik site (Table 1, Table 2). The significant difference was observed between the wood ash application rates at 1 Mg/ha and 5 Mg/ha.

The carbon associated with the sand fractions in the mineral layer significantly increased with ash loading at the Pineland site (Table 3, Table 4). The sand fraction carbon content in the mineral layers of the studied sites varied from 6.3 to as high as 82 g/kg of soil (Table 4). The silt and clay fraction carbon content in the mineral layers of the studied sites varied from 4 to as high as 61 g/kg of soil (Table 4). The average mass of the fractions recovered was 98.63% and the average carbon recovered was 95.38%. The sand fraction carbon constituted an average of 62.77% of the total carbon.

The sand fraction carbon concentration was 190% higher than that observed in the control treatment when wood ash was applied at the rate of 1.5 Mg/ha. At the same rate of ash application, the carbon concentration in the silt and clay fraction at the Pineland site also showed a significant increase of 69.7% relative to the control.

3.2 Effects of ash application on total nitrogen

The total nitrogen concentrations ranged from 0.5 to 18 g/kg of soil in the forest floor layers and 0.4 to 6.6 g/kg of soil in the mineral layers across the studied sites (Table 2).The total nitrogen content decreased significantly by 46% - 56% in the litter-moss layer at the Island Lake site and increased significantly by 63.2% in the mineral layer at the Pineland site (Table 1, Table 2). The significant decline at the Island Lake site was observed when ash was applied at the rate of 1.4 and 2.8 Mg/ha. The increase in the TN content at Pineland was observed at an ash application rate of 1.5 Mg/ha.

The nitrogen associated with the sand fraction and the silt and clay fraction also showed a significant increase with wood ash application at 1.5 Mg/ha at the Pineland site (Table 3, Table 4). The sand fraction N increased significantly by 122% and the silt and clay fraction N increased significantly by 55.5% when compared to the control. The sand fraction nitrogen content in the mineral layers of the studied sites ranged from 0.1 to 2.56 g/kg of soil and the silt and clay fraction nitrogen content in the mineral layers ranged from 0.3 to 3.7 g/kg of soil (Table 4).

Table 1. ANOVA table with F and p values indicating the significant effect of ash application at different rates on the carbon fractions present in the organic and mineral layer of soil. (Significant at p<0.05; * if p<0.05, ** if p<0.01 and *** if p<0.001). LM: litter-moss, FH: fibric-humic, LFH: litter-fibric-humic and MIN: mineral

Site	Layer	Total carbon (g/g of soil)		Total nitrogen (g/kg of soil)		CN ratio		Hot water extractable carbon (mg/g of soil)		Microbial biomass carbon (mg/g of soil)		Mineralizable carbon (mg CO_2-C/g of soil)	
		F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Aleza Lake North	LFH	0.91	0.45	1.14	0.38	0.35	0.72	0.32	0.74	0.36	0.71	2.20	0.20
	MIN	0.23	0.80	0.40	0.70	0.12	0.89	0.69	0.54	0.45	0.67	0.31	0.75
Aleza Lake South	LFH	1.53	0.30	2.15	0.19	1.69	0.26	0.32	0.74	1.40	0.33	1.20	0.37
	MIN	0.69	0.54	0.40	0.68	0.58	0.59	0.69	0.53	3.59	0.09	0.39	0.69
Eastern Township	LM	0.01	0.94	7.44	0.03*	5.70	0.04*	6.30	0.04*	8.64	0.02	0.01	0.93
	FH	2.28	0.17	0.92	0.37	3.60	0.09	0.11	0.75	0.00	0.95	0.21	0.66
	MIN	0.11	0.75	0.08	0.78	0.29	0.61	0.05	0.82	0.43	0.53	0.76	0.41
Haliburton	FH	0.34	0.91	0.85	0.55	1.30	0.30	0.53	0.78	0.86	0.54	0.91	0.51
	MIN	1.06	0.41	1.27	0.31	0.89	0.52	1.29	0.30	1.47	0.23	1.01	0.45
Island Lake	LM	7.20	0.00**	6.20	0.00**	0.40	0.81	0.90	0.50	1.86	0.17	0.27	0.89
	FH	1.33	0.31	0.97	0.45	0.55	0.70	2.15	0.12	0.77	0.56	0.78	0.56
	MIN	0.87	0.50	0.98	0.45	0.69	0.61	0.47	0.76	1.10	0.41	1.27	0.32
Mistik	LFH	0.14	0.87	0.19	0.83	0.06	0.94	0.03	0.97	2.91	0.14	0.59	0.59
	MIN	1.07	0.41	1.36	0.34	0.17	0.85	0.79	0.49	1.02	0.43	4.44	0.08
Pineland	LFH	0.77	0.41	0.48	0.51	0.05	0.83	0.85	0.38	0.27	0.61	0.69	0.43
	MIN	9.70	0.02*	13.09	0.01*	0.87	0.39	10.81	0.02*	1.09	0.34	7.70	0.03*
25th Side Road	LFH	0.54	0.60	0.81	0.47	0.14	0.87	0.43	0.66	1.15	0.36	1.34	0.30
	MIN	0.39	0.69	0.83	0.46	0.51	0.62	2.45	0.13	0.42	0.67	1.13	0.36

Table 2. Mean and standard deviation of total carbon and nitrogen and the carbon fractions present in the organic and mineral layer of soil at different rates of ash application per site. Different letters indicate statistically significant ($p < 0.05$) difference from Tukey's HSD. LM: litter-moss, FH: fibric-humic, LFH: litter-fibric-humic and MIN: mineral

Site	Ash application (Mg/ha)	Ash type	Layer	TC (g/g of soil)		TN (g/kg of soil)		CN ratio		HWEC (mg/g of soil)		MBC (mg/g of soil)		Min. C (mg CO_2-C/g of soil)	
				Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Aleza Lake North	0	No ash	LFH	0.22	0.04	7.50	0.80	29.30	2.56	8.69	0.84	2.06	0.31	0.68	0.07
	5C	Bottom ash-Boiler	LFH	0.32	0.08	9.60	1.65	32.83	3.52	7.58	1.31	2.59	0.96	0.90	0.11
	5U	Bottom ash-Gasifier	LFH	0.32	0.15	9.23	2.56	32.78	9.28	7.95	2.56	2.35	0.87	0.63	0.26
	0	No ash	MIN	0.03	0.01	1.60	0.44	15.30	3.96	0.56	0.17	0.20	0.12	0.16	0.15
	5C	Bottom ash-Boiler	MIN	0.03	0.01	1.77	0.23	14.77	2.22	0.65	0.04	0.21	0.01	0.21	0.04
	5U	Bottom ash-Gasifier	MIN	0.03	0.01	1.97	0.72	15.86	1.53	0.68	0.14	0.28	0.16	0.20	0.04
Aleza Lake South	0	No ash	LFH	0.30	0.08	11.50	4.26	26.38	2.87	8.69	0.84	2.38	0.82	0.87	0.20
	5C	Bottom ash-Boiler	LFH	0.22	0.02	6.87	1.91	33.21	7.21	7.58	1.31	1.68	0.16	0.62	0.08
	5U	Bottom ash-Gasifier	LFH	0.26	0.04	8.93	0.85	29.30	1.48	7.95	2.56	2.34	0.57	0.78	0.26
	0	No ash	MIN	0.02	0.00	1.70	0.26	13.82	3.36	0.56	0.17	0.18	0.08	0.15	0.12
	5C	Bottom ash-Boiler	MIN	0.03	0.02	1.80	0.78	16.04	2.28	0.65	0.04	0.28	0.04	0.13	0.12
	5U	Bottom ash-Gasifier	MIN	0.04	0.03	2.13	0.68	18.74	8.80	0.68	0.14	0.29	0.04	0.22	0.14
Eastern Township	0	No ash	LM	0.43	0.01	14.64 a	1.19	29.80 a	3.06	23.61 a	1.47	3.57 a	1.78	1.39	0.94
	20B	Bottom ash	LM	0.43	0.02	16.58 b	1.06	26.24 b	1.31	18.17 b	4.63	6.08 b	0.70	1.44	0.80
	0	No ash	FH	0.26	0.08	13.24	2.64	19.26	2.44	9.36	2.53	1.73	0.42	0.67	0.30
	20B	Bottom ash	FH	0.19	0.05	11.66	2.57	16.74	1.69	8.93	1.40	1.71	0.66	0.59	0.23
	0	No ash	MIN	0.04	0.01	3.18	1.09	14.21	2.81	0.61	0.18	0.29	0.22	0.15	0.07
	20B	Bottom ash	MIN	0.04	0.01	3.02	0.56	13.32	2.45	0.64	0.20	0.21	0.14	0.10	0.09

Site	Ash application (Mg/ha)	Ash type	Layer	TC (g/g of soil)		TN (g/kg of soil)		CN ratio		HWEC (mg/g of soil)		MBC (mg/g of soil)		Min. C (mg CO_2-C/g of soil)	
				Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Haliburton	0	No ash	FH	0.43	0.04	16.65	1.81	26.04	1.68	12.60	3.76	4.22	1.02	0.85	0.30
	1F	Fly ash	FH	0.44	0.03	16.63	0.87	26.21	2.13	15.18	2.72	3.60	1.67	0.78	0.15
	4F	Fly ash	FH	0.41	0.03	16.85	2.46	24.55	2.43	12.96	1.05	3.84	1.99	0.98	0.08
	8F	Fly ash	FH	0.40	0.01	16.03	0.06	25.19	0.49	13.32	1.58	3.10	0.99	0.67	0.07
	1B	Bottom ash	FH	0.43	0.04	17.80	0.83	24.47	2.66	14.35	1.60	3.26	1.16	0.76	0.23
	4B	Bottom ash	FH	0.43	0.02	18.08	1.51	23.66	1.91	12.31	3.15	2.16	1.62	0.67	0.37
	8B	Bottom ash	FH	0.41	0.07	15.08	4.33	28.16	4.44	11.78	3.44	3.43	0.99	0.67	0.25
	0	No ash	MIN	0.17	0.13	9.15	6.32	17.15	2.75	1.28	0.20	0.73	0.28	0.35	0.15
	1F	Fly ash	MIN	0.11	0.09	6.58	4.90	16.44	1.88	1.19	0.27	0.59	0.39	0.17	0.17
	4F	Fly ash	MIN	0.09	0.08	4.20	2.21	19.59	6.63	1.01	0.32	0.36	0.19	0.15	0.08
	8F	Fly ash	MIN	0.06	0.02	3.88	0.88	16.26	1.83	1.39	0.21	0.41	0.13	0.20	0.11
	1B	Bottom ash	MIN	0.07	0.02	4.48	1.45	16.51	1.54	1.26	0.36	0.40	0.11	0.17	0.10
	4B	Bottom ash	MIN	0.06	0.01	4.05	0.72	15.58	0.53	1.38	0.27	0.41	0.18	0.23	0.12
	8B	Bottom ash	MIN	0.14	0.10	6.63	3.52	19.60	4.77	0.94	0.44	0.46	0.07	0.20	0.16
Island Lake	0	No ash	LM	0.42 b	0.02	13.34 c	3.28	33.99	11.49	9.87	1.34	3.72	1.47	0.36	0.13
	0.7B	Bottom ash	LM	0.40 b	0.07	11abc	1.00	35.74	3.16	9.55	1.17	3.40	1.35	0.32	0.06
	1.4B	Bottom ash	LM	0.20 a	0.05	5.80 a	1.68	34.91	1.79	8.16	3.14	1.63	0.74	0.32	0.11
	2.8B	Bottom ash	LM	0.28 ab	0.14	7.23 ab	3.37	41.27	14.72	7.17	3.33	2.26	1.65	0.31	0.06
	5.6B	Bottom ash	LM	0.41 b	0.04	11.55 bc	2.67	36.42	6.46	9.65	3.00	3.20	1.11	0.31	0.05
	0	No ash	FH	0.26	0.11	7.32	3.14	35.81	13.57	5.81	2.99	1.04	0.42	0.30	0.23
	0.7B	Bottom ash	FH	0.20	0.10	6.88	3.29	28.24	3.26	9.60	2.54	1.50	1.20	0.42	0.16
	1.4B	Bottom ash	FH	0.16	0.07	4.50	2.15	35.35	5.79	5.19	2.11	0.68	0.19	0.45	0.14
	2.8B	Bottom ash	FH	0.24	0.06	6.83	0.63	35.64	8.26	7.32	1.52	1.10	0.30	0.47	0.11
	5.6B	Bottom ash	FH	0.28	0.08	7.95	2.44	35.56	6.65	9.21	3.36	1.00	0.43	0.39	0.09
	0	No ash	MIN	0.03	0.01	1.22	0.46	21.60	3.03	0.58	0.16	0.18	0.10	0.05	0.03
	0.7B	Bottom ash	MIN	0.03	0.01	1.18	0.25	21.65	2.55	0.66	0.30	0.15	0.01	0.06	0.03
	1.4B	Bottom ash	MIN	0.03	0.02	1.30	0.55	23.62	3.35	0.80	0.39	0.29	0.21	0.10	0.08
	2.8B	Bottom ash	MIN	0.04	0.01	1.55	0.21	23.18	4.28	0.71	0.42	0.29	0.14	0.10	0.04
	5.6B	Bottom ash	MIN	0.02	0.00	1.08	0.13	20.42	2.11	0.55	0.19	0.21	0.09	0.05	0.03

Site	Ash application (Mg/ha)	Ash type	Layer	TC (g/g of soil)		TN (g/kg of soil)		CN ratio		HWEC (mg/g of soil)		MBC (mg/g of soil)		Min. C (mg CO_2-C/g of soil)	
				Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Mistik	0	No ash	LFH	0.29	0.08	14.27	4.99	20.88	3.61	2.22	0.44	3.57	1.10	1.04	0.12
	1B	Bottom ash	LFH	0.25	0.14	11.93	5.22	20.14	2.99	2.10	1.05	1.66	0.25	1.10	0.73
	5B	Bottom ash	LFH	0.31	0.09	14.57	2.95	21.14	1.74	2.32	0.45	2.60	1.47	0.71	0.35
	0	No ash	MIN	0.01	0.00	0.93	0.25	14.50	2.14	0.40	0.13	0.17	0.11	0.08 ab	0.04
	1B	Bottom ash	MIN	0.04	0.04	2.17	1.69	15.30	3.77	0.97	1.01	0.29	0.19	0.20 b	0.08
	5B	Bottom ash	MIN	0.01	0.00	0.73	0.25	14.64	2.26	0.36	0.07	0.10	0.13	0.04 a	0.03
Pineland	0	No ash	LFH	0.20	0.13	6.18	2.42	29.86	9.16	8.78	4.86	1.16	1.29	0.43	0.10
	1.5F+B	Fly+Bottom mixture	LFH	0.14	0.06	5.14	2.32	28.73	6.35	6.30	3.56	0.82	0.67	0.39	0.09
	0	No ash	MIN	0.01 a	0.00	0.38 a	0.04	15.58	2.65	0.22 a	0.03	0.19	0.34	0.03	0.03
	1.5F+B	Fly+Bottom mixture	MIN	0.01 b	0.00	0.62 b	0.19	17.02	2.16	0.42 b	0.18	0.69	1.03	0.08	0.06
25th Side Road	0	No ash	LFH	0.11	0.10	5.23	2.94	19.95	5.01	4.92	2.13	1.83	0.79	0.40	0.14
	1F	Low carbon fly ash	LFH	0.09	0.06	4.10	2.21	20.98	2.07	5.15	2.57	1.42	0.45	0.41	0.22
	10F	Low carbon fly ash	LFH	0.07	0.02	3.42	1.02	20.89	2.10	3.91	1.28	1.17	0.61	0.31	0.07
	0	No ash	MIN	0.02	0.00	1.30	0.14	15.75	0.66	0.46	0.13	0.22	0.10	0.10	0.05
	1F	Low carbon fly ash	MIN	0.02	0.00	1.18	0.16	16.09	0.85	0.37	0.06	0.30	0.19	0.06	0.04
	10F	Low carbon fly ash	MIN	0.02	0.00	1.16	0.17	16.29	0.82	0.33	0.04	0.24	0.15	0.05	0.05

Table 3. ANOVA table with F and p values indicating the significant effect of ash application at different rates on the carbon and nitrogen concentrations, carbon and nitrogen stock in the sand fraction and silt and clay fraction of soil. (Significant at $p<0.05$; * if $p<0.05$, ** if $p<0.01$ and *** if $p<0.001$). LM: litter-moss, FH: fibric-humic, LFH: litter-fibric-humic and MIN: mineral

Site	Layer	Sand fraction C (g/kg of soil)		Sand fraction N (g/kg of soil)		Silt clay fraction C (g/kg of soil)		Silt clay fraction N (g/kg of soil)		C storage in sand fraction (g of C/m^2)		N storage in sand fraction (mg of N/m^2)		C storage in silt clay (g of C/m^2)		N storage in silt clay (g of N/m^2)	
		F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*P*
Aleza Lake North	MIN	0.13	0.88	0.21	0.82	0.34	0.72	0.61	0.60	0.34	0.73	0.54	0.61	1.43	0.31	3.04	0.12
Aleza Lake South	MIN	0.70	0.54	0.55	0.60	0.65	0.55	0.38	0.70	1.96	0.22	3.84	0.08	3.65	0.09	10.89	0.01*
Eastern Township	MIN	0.06	0.81	0.09	0.77	0.01	0.94	0.02	0.89	0.80	0.40	0.47	0.51	1.88	0.21	0.42	0.53
Haliburton	MIN	1.15	0.37	1.44	0.25	0.66	0.68	0.71	0.65	0.43	0.85	0.51	0.80	1.97	0.12	1.34	0.28
Island Lake	MIN	1.37	0.29	1.33	0.30	0.66	0.63	0.77	0.56	0.47	0.76	0.31	0.87	0.66	0.63	1.29	0.31
Mistik	MIN	1.16	0.37	1.30	0.34	1.50	0.30	2.81	0.14	1.11	0.39	1.25	0.35	1.27	0.35	2.17	0.20
Pineland	MIN	6.47	0.03*	10.58	0.01*	6.33	0.04*	7.34	0.03*	1.71	0.23	0.65	0.44	0.09	0.77	0.63	0.45
25th Side Road	MIN	1.07	0.38	1.19	0.34	0.04	0.96	0.47	0.83	1.52	0.26	0.58	0.57	0.68	0.53	0.07	0.93

Table 4. Mean and standard deviation of the carbon and nitrogen concentrations, carbon and nitrogen stock in the sand fraction and silt and clay fraction of soil at different rates of ash application per site. Different letters indicate statistically significant ($p < 0.05$) difference from Tukey's HSD.

Site	Ash application (Mg/ha)	Ash type	Sand fraction C (g/kg of soil)		Sand fraction N (g/kg of soil)		Silt+clay fraction C (g/kg of soil)		Silt+clay fraction N (g/kg of soil)		C store in sand fraction (g of C/m^2)		N store in sand fraction (mg of N/m^2)		C store in silt+clay (g of C/m^2)		N store in silt+clay (g of N/m^2)	
			Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Aleza Lake North	0	No ash	9.19	6.87	0.25	0.18	15.21	7.14	1.25	0.36	609.29	325.57	16.90	8.39	1045.89	261.46	87.71	7.21
	5C	Bottom ash-Boiler	10.32	2.80	0.31	0.13	18.98	6.10	1.59	0.52	762.58	107.11	22.80	6.90	1395.46	264.19	117.23	24.39
	5U	Bottom ash-Gasifier	8.51	1.99	0.25	0.05	16.33	3.05	1.41	0.20	722.61	223.40	21.09	5.89	1372.94	321.27	117.94	15.32
Aleza Lake South	0	No ash	7.23	3.33	0.24	0.06	14.94	1.08	1.45	0.23	351.47	174.33	11.60	3.60	734.93	165.39	70.98 ab	19.08
	5C	Bottom ash-Boiler	19.29	19.60	0.40	0.28	24.16	15.99	1.66	0.46	405.28	432.41	8.33	6.31	498.49	364.44	33.52 b	11.35
	5U	Bottom ash-Gasifier	12.64	8.81	0.39	0.25	16.75	8.48	1.38	0.47	1007.24	626.45	31.41	17.70	1342.48	554.38	111.87 a	27.86
Eastern Township	0	No ash	8.81	4.07	0.48	0.32	33.48	9.46	2.52	0.77	460.39	243.75	25.23	18.76	1680.96	448.16	125.98	37.60
	20B	Bottom ash	8.16	4.10	0.43	0.22	32.96	10.46	2.57	0.50	337.54	153.36	18.57	10.91	1379.38	202.18	112.42	27.63
Haliburton	0	No ash	82.02	70.33	3.78	3.14	60.90	40.20	4.16	2.92	1323.60	650.98	65.16	30.48	1173.95 b	333.93	81.71	28.05
	1F	Fly ash	47.90	48.66	2.22	1.95	52.61	32.83	3.64	2.22	1281.16	272.57	63.98	12.74	1694.66 ab	287.91	119.14	32.92
	4F	Fly ash	36.10	42.72	1.32	1.08	38.52	17.03	2.37	0.65	1237.25	650.68	52.94	10.07	1799.26 ab	531.67	117.48	40.89
	8F	Fly ash	22.46	8.81	1.14	0.36	38.68	6.10	2.55	0.44	1153.56	358.68	58.84	13.88	2036.63 a	204.18	135.03	24.42
	1B	Bottom ash	31.21	18.52	1.62	0.99	38.93	7.79	2.65	0.71	1285.10	582.96	65.68	28.64	1775.84 ab	634.29	121.68	52.55
	4B	Bottom ash	21.89	4.60	1.09	0.26	40.10	7.47	2.80	0.48	1059.18	204.96	52.70	11.39	1931.56 a	209.11	135.61	20.26
	8B	Bottom ash	58.82	44.13	2.46	1.47	55.51	27.42	3.17	1.36	1621.81	772.62	71.56	19.62	1683.77 ab	331.87	99.47	21.75
Island Lake	0	No ash	9.35	6.32	0.27	0.18	16.38	6.79	0.84	0.27	363.60	218.23	10.32	6.12	635.42	219.16	32.74	8.37
	0.7B	Bottom ash	10.44	3.33	0.30	0.09	15.41	4.66	0.77	0.22	351.74	70.70	10.17	2.06	517.91	79.51	26.11	4.67
	1.4B	Bottom ash	13.70	9.79	0.38	0.24	15.96	6.06	0.83	0.31	490.08	428.18	13.69	11.24	547.82	275.56	27.76	11.20
	2.8B	Bottom ash	16.72	8.52	0.45	0.17	19.76	1.83	1.01	0.11	575.50	480.71	14.97	10.96	597.12	284.96	29.47	10.86
	5.6B	Bottom ash	6.85	1.57	0.23	0.02	14.54	2.47	0.77	0.12	344.66	79.47	11.97	3.80	759.67	250.23	40.41	13.06
Mistik	0	No ash	6.25	2.54	0.30	0.12	6.52	2.05	0.64	0.11	206.01	133.88	9.94	6.71	205.70	119.62	19.90	8.76
	1B	Bottom ash	19.95	23.32	0.84	0.90	13.82	10.99	1.17	0.55	759.94	883.15	32.15	34.16	526.65	417.18	44.38	21.09
	5B	Bottom ash	4.55	1.08	0.20	0.05	5.37	1.31	0.57	0.14	223.33	80.25	9.42	1.65	269.36	124.83	28.24	11.06
Pineland	0	No ash	1.51 a	0.30	0.09 a	0.00	3.76 a	0.50	0.27 a	0.04	87.27	30.08	5.26	1.11	210.90	31.52	15.06	2.14
	1.5F+B	Fly+Bottom mixture	4.38 b	2.51	0.20 b	0.07	6.38 b	2.28	0.42 b	0.12	137.65	80.76	6.57	3.46	201.13	64.50	13.39	4.21
25th Side Road	0	No ash	7.16	1.16	0.40	0.11	12.46	0.99	0.87	0.08	620.51	44.98	34.29	5.84	1090.17	89.96	75.68	2.83
	1F	Low carbon fly ash	6.28	1.12	0.34	0.10	12.26	1.65	0.83	0.12	581.50	42.54	30.84	6.53	1140.53	60.20	77.44	3.46
	10F	Low carbon fly ash	6.45	0.67	0.32	0.01	12.17	2.19	0.78	0.14	627.15	46.79	31.40	3.41	1184.30	193.82	75.88	13.53

3.3 Effects of ash application on normalized labile carbon pools

A significant effect of the wood ash application was observed only in the HWEC/TC and MBC/TC (microbial quotient) ratios (Table 5). The range of HWEC/TC varied from 24 to 60.6 mg/g of C in the forest floor layers and from 11.9 to 38.3 mg/g of C in the mineral layers across the studied sites (Table 6).

In the forest floor layer at Aleza Lake North and Eastern Township, the proportion of hot water extractable carbon in the total carbon (HWEC/TC) significantly decreased at an ash application rate of 5 and 20 Mg/ha respectively (Table 5, Table 6). Contrary to that, the same layer at Island Lake showed a significant increase in the HWEC/TC ratio at an application rate of 1.4 Mg/ha (Table 5, Table 6). The decrease observed at the Aleza Lake North and the Eastern Township site was 31.4% and 23.3% respectively. The increase at the Island Lake site accounted for 70% relative to the control treatment.

A significant increase in the MBC/TC ratio at the Eastern Township site was observed with the highest rate of ash application (Table 5, Table 6). The range for microbial quotient for the forest floor layers varied from 0.7 to as high as 9 and 0.5 to 1.6 in the mineral layers across the studied sites (Table 6).

The microbial quotient increased by 73% in the litter-moss layer at the Eastern Township site when wood ash was applied at the rate of 20 Mg/ha.

There was also a significant effect of ash addition on the soil respiration rate in the litter-moss layer at the Island Lake site, which showed a significant increase at an ash application rate of 1.4 Mg/ha compared to 5.6 Mg/ha (Table 5, Table 6).

The mean of soil respiration rate in the forest floor layers ranged from 0.1 to 0.4 mg CO_2-C/g of C/day and 0.2 to 0.6 mg CO_2-C/g of C/day in the mineral layers across the studied sites

(Table 6). Even though there was a significant effect of wood ash application, the significance observed in the mineralizable carbon content and the soil respiration rate at the corresponding sites mentioned above were not different from the control treatment.

Table 5. ANOVA table with F and p values indicating the significant effect of ash application at different rates on the normalized carbon fractions of the organic and mineral layer of soil. (Significant at p<0.05; * if p<0.05, ** if p<0.01 and *** if p<0.001). LM: litter-moss, FH: fibric-humic, LFH: litter-fibric-humic and MIN: mineral

Site	Layer	HWE/TC (mg/g of C)		Respiration rate (mg CO_2-C/g of C/day)		Microbial quotient		Respiratory quotient		MBC: mineralizable C	
		F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Aleza Lake North	LFH	10.92	0.01*	0.36	0.71	1.19	0.37	0.31	0.75	0.61	0.57
	MIN	0.17	0.85	0.53	0.61	0.17	0.85	0.09	0.11	0.72	0.52
Aleza Lake South	LFH	0.01	0.99	0.09	0.92	1.16	0.37	0.52	0.62	0.32	0.74
	MIN	0.66	0.55	0.07	0.93	0.37	0.71	0.59	0.58	0.45	0.65
Eastern Township	LM	6.90	0.03*	0.01	0.92	9.33	0.02*	2.48	0.15	0.70	0.43
	FH	2.74	0.14	0.68	0.43	2.07	0.18	0.00	0.97	0.07	0.79
	MIN	0.21	0.66	0.65	0.44	0.35	0.57	0.36	0.57	1.04	0.34
Haliburton	FH	0.63	0.71	1.23	0.34	0.94	0.49	0.89	0.52	0.25	0.96
	MIN	0.86	0.54	1.76	0.16	0.23	0.96	0.46	0.83	0.47	0.82
Island Lake	LM	3.19	0.04*	4.02	0.02*	0.08	0.98	0.04	0.42	1.16	0.39
	FH	1.15	0.37	3.20	0.05	2.13	0.13	0.96	0.46	1.27	0.32
	MIN	0.40	0.80	0.12	0.97	0.44	0.78	0.44	0.78	0.47	0.76
Mistik	LFH	0.70	0.54	1.80	0.26	0.89	0.47	1.47	0.31	3.27	0.12
	MIN	1.42	0.32	0.08	0.92	0.35	0.72	1.63	0.28	0.24	0.79
Pineland	LFH	0.25	0.63	0.02	0.89	0.29	0.61	0.01	0.91	0.11	0.75
	MIN	0.84	0.39	1.05	0.35	0.71	0.43	0.14	0.72	0.01	0.93
25th Side Road	LFH	0.16	0.85	0.13	0.88	0.27	0.77	0.44	0.66	0.26	0.78
	MIN	2.60	0.12	0.71	0.51	0.55	0.59	0.38	0.69	0.86	0.45

Table 6. Mean and standard deviation of the normalized carbon fractions of the organic and mineral layer of soil at different rates of ash application per site. Different letters indicate statistically significant ($p < 0.05$) difference from Tukey's HSD. LM: litter-moss, FH: fibric-humic, LFH: litter-fibric-humic and MIN: mineral

Site	Ash application (Mg/ha)	Ash type	Layer	HWE/TC (mg/g of C)		Respiration rate (mg CO_2-C/g of C/day)		Microbial quotient		Metabolic quotient		MBC: Min. C	
				Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Aleza Lake North	0	No ash	LFH	39.71 b	2.68	0.23	0.00	0.95	0.15	0.17	0.02	5.93	0.92
	5C	Bottom ash-Boiler	LFH	24.2 a	1.86	0.21	0.04	0.80	0.12	0.19	0.05	5.74	1.83
	5U	Bottom ash-Gasifier	LFH	27.24 a	6.71	0.18	0.12	0.79	0.14	0.15	0.07	7.98	4.29
	0	No ash	MIN	23.80	5.35	0.42	0.30	0.79	0.21	0.44	0.35	7.09	9.45
	5C	Bottom ash-Boiler	MIN	25.25	3.31	0.59	0.05	0.80	0.12	0.52	0.08	1.96	0.31
	5U	Bottom ash-Gasifier	MIN	22.99	5.38	0.50	0.15	0.88	0.26	0.44	0.24	2.91	1.87
Aleza Lake South	0	No ash	LFH	31.63	1.77	0.22	0.05	0.79	0.11	0.20	0.06	5.56	2.00
	5C	Bottom ash-Boiler	LFH	31.30	9.59	0.20	0.01	0.77	0.05	0.18	0.01	5.42	0.25
	5U	Bottom ash-Gasifier	LFH	32.11	6.48	0.21	0.04	0.89	0.12	0.16	0.02	6.16	0.64
	0	No ash	MIN	30.03	7.62	0.46	0.33	0.79	0.30	0.37	0.21	3.77	2.86
	5C	Bottom ash-Boiler	MIN	27.72	3.38	0.36	0.38	1.10	0.45	0.22	0.18	7.90	6.92
	5U	Bottom ash-Gasifier	MIN	23.85	7.94	0.45	0.41	0.95	0.57	0.41	0.28	5.05	5.69
Eastern Township	0	No ash	LM	54.49 a	3.02	0.25	0.16	0.81 a	0.40	0.28	0.19	6.93	6.15
	20B	Bottom ash	LM	41.77 b	10.40	0.26	0.14	1.40 b	0.16	0.13	0.07	9.91	5.05
	0	No ash	FH	37.60	10.97	0.20	0.07	0.68	0.09	0.20	0.05	5.40	1.83
	20B	Bottom ash	FH	46.48	4.82	0.23	0.07	0.90	0.32	0.20	0.07	5.80	2.77
	0	No ash	MIN	15.10	6.86	0.27	0.12	0.65	0.36	0.31	0.10	3.58	1.35
	20B	Bottom ash	MIN	17.32	8.41	0.20	0.17	0.53	0.26	0.42	0.40	51.48	104.94

Site	Ash application (Mg/ha)	Ash type	Layer	HWE/TC (mg/g of C)		Respiration rate (mg CO_2-C/g of C/day)		Microbial quotient		Metabolic quotient		MBC: Min. C	
				Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Haliburton	0	No ash	FH	29.29	8.88	0.15	0.04	0.98	0.25	0.12	0.06	10.05	3.64
	1F	Fly ash	FH	34.84	5.58	0.14	0.02	0.82	0.31	0.12	0.03	8.92	2.88
	4F	Fly ash	FH	31.85	4.46	0.18	0.02	0.94	0.50	0.17	0.08	7.10	3.22
	8F	Fly ash	FH	33.04	4.58	0.13	0.01	0.77	0.26	0.12	0.04	8.69	2.96
	1B	Bottom ash	FH	33.01	2.11	0.13	0.03	0.75	0.24	0.14	0.06	8.48	3.83
	4B	Bottom ash	FH	28.79	6.83	0.12	0.07	0.51	0.38	4.81	9.37	13.63	19.26
	8B	Bottom ash	FH	28.18	4.17	0.13	0.04	0.83	0.14	0.11	0.03	9.94	3.10
	0	No ash	MIN	14.10	11.49	0.22	0.11	0.65	0.39	0.27	0.14	4.28	1.56
	1F	Fly ash	MIN	15.99	8.90	0.11	0.04	0.60	0.34	0.16	0.11	9.26	5.92
	4F	Fly ash	MIN	18.23	11.63	0.15	0.04	0.56	0.40	0.34	0.37	5.50	3.50
	8F	Fly ash	MIN	23.01	6.09	0.26	0.17	0.68	0.30	0.32	0.23	7.84	10.21
	1B	Bottom ash	MIN	17.64	3.24	0.18	0.10	0.57	0.15	0.22	0.08	5.05	1.66
	4B	Bottom ash	MIN	22.18	4.58	0.28	0.12	0.66	0.27	0.36	0.28	4.63	3.93
	8B	Bottom ash	MIN	11.90	10.92	0.11	0.06	0.46	0.26	0.22	0.15	8.61	8.81
Island Lake	0	No ash	LM	23.33 b	3.48	0.07 ab	0.02	0.88	0.34	0.07	0.07	22.96	14.70
	0.7B	Bottom ash	LM	24.31 ab	1.32	0.06 ab	0.01	0.83	0.21	0.06	0.02	19.07	4.99
	1.4B	Bottom ash	LM	39.66 a	6.03	0.12 a	0.03	0.80	0.25	0.12	0.04	9.31	2.55
	2.8B	Bottom ash	LM	29.89 ab	14.01	0.10 ab	0.05	0.77	0.49	0.18	0.22	15.33	14.43
	5.6B	Bottom ash	LM	24.02 ab	8.76	0.06 b	0.01	0.79	0.27	0.05	0.01	19.07	4.83
	0	No ash	FH	25.85	12.36	0.09	0.05	0.43	0.11	0.16	0.12	10.86	10.16
	0.7B	Bottom ash	FH	83.26	97.71	0.22	0.17	0.69	0.28	0.25	0.24	6.14	3.22
	1.4B	Bottom ash	FH	33.97	5.57	0.24	0.08	0.55	0.20	0.37	0.13	2.95	1.06
	2.8B	Bottom ash	FH	30.49	3.09	0.16	0.05	0.48	0.15	0.24	0.07	4.47	1.44
	5.6B	Bottom ash	FH	32.94	6.71	0.11	0.02	0.36	0.10	0.24	0.13	4.92	2.07
	0	No ash	MIN	23.81	9.38	0.20	0.16	0.71	0.47	0.27	0.27	11.61	14.85
	0.7B	Bottom ash	MIN	29.71	22.46	0.17	0.10	0.63	0.18	0.20	0.13	6.80	3.95
	1.4B	Bottom ash	MIN	29.09	13.31	0.22	0.06	0.83	0.27	0.19	0.03	5.33	0.72
	2.8B	Bottom ash	MIN	19.61	8.76	0.21	0.07	0.90	0.65	0.21	0.13	6.24	3.79
	5.6B	Bottom ash	MIN	24.86	6.51	0.18	0.12	1.00	0.48	0.13	0.06	9.60	4.98

Site	Ash application (Mg/ha)	Ash type	Layer	HWE/TC (mg/g of C)		Respiration rate (mg CO_2-C/g of C/day)		Microbial quotient		Metabolic quotient		MBC: Min. C	
				Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Mistik	0	No ash	LFH	38.73	3.66	0.29	0.07	1.23	0.26	0.17	0.07	6.48	2.19
	1B	Bottom ash	LFH	42.86	3.89	0.33	0.05	0.80	0.37	0.36	0.26	3.71	2.08
	5B	Bottom ash	LFH	38.09	5.56	0.18	0.10	1.01	0.61	0.12	0.02	8.26	1.42
	0	No ash	MIN	30.39	7.87	0.52	0.29	1.41	1.02	0.28	0.08	3.81	1.00
	1B	Bottom ash	MIN	24.65	4.25	0.63	0.41	0.98	0.31	0.43	0.23	2.77	1.24
	5B	Bottom ash	MIN	34.47	3.32	0.38	0.36	0.83	1.07	3.83	5.27	4.66	6.41
Pineland	0	No ash	LFH	45.28	8.51	0.27	0.23	0.80	1.08	0.44	0.48	4.67	4.12
	1.5F+B	Fly+Bottom mixture	LFH	41.89	12.55	0.25	0.17	0.53	0.25	0.41	0.35	3.95	2.74
	0	No ash	MIN	37.30	3.44	0.45	0.35	3.21	5.58	0.46	0.37	29.89	62.22
	1.5F+B	Fly+Bottom mixture	MIN	38.33	1.51	0.51	0.28	9.07	14.53	0.57	0.51	26.35	43.54
25th Side Road	0	No ash	LFH	53.53	24.44	0.35	0.15	1.92	0.58	0.13	0.05	8.50	2.57
	1F	Low carbon fly ash	LFH	60.61	10.51	0.38	0.08	1.87	0.66	0.17	0.08	7.15	2.96
	10F	Low carbon fly ash	LFH	56.40	20.02	0.35	0.10	1.64	0.63	0.17	0.08	7.15	3.73
	0	No ash	MIN	22.30	4.93	0.36	0.21	1.05	0.41	0.24	0.09	4.71	2.17
	1F	Low carbon fly ash	MIN	19.56	1.31	0.25	0.18	1.56	0.95	0.21	0.24	136.41	287.11
	10F	Low carbon fly ash	MIN	17.58	1.93	0.22	0.20	1.21	0.76	0.15	0.10	16.24	21.33

3.4 Effects of ash application on carbon and nitrogen stores

There was no significant effect of ash addition on total carbon stocks at any site to the depth measured in the study (Table 7). The total carbon stores estimated across the studied sites ranged from 757.8 to 4993 g C/m^2 (Table 8). When examined by layer, the forest floor layer at the Aleza Lake South site showed a significant decline in C storage (Table 7). The decline in storage was 11% compared to the control treatment at an ash application rate of 5 Mg/ha.

At the Haliburton site, there was a significant increase in the carbon store in the silt and clay fraction when fly ash was applied at 8 Mg/ha and bottom ash was applied at 4 Mg/ha (Table 3, Table 4). The sand fraction and the silt and clay fraction carbon stores in the mineral layers of the studied soils varied from 87.3 to 1323.6 g C/m^2 and 201 to 1931.6 g C/ m^2 respectively (Table 4). The increase in the silt and clay fraction store was 64.5% and 73.5% compared to the control.

There was a significant decline of total nitrogen store in the litter-moss layer at the Island Lake site and a significant increase in the same layer at the Eastern Township site (Table 7, Table 8). The total nitrogen stores among the studied sites ranged from 0.2 to 12.5 mg N/m^2 (Table 8). Total nitrogen stores significantly declined at the Island Lake site, mainly at an ash application rate at 1.4 Mg/ha. The significant decline in the litter-moss layer observed at the site accounted for 78.3% relative to the control. The total nitrogen stores in the litter-moss layer at the Eastern Township site significantly increased (13.7%) at the 20 Mg/ha rate of ash application. The significant increase at the Pineland site was observed in the mineral layer which increased by 236% at the ash application 1.5 Mg/ha relative to the control treatment.

The sand fraction and silt and clay fraction nitrogen stores in the mineral layers of the studied soils varied from 8.3 to 65.7 mg of N/m^2 and 13.4 to 135.6 g N/m^2 respectively (Table 4). The nitrogen stock associated with the silt and clay fraction significantly increased (57.6%) at the Aleza Lake South site at an ash application rate of 5 Mg/ha.

3.5 Effects of ash application on soil pH

The application of wood ash significantly increased the soil pH at only a few of the studied sites (Table 7) but resulted in an overall increase in the pH at all sites. The soil pH ranged from 3.3 to 6.7 in the forest floor layers and from 4.1 to 6.2 in the mineral layers across the studied sites (Table 8). The soil pH in the forest floor and mineral layer at the Aleza Lake South site increased significantly at an ash application rate of 5 Mg/ha. At the Eastern Township site, the application of wood ash at 20 Mg/ha significantly increased the soil pH in the litter-moss layer (Table 7, Table 8). The addition of fly and bottom ash mixture at the rate of 1.5 Mg/ha significantly increased the soil pH in the organic layer at the Pineland site. The soil pH also showed a significant increase in the mineral layer at the 25th Side Road site when low carbon fly ash was added at the rate of 10 Mg/ha (Table 7).

Table 7. ANOVA table with F and p values indicating the significant effect of ash application at different rates on the carbon stock, nitrogen stock and pH of the organic and mineral layer of soil. (Significant at $p<0.05$; * if $p<0.05$, ** if $p<0.01$ and *** if $p<0.001$). LM: litter-moss, FH: fibric-humic, LFH: litter-fibric-humic and MIN: mineral

Site	Layer	Total carbon store (g of C/m^2)		Total nitrogen store (mg of N/m^2)		pH	
		F	*p*	*F*	*p*	*F*	*P*
Aleza Lake North	LFH	0.91	0.45	1.12	0.38	2.31	0.18
	MIN	0.91	0.45	0.32	0.74	0.10	0.91
Aleza Lake South	LFH	3.40	0.10	1.91	0.23	9.73	0.01*
	MIN	3.05	0.12	0.67	0.55	8.64	0.02*
Eastern Township	LM	0.08	0.78	5.72	0.04*	5.47	0.05*
	FH	2.55	0.15	1.55	0.25	0.01	0.91
	MIN	2.30	0.17	0.18	0.68	0.18	0.69
Haliburton	FH	1.49	0.23	0.56	0.76	0.86	0.54
	MIN	0.76	0.61	1.31	0.29	0.71	0.64
Island Lake	LM	2.44	0.09	8.61	0.00***	2.84	0.06
	FH	0.76	0.56	0.94	0.47	1.20	0.35
	MIN	0.19	0.94	0.88	0.49	0.22	0.92
Mistik	LFH	2.87	0.15	0.12	0.89	0.35	0.72
	MIN	1.16	0.38	0.91	0.46	0.12	0.89
Pineland	LFH	3.06	0.12	0.84	0.39	5.95	0.04*
	MIN	0.97	0.36	8.13	0.03*	0.76	0.42
25th Side Road	LFH	0.78	0.48	0.72	0.51	1.68	0.23
	MIN	0.49	0.62	0.57	0.58	45.27	0.00***

Table 8. Mean and standard deviation of the carbon stock, nitrogen stock and pH of the organic and mineral layer of soil at different rates of ash application per site. Different letters indicate statistically significant ($p < 0.05$) difference from Tukey's HSD. LM: litter-moss, FH: fibric-humic, LFH: litter-fibric-humic and MIN: mineral

Site	Ash application (Mg/ha)	Ash type	Layer	Total carbon store (g of C/m^2)		Total nitrogen store (mg of N/m^2)		pH	
				Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
Aleza Lake North	0	No ash	LFH	212.43	86.62	1.67	0.46	4.82	0.36
	5C	Bottom ash-Boiler	LFH	341.62	49.64	3.13	1.33	5.69	0.07
	5U	Bottom ash-Gasifier	LFH	294.72	180.14	3.17	1.96	5.48	0.81
	0	No ash	MIN	1744.78	565.96	0.05	0.04	4.29	0.15
	5C	Bottom ash-Boiler	MIN	2197.00	564.61	0.05	0.01	4.34	0.14
	5U	Bottom ash-Gasifier	MIN	2260.68	373.81	0.06	0.04	4.25	0.36
Aleza Lake South	0	No ash	LFH	818.93 b	336.70	3.65	2.17	4.89 b	0.13
	5C	Bottom ash-Boiler	LFH	281.48 b	12.92	1.53	0.54	5.60 a	0.17
	5U	Bottom ash-Gasifier	LFH	728.76 a	325.01	2.37	0.58	5.83 a	0.42
	0	No ash	MIN	1122.16	225.00	0.04	0.00	4.19 a	0.18
	5C	Bottom ash-Boiler	MIN	2385.06	1110.57	0.06	0.06	4.27 b	0.11
	5U	Bottom ash-Gasifier	MIN	907.32	774.52	0.11	0.12	4.61 a	0.08
Eastern Township	0	No ash	LM	654.96	145.42	6.34 a	0.49	4.42 a	0.34
	20B	Bottom ash	LM	685.28	190.13	7.21 b	0.64	4.87 b	0.27
	0	No ash	FH	2050.30	795.80	3.58	1.92	4.16	0.85
	20B	Bottom ash	FH	1358.50	552.83	2.36	1.05	4.21	0.46
	0	No ash	MIN	2196.90	614.97	0.15	0.07	4.27	0.78
	20B	Bottom ash	MIN	1719.57	343.78	0.13	0.06	4.11	0.29

Site	Ash application (Mg/ha)	Ash type	Layer	Total carbon store (g of C/m²)		Total nitrogen store (mg of N/m²)		pH	
				Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
Haliburton	0	No ash	FH	596.09	125.47	7.25	1.36	5.15	0.47
	1F	Fly ash	FH	802.64	310.52	7.24	0.74	4.79	0.53
	4F	Fly ash	FH	890.21	465.48	6.95	1.51	4.94	0.49
	8F	Fly ash	FH	905.64	328.26	6.48	0.15	5.01	0.30
	1B	Bottom ash	FH	1097.07	245.55	7.72	0.60	4.74	0.53
	4B	Bottom ash	FH	601.95	376.29	7.70	0.80	4.84	0.42
	8B	Bottom ash	FH	580.72	247.38	6.42	2.56	5.35	0.44
	0	No ash	MIN	2811.05	569.89	2.11	2.30	4.54	0.91
	1F	Fly ash	MIN	3266.79	154.77	1.08	1.61	4.34	0.67
	4F	Fly ash	MIN	3625.56	983.06	0.52	0.70	3.96	0.21
	8F	Fly ash	MIN	3291.81	555.14	0.26	0.13	4.10	0.38
	1B	Bottom ash	MIN	3211.53	803.60	0.36	0.20	4.74	1.11
	4B	Bottom ash	MIN	3044.95	379.15	0.26	0.09	4.14	0.26
	8B	Bottom ash	MIN	3988.48	1757.22	1.21	1.27	4.40	0.32
Island Lake	0	No ash	LM	680.70	128.25	5.66 c	1.44	3.69	0.22
	0.7B	Bottom ash	LM	756.68	317.86	4.39 bc	1.05	3.95	0.37
	1.4B	Bottom ash	LM	422.57	103.62	1.23 a	0.64	4.31	0.33
	2.8B	Bottom ash	LM	494.67	39.00	2.27 ab	1.71	4.10	0.48
	5.6B	Bottom ash	LM	580.37	170.58	4.76 bc	1.36	4.36	0.30
	0	No ash	FH	896.35	385.92	2.07	1.51	3.33	0.29
	0.7B	Bottom ash	FH	665.03	91.38	1.62	1.19	3.68	0.42
	1.4B	Bottom ash	FH	857.09	437.05	0.82	0.65	3.86	0.49
	2.8B	Bottom ash	FH	1069.96	919.66	1.68	0.57	3.79	0.51
	5.6B	Bottom ash	FH	1282.38	804.89	2.33	1.38	3.70	0.26
	0	No ash	MIN	1065.04	503.56	0.04	0.04	3.97	0.18
	0.7B	Bottom ash	MIN	866.07	132.87	0.03	0.02	3.90	0.19
	1.4B	Bottom ash	MIN	1109.97	725.80	0.05	0.04	3.87	0.42
	2.8B	Bottom ash	MIN	1173.95	762.91	0.06	0.02	3.81	0.38
	5.6B	Bottom ash	MIN	1130.41	312.21	0.02	0.01	3.93	0.14

Site	Ash application (Mg/ha)	Ash type	Layer	Total carbon store (g of C/m^2)		Total nitrogen store (mg of N/m^2)		pH	
				Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
Mistik	0	No ash	LFH	1436.53	421.41	4.37	2.69	6.34	0.33
	1B	Bottom ash	LFH	837.07	29.95	3.43	3.26	6.71	0.93
	5B	Bottom ash	LFH	2591.87	1762.15	4.71	2.35	6.40	0.20
	0	No ash	MIN	423.77	226.11	0.01	0.01	5.59	1.18
	1B	Bottom ash	MIN	1422.87	1422.55	0.12	0.18	5.51	0.74
	5B	Bottom ash	MIN	525.30	244.21	0.01	0.00	4.88	0.60
Pineland	0	No ash	LFH	723.66	153.70	1.47	1.43	5.00 a	0.35
	1.5F+B	Fly+Bottom mixture	LFH	537.44	181.78	0.84	0.61	5.99 b	0.84
	0	No ash	MIN	334.31	82.66	0.00 a	0.00	4.97	0.12
	1.5F+B	Fly+Bottom mixture	MIN	343.72	152.13	0.01 b	0.01	5.27	0.34
25th Side Road	0	No ash	LFH	194.78	26.73	0.81	1.12	5.62	0.24
	1F	Low carbon fly ash	LFH	195.20	30.96	0.47	0.58	5.58	0.16
	10F	Low carbon fly ash	LFH	261.04	151.41	0.26	0.16	5.83	0.24
	0	No ash	MIN	1784.32	122.94	0.03	0.01	5.18 b	0.18
	1F	Low carbon fly ash	MIN	1762.67	56.96	0.02	0.01	5.25 b	0.20
	10F	Low carbon fly ash	MIN	1843.08	291.88	0.02	0.01	6.20 a	0.25

3.6 Multivariate analyses

The PCA showed that 54.3% of the total variance in the dataset was explained by the loadings on the first two principal components. The contribution of individual principle components to total variance was 41.74% (PCA 1) and 12.53% (PCA 2) (Figure 1). Among the different soil carbon fractions, carbon stores and the normalized fractions analyzed, the impact of wood ash application on forest soils was most strongly observed with the total carbon, total nitrogen, nitrogen store, HWEC, MBC, sand fraction C, mineralizable C and C:N. These variables significantly ($p<0.05$) contributed to PCA 1 with a strong positive correlation (Correlation coefficient R^2: 0.98, 0.95, 0.95, 0.88, 0.87, 0.83, 0.77 and 0.57) (Figure 2). The HWEC/TC also significantly contributed to the first axis but with a weak positive correlation coefficient of 0.13 (Figure 2). Total carbon stores and the respiration rate showed a significant ($p<0.05$) weak negative correlation to the first component (R^2: -0.27 and -0.42 respectively) (Figure 2). Variation in the second principal component was mainly explained by HWE/TC, respiration rate, pH, MBC/TC, mineralizable C, HWEC and MBC with a significant ($p<0.05$) positive correlation (R^2: 0.69, 0.54, 0.49, 0.39, 0.25, 0.17 and 0.16) (Figure 2). Sand fraction C and total carbon storage showed a significant ($p<0.05$) weak negative correlation to the second component with correlation coefficients equal to -0.31, -0.67 respectively (Figure 2).

The soil layer, site and the rate of ash application significantly ($p<0.05$) contributed to the first component with correlation coefficients of 0.7, 0.2 and 0.1 respectively. Of the soil layers, the LM and FH layers at the Eastern Township and Haliburton sites have eigenvalues significantly greater than zero indicating that these variables explain a significant proportion of the variation captured in the first principal component (Table 9).

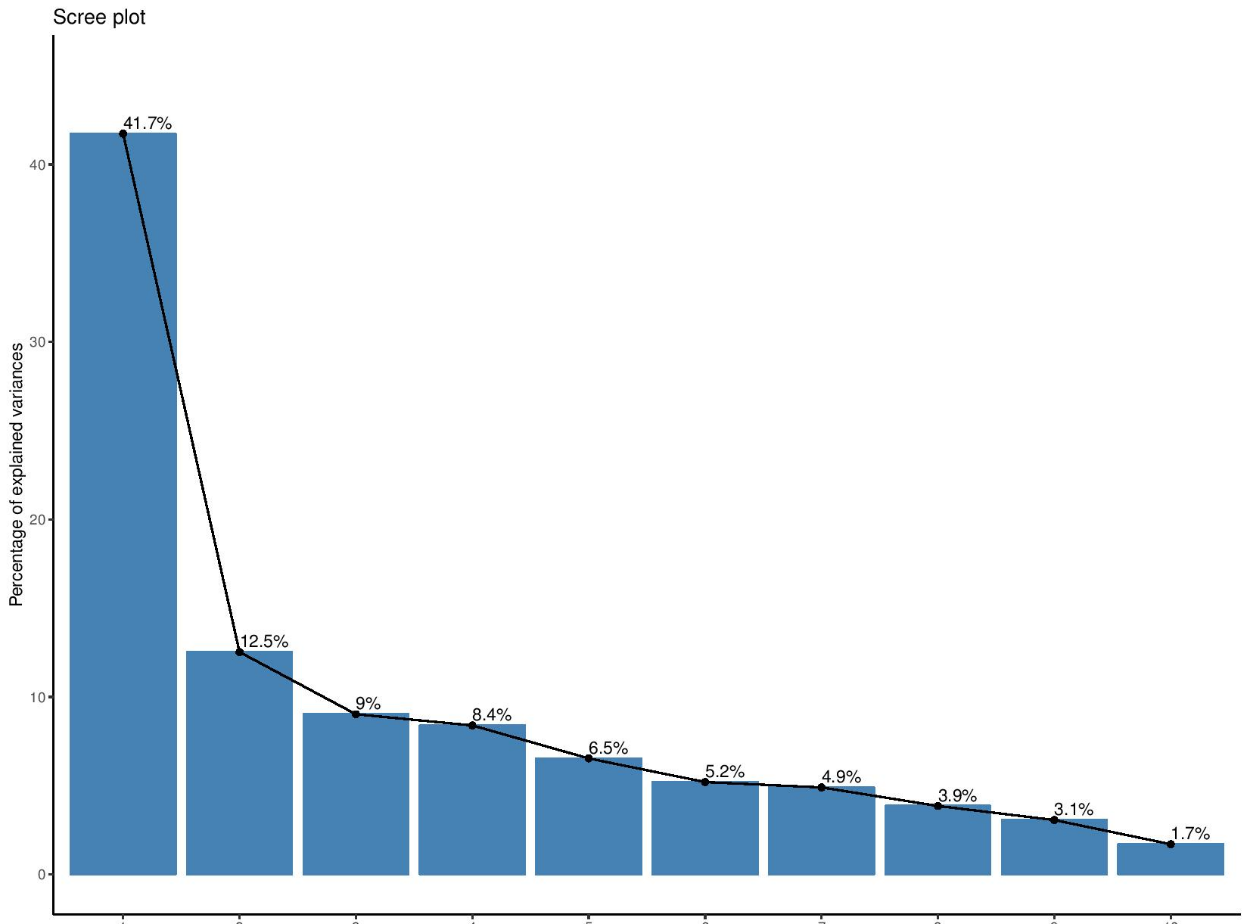

Figure 1. Scree plot of PCA showing percentage of explained variance of each dimension.

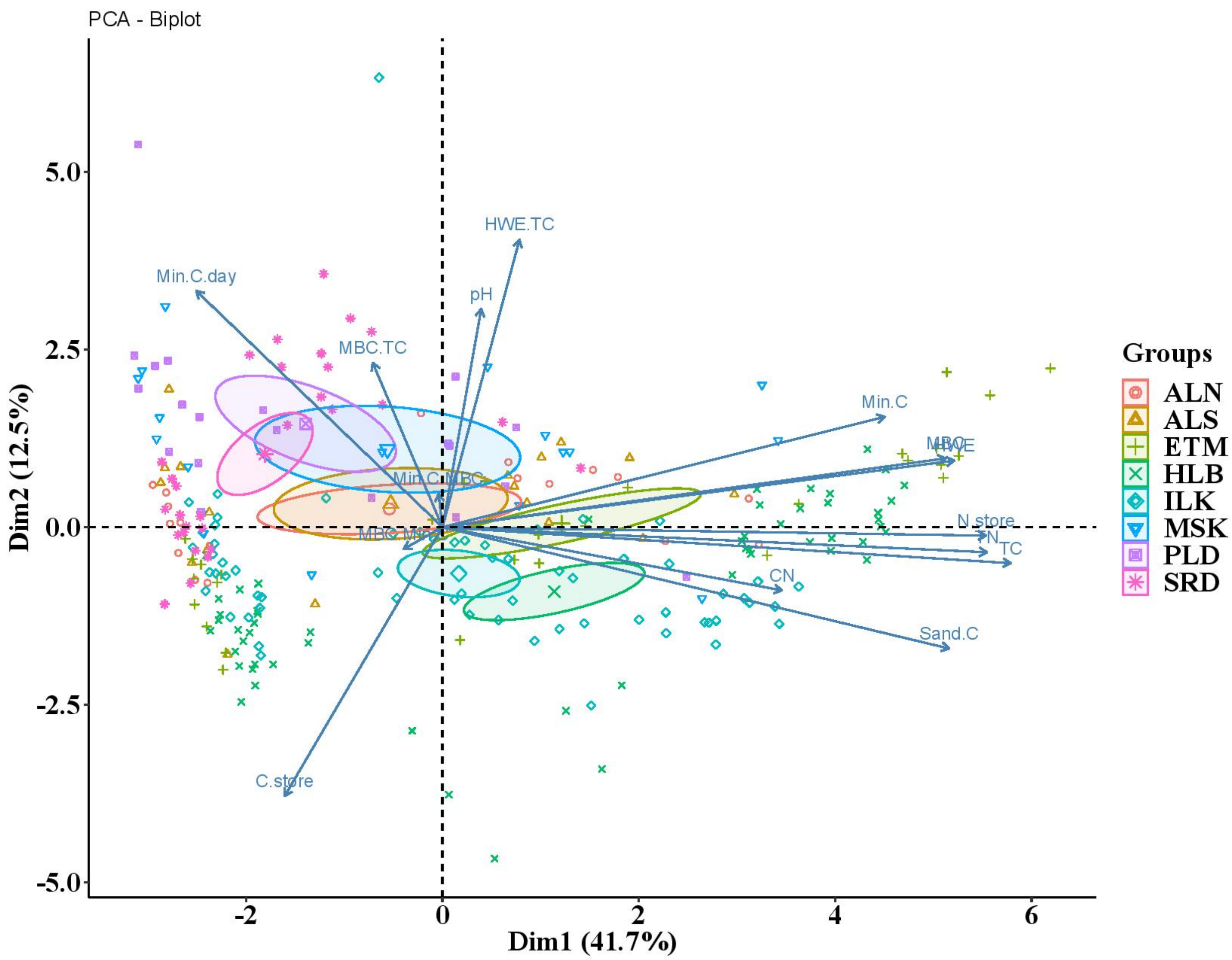

Figure 2. Biplot of PCA showing correlation of quantitative variables and the patterns adopted by the studied sites (in confidence ellipse).

Legend (Appendix 4)

Site Code	Site Name
ALN	Aleza Lake North, BC
ALS	Aleza Lake South, BC
ETM	Eastern Township Maple Sites, QC
SRD	25th Side Road, Thunder Bay, ON
ILK	Island Lake, ON
HLB	Haliburton, ON
PLD	Pineland, MB
MSK	Mistik, SK

Site, soil layer and rate of ash application also showed a weak but significant contribution to the second component with R^2 values of 0.4, 0.2 and 0.3 respectively. The LFH layer at the Pineland, 25th Side Road and Mistik site, and the ash application rates at 1, 1.5 and 10 Mg/ha have eigenvalues greater than zero indicating a significant contribution of these variables towards the second principal component (Table 9).

Table 9. Contribution of the qualitative variables studied towards PCA axes ($p<0.05$) (LM: litter-moss, FH: fibric-humic, LFH: litter-fibric-humic)

Dimension 1 (PCA 1)		**Dimension 2 (PCA 2)**	
Category	**Estimate**	**Category**	**Estimate**
Layer : FH	1.32	Layer : LFH	1.04
Layer : LM	2.05	Site : Pineland	1.18
Site : Haliburton	1.52	Site : 25th Side Road	0.7
Site : Eastern Township	1.46	Site : Mistik	0.68
		Treatment : 1	1.28
		Treatment : 1.5	1.93
		Treatment : 10	1.24

The loading plot of individual soil samples obtained from FAMD showed the clustering of samples according to the studied site, soil layer and the rate of ash application (Figure 3). The FAMD axes accounted for 25.1% of the total variance in the data set. Individual contribution of each axes to total variance was 17.2% (Dimension 1) and 7.9% (Dimension 2) (Figure 3). Even though the total variance explained was less than that of the PCA, the significant correlation of each quantitative variable to the FAMD axes were similar with the same R^2 values as of the PCA.

The soil layers, studied sites and ash application rates significantly contributed to the first dimension of FAMD at an R^2 value of 0.73, 0.28 and 0.21 respectively. The litter moss layer and the fermented humus layer, and the Haliburton and Eastern Township site as well as ash application rates 1 (fly ash) and 20 Mg/ha have eigenvalues greater than zero indicating a significant contribution of these variables towards the first dimension of FAMD (Table 10).

The studied sites, soil layers and rate of ash application also significantly contributed to the second dimension at an R^2 value of 0.67, 0.55 and 0.58 respectively. The forest floor layer and the 25th Side Road, Mistik and Pineland sites as well as ash application rates 1, 1.5, 5 and 10 Mg/ha have eigenvalues greater than zero indicating a significant contribution of these variables toward the second dimension of FAMD (Table 10). The Aleza Lake North and South sites also contributed to this dimension with eigenvalues closer to zero (Table 10).

The Mistik, Pineland and 25th Side Road sites differ from the Eastern Township, Haliburton and Island Lake sites (Figure 3). The soil samples from the Aleza Lake North and South are similar to the Mistik, Pineland and 25th Side Road sites as they shared the same quadrant of the FAMD plot (Figure 3). Ash application rates at each site were in the same quadrants as that of the sites on the FAMD plot and the Eastern Township site with the application rate 20 Mg/ha stood separated from the rest of the sites (Figure 3).

Table 10. Contribution of the qualitative variables studied towards FAMD axes ($p<0.05$) (LM: litter-moss, FH: fibric-humic, LFH: litter-fibric-humic)

Dimension 1		**Dimension 2**	
Category	**Estimate**	**Category**	**Estimate**
Layer : FH	1.71	Layer : LFH	2.45
Layer : LM	2.4	Site : Pineland	1.4
Site : Haliburton	1.99	Site : 25th Side Road	1.15
Site : Eastern Township	2.11	Site : Mistik	1.63
Treatment : 1 Fly ash	1.83	Site : Aleza Lake South	0.36
Treatment : 20	1.6	Site : Aleza Lake North	0.29
		Treatment : 1	2.47
		Treatment : 1.5	2.82
		Treatment : 5	2.25
		Treatment : 10	2.3
		Treatment : 5 UNBC ash	1.37
		Treatment : 5 CPLP ash	1.23

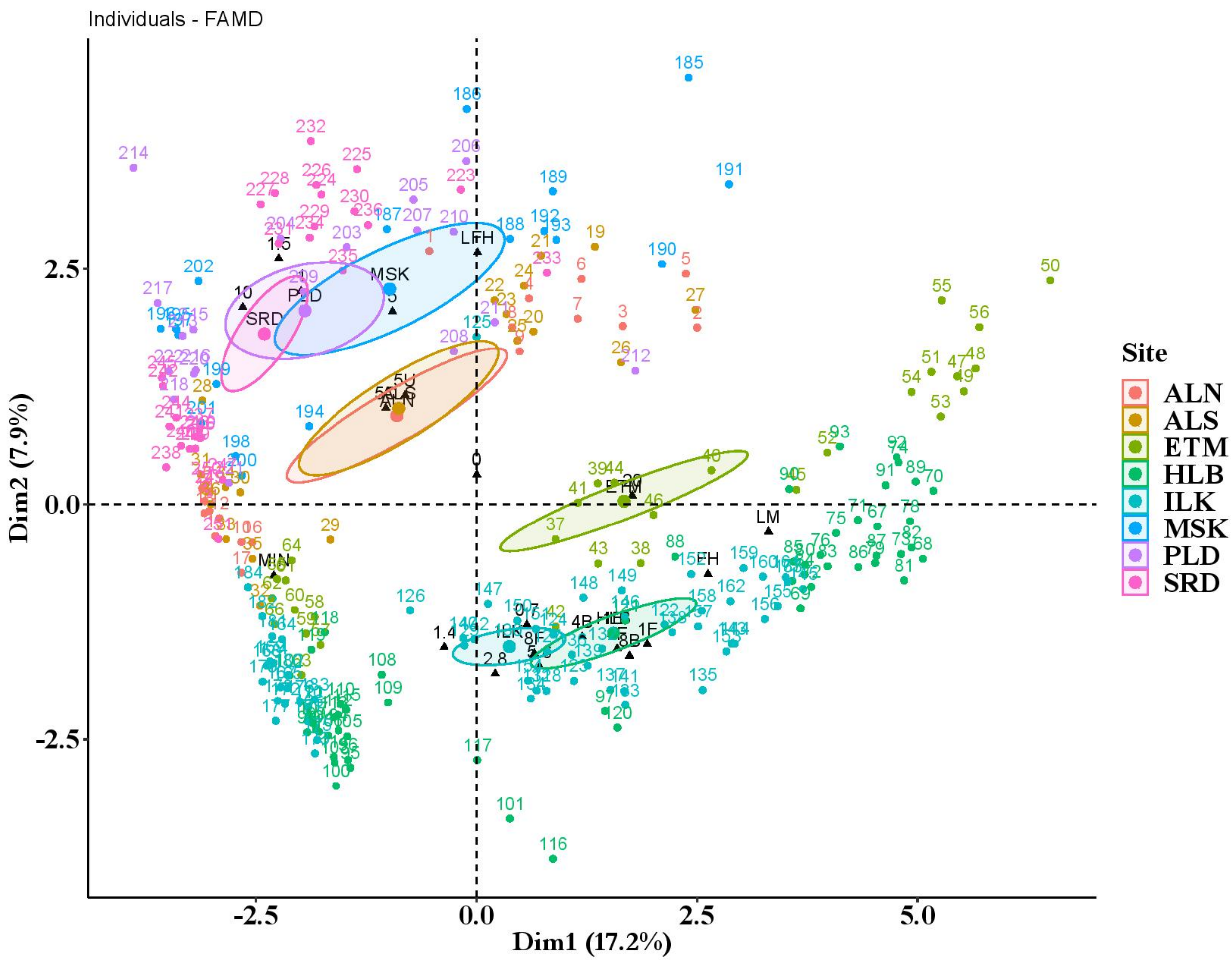

Figure 3. Loading plot of individual soil samples of the FAMD showing the patterns adopted by the samples in each soil layer according to the studied sites and the ash treatment at each site.

Legend (Appendix 4)

Soil Layer Code	Soil Layer Name
LM	Surface litter and/or moss layer
FH	Fibric and humic layer
LFH	Litter, fibric and humic layers
MIN	Mineral soil

4. Discussion

Most of the research investigating the effect of wood ash addition on forest soils has focused on the changes in soil pH and base cations following ash application. Relatively little is known about the influence of wood ash addition on soil organic matter attributes in forest soils. This study, which focuses on the effect of wood ash addition on soil carbon fractions in the forest soils collected from eight different sites located across five provinces, is the first of its kind in Canada.

The significant response of total carbon and labile carbon fractions to wood ash amendment in this study varied among the soil layers and the studied sites, which is consistent with the findings of Brais et al. (2015). The general trend observed across the sites was a significant decline in the carbon concentrations in the forest floor layers and a significant increase in carbon concentrations in the mineral layers. The decline in carbon concentrations in the forest floor may be a function of enhanced decomposition with wood ash addition followed by a vertical transport of organic compounds down to the mineral soils. Wardle et al. (2008) reported that charcoal promoted rapid loss of organic matter from the forest floor by providing a surface for the adsorption of labile organic compounds. This could have created a favorable environment for enhanced microbial growth and activity and accelerated the decomposition of the organic matter and carbon loss from the forest floor. The increased microbial activity might also have resulted in mass loss and carbon loss due to accelerated microbial respiration or leaching of soluble compounds that prompted downward transfer to the mineral layers (Wardle et al., 2008). Norris et al. (2009) reported a vertical transfer of char from the forest floor to the mineral layer following a fire in boreal forests. Brais et al. (2015) also reported a significant decline in carbon concentrations in the forest floor following ash application. A gradual decrease in labile organic carbon content with increasing depth in different forest types was also previously reported by Xiao et.al. (2016).

4.1 Response of total carbon and nitrogen concentration to wood ash amendment

Though there was a general trend towards a decline in carbon concentrations in the forest floor and an increase in the mineral soil, a significant effect of ash amendment on total carbon was only observed at two sites. The carbon concentration declined significantly in the litter moss layer at the Island Lake site and increased significantly in the mineral layer at the Pineland site. The significant decrease in total carbon concentration with wood ash addition observed at the Island Lake site could also be due to the higher C:N (>30) observed at the site (Rosenberg et al., 2010). Lower C:N favors increased litter turnover, high carbon-use efficiency of decomposer microbes, thus higher accumulation of SOC and transportation to deeper layers (Zhou et al., 2019). The increase in total carbon observed in the mineral layer at Pineland is consistent with a vertical transfer of the labile carbon pools which was previously reported by Xiao et al.(2016). In addition, the Pineland site was treated with mixed wood ash that had more organic matter (Merino et al., 2017) than the bottom ash applied at the Island Lake site. This might also have contributed to the significant increase observed in the mineral layer at the Pineland site. The range of total carbon concentrations found in this study is similar to that reported by Ingerslev et al. (2014) (forest floor: 0.3-0.4 g/g; mineral layer: 0.01-0.02 g/g) and Rosenberg et al. (2010) (forest floor: 0.3-0.4 g/g; mineral layer: 0.02-0.05 g/g).

The observed decline in the C and N concentration after the ash amendment is not commonly reported in the literature (Gömöryová et al., 2016, and Saarsalmi et al., 2001). This could be due to the difference in time since ash application and the different N content in the soil prior to ash application (Gömöryová et al., 2016). The sites that are N limited might not respond positively to the wood ash amendment, which is also deficient in N. Rosenberg et al. (2010) found no significant effect of wood ash addition on the C and N concentrations and the corresponding pools after 12 years.

Gömöryová et al. (2016) found that the decrease in C and N concentration in the forest floor layer was associated with the increase of soil pH and base cation content down the forest floor layer over time that led to increased mineralization of organic matter resulting in the loss of C and N content.

Regardless of the limited nitrogen content in the wood ash applied, the increase observed in the soil pH (not significant) in the litter-moss layer at the Island Lake site might have enhanced microbial activity and N mineralization (Vestergård et al., 2018) which may explain the significant decline in the N concentration observed in this study. The range of total nitrogen concentration reported in this study is comparable to the findings of Ingerslev et al. (2014) (forest floor: 12-13.7 g/kg; mineral layer: 0.5-0.73 g/kg) and Rosenberg et al. (2010) (forest floor: 9.8-16.7 g/kg; mineral layer: 0.9-2.3 g/kg). Also, the range of C:N reported in this study for the forest floor layer and the mineral layer falls within the range reported by Ingerslev et al. (2014) (forest floor: 27-31.6; mineral layer: 23.2-33.8) and Rosenberg et al. (2010) (forest floor: 25.4-35.3; mineral layer:22.9-33.2).

The significant decline in the C:N ratio observed in the litter moss layer at the Eastern Township site could be attributed to the significant increase in the total N concentration observed in the same layer at the site. This might be because of the slower rate of N loss compared to the C loss from the litter decomposition of hardwood species and microbial immobilization at the sites with limited N (Bélanger et al., 2019).

Wood ash application could have influenced the conversion rate of inorganic nitrogen (Pugliese et al., 2014). In accordance with previous studies, wood ash may or may not have any effect on the N dynamics of N limited soils. The Haliburton site studied by Pugliese et al. (2014) has a high rate of atmospheric deposition of N, which may have resulted in high N availability at the site. An indirect increase in N availability could also be possible from the ash application due to an increase in soil pH that stimulated N mineralization (Pitman, 2006). The reason for the increase in N mineralization may be attributed to an increase in soil microbial biomass (Pitman, 2006) which was observed at the Eastern Township site.

4.2 Response of soil carbon fractions to wood ash amendment

The labile carbon fractions were more responsive than total carbon to wood ash amendment across the studied sites but the sensitivity of these carbon pools was not consistent across the sites. The HWEC, MBC and sand C fractions showed the greatest change with ash amendment of all the carbon fractions. HWEC and MBC fractions are typically correlated with each other and with the rate of soil respiration (Bera et al., 2019 and Weigel et al., 2011), which was also observed in this study. The increases in the extractable carbon content in the mineral layer observed in this study was also observed by Bera et al. (2019) in a biochar experiment conducted in sandy soil. There is limited data available on the impact of wood ash addition or comparable management induced changes on the HWEC in forest soils. A standard HWEC concentration classification derived for sandy and loamy soils under the northern European climatic conditions classifies soils with less than 0.2 mg/g as being SOC depleted while soils with greater than 0.4 mg/g of carbon were classified as high SOC (Weigel et al., 2011). Using this classification the HWEC range obtained for the forest floor and the mineral layers in this study indicate that the soils at all sites are not depleted in SOC. The significant decrease observed in the HWEC concentration with ash application in the litter moss layer at the Eastern Township site could be due to the increased microbial activity with the highest rate of ash application. The highest rate of ash could have produced more available carbon forms (easily extractable carbon) that are energy sources for microbes. With the availability of these labile pools, microbial activity increased and could have caused rapid decomposition resulting in a decline in the extractable pool of carbon. The litter moss layer at Eastern Township showed a significant increase in the soil pH which could have increased microbial activity as a stress response. The significant increase in pH resulting from the highest addition of base cations from the wood ash may have promoted the growth of the bacterial community which was reflected in the microbial carbon. This was previously reported in a Podzol in Finland (Perkiömäki, 2004). The significant increase in the HWEC observed at the Pineland site could also be from the additional organic matter inputs from the mixed wood ash which induced an increased availability of the labile carbon content in the mineral layer. Norström et al. (2012) reported that the increase in the dissolved organic carbon concentration in the soil with wood ash application was a fertilizer effect from the ash treatment that increases plant nutrient availability which in turn increases biological activity and turn over time for different carbon compounds in the soil. The increase observed in the mineral layer at the Pineland site could also be explained by the translocation of soluble organic matter from the litter layer to the underlying mineral layer which was reported by McFee and Kelly (1995).

The significant increase in the microbial biomass carbon and the proportion of soil carbon in MBC (MBC/TC) in the litter moss layer at the Eastern Township site could be attributed to increased microbial activity (Saarsalmi et al., 2012) reflected as the significant decline in the HWEC content. The reduction in soluble organic matter due to microbial uptake was also reported by McFee and Kelly (1995). The significant decline in the HWEC indicates increased uptake of dissolved organic carbon by microbes due to enhanced activity, which was observed at the Eastern Township site. This could also be due to the persistent significant increase in the soil pH at the site resulting in enhanced microbial activity and the rate of carbon cycling (Reed et al., 2017). Perkiömäki (2004) reported an increase in microbial activity following wood ash application when measured as either mineralization rate or respiration rate in the humus (forest floor layer) of the boreal forest. Saarsalmi et al. (2012) and Perkiömäki (2004) also reported no effect of the wood ash amendment on MBC content in a boreal forest. The value of MBC reported by Noyce et al. (2016) for the Island Lake and the Haliburton site (organic horizon: 0.92-4.2 mg/g, mineral layer: 0.09-0.52 mg/g) falls within the range found in study (forest floor: 0.68-4.2 mg/g, mineral layer: 0.15-0.73 mg/g). The increase in the MBC concentration reported by Perkiömäki and Fritze (2002) was related to the rate and type of ash applied and was detectable even after 18 years. An increase in the MBC concentration could also be attributed to the fine granulometry of the wood ash that permits a weak and quick increase in soil pH and promotes the supply of nutrients (Perucci et al., 2006). This incites microbial growth and activity due to the availability of easily accessible energy sources. Perucci et al. (2006) further reported a contradictory decline observed in microbial biomass carbon at an ash application rate of 20 tons/ha and explained it as the toxicity from heavy metal accumulation from a high rate of application which resulted in the partial death of soil microflora. Bååth et al. (1995) also found a significant reduction in the MBC at a high rate of wood ash application in coniferous forest soils.

Even though not different from the control, the significant difference in the soil respiration rate between treatments observed in the litter moss layer at Island Lake could reflect increased microbial activity. The significant increase observed after 23 years of ash application in the mineralizable carbon content in the mineral layer at the Mistik site was previously observed by Rosenberg et al. (2010) from a 90 day incubation study conducted on samples collected 12 years after granulated ash application to Norway spruce and Scots pine stand. Soil respiration, microbial biomass C and N and enzyme activities are often correlated with soil organic matter content and the age of successional stages (Cardoso et al., 2013). Application of wood ash to mineral forest soils and soils experiencing cold climatic conditions promotes soil respiration (Fritze et al., 1994; Khanna et al. 1994) but Gómez-Rey et al. (2012) did not find any significant effect on the basal respiration and rate in their study. The mineralizable carbon concentrations reported in the mineral layer by Merino et al. (2016) (0.22-0.45 mg/g) over a 24 hour incubation period in a Dystric and Gleyic Cambisol are comparable with the range found in this study. The range of respiration rate measured from the forest floor layer and mineral layer documented by Rosenberg et al. (2010) (forest floor: 0.51-0.33 mg/g of C/day, mineral layer: 0.5-0.31 mg/g of C/day) falls within the range found in this study (forest floor: 0.02-0.44 mg/g of C/day, mineral layer: 0.01-0.9 mg/g of C/day). Zimmermann and Frey (2002) reported that wood ash addition on microbiological properties has short term (less than 2 years) effect whereas the effect on chemical properties, especially the change in soil pH are long-term and are visible in deeper layers indicating slow downward transfer of activity (Gömöryová et al., 2016).

The carbon content in the mineral layers in the current study was mostly associated with the sand sized fraction, which is consistent with findings by Norris et al. (2009) from a natural fire in a jack pine stand. The value reported for the sand fraction carbon (fine sand >53µm) concentration reported by Norris et al. (2009) (20 g/kg) falls within the range found in this study. The silt and clay fraction range reported by Norris et al. (2009) (50-88 g/kg) was also comparable to the range found in this study. When organic carbon stores (g of C/m^2) were partitioned between the size fractions in the mineral layer the range reported in this study falls within the range reported by Norris et al. (2009) for fine sand fractions (125-297 g of C/m^2) and silt and clay fractions (23-572 g of C/m^2).

The significant increase in the carbon associated with the sand fraction in the mineral layer at Pineland may be explained by the carbon saturation of the silt and clay fractions, which was previously reported in a Chinese Mollisol by Yan et al. (2012). The Brunisol at Pineland has a sandy texture with more than 90% sand particles and less than 10% silt and clay particles. The clay fraction can reach its maximum carbon holding capacity (carbon saturation) with increased input of organic matter and any further addition accumulates in the sand fraction (Hassink, 1997). The forest floor thickness might also play a role. The thin (2 cm) forest floor layer at Pineland has a lower capacity to hold cations added from wood ash than a thick forest floor layer (Gömöryová et al., 2016) and may easily get transported to deeper layers. Yan et al. (2012) also reported that the soil organic matter associated with coarse fractions are more sensitive to fertilization which might be the reason for the significant effects observed in the mineral layer at the Pineland site.

No significant effect of ash addition was observed in total carbon and nitrogen stores at any site. The total carbon storages reported here are consistent with those of Rosenberg et al. (2010) (forest floor: 4290 g/m^2, mineral layer: 2450 g/ m^2). The significant decline in the total carbon storage in the forest floor layer at the Aleza Lake South site may be because of the previous site management, where the site was broadcast burned before replanting. This might have reduced the organic inputs from the forest floor layer that would otherwise be present *in situ*.

4.3 Effect of wood ash amendment on soil pH

There was a significant increase in the soil pH observed in the forest floor layer at the Aleza Lake South, Pineland and in the litter moss layer at Eastern Township site which is consistent with previous studies (Noyce et al., 2016; Fritze et al., 1994; Jacobson et al., 2004; Perucci et al., 2006; & Saarsalmi et al., 2001). The range of pH reported in this study is similar to that reported by Jacobson et al. (2004). The significant increase in pH was also observed in the mineral layer at Aleza Lake South and 25th Side Road. Gömöryová et al. (2016) reported that increases in soil pH with depth will be more pronounced in the longer term, which reflects a downward transfer of ash from topsoil. The persistence of a significant increase in pH at the Aleza Lake South site was expected by Domes et al. (2018). The Aleza Lake South site was managed through clear-cutting and broadcast burning before replanting in 1991 (NRCan, 2018). The charcoal produced from surface burning is known to stimulate soil nitrification and the maintenance of a more favourable soil pH (Bansal et al., 2014). This might explain the persistence of a significant increase in pH in both layers at the South site. Reduction in soil acidity through wood ash application might persist for several years as reported by Augusto et al. (2008). This prolonged effect could be attributed to the slower solubility of carbonate compounds added from the wood ash compared to oxides and hydroxides of K and Na (Demeyer et al., 2001). The significant increase observed in the mineral layer at the 25th Side Road site could be because of the fly ash application. Due to its fine texture, fly ash is expected to increase water holding capacity (Demeyer et al., 2001) and have a much stronger effect than bottom ash (Noyce et al., 2016). It could also be attributed to the limited forest floor layer at this site as a thin forest floor layer has limited capacity to hold cations added from the ash (Gömöryová et al., 2016) and ash gets transported down to the underlying mineral layer. Further addition of K, Na and excess Ca from fly ash resulted in the formation of calcium oxides and hydroxides that significantly increased the pH in the mineral layer. The mineral layer at the 25th Side Road site has a better buffering capacity due to the moderate pH value (Noyce et al., 2016). The 25th Side Road site was a nursery before replanting and it currently lacks the natural forest floor cover that a conifer stand usually has. This might also have added to the ease of transfer of the base cations to the exposed mineral layer.

Results from the PCA indicated that the most responsive labile carbon fractions were HWEC, MBC and sand fraction C, followed by mineralizable carbon content. The HWEC and MBC are significantly and positively correlated and this strong correlation has been documented by Bera et al. (2019). The close correlation between MBC and mineralizable carbon indicates that the same sets of soil properties govern both variables (McFee and Kelly, 1995). The sensitivity of these fractions was associated with the soil layers, which was reflected by the strong correlation between the forest floor layers and these fractions. The impact of wood ash addition observed in the LM and FH layers of the Haliburton and Eastern Township sites was different from that observed in the LFH layers of the Pineland, 25th Side Road and Mistik sites. This could be because of the difference in thickness of the organic layer at these sites where the former sites had thick forest floor layer (5-10 cm) and latter with less than a few centimeters. The Eastern Township site with the rate of ash application 20 Mg/ha which is clearly the highest of all other rates opposed the application rates 1, 1.5, 5 and 10 Mg/ha.When the site difference and ash application rate were considered, the litter moss layer and the rate of application at the Island Lake site were unique. Even though the Island Lake and the Haliburton site had similar soil types (Eluviated Dystric Brunisol and Orthic Eluviated Dystric Brunisol respectively), the distinction observed might be because of the difference in the vegetation at these sites. The litter inputs from different tree species also play a major in maintaining the soil organic matter quality (Sahoo et al., 2019). The diverse response of soil carbon pools at the Island Lake and the Haliburton site may be due to the difference in the organic carbon composition in the leaves and roots of broadleaf and conifer species (Guo et al., 2016). The contribution of tree species diversity and physiochemical properties of soil to shifts associated with soil organic carbon chemical composition was evident from the correlation between them (Guo et al., 2016). The application rate of 1.4 Mg/ha at the Island Lake site was different from the rest. The minimal response of carbon pools to wood ash addition at the 25th Side Road site could be attributed to the previous land use history (Sahoo et al., 2019). The site was previously a nursery and intensive use shifted the site conditions from a natural undisturbed forest.

5. Summary and Conclusion

The sensitivity of labile carbon pools varied across the sites and results suggest that the variability may be related to the initial carbon and nitrogen contents of the soils. Wood ash application had no negative impact on the labile C pools that influence soil organic matter quality. The sensitivity of the physically extracted carbon fraction (sand fraction) was dependent on soil texture, which was evident in the sandy textured soil at the Pineland site. The particulate organic matter associated with sand particles in the mineral layer was easily accessible and the clay content at the Pineland site limited organo-mineral stabilization. In soils with a higher clay content, carbon may be less available because of stabilization processes that offer chemical and physical protection. The sensitivity of the hot water extractable pool corresponded to a decrease in soil acidity, which was observed at the Eastern Township and the Pineland sites. The neutralizing effect of wood ash created a favorable environment for the microbes through increased availability of labile carbon and thus resulted in the enhanced microbial growth and activity. The HWEC fraction may be a better indicator for soils with clay contents between 15-44% as sufficient extraction is not easily achieved in clayey soils due to their occlusive nature (Weigel et al., 2011). The sensitivity of biological fractions of soil carbon was dependent on the availability of extractable carbon, which was clearly evident at the Eastern Township site.

The response of soil carbon fractions to ash addition may be better explained by the type of ash used, rate of application and time since application. The lack of significant treatment effects might be due to the less pronounced change in pH (Reed et al., 2017). The microbial activity showed a greater response to loose wood ash than hardened ash when applied at similar rates due to a slower dissolution rate of hardened ash (Perkiömäki and Fritze, 2002). The significant higher carbon mineralization observed in the mineral layer amended with ash at the

Mistik site even after two decades may be because of the application of self-hardened ash. The effect of ash addition on these labile pools was greatest in the forest floor layer at most of the sites. This might be because the experiments are still young. Over time these actively cycling pools might be redistributed along the soil profile (Forstner et al., 2019).

The responsiveness of the indicators studied was variable and selection of indicators should be site specific. Using labile carbon pools will nevertheless assist with monitoring the impact of ash amendment which might not be visible otherwise. There were no detrimental effects on soil organic matter attributes when forest soils were treated with wood ash in this study and in some cases soil quality was enhanced. The organic matter attributes examined in this study correspond to functional aspects of the physical, chemical and biological properties of soil. Though not all indicators responded to the addition of wood ash, they do support the finding that ash application either had no effect or enhanced soil quality.

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Appendix 1. Moisture contents, pH, carbon and nitrogen concentrations and stores for the sites. (C = CPLP boiler, U = UNBC gasifier, B = Bottom ash, F = Fly ash)

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Replicate	Moisture content (g/g)	pH	C (g/g)	N (g/g)	C:N	Mass of Layer (g/m^2)	C storage (gC/m^2)	N storage (kg N/m^2)
ALN	0	LFH	1	2.16	5.023	0.26	0.01	31.8	457.47	120.63	2.19
ALN	0	MIN	1	0.45	4.337	0.04	0	19.9	57290.8	2389.03	0.09
ALN	5C	LFH	1	1.1	6.28	0.14	0.01	23	668.41	96.85	0.91
ALN	5C	MIN	1	0.45	4.601	0.04	0	14.6	65766.44	2689.85	0.11
ALN	5U	LFH	1	1.75	5.631	0.25	0.01	28.8	1378.82	349.26	2.23
ALN	5U	MIN	1	0.39	4.199	0.03	0	16.7	88975.52	2829.42	0.06
ALN	0	LFH	2	1.44	5.037	0.2	0.01	26.7	1464.3	292.71	1.5
ALN	0	MIN	2	0.27	4.419	0.02	0	13.4	81155.2	1517.6	0.03
ALN	5C	LFH	2	2.79	4.655	0.43	0.01	41.5	783.93	338.11	4.49
ALN	5C	MIN	2	0.3	4.279	0.02	0	15.4	86847.03	2006.17	0.03
ALN	5U	LFH	2	2.3	5.767	0.4	0.01	35.2	956.96	387	4.65
ALN	5U	MIN	2	0.33	4.342	0.02	0	12.4	74195.65	1743.6	0.04
ALN	0	LFH	3	1.61	4.401	0.2	0.01	29.5	1133.95	223.95	1.32
ALN	0	MIN	3	0.28	4.124	0.02	0	12.7	80466.77	1327.7	0.02
ALN	5C	LFH	3	2.08	5.493	0.37	0.01	33.9	1205.25	449.2	4.1
ALN	5C	MIN	3	0.29	3.881	0.03	0	17.6	74235.62	2086.02	0.04
ALN	5U	LFH	3	2.1	5.666	0.29	0.01	34.6	982.63	288.6	2.5
ALN	5U	MIN	3	0.33	4.476	0.02	0	15.2	88507.79	2017.98	0.03
ALS	0	LFH	1	1.54	5.018	0.2	0.01	27.4	3208.96	651.1	1.5
ALS	0	MIN	1	0.4	4.332	0.03	0	17.3	50779.33	1315.18	0.04
ALS	5C	LFH	1	2.04	6.093	0.31	0.01	31	2258.21	692.59	3.04
ALS	5C	MIN	1	0.35	4.601	0.02	0	15	20614.04	494.74	0.04
ALS	5U	LFH	1	1.39	5.586	0.21	0.01	31.9	1395.23	293.42	1.39

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Replicate	Moisture content (g/g)	pH	C (g/g)	N (g/g)	C:N	Mass of Layer (g/m^2)	C storage (gC/m^2)	N storage (kg N/m^2)
ALS	5U	MIN	1	0.3	4.166	0.02	0	16.6	87393.81	2027.54	0.03
ALS	0	LFH	2	2.25	4.76	0.32	0.01	28.6	3769.33	1206.56	3.59
ALS	0	MIN	2	0.37	3.98	0.02	0	13.6	40139.28	875.04	0.03
ALS	5C	LFH	2	1.58	5.352	0.24	0.01	28.2	4411.96	1070.34	2.09
ALS	5C	MIN	2	0.73	4.696	0.08	0	28.8	21566.19	1800.78	0.24
ALS	5U	LFH	2	1.46	5.781	0.21	0.01	41	1354.68	283.26	1.07
ALS	5U	MIN	2	0.52	4.252	0.05	0	18	74698.79	3630.36	0.13
ALS	0	LFH	3	3.34	4.904	0.37	0.02	23.1	1628.51	599.13	5.85
ALS	0	MIN	3	0.36	4.244	0.02	0	10.6	55746.7	1176.26	0.04
ALS	5C	LFH	3	1.89	6.054	0.24	0.01	28.7	1776.48	423.34	1.98
ALS	5C	MIN	3	0.39	4.537	0.02	0	12.4	18069.01	426.43	0.04
ALS	5U	LFH	3	1.97	5.433	0.24	0.01	26.8	1123.62	267.76	2.12
ALS	5U	MIN	3	0.33	4.392	0.02	0	13.5	85072.92	1497.28	0.02
ETM	0	LM	1	0.24	3.571	0.41	0.02	26.2	2162.07	888.18	6.45
ETM	0	FH	1	0.87	4.335	0.2	0.01	18.8	15905.66	3171.59	2.11
ETM	0	MIN	1	0.24	3.707	0.03	0	16.9	59052.13	1594.41	0.04
ETM	20	LM	1	0.31	3.905	0.42	0.02	27.9	1195.73	506.75	6.44
ETM	20	FH	1	1.07	4.905	0.16	0.01	16.9	9294.64	1458.33	1.46
ETM	20	MIN	1	0.59	4.205	0.05	0	15.8	32340.63	1733.46	0.18
ETM	0	LM	2	0.17	3.416	0.45	0.01	30	1489.68	666.03	6.66
ETM	0	FH	2	1.02	4.089	0.21	0.01	18.9	9148.94	1918.53	2.33
ETM	0	MIN	2	0.46	3.713	0.05	0	17.1	49063.81	2678.88	0.17
ETM	20	LM	2	0.24	3.65	0.45	0.02	26.4	1427.16	647.36	7.8
ETM	20	FH	2	0.56	5.191	0.24	0.01	19.4	5491.32	1319.56	2.98
ETM	20	MIN	2	0.49	3.652	0.05	0	15.8	33510.43	1642.01	0.15
ETM	0	LM	3	0.13	5.512	0.43	0.02	28.4	1500.91	644.64	6.49

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Replicate	Moisture content (g/g)	pH	C (g/g)	N (g/g)	C:N	Mass of Layer (g/m^2)	C storage (gC/m^2)	N storage (kg N/m^2)
ETM	0	FH	3	1.5	4.734	0.23	0.01	16.6	10786.99	2502.58	3.25
ETM	0	MIN	3	0.52	5.507	0.05	0	11.6	55596.31	2974.4	0.25
ETM	20	LM	3	0.1	4.837	0.43	0.02	24.2	2334.27	1006.07	7.67
ETM	20	FH	3	0.68	4.928	0.17	0.01	14.8	12492	2127.39	1.96
ETM	20	MIN	3	0.34	4.455	0.05	0	12.5	49659.1	2289.28	0.17
ETM	0	LM	4	1.87	4.442	0.44	0.01	34.5	1319.19	573.98	5.48
ETM	0	FH	4	3.51	4.826	0.4	0.02	23.3	3538.07	1414.87	6.88
ETM	0	MIN	4	0.21	4.593	0.04	0	11.1	41201.09	1648.04	0.14
ETM	20	LM	4	2.72	4.406	0.45	0.02	26.4	1334.28	594.82	7.53
ETM	20	FH	4	2.02	4.893	0.25	0.02	15.9	5290.93	1314.8	3.88
ETM	20	MIN	4	0.39	4.176	0.02	0	10.1	64047.75	1549.96	0.06
ETM	0	LM	5	2.33	3.869	0.44	0.01	29.8	1129.27	501.96	6.62
ETM	0	FH	5	1.42	4.123	0.25	0.01	18.8	4987.78	1243.95	3.32
ETM	0	MIN	5	0.48	3.824	0.04	0	14.4	50090.29	2088.76	0.12
ETM	20	LM	5	2.28	4.273	0.42	0.02	26.3	1613.19	671.41	6.58
ETM	20	FH	5	1.27	4.454	0.16	0.01	16.7	3602.52	572.44	1.51
ETM	20	MIN	5	0.42	4.07	0.03	0	12.5	44330.62	1383.12	0.08
ILK	0	LM	1	0.69	3.1535	0.41	0.01	27.4	1566.51	640.39	6.09
ILK	0	FH	1	1.32	4.004	0.36	0.01	30	2333.25	832.74	4.25
ILK	0	MIN	1	0.24	3.8845	0.03	0	22.3	39830.39	1067.45	0.03
ILK	0.7	LM	1	0.48	3.448	0.4	0.01	35.1	2732.97	1104.12	4.65
ILK	0.7	FH	1	0.91	3.663	0.29	0.01	28.4	2491.77	728.34	3.01
ILK	0.7	MIN	1	0.2	3.9195	0.02	0	19	61732.91	1055.63	0.02
ILK	1.4	LM	1	0.21	4.5855	0.14	0	35.2	2606.99	376.45	0.59
ILK	1.4	FH	1	0.31	4.787	0.08	0	30.2	4776.8	360.65	0.19
ILK	1.4	MIN	1	0.17	4.3995	0.02	0	20.2	34530.12	697.51	0.02

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Replicate	Moisture content (g/g)	pH	C (g/g)	N (g/g)	C:N	Mass of Layer (g/m^2)	C storage (gC/m^2)	N storage (kg N/m^2)
ILK	2.8	LM	1	0.47	3.926	0.18	0.01	29.9	2739.51	499.96	1.11
ILK	2.8	FH	1	0.51	3.997	0.17	0.01	25.9	3544.67	605.78	1.13
ILK	2.8	MIN	1	0.24	3.9245	0.03	0	21.2	21183.2	673.63	0.05
ILK	0	LM	2	0.29	3.146	0.41	0.01	32.9	1734.67	712.78	5.14
ILK	0	FH	2	0.9	3.621	0.29	0.01	31.5	3382.79	979.99	2.67
ILK	0	MIN	2	0.19	3.8555	0.02	0	20.6	53464.44	1101.37	0.02
ILK	0.7	LM	2	0.42	3.281	0.41	0.01	36	2290.9	939.27	4.67
ILK	0.7	FH	2	1.1	3.6105	0.25	0.01	32.2	2403.49	595.1	1.91
ILK	0.7	MIN	2	0.24	3.6285	0.03	0	22.8	31499.01	859.92	0.03
ILK	1.4	LM	2	0.43	3.5145	0.22	0.01	36.4	2582.61	573.86	1.36
ILK	1.4	FH	2	0.89	4.159	0.22	0.01	30.6	3848.74	835.18	1.54
ILK	1.4	MIN	2	0.17	3.8425	0.01	0	21.3	27630.67	411.7	0.01
ILK	5.6	LM	2	0.76	3.3845	0.41	0.01	28.2	1403.33	570.03	5.85
ILK	5.6	FH	2	0.72	4.093	0.2	0.01	29.3	3156.89	638.64	1.4
ILK	5.6	MIN	2	0.23	3.8785	0.02	0	22	27863.94	674.31	0.03
ILK	0	LM	3	0.38	3.2585	0.42	0.02	28	1989.75	840.07	6.38
ILK	0	FH	3	0.54	3.57	0.13	0	26.8	5480.71	689.47	0.59
ILK	0	MIN	3	0.2	3.951	0.02	0	18.8	35229.02	729.24	0.02
ILK	0.7	LM	3	0.35	3.7485	0.46	0.01	39.8	1207.46	557.12	5.35
ILK	0.7	FH	3	0.89	4.193	0.2	0.01	28.3	3777.5	758.15	1.42
ILK	0.7	MIN	3	0.3	3.9855	0.04	0	24.7	20679.19	765.13	0.06
ILK	2.8	LM	3	0.19	4.2815	0.3	0.01	27.4	1506.46	457.66	3.37
ILK	2.8	FH	3	0.79	4.5805	0.22	0.01	31.7	11294.93	2437.45	1.47
ILK	2.8	MIN	3	0.36	3.8265	0.05	0	25.9	32426.47	1514.32	0.08
ILK	5.6	LM	3	0.28	3.6135	0.45	0.01	34.8	1730.87	776.82	5.79
ILK	5.6	FH	3	1.36	4.334	0.38	0.01	32.4	6200.23	2330.05	4.36

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Replicate	Moisture content (g/g)	pH	C (g/g)	N (g/g)	C:N	Mass of Layer (g/m^2)	C storage (gC/m^2)	N storage (kg N/m^2)
ILK	5.6	MIN	3	0.16	3.771	0.02	0	19.6	68798.52	1210.85	0.02
ILK	0	LM	4	0.96	3.2465	0.43	0.01	54.1	1132.36	490.42	3.46
ILK	0	FH	4	1.45	3.442	0.36	0.01	59.9	4181.09	1501.85	2.16
ILK	0	MIN	4	0.33	3.8775	0.05	0	26.5	35241.95	1867.82	0.11
ILK	0.7	LM	4	0.3	4.243	0.31	0.01	32.1	1397.35	426.19	2.9
ILK	0.7	FH	4	0.35	4.3475	0.06	0	24.2	9974.65	578.53	0.14
ILK	0.7	MIN	4	0.23	4.0515	0.02	0	20.2	35296.83	783.59	0.02
ILK	1.4	LM	4	0.36	3.6595	0.26	0.01	32.3	1318.64	341.13	2.07
ILK	1.4	FH	4	0.9	4.0555	0.22	0.01	41.3	6397.07	1425.91	1.2
ILK	1.4	MIN	4	0.37	3.8335	0.05	0	26.4	25434.86	1274.29	0.1
ILK	2.8	LM	4	0.25	3.8805	0.48	0.01	56	995.92	474.06	4.05
ILK	2.8	FH	4	1.73	4.341	0.27	0.01	43.2	1754.18	470.3	1.66
ILK	2.8	MIN	4	0.3	4.188	0.02	0	18.2	18099.42	427.15	0.03
ILK	5.6	LM	4	0.29	3.7895	0.42	0.01	39.5	1461.48	612.36	4.44
ILK	5.6	FH	4	0.75	4.787	0.23	0.01	35.8	2842.88	662.11	1.51
ILK	5.6	MIN	4	0.22	3.982	0.02	0	22.3	56283.99	1378.96	0.03
ILK	0	LM	5	0.08	3.8405	0.45	0.02	27.5	1613.59	719.82	7.23
ILK	0	FH	5	0.48	3.8185	0.15	0	31	3214.8	477.72	0.71
ILK	0	MIN	5	0.18	4.276	0.02	0	19.8	35399.15	559.31	0.01
ILK	1.4	LM	5	0.26	3.6685	0.18	0.01	35.7	2236.97	398.85	0.89
ILK	1.4	FH	5	0.63	4.2495	0.12	0	39.4	6829.92	806.61	0.35
ILK	1.4	MIN	5	0.24	3.3845	0.04	0	26.6	48271.25	2056.36	0.07
ILK	2.8	LM	5	0.36	3.0715	0.17	0	51.8	3299.24	547.01	0.53
ILK	2.8	FH	5	0.9	3.4825	0.32	0.01	41.7	2387.95	766.29	2.47
ILK	2.8	MIN	5	0.2	3.2855	0.04	0	27.4	47396.65	2080.71	0.07
ILK	5.6	LM	5	0.19	3.9985	0.36	0.01	43.2	1011.05	362.26	2.97

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Replicate	Moisture content (g/g)	pH	C (g/g)	N (g/g)	C:N	Mass of Layer (g/m^2)	C storage (gC/m^2)	N storage (kg N/m^2)
ILK	5.6	FH	5	0.84	4.2105	0.3	0.01	44.7	4930.03	1498.73	2.07
ILK	5.6	MIN	5	0.25	4.1045	0.02	0	17.8	58763.07	1257.53	0.03
PLD	0	LFH	1	0.55	4.895	0.18	0.01	32.2	5268.17	965.66	1.04
PLD	0	MIN	1	0.07	4.837	0.01	0	15.5	66453.26	412.01	0
PLD	1.5	LFH	1	0.31	6.317	0.1	0	39.7	5237.29	541.01	0.27
PLD	1.5	MIN	1	0.12	5.032	0.02	0	19.1	24970.54	429.49	0.02
PLD	0	LFH	2	0.27	5.06	0.06	0	20.9	9658.59	606.56	0.19
PLD	0	MIN	2	0.08	5.107	0	0	12.3	51068.86	250.24	0
PLD	1.5	LFH	2	0.3	5.052	0.07	0	23.3	8739.5	569.82	0.18
PLD	1.5	MIN	2	0.09	4.863	0.01	0	14.6	34249.18	250.02	0
PLD	0	LFH	3	0.55	5.536	0.13	0.01	24.2	4572.55	575.68	0.65
PLD	0	MIN	3	0.08	5.03	0.01	0	15	70050.04	420.3	0
PLD	1.5	LFH	3	0.73	6.31	0.17	0.01	26.4	2962.34	507.45	1.11
PLD	1.5	MIN	3	0.1	5.739	0.01	0	18.3	22755.36	250.31	0.01
PLD	0	LFH	4	0.81	4.954	0.21	0.01	27.5	3442.58	730.17	1.63
PLD	0	MIN	4	0.09	4.86	0.01	0	19.7	57170.23	337.3	0
PLD	1.5	LFH	4	0.86	7.049	0.21	0.01	27	3751.07	789.6	1.64
PLD	1.5	MIN	4	0.09	5.415	0.01	0	14.8	36863.84	217.5	0
PLD	0	LFH	5	0.89	4.57	0.41	0.01	44.5	1789.72	740.23	3.85
PLD	0	MIN	5	0.08	4.999	0.01	0	15.5	40599.96	251.72	0
PLD	1.5	LFH	5	0.47	5.227	0.16	0.01	27.3	1705.21	279.31	0.98
PLD	1.5	MIN	5	0.12	5.314	0.01	0	18.3	44630.54	571.27	0.01
SRD	0	LFH	1	0.72	5.90	0.26	0.01	27.1	840.02	218.57	2.5
SRD	0	MIN	1	0.16	5.37	0.02	0	15.1	71450.79	1614.79	0.03
SRD	1	LFH	1	0.54		0.19	0.01	24	914.54	173.31	1.5
SRD	1	MIN	1	0.15	5.52	0.02	0	16.5	82526.27	1774.31	0.03

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Replicate	Moisture content (g/g)	pH	C (g/g)	N (g/g)	C:N	Mass of Layer (g/m^2)	C storage (gC/m^2)	N storage (kg N/m^2)
SRD	10	LFH	1	0.29	6.179	0.06	0	18.1	2944.99	170.52	0.19
SRD	10	MIN	1	0.13	6.138	0.02	0	15.3	109179.3	2008.9	0.02
SRD	0	LFH	2	0.25	5.592	0.06	0	16.2	2853.57	157.23	0.19
SRD	0	MIN	2	0.13	5.061	0.02	0	15.5	90930.08	1827.69	0.03
SRD	1	LFH	2	0.3	5.662	0.07	0	21.2	2290.92	160.36	0.23
SRD	1	MIN	2	0.13	5.104	0.02	0	15.3	99990.78	1679.85	0.02
SRD	10	LFH	2	0.36	5.72	0.08	0	23.5	2317.43	190.96	0.29
SRD	10	MIN	2	0.15	6.241	0.02	0	16.5	85710.05	1979.9	0.03
SRD	0	LFH	3		6.236						
SRD	0	MIN	3	0.17	5.347	0.02	0	16.8	88365.03	1926.36	0.03
SRD	1	LFH	3	0.44	5.566	0.08	0	20.9	2568	209.55	0.32
SRD	1	MIN	3	0.17	5.391	0.02	0	16	82124.91	1839.6	0.03
SRD	10	LFH	3	0.41	5.92	0.1	0.01	19.9	2162.92	219.54	0.52
SRD	10	MIN	3	0.16	6.201	0.02	0	17.5	101364.6	2128.66	0.03
SRD	0	LFH	4	0.3	5.668	0.07	0	16.8	2946.15	207.7	0.3
SRD	0	MIN	4	0.13	5.18	0.02	0	16	88723.31	1845.44	0.03
SRD	1	LFH	4	0.33	5.739	0.07	0	20.6	2937.74	193.6	0.21
SRD	1	MIN	4	0.13	5.061	0.02	0	17.3	101431.8	1754.77	0.02
SRD	10	LFH	4	0.27	5.808	0.05	0	22.2	9945.61	530.1	0.13
SRD	10	MIN	4	0.14	6.568	0.02	0	16.3	103704.7	1690.39	0.02
SRD	0	LFH	5	0.33	5.332	0.07	0	19.7	2683.29	195.61	0.27
SRD	0	MIN	5	0.13	4.94	0.02	0	15.5	100431.4	1707.33	0.02
SRD	1	LFH	5	0.21	5.359	0.04	0	18.2	5979.3	239.17	0.09
SRD	1	MIN	5	0.13	5.174	0.02	0	15.4	104426.9	1764.81	0.02
SRD	10	LFH	5	0.37	5.524	0.06	0	20.7	3229.37	194.09	0.17
SRD	10	MIN	5	0.12	5.858	0.02	0	15.8	89085.45	1407.55	0.02

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Replicate	Moisture content (g/g)	pH	C (g/g)	N (g/g)	C:N	Mass of Layer (g/m^2)	C storage (gC/m^2)	N storage (kg N/m^2)
HLB	0	FH	1	0.91	4.979	0.37	0.01	25.1	1375.47	515.39	5.58
HLB	0	MIN	1	0.36	4.322	0.06	0	15.3	37142.25	2217.39	0.23
HLB	1F	FH	1	0.8	4.906	0.42	0.02	26	1416.64	596.83	6.83
HLB	1F	MIN	1	0.51	4.273	0.06	0	13.8	57397.4	3334.79	0.24
HLB	4F	FH	1	1.18	4.89	0.38	0.02	23.7	2171.43	832.09	6.21
HLB	4F	MIN	1	0.43	4.088	0.04	0	14.3	70445.34	3120.73	0.14
HLB	8F	FH	1	0.99	5.353	0.39	0.02	24.6	3259.42	1284.54	6.31
HLB	8F	MIN	1	0.44	4.137	0.05	0	13.6	62650.76	2900.73	0.16
HLB	1B	FH	1	0.75	5.226	0.45	0.02	25.8	2046.74	924.31	7.9
HLB	1B	MIN	1	0.48	4.101	0.07	0	15.8	58542.64	4068.71	0.31
HLB	4B	FH	1	1.71	4.382	0.43	0.02	22.3	2535.06	1097.43	8.4
HLB	4B	MIN	1	0.7	4.142	0.07	0	15.1	50577.14	3580.86	0.33
HLB	8B	FH	1	0.65	4.917	0.44	0.02	25.7	1547.99	675.39	7.42
HLB	8B	MIN	1	0.32	4.063	0.06	0	15.5	49857.41	2936.6	0.22
HLB	0	FH	2	0.97	4.804	0.46	0.02	26.7	1487.95	686.84	7.99
HLB	0	MIN	2	0.34	3.836	0.06	0	14.7	46833.78	2688.26	0.22
HLB	1F	FH	2	1.33	4.326	0.46	0.02	25.5	2100.66	958.32	8.17
HLB	1F	MIN	2	0.59	3.983	0.08	0	16.3	45237.37	3397.33	0.35
HLB	4F	FH	2	1.29	4.518	0.4	0.02	24.5	3739.85	1477.99	6.36
HLB	4F	MIN	2	0.31	3.722	0.04	0	14.1	63078.48	2491.6	0.11
HLB	8F	FH	2	0.83	4.887	0.41	0.02	25.4	1728.45	707.28	6.59
HLB	8F	MIN	2	0.34	3.74	0.06	0	17.1	52316.21	3123.28	0.21
HLB	1B	FH	2	0.89	4.799	0.43	0.02	22.4	3098.51	1320.28	8.1
HLB	1B	MIN	2	0.35	3.889	0.04	0	16	53993.6	2251.53	0.11
HLB	4B	FH	2	0.92	4.829	0.44	0.02	24	1488.41	661.3	8.22
HLB	4B	MIN	2	0.33	3.884	0.05	0	15.2	56656.38	2753.5	0.16

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Replicate	Moisture content (g/g)	pH	C (g/g)	N (g/g)	C:N	Mass of Layer (g/m^2)	C storage (gC/m^2)	N storage (kg N/m^2)
HLB	8B	FH	2	1.1	5.055	0.45	0.02	24.1	1615.43	723.23	8.33
HLB	8B	MIN	2	0.39	4.396	0.06	0	16.6	41742.82	2421.08	0.2
HLB	0	FH	3	2.27	4.986	0.46	0.02	24.3	1566.48	718.39	8.67
HLB	0	MIN	3	2.18	4.128	0.25	0.01	20.7	14175.04	3587.7	3.09
HLB	1F	FH	3	0.64	4.433	0.4	0.02	24.2	2928.18	1160.44	6.5
HLB	1F	MIN	3	0.34	3.807	0.06	0	17.6	48165.27	3044.05	0.23
HLB	4F	FH	3	1.62	4.712	0.45	0.02	22.1	2013.71	908.99	9.21
HLB	4F	MIN	3	0.48	3.85	0.08	0	22.2	57699.54	4356.32	0.26
HLB	8F	FH	3	1.07	4.796	0.41	0.02	25.5	1775.91	725.1	6.53
HLB	8F	MIN	3	0.49	3.908	0.06	0	17.8	50166.17	3030.04	0.21
HLB	1B	FH	3	1.08	4.957	0.39	0.02	22.1	2182.94	848.29	6.84
HLB	1B	MIN	3	0.51	6.344	0.09	0	18.8	40290.64	3634.22	0.43
HLB	4B	FH	3	0.75	4.736	0.41	0.02	22.1	1049.5	429.04	7.56
HLB	4B	MIN	3	0.8	4.034	0.07	0	16.1	37811.14	2801.81	0.34
HLB	8B	FH	3	0.67	5.878	0.3	0.01	34.1	2374.58	713.33	2.64
HLB	8B	MIN	3	0.98	4.308	0.27	0.01	26.1	23249.79	6363.47	2.87
HLB	0	FH	4	3.48	5.849	0.44	0.02	28.1	1065.77	463.72	6.74
HLB	0	MIN	4	2.94	5.875	0.3	0.02	17.8	9293.37	2750.84	4.91
HLB	1F	FH	4	2.04	5.48	0.47	0.02	29.2	1060.15	494.98	7.47
HLB	1F	MIN	4	2.46	5.295	0.25	0.01	18.1	13116.74	3290.99	3.49
HLB	4F	FH	4	1.53	5.641	0.41	0.01	27.9	834.35	341.75	6.02
HLB	4F	MIN	4	1.35	4.167	0.21	0.01	27.8	21775.12	4533.58	1.56
HLB	8F	FH	4		5.112						
HLB	8F	MIN	4	0.73	4.622	0.09	0.01	16.6	47661.58	4113.19	0.45
HLB	1B	FH	4	2.2	3.995	0.47	0.02	27.6	2747.97	1295.39	8.06

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Replicate	Moisture content (g/g)	pH	C (g/g)	N (g/g)	C:N	Mass of Layer (g/m^2)	C storage (gC/m^2)	N storage (kg N/m^2)
HLB	1B	MIN	4	1.17	4.606	0.09	0.01	15.4	30762.49	2891.67	0.57
HLB	4B	FH	4	1.33	5.4	0.42	0.02	26.2	527.62	220.02	6.63
HLB	4B	MIN	4	0.63	4.503	0.06	0	15.9	51586.65	3043.61	0.22
HLB	8B	FH	4	2.15	5.546	0.46	0.02	28.8	461.06	210.94	7.27
HLB	8B	MIN	4	1.51	4.837	0.18	0.01	20.3	23995.38	4232.78	1.53
MSK	0	LFH	1	2.09	6.707	0.38	0.02	19	2944.13	1109.05	7.46
MSK	0	MIN	1	0.26	4.894	0.02	0	14.3	38942.39	669.81	0.02
MSK	1	LFH	1	2.98	7.071	0.4	0.02	22.4	2061.67	824.87	7.16
MSK	1	MIN	1	0.61	5.988	0.08	0	19.7	37932.96	3057.4	0.33
MSK	5	LFH	1	1.22	6.444	0.27	0.01	19.9	4320.38	1160.02	3.62
MSK	5	MIN	1	0.19	5.115	0.01	0	15.4	51504.56	396.59	0
MSK	0	LFH	2	1.79	6.063	0.24	0.01	18.6	5380.25	1288.57	3.09
MSK	0	MIN	2	0.27	4.913	0.01	0	12.4	20096.41	225.08	0.01
MSK	1	LFH	2	0.87	7.408	0.21	0.01	21.3	3939.82	815.15	2.01
MSK	1	MIN	2	0.23	5.884	0.01	0	13.1	35463.06	464.57	0.01
MSK	5	LFH	2	1.45	6.178	0.25	0.01	20.4	8187.17	2055.8	3.09
MSK	5	MIN	2	0.21	4.205	0.01	0	16.4	70168.64	806.94	0.01
MSK	0	LFH	3	0.91	6.261	0.25	0.01	25	7560.13	1911.96	2.55
MSK	0	MIN	3	0.18	6.955	0.01	0	16.7	32172.28	376.42	0.01
MSK	1	LFH	3	0.82	5.664	0.14	0.01	16.7	6345.13	871.19	1.13
MSK	1	MIN	3	0.29	4.652	0.02	0	13.1	40578.37	746.64	0.03
MSK	5	LFH	3	1.61	6.573	0.41	0.02	23.1	11016.67	4559.8	7.41
MSK	5	MIN	3	0.23	5.327	0.01	0	12.1	30773.84	372.36	0.01

Appendix 2A. Mass, C and N recoveries (percentage) from the physical fractionation of the mineral soil and mass of sand fraction and silt and clay fraction recovered.

Site	Rate of Ash Application (Mg/ha)	Mass Recovery (%)	C Recovery (%)	N Recovery (%)	Mass Sand (%)	Mass Silt and Clay (%)
ALN	0	99	97	100	10	89
ALN	5C	98	96	95	7	91
ALN	5U	99	95	96	12	87
ALN	0	100	94	84	10	90
ALN	5C	99	97	102	10	89
ALN	5U	100	96	92	6	93
ALN	0	99	91	93	4	95
ALN	5C	100	93	95	8	92
ALN	5U	99	95	94	8	91
ALS	0	99	98	100	13	86
ALS	5C	99	99	96	9	90
ALS	5U	100	98	100	13	88
ALS	0	99	95	104	4	95
ALS	5C	97	101	99	14	83
ALS	5U	98	100	96	13	85
ALS	0	98	97	94	8	90
ALS	5C	98	93	93	12	86
ALS	5U	99	95	103	12	87
ETM	0	100	95	96	42	57
ETM	20	96	103	102	19	77
ETM	0	97	98	96	28	69
ETM	20	97	108	105	22	75

Site	Rate of Ash Application (Mg/ha)	Mass Recovery (%)	C Recovery (%)	N Recovery (%)	Mass Sand (%)	Mass Silt and Clay (%)
ETM	0	94	93	92	34	60
ETM	20	98	97	101	33	65
ETM	0	96	94	89	23	73
ETM	20	99	97	98	22	76
ETM	0	97	108	102	29	68
ETM	20	97	94	88	30	67
ILK	0	99	98	93	46	53
ILK	0.7	100	100	78	66	33
ILK	1.4	99	92	89	71	28
ILK	2.8	100	95	91	63	37
ILK	0	100	90	80	64	36
ILK	0.7	100	99	91	73	27
ILK	1.4	100	94	96	71	30
ILK	5.6	100	96	91	57	43
ILK	0	100	97	94	56	43
ILK	0.7	99	96	94	38	61
ILK	2.8	99	97	94	29	70
ILK	5.6	100	98	91	69	30
ILK	0	99	90	93	47	51
ILK	0.7	100	107	98	51	49
ILK	1.4	99	90	95	33	66
ILK	2.8	99	109	102	36	63
ILK	5.6	99	103	103	51	49
ILK	0	100	101	92	61	39
ILK	1.4	100	96	91	76	24
ILK	2.8	100	102	92	76	24

Site	Rate of Ash Application (Mg/ha)	Mass Recovery (%)	C Recovery (%)	N Recovery (%)	Mass Sand (%)	Mass Silt and Clay (%)
ILK	5.6	99	92	88	44	55
PLD	0	101	88	87	92	8
PLD	1.5	101	105	97	89	11
PLD	0	101	97	84	92	8
PLD	1.5	101	89	97	93	8
PLD	0	101	80	80	93	8
PLD	1.5	101	98	94	92	8
PLD	0	101	91	130	91	10
PLD	1.5	102	112	114	91	11
PLD	0	100	96	104	92	8
PLD	1.5	100	93	101	91	9
SRD	0	100	99	103	79	21
SRD	1	99	100	103	78	21
SRD	10	99	93	93	80	20
SRD	0	99	94	96	80	20
SRD	1	100	100	96	80	20
SRD	10	100	98	91	77	22
SRD	0	99	93	99	79	20
SRD	1	100	95	102	79	21
SRD	10	100	97	95	79	21
SRD	0	99	94	97	82	17
SRD	1	100	100	101	80	20
SRD	10	100	103	102	82	18
SRD	0	99	101	92	81	19
SRD	1	99	94	92	82	17
SRD	10	99	102	94	83	16

Site	Rate of Ash Application (Mg/ha)	Mass Recovery (%)	C Recovery (%)	N Recovery (%)	Mass Sand (%)	Mass Silt and Clay (%)
HLB	0	98	94	94	61	36
HLB	1F	98	95	95	56	41
HLB	4F	99	89	95	59	40
HLB	8F	99	97	95	59	40
HLB	1B	97	95	97	53	44
HLB	4B	97	99	98	49	48
HLB	8B	98	86	87	62	36
HLB	0	98	94	92	58	40
HLB	1F	98	81	85	50	47
HLB	4F	100	95	92	62	37
HLB	8F	98	102	102	62	36
HLB	1B	99	99	101	57	42
HLB	4B	99	95	94	52	47
HLB	8B	99	104	102	63	36
HLB	0	87	88	92	57	30
HLB	1F	98	100	98	62	36
HLB	4F	99	81	91	55	43
HLB	8F	99	98	97	58	41
HLB	1B	96	96	98	59	37
HLB	4B	98	97	95	54	45
HLB	8B	95	64	70	57	38
HLB	0	85	80	80	32	54
HLB	1F	95	89	87	42	53
HLB	4F	95	77	82	56	39
HLB	8F	95	92	89	55	40
HLB	1B	96	92	90	55	41

Site	Rate of Ash Application (Mg/ha)	Mass Recovery (%)	C Recovery (%)	N Recovery (%)	Mass Sand (%)	Mass Silt and Clay (%)
HLB	4B	98	101	97	57	41
HLB	8B	94	98	95	46	49
MSK	0	101	102	101	56	45
MSK	1	98	91	90	48	50
MSK	5	100	96	123	47	53
MSK	0	100	86	94	42	58
MSK	1	100	85	102	40	60
MSK	5	100	90	106	52	49
MSK	0	100	95	113	51	49
MSK	1	100	92	95	45	54
MSK	5	100	99	96	50	51

Appendix 2B. Sand fraction C and N concentration (per kg of sand and kg of soil), C:N ratio, contribution of sand fraction C and N to TC and TN.

Site	Rate of Ash Application (Mg/ha)	C Concentration Sand (g C/kg sand)	N Concentration Sand (g N/kg sand)	Sand C:N	Sand C Concentration (g sand C/kg soil)	Sand N Concentration (g sand N/kg soil)	Sand Fraction Contribution to TC%	Sand Fraction Contribution to TN %
ALN	0	173.6	4.6	37.7	17.1	0.5	42	21
ALN	5C	186.1	6.4	29.1	13.5	0.5	34	17
ALN	5U	86.8	2.5	34.7	10.7	0.3	35	17
ALN	0	62.8	2	31.4	6.0	0.2	34	16
ALN	5C	81.3	2.4	33.9	8.1	0.2	36	16
ALN	5U	109.1	3.4	32.1	6.8	0.2	30	12
ALN	0	113.1	2.9	39.0	4.5	0.1	30	10
ALN	5C	122	3	40.7	9.4	0.2	36	15
ALN	5U	102.5	2.9	35.3	8.0	0.2	37	16
ALS	0	83.2	2.3	36.2	10.9	0.3	43	20
ALS	5C	105.1	3.1	33.9	9.4	0.3	39	18
ALS	5U	86.8	2.8	31.0	11.0	0.4	49	25
ALS	0	143.3	4.5	31.8	6.4	0.2	31	12
ALS	5C	290.7	5	58.1	41.9	0.7	50	25
ALS	5U	174.6	5.2	33.6	22.1	0.7	45	26
ALS	0	53.4	2.5	21.4	4.4	0.2	21	11
ALS	5C	54	1.7	31.8	6.6	0.2	30	12
ALS	5U	40.7	1.4	29.1	4.7	0.2	28	12
ETM	0	17.9	0.8	22.4	7.6	0.3	29	22
ETM	20	65.5	2.4	27.3	12.4	0.5	23	13
ETM	0	36.7	1.6	22.9	10.3	0.4	19	15
ETM	20	42.6	2.1	20.3	9.2	0.5	17	14

Site	Rate of Ash Application (Mg/ha)	C Concentration Sand (g C/kg sand)	N Concentration Sand (g N/kg sand)	Sand C:N	Sand C Concentration (g sand C/kg soil)	Sand N Concentration (g sand N/kg soil)	Sand Fraction Contribution to TC%	Sand Fraction Contribution to TN %
ETM	0	45.1	3.1	14.5	15.1	1.0	30	25
ETM	20	34.6	2.3	15.0	11.5	0.8	26	20
ETM	0	21.6	1.1	19.6	4.9	0.3	13	8
ETM	20	14.8	1	14.8	3.3	0.2	14	10
ETM	0	21	1.1	19.1	6.1	0.3	14	11
ETM	20	14.6	0.8	18.3	4.4	0.2	15	11
ILK	0	21.9	0.6	36.5	10.1	0.3	39	25
ILK	0.7	10.7	0.3	35.7	7.1	0.2	42	28
ILK	1.4	8.3	0.3	27.7	5.9	0.2	32	24
ILK	2.8	17.2	0.6	28.7	10.8	0.4	36	27
ILK	0	10.7	0.3	35.7	6.8	0.2	37	24
ILK	0.7	16.6	0.5	33.2	12.1	0.4	45	33
ILK	1.4	6.5	0.2	32.5	4.6	0.1	33	21
ILK	5.6	15.3	0.4	38.3	8.7	0.2	37	23
ILK	0	8.6	0.3	28.7	4.8	0.2	24	16
ILK	0.7	37.4	1	37.4	14.3	0.4	40	27
ILK	2.8	81.4	2	40.7	23.3	0.6	51	34
ILK	5.6	7.9	0.3	26.3	5.5	0.2	32	26
ILK	0	42.2	1.2	35.2	20.0	0.6	42	31
ILK	0.7	16.2	0.5	32.4	8.3	0.3	35	24
ILK	1.4	67.5	1.7	39.7	22.3	0.6	49	31
ILK	2.8	22.4	0.7	32.0	8.1	0.3	31	19

Site	Rate of Ash Application (Mg/ha)	C Concentration Sand (g C/kg sand)	N Concentration Sand (g N/kg sand)	Sand C:N	Sand C Concentration (g sand C/kg soil)	Sand N Concentration (g sand N/kg soil)	Sand Fraction Contribution to TC%	Sand Fraction Contribution to TN %
ILK	5.6	15.1	0.5	30.2	7.6	0.3	30	22
ILK	0	8.1	0.2	40.5	4.9	0.1	31	17
ILK	1.4	29.1	0.8	36.4	22.0	0.6	54	42
ILK	2.8	32.6	0.8	40.8	24.7	0.6	55	41
ILK	5.6	12.7	0.5	25.4	5.6	0.2	28	21
PLD	0	2.2	0.1	22.0	2.0	0.1	37	27
PLD	1.5	8.8	0.3	29.3	7.9	0.3	44	31
PLD	0	1.5	0.1	15.0	1.4	0.1	29	27
PLD	1.5	2.4	0.2	12.0	2.2	0.2	34	38
PLD	0	1.5	0.1	15.0	1.4	0.1	29	29
PLD	1.5	4.9	0.2	24.5	4.5	0.2	42	33
PLD	0	1.4	0.1	14.0	1.3	0.1	24	23
PLD	1.5	1.9	0.1	19.0	1.7	0.1	26	20
PLD	0	1.6	0.1	16.0	1.5	0.1	25	22
PLD	1.5	6.1	0.3	20.3	5.6	0.3	47	39
SRD	0	11.1	0.7	15.9	8.8	0.6	39	36
SRD	1	9.7	0.5	19.4	7.6	0.4	35	29
SRD	10	7.3	0.4	18.3	5.8	0.3	34	29
SRD	0	9.3	0.5	18.6	7.4	0.4	39	32
SRD	1	6.8	0.3	22.7	5.4	0.2	33	23
SRD	10	9.6	0.4	24.0	7.4	0.3	33	24
SRD	0	8.5	0.5	17.0	6.8	0.4	33	31
SRD	1	9.3	0.6	15.5	7.4	0.5	35	33
SRD	10	8.6	0.4	21.5	6.8	0.3	34	28

Site	Rate of Ash Application (Mg/ha)	C Concentration Sand (g C/kg sand)	N Concentration Sand (g N/kg sand)	Sand C:N	Sand C Concentration (g sand C/kg soil)	Sand N Concentration (g sand N/kg soil)	Sand Fraction Contribution to TC%	Sand Fraction Contribution to TN %
SRD	0	8.9	0.5	17.8	7.3	0.4	37	32
SRD	1	6.5	0.3	21.7	5.2	0.2	30	24
SRD	10	7.2	0.4	18.0	5.9	0.3	35	32
SRD	0	6.9	0.3	23.0	5.6	0.2	32	24
SRD	1	7	0.4	17.5	5.8	0.3	36	32
SRD	10	7.6	0.4	19.0	6.3	0.3	39	35
HLB	0	44.1	2.4	18.4	27.1	1.5	49	40
HLB	1F	35.8	2.1	17.0	20.2	1.2	36	30
HLB	4F	16.5	1	16.5	9.7	0.6	25	20
HLB	8F	18.3	1.1	16.6	10.8	0.6	24	20
HLB	1B	36.5	1.6	22.8	19.3	0.8	29	20
HLB	4B	52.8	2.8	18.9	26.0	1.4	37	30
HLB	8B	28.5	1.7	16.8	17.7	1.1	35	32
HLB	0	32.5	1.9	17.1	18.7	1.1	35	30
HLB	1F	42.4	2	21.2	21.4	1.0	35	26
HLB	4F	24.9	1.5	16.6	15.5	0.9	42	36
HLB	8F	39.2	2.1	18.7	24.4	1.3	40	37
HLB	1B	21.1	1.2	17.6	12.0	0.7	29	26
HLB	4B	29.7	1.6	18.6	15.5	0.8	33	28
HLB	8B	41.9	2.3	18.2	26.2	1.4	44	40
HLB	0	281.9	13.6	20.7	161.4	7.8	72	69
HLB	1F	47.2	2.5	18.9	29.4	1.6	46	44
HLB	4F	34.8	1.5	23.2	19.3	0.8	32	27
HLB	8F	38.7	1.9	20.4	22.5	1.1	38	33

Site	Rate of Ash Application (Mg/ha)	C Concentration Sand (g C/kg sand)	N Concentration Sand (g N/kg sand)	Sand C:N	Sand C Concentration (g sand C/kg soil)	Sand N Concentration (g sand N/kg soil)	Sand Fraction Contribution to TC%	Sand Fraction Contribution to TN %
HLB	1B	86.9	4.3	20.2	51.0	2.5	59	54
HLB	4B	45	2.3	19.6	24.1	1.2	33	28
HLB	8B	191.6	7.3	26.2	109.3	4.2	63	57
HLB	0	383.6	15.1	25.4	120.8	4.8	51	36
HLB	1F	284.5	12.1	23.5	120.6	5.1	54	43
HLB	4F	178.2	5.2	34.3	99.9	2.9	62	48
HLB	8F	58.4	2.7	21.6	32.1	1.5	40	32
HLB	1B	77.1	4.4	17.5	42.6	2.4	49	44
HLB	4B	38.4	1.6	24.0	21.9	0.9	37	25
HLB	8B	179.7	7	25.7	82.1	3.2	48	39
MSK	0	15.8	0.8	19.8	8.8	0.4	50	37
MSK	1	97.1	3.9	24.9	46.8	1.9	64	51
MSK	5	7.4	0.4	18.5	3.5	0.2	47	31
MSK	0	8.8	0.5	17.6	3.7	0.2	38	25
MSK	1	12	0.6	20.0	4.8	0.2	43	24
MSK	5	8.7	0.3	29.0	4.5	0.2	43	21
MSK	0	12.2	0.5	24.4	6.2	0.3	56	32
MSK	1	18.1	0.9	20.1	8.2	0.4	49	31
MSK	5	11.4	0.5	22.8	5.7	0.2	47	26

Appendix 2C. Silt and clay fraction C and N concentration (per kg of sand and kg of soil), C:N ratio, contribution of silt and clay fraction C and N to TC and TN.

Site	Rate of Ash Application (Mg/ha)	C Concentration S&C (g C/kg sand)	N Concentration S&C (g N/kg sand)	S&C C:N	S&C C Concentration (g sand C/kg soil)	S&C N Concentration (g sand N/kg soil)	S&C Fraction Contribution to TC%	S&C Fraction Contribution to TN %
ALN	0	26.2	1.9	14.2	23.4	1.7	58	79
ALN	5C	28.4	2.4	11.8	25.9	2.2	66	83
ALN	5U	22.7	1.8	12.9	19.6	1.5	65	83
ALN	0	13.0	1.1	11.8	11.7	1.0	66	84
ALN	5C	16.0	1.5	11.0	14.2	1.3	64	84
ALN	5U	17.0	1.7	10.3	15.8	1.5	70	88
ALN	0	11.1	1.2	9.7	10.5	1.1	70	90
ALN	5C	18.3	1.4	13.1	16.8	1.3	64	85
ALN	5U	14.9	1.3	11.5	13.6	1.2	63	84
ALS	0	16.8	1.4	12.0	14.4	1.2	57	80
ALS	5C	16.1	1.4	11.5	14.5	1.3	61	82
ALS	5U	13.4	1.2	11.1	11.7	1.1	51	75
ALS	0	15.1	1.6	9.7	14.2	1.5	69	88
ALS	5C	51.3	2.6	19.7	42.6	2.2	50	75
ALS	5U	31.1	2.3	13.8	26.5	1.9	55	74
ALS	0	18.0	1.9	9.7	16.2	1.7	79	89
ALS	5C	17.9	1.8	9.9	15.4	1.5	70	88
ALS	5U	13.8	1.4	10.2	12.0	1.2	72	88
ETM	0	31.5	2.1	15.0	18.1	1.2	71	78
ETM	20	55.2	3.9	14.2	42.6	3.0	77	87
ETM	0	62.6	3.8	16.5	43.0	2.6	81	85
ETM	20	58.4	3.8	15.6	43.8	2.8	83	86

Site	Rate of Ash Application (Mg/ha)	C Concentration S&C (g C/kg sand)	N Concentration S&C (g N/kg sand)	S&C C:N	S&C C Concentration (g sand C/kg soil)	S&C N Concentration (g sand N/kg soil)	S&C Fraction Contribution to TC%	S&C Fraction Contribution to TN %
ETM	0	58.0	5.3	10.9	34.8	3.2	70	75
ETM	20	51.5	4.6	11.2	33.2	3.0	74	80
ETM	0	45.0	4.1	11.1	32.7	2.9	87	92
ETM	20	26.5	2.8	9.5	20.2	2.1	86	90
ETM	0	57.3	3.9	14.7	38.8	2.6	86	89
ETM	20	37.2	2.9	12.8	25.0	1.9	85	89
ILK	0	30.6	1.6	19.1	16.1	0.8	61	75
ILK	0.7	29.8	1.5	19.9	10.0	0.5	58	72
ILK	1.4	44.9	2.4	18.7	12.8	0.7	68	76
ILK	2.8	52.6	2.7	19.5	19.4	1.0	64	73
ILK	0	32.7	1.7	19.2	11.8	0.6	63	76
ILK	0.7	54.9	2.7	20.3	14.8	0.7	55	67
ILK	1.4	31.5	1.8	17.5	9.3	0.5	67	79
ILK	5.6	34.0	1.8	18.9	14.6	0.8	63	77
ILK	0	35.1	2.0	17.6	15.2	0.9	76	84
ILK	0.7	35.1	1.7	20.6	21.3	1.0	60	73
ILK	2.8	31.6	1.6	19.8	22.1	1.1	49	66
ILK	5.6	38.6	2.0	19.3	11.7	0.6	68	74
ILK	0	54.4	2.5	21.8	27.9	1.3	58	69
ILK	0.7	32.0	1.7	18.8	15.6	0.8	65	76
ILK	1.4	34.8	1.9	18.3	22.9	1.2	51	69
ILK	2.8	28.1	1.7	16.5	17.7	1.1	69	81

Site	Rate of Ash Application (Mg/ha)	C Concentration S&C (g C/kg sand)	N Concentration S&C (g N/kg sand)	S&C C:N	S&C C Concentration (g sand C/kg soil)	S&C N Concentration (g sand N/kg soil)	S&C Fraction Contribution to TC%	S&C Fraction Contribution to TN %
ILK	5.6	36.2	1.8	20.1	17.7	0.9	70	78
ILK	0	28.5	1.6	17.8	11.0	0.6	69	83
ILK	1.4	77.8	3.5	22.2	18.9	0.8	46	58
ILK	2.8	82.4	3.6	22.9	19.8	0.9	45	59
ILK	5.6	25.5	1.5	17.0	14.1	0.8	72	79
PLD	0	41.8	3.1	13.5	3.4	0.3	63	73
PLD	1.5	88.5	5.3	16.7	10.1	0.6	56	69
PLD	0	40.2	2.9	13.9	3.4	0.2	71	73
PLD	1.5	55.3	3.9	14.2	4.3	0.3	66	62
PLD	0	42.0	2.8	15.0	3.4	0.2	71	71
PLD	1.5	73.8	4.5	16.4	6.2	0.4	58	67
PLD	0	42.9	3.1	13.8	4.1	0.3	76	77
PLD	1.5	44.1	3.3	13.4	4.9	0.4	74	80
PLD	0	55.2	4.0	13.8	4.5	0.3	75	78
PLD	1.5	73.5	5.0	14.7	6.4	0.4	53	61
SRD	0	64.1	4.7	13.6	13.5	1.0	61	64
SRD	1	65.5	4.5	14.6	13.8	1.0	65	71
SRD	10	58.0	4.1	14.1	11.3	0.8	66	71
SRD	0	58.7	4.3	13.7	11.5	0.8	61	68
SRD	1	57.1	4.1	13.9	11.3	0.8	67	77
SRD	10	68.1	4.3	15.8	15.3	1.0	67	76
SRD	0	68.6	4.5	15.2	13.5	0.9	67	69
SRD	1	67.4	4.6	14.7	14.0	1.0	65	67
SRD	10	65.4	4.0	16.4	13.5	0.8	66	72

Site	Rate of Ash Application (Mg/ha)	C Concentration S&C (g C/kg sand)	N Concentration S&C (g N/kg sand)	S&C C:N	S&C C Concentration (g sand C/kg soil)	S&C N Concentration (g sand N/kg soil)	S&C Fraction Contribution to TC%	S&C Fraction Contribution to TN %
SRD	0	70.4	4.9	14.4	12.2	0.9	63	68
SRD	1	60.1	3.8	15.8	12.1	0.8	70	76
SRD	10	60.3	3.8	15.9	10.9	0.7	65	68
SRD	0	61.7	4.1	15.0	11.6	0.8	68	76
SRD	1	60.4	4.1	14.7	10.1	0.7	64	68
SRD	10	59.7	3.7	16.1	9.8	0.6	61	65
HLB	0	79.4	6.1	13.0	28.7	2.2	51	60
HLB	1F	85.5	6.8	12.6	35.2	2.8	64	70
HLB	4F	74.0	5.9	12.5	29.7	2.4	75	80
HLB	8F	86.4	6.5	13.3	34.1	2.6	76	80
HLB	1B	104.7	7.7	13.6	46.4	3.4	71	80
HLB	4B	91.2	6.7	13.6	43.9	3.2	63	70
HLB	8B	92.0	6.3	14.6	33.0	2.3	65	68
HLB	0	87.5	6.2	14.1	35.4	2.5	65	70
HLB	1F	83.8	6.1	13.7	39.7	2.9	65	74
HLB	4F	58.6	4.4	13.3	21.8	1.6	58	64
HLB	8F	100.8	6.3	16.0	36.2	2.3	60	63
HLB	1B	69.6	4.6	15.1	29.3	1.9	71	74
HLB	4B	65.4	4.6	14.2	30.8	2.2	67	72
HLB	8B	93.8	5.9	15.9	33.9	2.1	56	60
HLB	0	208.4	11.5	18.1	62.4	3.4	28	31
HLB	1F	94.6	5.5	17.2	33.9	2.0	54	56
HLB	4F	96.2	5.2	18.5	41.6	2.3	68	73
HLB	8F	90.0	5.4	16.7	36.6	2.2	62	67

Site	Rate of Ash Application (Mg/ha)	C Concentration S&C (g C/kg sand)	N Concentration S&C (g N/kg sand)	S&C C:N	S&C C Concentration (g sand C/kg soil)	S&C N Concentration (g sand N/kg soil)	S&C Fraction Contribution to TC%	S&C Fraction Contribution to TN %
HLB	1B	96.2	5.8	16.6	36.0	2.2	41	46
HLB	4B	107.5	7.0	15.4	47.9	3.1	67	72
HLB	8B	171.0	8.4	20.4	65.1	3.2	37	43
HLB	0	218.5	15.8	13.8	117.1	8.5	49	64
HLB	1F	193.0	13.1	14.7	101.7	6.9	46	57
HLB	4F	155.5	8.2	19.0	61.0	3.2	38	52
HLB	8F	117.9	7.8	15.1	47.7	3.2	60	68
HLB	1B	107.0	7.5	14.3	44.0	3.1	51	56
HLB	4B	91.4	6.5	14.1	37.7	2.7	63	75
HLB	8B	184.5	10.4	17.7	90.0	5.1	52	61
MSK	0	19.6	1.7	11.5	8.8	0.8	50	63
MSK	1	53.0	3.6	14.7	26.4	1.8	36	49
MSK	5	7.3	0.8	9.1	3.9	0.4	53	69
MSK	0	10.3	1.1	9.4	6.0	0.6	62	75
MSK	1	10.5	1.3	8.1	6.3	0.8	57	76
MSK	5	12.1	1.2	10.1	5.9	0.6	57	79
MSK	0	9.9	1.1	9.0	4.8	0.5	44	68
MSK	1	16.1	1.7	9.5	8.7	0.9	51	69
MSK	5	12.5	1.4	8.9	6.3	0.7	53	74

Appendix 3. Chemical and biological soil organic C fractions and the normalized fractions.

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Hot Water Extractable C (mg C/g soil)	Microbial Respiration Rate (ug C/ g/d)	Total Microbial Respiration 7d (mg C/g soil)	Microbial Biomass Carbon (mg C/g soil)	MBC:TOC	Min C:MBC	Hot Water Extractable C (mg C/g C)	Microbial Respiration Rate (ug C/gC/d)
ALN	0	LFH	9.66	58.76	0.41	2.27	0.009	0.18	36.62	222.83
ALN	0	MIN	0.76	23.96	0.17	0.33	0.008	0.51	18.16	574.56
ALN	5C	LFH	5.07	44.45	0.31	1.38	0.010	0.23	34.99	306.78
ALN	5C	MIN	0.72	13.22	0.09	0.46	0.011	0.20	17.64	323.25
ALN	5U	LFH	6.63	55.43	0.39	1.68	0.007	0.23	26.16	218.84
ALN	5U	MIN	0.69	18.44	0.13	0.21	0.007	0.61	21.76	579.92
ALN	0	LFH	8.23	46.41	0.32	1.71	0.009	0.19	41.16	232.16
ALN	0	MIN	0.46	1.48	0.01	0.19	0.010	0.06	24.43	78.95
ALN	5C	LFH	9.96	64.92	0.45	3.06	0.007	0.15	23.09	150.52
ALN	5C	MIN	0.53	12.85	0.09	0.20	0.009	0.44	22.94	556.12
ALN	5U	LFH	9.08	65.76	0.46	3.60	0.009	0.13	22.46	162.62
ALN	5U	MIN	0.60	12.83	0.09	0.20	0.009	0.44	25.65	546.16
ALN	0	LFH	8.17	45.13	0.32	2.21	0.011	0.14	41.36	228.50
ALN	0	MIN	0.48	10.23	0.07	0.10	0.006	0.75	28.80	619.91
ALN	5C	LFH	8.81	29.13	0.20	2.60	0.007	0.08	23.65	78.17
ALN	5C	MIN	0.80	17.09	0.12	0.17	0.006	0.69	28.39	608.17
ALN	5U	LFH	7.04	70.44	0.49	2.51	0.009	0.20	23.97	239.82
ALN	5U	MIN	0.65	14.62	0.10	0.20	0.009	0.51	28.35	641.16
ALS	0	LFH	6.51	53.20	0.37	1.44	0.007	0.26	32.10	262.18
ALS	0	MIN	0.67	18.73	0.13	0.24	0.009	0.54	25.96	723.16
ALS	5C	LFH	9.14	76.65	0.54	2.95	0.010	0.18	29.80	249.93

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Hot Water Extractable C (mg C/g soil)	Microbial Respiration Rate (ug C/ g/d)	Total Microbial Respiration 7d (mg C/g soil)	Microbial Biomass Carbon (mg C/g soil)	MBC:TOC	Min C:MBC	Hot Water Extractable C (mg C/g C)	Microbial Respiration Rate (ug C/gC/d)
ALS	5U	LFH	6.66	44.08	0.31	1.73	0.008	0.18	31.69	209.62
ALS	5U	MIN	0.73	18.36	0.13	0.31	0.014	0.41	31.52	791.35
ALS	0	LFH	9.50	54.08	0.38	2.94	0.009	0.13	29.67	168.95
ALS	0	MIN	0.85	1.97	0.01	0.10	0.004	0.14	38.82	90.43
ALS	5C	LFH	6.58	41.18	0.29	1.80	0.007	0.16	27.11	169.75
ALS	5C	MIN	1.23	20.76	0.15	0.26	0.003	0.56	14.73	248.60
ALS	5U	LFH	4.50	39.10	0.27	1.51	0.007	0.18	21.53	187.01
ALS	5U	MIN	1.22	7.32	0.05	0.29	0.006	0.18	25.05	150.62
ALS	0	LFH	12.18	78.59	0.55	2.77	0.008	0.20	33.11	213.62
ALS	0	MIN	0.53	12.27	0.09	0.21	0.010	0.41	25.32	581.34
ALS	5C	LFH	9.40	48.25	0.34	2.28	0.010	0.15	39.43	202.50
ALS	5C	MIN	0.65	4.10	0.03	0.33	0.014	0.09	27.61	173.67
ALS	5U	LFH	9.70	50.27	0.35	1.81	0.008	0.19	40.69	210.97
ALS	5U	MIN	0.47	2.20	0.02	0.24	0.014	0.06	26.58	124.76
ETM	0	LM	23.07	55.07	0.39	0.92	0.002	0.42	56.15	134.06
ETM	0	FH	7.89	20.99	0.15	1.25	0.006	0.12	39.57	105.28
ETM	0	MIN	0.70	9.86	0.07	0.17	0.006	0.40	25.75	365.23
ETM	20	LM	20.07	62.82	0.44	7.03	0.017	0.06	47.36	148.22
ETM	20	FH	7.07	42.83	0.30	1.06	0.007	0.28	45.07	272.97
ETM	20	MIN	0.62	0.26	0.00	0.43	0.008	0.00	11.61	4.80
ETM	0	LM	26.16	50.66	0.35	5.34	0.012	0.07	58.51	113.30
ETM	0	FH	10.60	37.27	0.26	1.43	0.007	0.18	50.54	177.72
ETM	0	MIN	0.85	4.25	0.03	0.14	0.003	0.21	15.51	77.79

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Hot Water Extractable C (mg C/g soil)	Microbial Respiration Rate (ug C/ g/d)	Total Microbial Respiration 7d (mg C/g soil)	Microbial Biomass Carbon (mg C/g soil)	MBC:TOC	Min C:MBC	Hot Water Extractable C (mg C/g C)	Microbial Respiration Rate (ug C/gC/d)
ETM	20	LM	18.80	80.09	0.56	6.08	0.013	0.09	41.44	176.57
ETM	20	FH	10.24	35.05	0.25	1.07	0.004	0.23	42.62	145.84
ETM	20	MIN	0.87	16.30	0.11	0.22	0.005	0.51	17.80	332.63
ETM	0	LM	23.50	57.69	0.40	4.87	0.011	0.08	54.71	134.32
ETM	0	FH	5.62	68.95	0.48	1.90	0.008	0.25	24.24	297.19
ETM	0	MIN	0.47	17.95	0.13	0.66	0.012	0.19	8.77	335.44
ETM	20	LM	22.69	59.36	0.42	5.50	0.013	0.08	52.65	137.73
ETM	20	FH	8.89	50.05	0.35	1.88	0.011	0.19	52.19	293.92
ETM	20	MIN	0.33	8.83	0.06	0.06	0.001	1.00	7.22	191.44
ETM	0	LM	22.50	192.62	1.35	2.78	0.006	0.49	51.71	442.71
ETM	0	FH	11.50	77.01	0.54	2.33	0.006	0.23	28.75	192.57
ETM	0	MIN	0.65	10.44	0.07	0.19	0.005	0.38	16.14	260.93
ETM	20	LM	18.92	192.37	1.35	6.47	0.015	0.21	42.44	431.51
ETM	20	FH	10.34	72.65	0.51	2.61	0.011	0.19	41.61	292.36
ETM	20	MIN	0.70	1.84	0.01	0.17	0.007	0.07	28.91	76.05
ETM	0	LM	22.84	180.33	1.26	3.93	0.009	0.32	51.38	405.69
ETM	0	FH	11.20	51.97	0.36	1.73	0.007	0.21	44.92	208.38
ETM	0	MIN	0.39	13.89	0.10	0.27	0.006	0.37	9.32	333.16
ETM	20	LM	10.39	161.21	1.13	5.31	0.013	0.21	24.96	387.33
ETM	20	FH	8.09	25.80	0.18	1.91	0.012	0.09	50.93	162.40
ETM	20	MIN	0.66	12.50	0.09	0.17	0.005	0.51	21.04	400.67
ILK	0	LM	10.29	27.85	0.19	2.76	0.007	0.07	25.17	68.12
ILK	0	FH	9.79	32.64	0.23	1.75	0.005	0.13	27.42	91.46

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Hot Water Extractable C (mg C/g soil)	Microbial Respiration Rate (ug C/ g/d)	Total Microbial Respiration 7d (mg C/g soil)	Microbial Biomass Carbon (mg C/g soil)	MBC:TOC	Min C:MBC	Hot Water Extractable C (mg C/g C)	Microbial Respiration Rate (ug C/gC/d)
ILK	0	MIN	0.50	0.72	0.01	0.19	0.007	0.03	18.68	26.76
ILK	0.7	LM	10.08	24.21	0.17	3.42	0.008	0.05	24.96	59.92
ILK	0.7	FH	9.08	50.04	0.35	3.16	0.011	0.11	31.08	171.20
ILK	0.7	MIN	1.07	3.22	0.02	0.15	0.009	0.15	62.52	188.14
ILK	1.4	LM	4.74	17.29	0.12	1.21	0.008	0.10	32.84	119.74
ILK	1.4	FH	2.73	20.66	0.14	0.59	0.008	0.24	36.19	273.60
ILK	1.4	MIN	0.56	3.38	0.02	0.11	0.006	0.21	27.49	167.10
ILK	2.8	LM	6.72	25.49	0.18	1.58	0.009	0.11	36.82	139.67
ILK	2.8	FH	5.70	36.01	0.25	0.95	0.006	0.27	33.35	210.69
ILK	2.8	MIN	0.52	6.72	0.05	0.12	0.004	0.38	16.42	211.30
ILK	0	LM	9.67	25.94	0.18	4.81	0.012	0.04	23.55	63.14
ILK	0	FH	7.74	15.77	0.11	1.03	0.004	0.11	26.73	54.45
ILK	0	MIN	0.75	4.03	0.03	0.04	0.002	0.71	36.54	195.79
ILK	0.7	LM	9.83	23.49	0.16	3.44	0.008	0.05	23.98	57.29
ILK	0.7	FH	7.83	21.48	0.15	1.16	0.005	0.13	31.63	86.76
ILK	0.7	MIN	0.67	7.93	0.06	0.14	0.005	0.39	24.56	290.30
ILK	1.4	LM	8.48	35.60	0.25	2.32	0.010	0.11	38.15	160.23
ILK	1.4	FH	7.75	46.35	0.32	0.90	0.004	0.36	35.69	213.57
ILK	1.4	MIN	0.66	2.56	0.02	0.10	0.007	0.18	44.31	172.10
ILK	5.6	LM	9.06	27.36	0.19	4.85	0.012	0.04	22.30	67.37
ILK	5.6	FH	5.92	19.37	0.14	0.91	0.005	0.15	29.29	95.73
ILK	5.6	MIN	0.83	1.26	0.01	0.09	0.004	0.10	34.49	51.89
ILK	0	LM	10.20	27.21	0.19	4.65	0.011	0.04	24.16	64.44

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Hot Water Extractable C (mg C/g soil)	Microbial Respiration Rate (ug C/ g/d)	Total Microbial Respiration 7d (mg C/g soil)	Microbial Biomass Carbon (mg C/g soil)	MBC:TOC	Min C:MBC	Hot Water Extractable C (mg C/g C)	Microbial Respiration Rate (ug C/gC/d)
ILK	0	FH	5.04	15.74	0.11	0.66	0.005	0.17	40.03	125.13
ILK	0	MIN	0.61	5.80	0.04	0.13	0.006	0.31	29.56	280.22
ILK	0.7	LM	10.44	30.78	0.22	5.02	0.011	0.04	22.63	66.72
ILK	0.7	FH	8.16	31.72	0.22	1.37	0.007	0.16	40.64	158.03
ILK	0.7	MIN	0.45	2.07	0.01	0.18	0.005	0.08	12.15	55.92
ILK	2.8	LM	11.94	16.89	0.12	4.19	0.014	0.03	39.31	55.60
ILK	2.8	FH	7.05	26.24	0.18	1.18	0.005	0.16	32.67	121.60
ILK	2.8	MIN	0.45	5.28	0.04	0.25	0.005	0.15	9.58	113.16
ILK	5.6	LM	11.37	23.57	0.16	2.85	0.006	0.06	25.34	52.51
ILK	5.6	FH	13.79	35.18	0.25	1.59	0.004	0.16	36.70	93.63
ILK	5.6	MIN	0.41	1.86	0.01	0.21	0.012	0.06	23.16	105.92
ILK	0	LM	11.42	43.27	0.30	1.60	0.004	0.19	26.36	99.90
ILK	0	FH	2.14	49.26	0.34	0.98	0.003	0.35	5.96	137.13
ILK	0	MIN	0.67	3.87	0.03	0.30	0.006	0.09	12.60	72.96
ILK	0.7	LM	7.83	20.75	0.15	1.72	0.006	0.08	25.67	68.02
ILK	0.7	FH	13.32	26.87	0.19	0.31	0.005	0.61	229.67	463.26
ILK	0.7	MIN	0.44	3.58	0.03	0.15	0.007	0.17	19.61	161.38
ILK	1.4	LM	12.26	26.02	0.18	2.19	0.008	0.08	47.40	100.58
ILK	1.4	FH	5.75	31.53	0.22				25.78	141.44
ILK	1.4	MIN	0.61	13.92	0.10	0.46	0.009	0.21	12.16	277.83
ILK	2.8	LM	4.33	27.62	0.19	2.90	0.006	0.07	9.09	58.02
ILK	2.8	FH	7.17	46.58	0.33	1.49	0.006	0.22	26.76	173.73
ILK	2.8	MIN	0.52	5.45	0.04	0.43	0.018	0.09	22.20	231.10

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Hot Water Extractable C (mg C/g soil)	Microbial Respiration Rate (ug C/ g/d)	Total Microbial Respiration 7d (mg C/g soil)	Microbial Biomass Carbon (mg C/g soil)	MBC:TOC	Min C:MBC	Hot Water Extractable C (mg C/g C)	Microbial Respiration Rate (ug C/gC/d)
ILK	5.6	LM	5.69	19.33	0.14	2.68	0.006	0.05	13.59	46.13
ILK	5.6	FH	9.36	33.44	0.23	0.54	0.002	0.43	40.21	143.58
ILK	5.6	MIN	0.52	6.49	0.05	0.23	0.009	0.20	21.13	264.82
ILK	0	LM	7.77	15.43	0.11	4.80	0.011	0.02	17.41	34.58
ILK	0	FH	4.33	3.92	0.03	0.78	0.005	0.04	29.12	26.39
ILK	0	MIN	0.34	6.52	0.05	0.23	0.015	0.20	21.69	412.62
ILK	1.4	LM	7.17	19.45	0.14	0.80	0.004	0.17	40.24	109.07
ILK	1.4	FH	4.51	39.45	0.28	0.55	0.005	0.50	38.22	334.01
ILK	1.4	MIN	1.38	11.39	0.08	0.49	0.012	0.16	32.41	267.37
ILK	2.8	LM	5.69	25.73	0.18	0.36	0.002	0.49	34.34	155.18
ILK	2.8	FH	9.36	36.18	0.25	0.79	0.002	0.32	29.18	112.74
ILK	2.8	MIN	1.33	12.21	0.09	0.37	0.008	0.23	30.22	278.09
ILK	5.6	LM	12.48	25.04	0.18	2.43	0.007	0.07	34.83	69.88
ILK	5.6	FH	7.77	32.56	0.23	0.96	0.003	0.24	25.55	107.11
ILK	5.6	MIN	0.44	6.53	0.05	0.32	0.015	0.14	20.67	305.21
PLD	0	LFH	8.07	29.03	0.20	0.64	0.003	0.32	44.04	158.39
PLD	0	MIN	0.24	4.93	0.03	0.03	0.005	1.05	39.38	795.36
PLD	1.5	LFH	2.66	19.94	0.14	0.55	0.005	0.25	25.75	193.02
PLD	1.5	MIN	0.67	11.83	0.08	0.08	0.005	1.01	39.00	688.01
PLD	0	LFH	2.34	40.77	0.29	0.22	0.004	1.28	37.19	649.14
PLD	0	MIN	0.19	1.62	0.01	0.03	0.005	0.42	37.78	331.10
PLD	1.5	LFH	2.36	36.62	0.26	0.25	0.004	1.01	36.24	561.72
PLD	1.5	MIN	0.30	3.52	0.02	1.89	0.258	0.01	40.57	481.75

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Hot Water Extractable C (mg C/g soil)	Microbial Respiration Rate (ug C/ g/d)	Total Microbial Respiration 7d (mg C/g soil)	Microbial Biomass Carbon (mg C/g soil)	MBC:TOC	Min C:MBC	Hot Water Extractable C (mg C/g C)	Microbial Respiration Rate (ug C/gC/d)
PLD	0	LFH	6.98	41.87	0.29	3.42	0.027	0.09	55.43	332.54
PLD	0	MIN	0.22	0.80	0.01	0.79	0.132	0.01	36.62	133.07
PLD	1.5	LFH	7.58	30.94	0.22	0.91	0.005	0.24	44.23	180.64
PLD	1.5	MIN	0.41	4.11	0.03				36.98	373.50
PLD	0	LFH	11.15	31.17	0.22	0.83	0.004	0.26	52.59	146.97
PLD	0	MIN	0.19	0.91	0.01	0.02	0.003	0.42	31.85	153.72
PLD	1.5	LFH	9.08	33.53	0.23	1.94	0.009	0.12	43.15	159.28
PLD	1.5	MIN	0.22	0.84	0.01				36.97	142.09
PLD	0	LFH	15.37	24.50	0.17	0.68	0.002	0.25	37.16	59.23
PLD	0	MIN	0.25	5.30	0.04	0.10	0.015	0.39	40.86	855.61
PLD	1.5	LFH	9.84	26.84	0.19	0.44	0.003	0.43	60.07	163.83
PLD	1.5	MIN	0.49	11.25	0.08	0.11	0.009	0.70	38.15	879.28
SRD	0	LFH	7.23	46.81	0.33	2.92	0.011	0.11	27.78	179.92
SRD	0	MIN	0.63	5.46	0.04	0.32	0.014	0.12	27.70	241.41
SRD	1	LFH	9.04	61.73	0.43	1.43	0.008	0.30	47.69	325.76
SRD	1	MIN	0.45	3.93	0.03	0.53	0.025	0.05	20.96	182.81
SRD	10	LFH	2.93	24.50	0.17	0.64	0.011	0.27	50.55	423.10
SRD	10	MIN	0.33	8.16	0.06	0.42	0.023	0.14	17.83	443.24
SRD	0	LFH	3.11	29.46	0.21	1.06	0.019	0.20	56.51	534.64
SRD	0	MIN	0.55	13.53	0.09	0.25	0.012	0.38	27.24	673.05
SRD	1	LFH	4.01	25.79	0.18	1.47	0.021	0.12	57.32	368.39
SRD	1	MIN	0.34	0.10	0.00	0.45	0.027	0.00	20.16	5.87
SRD	10	LFH	3.91	27.83	0.19	0.78	0.010	0.25	47.45	337.79

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Hot Water Extractable C (mg C/g soil)	Microbial Respiration Rate (ug C/ g/d)	Total Microbial Respiration 7d (mg C/g soil)	Microbial Biomass Carbon (mg C/g soil)	MBC:TOC	Min C:MBC	Hot Water Extractable C (mg C/g C)	Microbial Respiration Rate (ug C/gC/d)
SRD	10	MIN	0.39	1.04	0.01	0.35	0.015	0.02	17.03	45.04
SRD	0	LFH								
SRD	0	MIN	0.39	7.83	0.05	0.21	0.010	0.26	17.69	359.09
SRD	1	LFH	6.26	26.36	0.18	2.03	0.025	0.09	76.74	323.07
SRD	1	MIN	0.42	4.67	0.03	0.22	0.010	0.15	18.93	208.60
SRD	10	LFH	4.76	23.32	0.16	2.12	0.021	0.08	46.86	229.72
SRD	10	MIN	0.31	6.73	0.05	0.18	0.009	0.26	14.66	320.57
SRD	0	LFH		22.10	0.15	1.76	0.025	0.09		313.49
SRD	0	MIN	0.44	8.60	0.06	0.26	0.013	0.23	21.18	413.47
SRD	1	LFH	4.09	24.92	0.17	1.41	0.021	0.12	62.04	378.19
SRD	1	MIN	0.30	6.20	0.04	0.19	0.011	0.23	17.61	358.34
SRD	10	LFH	2.40	15.61	0.11	0.87	0.016	0.13	45.12	292.93
SRD	10	MIN	0.30	-0.05		0.19	0.011		18.56	
SRD	0	LFH	6.24	26.17	0.18	1.58	0.022	0.12	85.66	358.93
SRD	0	MIN	0.30	2.10	0.01	0.06	0.004	0.23	17.68	123.52
SRD	1	LFH	2.37	20.41	0.14	0.75	0.019	0.19	59.27	510.14
SRD	1	MIN	0.34	8.20	0.06	0.10	0.006	0.60	20.14	485.30
SRD	10	LFH	5.53	29.42	0.21	1.46	0.024	0.14	92.04	489.54
SRD	10	MIN	0.31	1.03	0.01	0.04	0.003	0.18	19.82	64.98
HLB	0	FH	13.54	43.28	0.30	3.82	0.010	0.08	36.14	115.50
HLB	0	MIN	1.31	16.82	0.12	0.55	0.009	0.21	21.87	281.81
HLB	1F	FH	17.54	61.56	0.43	3.05	0.007	0.14	41.62	146.11
HLB	1F	MIN	1.41	6.48	0.05	0.64	0.011	0.07	24.25	111.54

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Hot Water Extractable C (mg C/g soil)	Microbial Respiration Rate (ug C/ g/d)	Total Microbial Respiration 7d (mg C/g soil)	Microbial Biomass Carbon (mg C/g soil)	MBC:TOC	Min C:MBC	Hot Water Extractable C (mg C/g C)	Microbial Respiration Rate (ug C/gC/d)
HLB	4F	FH	13.41	77.86	0.55	4.28	0.011	0.13	35.01	203.19
HLB	4F	MIN	1.04	7.02	0.05	0.41	0.009	0.12	23.41	158.54
HLB	8F	FH	14.98	49.27	0.34	4.17	0.011	0.08	38.01	125.01
HLB	8F	MIN	1.32	21.44	0.15	0.47	0.010	0.32	28.49	462.99
HLB	1B	FH	16.00	49.72	0.35	4.60	0.010	0.08	35.43	110.09
HLB	1B	MIN	1.15	21.95	0.15	0.49	0.007	0.31	16.56	315.85
HLB	4B	FH	15.81	72.82	0.51	3.86	0.009	0.13	36.51	168.20
HLB	4B	MIN	1.67	25.56	0.18	0.66	0.009	0.27	23.62	360.98
HLB	8B	FH	13.77	34.69	0.24	3.51	0.008	0.07	31.55	79.51
HLB	8B	MIN	1.07	2.66	0.02	0.40	0.007	0.05	18.14	45.15
HLB	0	FH	16.17	56.85	0.40	4.01	0.009	0.10	35.03	123.15
HLB	0	MIN	1.49	19.08	0.13	0.60	0.010	0.22	25.99	332.39
HLB	1F	FH	16.82	70.00	0.49				36.86	153.43
HLB	1F	MIN	1.42	3.67	0.03	0.37	0.005	0.07	18.92	48.86
HLB	4F	FH	14.22	66.39	0.46	1.71	0.004	0.27	35.98	168.00
HLB	4F	MIN	1.18	5.95	0.04	0.35	0.009	0.12	29.86	150.52
HLB	8F	FH	13.15	57.42	0.40	2.90	0.007	0.14	32.13	140.31
HLB	8F	MIN	1.66	3.02	0.02	0.49	0.008	0.04	27.86	50.51
HLB	1B	FH	12.93	53.85	0.38	3.72	0.009	0.10	30.34	126.37
HLB	1B	MIN	0.90	6.39	0.04	0.28	0.007	0.16	21.50	153.35
HLB	4B	FH	12.76	64.93	0.45	0.02	0.000	18.86	28.72	146.14
HLB	4B	MIN	1.14	16.24	0.11	0.36	0.007	0.32	23.56	334.20
HLB	8B	FH	12.93	48.65	0.34	3.18	0.007	0.11	28.88	108.67

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Hot Water Extractable C (mg C/g soil)	Microbial Respiration Rate (ug C/ g/d)	Total Microbial Respiration 7d (mg C/g soil)	Microbial Biomass Carbon (mg C/g soil)	MBC:TOC	Min C:MBC	Hot Water Extractable C (mg C/g C)	Microbial Respiration Rate (ug C/gC/d)
HLB	8B	MIN	1.40	8.19	0.06	0.39	0.007	0.15	24.07	141.24
HLB	0	FH	13.40	98.26	0.69	3.37	0.007	0.20	29.22	214.26
HLB	0	MIN	1.30	42.42	0.30	0.62	0.002	0.48	5.14	167.58
HLB	1F	FH	11.45	43.79	0.31	2.28	0.006	0.13	28.90	110.49
HLB	1F	MIN	1.10	9.82	0.07	0.23	0.004	0.30	17.42	155.38
HLB	4F	FH	11.95	75.69	0.53	3.00	0.007	0.18	26.48	167.68
HLB	4F	MIN	1.28	14.57	0.10	0.11	0.002	0.89	16.97	192.94
HLB	8F	FH	11.84	47.09	0.33	2.22	0.005	0.15	28.99	115.33
HLB	8F	MIN	1.17	18.31	0.13	0.21	0.003	0.61	19.32	303.12
HLB	1B	FH	13.04	45.40	0.32	1.92	0.005	0.17	33.54	116.83
HLB	1B	MIN	1.25	7.20	0.05	0.33	0.004	0.15	13.84	79.86
HLB	4B	FH	8.15	60.29	0.42	2.00	0.005	0.21	19.92	147.48
HLB	4B	MIN	1.15	23.20	0.16	0.22	0.003	0.75	15.53	313.12
HLB	8B	FH	6.65	44.12	0.31	2.32	0.008	0.13	22.14	146.87
HLB	8B	MIN	0.92	20.16	0.14	0.49	0.002	0.29	3.38	73.65
HLB	0	FH	7.30	64.37	0.45	5.70	0.013	0.08	16.78	147.95
HLB	0	MIN	1.01	28.05	0.20	1.14	0.004	0.17	3.41	94.75
HLB	1F	FH	14.93	63.97	0.45	5.48	0.012	0.08	31.98	137.01
HLB	1F	MIN	0.85	31.63	0.22	1.12	0.004	0.20	3.38	126.05
HLB	4F	FH	12.26	81.36	0.57	6.38	0.016	0.09	29.93	198.63
HLB	4F	MIN	0.56	19.29	0.14	0.57	0.003	0.24	2.68	92.64
HLB	8F	FH								
HLB	8F	MIN	1.41	18.78	0.13	0.45	0.005	0.29	16.38	217.57

Site	Rate of Ash Application (Mg/ha)	Soil Layer	Hot Water Extractable C (mg C/g soil)	Microbial Respiration Rate (ug C/ g/d)	Total Microbial Respiration 7d (mg C/g soil)	Microbial Biomass Carbon (mg C/g soil)	MBC:TOC	Min C:MBC	Hot Water Extractable C (mg C/g C)	Microbial Respiration Rate (ug C/gC/d)
HLB	1B	FH	15.43	83.83	0.59	2.82	0.006	0.21	32.74	177.82
HLB	1B	MIN	1.76	17.47	0.12	0.51	0.005	0.24	18.67	185.83
HLB	4B	FH	12.52	9.33	0.07	2.75	0.007	0.02	30.02	22.38
HLB	4B	MIN	1.53	5.51	0.04	0.40	0.007	0.10	26.01	93.43
HLB	8B	FH	13.78	79.67	0.56	4.72	0.010	0.12	30.13	174.13
HLB	8B	MIN	0.35	30.35	0.21	0.54	0.003	0.40	1.99	172.07
MSK	0	LFH	13.45	85.06	0.60	4.55	0.012	0.13	35.70	225.82
MSK	0	MIN	0.50	3.57	0.02	0.10	0.006	0.25	28.93	207.39
MSK	1	LFH	16.04	146.45	1.03	1.54	0.004	0.67	40.09	366.03
MSK	1	MIN	2.13	18.51	0.13	0.51	0.006	0.25	26.37	229.68
MSK	5	LFH	9.64	24.07	0.17	1.56	0.006	0.11	35.89	89.63
MSK	5	MIN	0.28	6.12	0.04	0.01	0.001	7.56	35.83	794.16
MSK	0	LFH	9.03	85.53	0.60	2.37	0.010	0.25	37.70	357.11
MSK	0	MIN	0.26	6.47	0.05	0.12	0.011	0.37	23.35	577.81
MSK	1	LFH	9.79	69.57	0.49	1.95	0.009	0.25	47.31	336.25
MSK	1	MIN	0.26	7.95	0.06	0.16	0.012	0.34	19.81	606.67
MSK	5	LFH	11.15	71.65	0.50	3.64	0.014	0.14	44.41	285.36
MSK	5	MIN	0.42	1.22	0.01				36.89	106.11
MSK	0	LFH	10.83	69.05	0.48	3.80	0.015	0.13	42.80	273.02
MSK	0	MIN	0.45	9.02	0.06	0.30	0.026	0.21	38.88	771.33
MSK	1	LFH	5.65	37.60	0.26	1.48	0.011	0.18	41.18	273.88
MSK	1	MIN	0.51	19.14	0.13	0.20	0.011	0.68	27.78	1039.98
MSK	5	LFH	14.06	68.82	0.48				33.97	166.27
MSK	5	MIN	0.37	2.98	0.02	0.19	0.016	0.11	30.68	246.15

Appendix 4. Codes for the sites and soil layers

Site Code	Site Name
ALN	Aleza Lake North, BC
ALS	Aleza Lake South, BC
ETM	Eastern Township Maple Sites, QC
SRD	25th Side Road, Thunder Bay, ON
ILK	Island Lake, ON
HLB	Haliburton, ON
PLD	Pineland, MB
MSK	Mistik, SK
Soil Layer Code	Soil Layer Name
LM	Surface litter and/or moss layer
FH	Fibric and humus layer
LFH	Litter, fibric and humus layers
MIN	Mineral soil