An Assessment of Wood Ash on Perennial Forage Stands

by

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DEDICATION

This thesis is dedicated to all of my family and friends who encouraged and supported me throughout my graduate studies.

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ABSTRACT

Agricultural soils in Nova Scotia are usually limed in order to raise soil pH to ensure optimum availability of soil nutrients. Wood ash, produced by burning wood-based fuels, is promoted as a substitute for agricultural lime. This study individually assessed two wood ash sources available to Nova Scotia producers through on-farm sampling as well as greenhouse bioassay and incubation experiments. The variables measured were soil pH, plant-available and total element concentrations in soil, total element concentrations in above ground plant tissue, botanical composition and pasture condition scores (PCS). Soil pH was significantly increased after the application of wood ashes, however the effect was short-lived for one ash (NewPage). Agricultural lime was the most effective at increasing pH. Total soil concentrations of Al, Cr, K and Na remained elevated one year after ash application to NewPage sites. Brooklyn Power ash contained excessive levels of Zn, Cd, Pb and As.

LIST OF ABBREVIATIONS USED

Al	Aluminum
As	Arsenic
B	Boron
Ca	Calcium
CCE	Calcium Carbonate Equivalent
CCME	Canadian Council for Ministers of the Environment
Cd	Cadmium
CEC	Cation Exchange Capacity
cmolc kg-1	Centimoles of charge per kilogram
Co	Cobalt
Conc	Concentration
Cr	Chromium
Cu	Copper
ECCE	Effective Calcium Carbonate Equivalent
Fe	Iron
g	gram
H	Hydrogen
ha	Hectare
Hwy	Highway
ICP-MS	Inductively Coupled Plasma Mass-Spectrometry
K	Potassium
kg	Kilogram
Mg	Magnesium
MAAD	Microwave Assisted Acid Digestion
Mn	Molybdenum
Na	Sodium
Ni	Nickel
NS	Nova Scotia
P	Phosphorus
Pb	Lead
PCS	Pasture Condition Score
S	Sulfur
t	tonne
Yrs	Years
Zn	Zinc

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CHAPTER 1.0 INTRODUCTION

1.1 Wood Ash in Nova Scotia

Wood ash from pulp and paper mills is promoted in Nova Scotia as a substitute for agricultural lime that can also increase soil plant nutrient levels. In 2009, wood ash was available to Nova Scotia producers upon the completion of a nutrient management plan, and was available from two sources. Producers in the southern region of Nova Scotia had access to wood ash from Brooklyn Power, in Liverpool, and wood ash available to the northern half of Nova Scotia came from NewPage Corporation, in Port Hawkesbury. The ash was so popular in 2009, that demand for wood ash from Brooklyn Power was backlogged with orders up until October 2012. This was beneficial to ash suppliers who no longer had to pay for disposal of wood ash in landfills, and also beneficial to producers who could benefit from an inexpensive, locally-sourced soil amendment.

One of the greatest selling points of wood ash as a soil amendment is cost. Agricultural lime, sold by Mosher Limestone Co. Ltd., is commonly used throughout Atlantic Canada to increase soil pH and sells in Nova Scotia for \$28.00 t^{-1}, approximately \$775.00 per truck load. In 2009, wood ash being sold in Nova Scotia could be purchased for approximately \$9.00 t^{-1}, translating to \$250.00 per truck load. These prices do not include trucking/shipping costs which can range from \$2.30 – \$5.85 km^{-1} depending on fuel costs, trucking distance and source of the wood ash. This price difference between agricultural lime and wood ash is one of the main reasons why wood ash is being used as a substitute for agricultural lime, despite that at best, twice as much wood ash have to be purchased to obtain a similar increase in pH.

Despite the fact that wood ash from pulp mills is relatively inexpensive and is being promoted by J.D. Irving Ltd as a product that will help farmers “improve productivity and the environment” (J.D. Irving Ltd 2007), some producers have concerns. They are concerned about the quantity of nutrients the ash is adding to their soils and possibility of future detrimental effects as a result of applying wood ash to their fields.

In 2009, the Soil & Crop Improvement Association of Nova Scotia (SCIANS) obtained funding for research to determine how soil element concentrations were changed after the application of wood ash in order to determine its fertilizer and liming value. This presented the opportunity to conduct on-farm research to analyze soil and plant tissues before and after the application of locally-sourced wood ashes.

The criteria which had to be met in order to become eligible for this study was that the site must not have received wood ash previously and no other fertility treatments were to be added to the site for the duration of the study. These sites also required approval to receive wood ash at the time when the study was beginning. Nine farms met the requirements and were willing to refrain from performing any additional management practices.

This study determined elemental composition of two Nova Scotia wood ash products. This study also determined if there were any consistent effects on soil and plant tissue element concentrations over time, for farms that received ash from the same source. Rosmann (1994) summarized the advantages of on-farm research as follows. “It uses realistic conditions on actual working farms; it enhances farmers’ confidence in their problem-solving ability; it leads to more rigorous research by scientists; it provides statistically reliable answers; and farmers find the results more believable.”

On-farm research, however presents its challenges. Variables such as application rates and soil characteristics are more difficult to control and “control” treatments may be resisted. In this study, the only “control” selected was the situation immediately prior to wood ash application, therefore, the main treatment was “time”, and samples were taken once before and four times post-wood ash application.

Raw, unpublished data from controlled pH incubation and bioassay experiments were supplied by Dr. Mehdi Sharifi of the Nova Scotia Agricultural College. The raw data from these experiments were analyzed and used to support or refute any findings derived from the on-farm portion of the project.

1.2 Objectives

- Establish the utility of using wood ash as an amendment on perennial forage stands (on-farm, incubation and bioassay experiments).
- Evaluate the chemical characteristics of wood ash (on-farm and incubation experiments).
- Determine the influence of wood ash on soil pH (on-farm and incubation experiments).
- Ascertain total and plant-available concentrations of elements in soil after wood ash application (on-farm experiment).
- Determine total concentrations of elements in plant tissues following wood ash application (on-farm and bioassay experiments)
- Determine if botanical composition changes after wood ash is applied (on-farm experiment)

CHAPTER 2.0 LITERATURE REVIEW

2.1 Wood Ash

Wood ash is the material left behind after burning wood. The process known as burning encompasses the sub-processes of pyrolysis, combustion and char-oxidation (Harmathy 1984). In the process of wood burning, the reaction essentially releases CO_2, CO and H_2O into the air and leaves behind what was not lost by the reaction (wood ash) (Tillman et al. 1981).

Generally wood ash is known to contain elements at varying concentrations (Demeyr et al. 2001). This is due to the variability in terms of element concentrations of the wood being burned and also due to the temperature at which the burning takes place (Misra et al. 1993; Demeyr et al. 2001). Reimann et al. (2008) observed that wood ash derived from burning birch (*Betula pendula*), contained higher mean concentrations of undesirable trace elements including As, Cd, Cr and Pb than wood ashes from spruce (*Picea abies*). In fact, some tree species such as willow (*Salix spp.*) are known to hyper-accumulate the element Cd (Mertens et al. 2006; Wieshammer et al. 2007), while others such as poplar (*Populus spp.*) can also accumulate Cd, as well as Zn (Wieshammer et al. 2007).

Wood ash element concentrations can also be affected by the part of the tree which is being burned. Werkelin et al. (2005) determined that when comparing the ash element composition of wood, bark and foliage ashes, the highest concentration of elements was found in the foliage followed by the bark. Thus, it would stand to reason that a wood ash derived primarily from wood bark (such as the wood ash produced by Irving Ltd., in NewBrunswick) would have a higher concentration of elements than a wood ash derived from the burning of whole trees.

Another critical aspect that can determine the element concentration of an ash is the temperature at which the wood was burned. As the temperature of wood burning increases, there is a decrease of overall ash mass due to $CaCO_3$ and KCO_3 decomposition, regardless of the type of wood being burned at temperatures >900˚C (Misra et al. 1993).

The ultimate result of ash burned at higher temperatures (>1300˚C) is that Ca is predominantly in the form of CaO and K and S volatilize at temperatures $\geq$ 800˚C (Misra et al. 1993). Wood ash is primarily applied to agricultural soils to increase pH, due to its concentrations of $CaCO_3$ (as will be discussed later) and is also promoted as a good source of K, however the higher the burning temperature, the less effective one could expect the wood ash to be when used as an agricultural soil amendment.

Despite the range of element concentrations in wood ashes due to species, the part of the trees being burned and temperature at which the burning is taking place, mean values are generally presented. A review by Pitman (2006) reported that mean element concentrations (mg kg^{-1}) from various studies of wood ashes derived from pulp and paper mills are Ca (170,000), K (26,000), Mg (10,000), Al (9,000), P (4,000) and Mn (3,000).

2.2 Total Elements in Wood Ash

A method of extraction that is commonly used to determine the total concentration of elements in wood ashes and soil is HNO_3 and or HCl acid digestion. Voundie Nkana et al. (1998) used an HNO_3 extraction to determine the total concentrations of elements in wood ash and determined that Ca followed by K, Mg and Fe were the elements present in the greatest quantity at levels of approximately 78,000, 17,000, 8,000 and 6,000 mg kg^{-1}. HNO_3 digestion was also used by Ludwig et al. (2005) as a method to determine total metal concentrations in wood, municipal solid waste, brown coal and hard coal ashes. Out of the four ashes, wood ash contained the greatest concentration of K, Mg and Cd, however wood ash contained substantially less Cr, Cu, Ni and Zn than ash derived from municipal solid waste (Ludwig et al. 2005). Ravila and Holm (1996) also used HNO_3 digestion for both wood ash and soil samples prior to elemental analysis, while Reimann et al. (2008) used a combination of HCl and HNO_3. HCl was used for extraction by Misra et al. (1993) to determine total element concentrations in wood ashes as a function of furnace temperature. Using various ashes resulting from various types of wood it was determined that Ca, followed by K, Mg and S tended to be present in the ashes in the greatest quantity (Misra et al. 1993). Overall, using either HCl or HNO_3 acid or a combination of the two has been the preferred digestion method for extracting elements in either wood ashes, or soils (Misra et al. 1993; Voundie Nkana et al. 1998; Ludwig et al. 2005; Reimann et al. 2008; Odlare and Pell 2009; Park et al. 2011). However, hydrofluoric and perchloric acids have also been used (Ozolincius et al. 2007).

Wood ashes can contain total concentrations of elements present at varying quantities. In a study conducted by Reimann et al. (2008), it was shown through sampling wood from spruce and birch trees as far from anthropogenic sources of contamination as possible, that pure wood ashes can contain disturbingly high concentrations of metals; Cd at 65 mg kg^{-1}, Cr at 316 mg kg^{-1}, Cu at 579 mg kg^{-1} and Pb at 965 mg kg^{-1}. The researchers concluded that the element levels in wood ashes "are by no means harmless due to their natural origin" (Reimann et al. 2008). Other researchers have also concluded that wood ashes can contain excessively high concentrations of some trace elements. A review conducted by Narodoslawsky and Obernberger (1996) describes how Cd in wood ashes is of gravest concern and that levels are high in wood ashes due to atmospheric fallout from the burning of fossil fuels. Cd was also the element of greatest concern to Zhan et al. (1996) when three wood ashes were investigated and total Cd levels ranged from 1.9 to 12 mg kg^{-1}. In another study 16 different wood ashes were examined and it was determined that Cd (0 – 22 mg kg^{-1}) and Zn (100 – 5,000 mg kg^{-1}) levels were elevated. However, Kopeckyl and Meyers (2009) reported that regular application to agricultural fields should not result in unacceptable levels being accumulated in the soils. In a review conducted on wood ashes by Demeyer et al. (2001) the variability of wood ash element concentrations was highlighted. Fe concentrations in wood ash ranged from approximately 3,000 to 20,000 mg kg^{-1}, and Zn concentrations ranged from approximately 200 to 800 mg kg^{-1} (Demeyer et al. 2001). Levels of Cd are reported by Ohno and Erich (1993) as being <1 mg kg^{-1}, while Etiegni et al. (1991) reported wood ash to contain 21 mg kg^{-1} Cd. Huang et al. (1992) report Cr concentrations in wood and bark ashes of 14 mg kg^{-1}, while Cr in paper and pulp ashes was 1036 mg kg^{-1}. Pb concentrations in ash have been reported by Ohno and Erich (1993) as being as low as 32 mg kg^{-1}, while Etiegni et al. (1991) report Pb concentrations of 130 mg kg^{-1}. Wood fly ash was reported by Odlare and Pell (2009) to reduce potential denitrification rates in agricultural soils. This is assumed to be caused by excessive metal concentrations of Pb and Zn which were at levels as high as 553 and 2,600 mg kg^{-1}, respectively.

Overall, wood ashes are known to contain the following elements to a greater or lesser degree; Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Zn (Etiegni et al. 1991; Huang et al. 1992; Ohno and Erich 1993; Muse and Mitchell 1995; Reimann et al. 2008; Solla-Gullon et al. 2008; Park et al. 2011), Hg, V (Solla-Gullon et al. 2008; Hakkila 1989; Park et al. 2011) and Ti (Reimann et al. 2008).

2.3 Plant-Available Nutrients

The nutrients required by plants in order to sustain their growth and development occur naturally in eastern Canadian soils at varied concentrations. Sheppard et al. (2007) examined 112 soil samples from agricultural soils representing a range of ecozones across Canada, and found that almost all nutrients tend to vary greatly in concentration. The main reason for the range of naturally occurring concentrations is the parent material and surrounding soil types. For instance, Cu, Ni and Fe tend to be found at higher concentrations in basalt rock types, and Mn, which tends to be the most abundant micronutrient, can be found in most abundance in pyroxenes, which are rock forming minerals found in many rock types (Morimoto 1988). If one were to generalize as to what concentrations of nutrients would be present in Nova Scotia soils, they would start by looking at the parent material and determining the soil order. The primary order of soil in the Atlantic Provinces is Podzolic (CANSIS 2010). Podzolic soils are known to be acidic, and contain higher levels of Fe and Al in their B horizons (CANSIS 2010). The fact that Nova Scotia soils are generally acidic plays a critical role in determining which nutrients are plant-available. Plant-available nutrients are, as the name suggests, nutrients which are readily available for plant uptake. These are nutrients including plant micro and macronutrients that are in the soil solution or on soil colloids yet not tightly bound to the soil matrix in plant-unavailable form (Plaster 2003). A key factor that determines the plant availability of a particular nutrient is soil pH. While some elements such as K and Mg tend to be plant-available over a range of soil pH (Truog 1946), others such as P are less available at low pH (Tisdale and Nelson 1975) and some such as B, Co, Cu, Mn and Zn can decrease in plant- availability as pH increases (Coppenet et al. 1972; Tisdale and Nelson 1975; Peterson and Newman 1976; Giordano and Mortvedt 1980; Zhou and Wong 1999).

A key extraction method used to determine plant available nutrients is Mehlich 3. Provincial soil test laboratories in Nova Scotia and Prince Edward Island use the Mehlich 3 extraction as their primary soil nutrient assessment method. Mehlich 3 is an extractant which consists of acetic acid, nitric acid and ethylenediaminetetraacetic acid (EDTA) (Mehlich 1984). Mehlich 3 extract is effective over a range of soil pH and has been shown to be a more accurate extractor of K, Mg and Ca than ammonium acetate, and more effective at determining P than both the Mehlich 2 and Bray extractants (Mehlich 1984). Plant-available soil nutrient levels were determined by the PEI soil testing laboratory. Mehlich 3 has been used by other researchers to determine nutrient plant-availability in more than just soil. Wood ashes have been tested via Mehlich 3 by several researchers in order to determine the proportion of nutrients that would actually be plant available (Omil et al. 2007; Solla-Gullon et al. 2008; Park et al. 2011; Pousada-Ferradás et al. 2011). Mehlich 3 was used by Omil et al. (2007) to determine extractable concentrations of elements in both the wood ash and in the soil. The study determined that extractable levels of As, Cd, Cr, Cu, Hg Mn, Ni, Pb and Zn in the wood ash with total concentrations being greater than extractable levels (Omil et al. 2007). The elements with the greatest extractability in the wood ashes (Mn and Zn) also significantly increased in the soil after wood ash application (Omil et al. 2007). Solla-Gullon et al. (2008) determined via Mehlich 3 that wood ash derived from pine bark and untreated wood residue caused a short lived increase of available Ca, Mg, K and P when applied to soil at the rates of 5 and 10 t ha^{-1}. Mn and Zn were present in the greatest quantity behind Fe (Solla-Gullon et al. 2008). This same study showed no significant change in plant-available Fe, Mn, Cu, Zn and Ni post ash application (Solla-Gullon et al. 2008). Park et al. (2011) used Mehlich 3 to determine nutrient availability in soil/ash mixtures and found Mehlich 3 to be an accurate predictor of available K and Zn in the soil/ash mixtures that translated to increased K and Zn uptake in plant tissues. There was however no significant correlation between Mehlich 3 extractable P in the mixtures and the concentrations present in plant tissues (Park et al. 2011). Pousada-Ferradás et al. (2011) used Mehlich 3 to determine the level of plant-available elements in ash derived from pine bark and untreated wood products. Compared to levels of water soluble elements in the same ash, the Mehlich 3 extraction resulted in consistently greater levels of 19 extracted elements than what was extracted aqueously (Pousada-Ferradás et al. 2011). Overall, nutrient availability can correlate with the amount of wood ash applied, with increasing application rates leading to increased available nutrients (Williams et al. 1996; Augusto et al. 2008).

2.4 Soil pH

Soil pH is a measure of the hydrogen ion concentration in a soil, and is measured via a numerical scale ranging from 0-14. Depending on the species, the optimum pH for supporting plant growth ranges from 5.5 to 6.5 (Asher et al. 1980). This pH range ensures optimal availability of soil macro and micronutrients to plant roots. A pH which is too low can reduce availability of elements including: P and Mo, while a pH which is too high can limit the availability of P, Al, Fe, Cu, Mn, B and Zn (Christensen et al. 1951; Jenne 1968).

Agricultural soils in Nova Scotia can become acidic due to a combination of factors including: acidic parent material, application of nitrogen fertilizers and heavy precipitation (Shaw 1979). Thus, one of the primary reasons why wood ash is used as a soil amendment is to counteract these acidifying processes and increase soil pH.

Wood ash increases soil pH chiefly due to Ca, K and Na oxides, hydroxides and carbonates (Ulery et al. 1993). In terms of the carbonates, including $CaCO_3$ and K_2CO_3, a reaction with water causes the formation of hydroxyls (OH) and CO_2 (Demeyer et al. 2001). This leads to a rapid influx of OH, thus quickly reducing the active acidity. This activity in the soil causes hydrogen and aluminum ions to be displaced from exchange sites on negatively-charged soil colloid particles, by cations including Ca and Mg. The aluminum is then converted into insoluble aluminum hydroxide and the hydrogen reacts to form water (Plaster 2003). This process ultimately contributes to increasing and sustaining an increased soil pH by acting upon the reserve acidity. In comparison to agricultural lime, some studies have found that wood ash can increase pH faster, however the neutralizing effects tend to be short lived (Clapham and Zibilske 1992; Muse and Mitchell 1995). Other researchers have found that wood ashes can actually maintain an increase of soil pH when applied at rates as low as 3.6 t ha^{-1} for up to 6 years post application (Jacobson et al. 2004). In a study conducted by Arvidsson and Lundkvist

(2003) wood ashes derived from the burning of 90% wood chips and 10% peat, significantly increased soil pH by 0.5 units in the top 0-5 cm of the soil profile when applied at 3 t ha^{-1}. This significant increase of soil pH was observed up to six years post ash application (Arvidsson and Lundkvist 2003). Wood ash was also observed to increase soil pH over the span of a year when applied at rates ranging from 2.5 to 5 t ha^{-1} (Mandre et al. 2006). The degree of this pH increase tended to correlate with the rate at which the ash was applied, with the highest rate causing the highest soil pH increase (Mandre et al. 2006). Omil et al. (2007) observed that when applying a single application of wood ash to acidic forest soils in Spain, there was no significant change in pH, however after repeated applications over several years, soil pH did increase. Solla-Gullon et al. (2008) observed a significant increase of soil pH of 0.4-0.6 units in comparison to the control when wood ash was applied at a rate of 5 t ha^{-1}.

Overall, when applied as a soil amendment, wood ashes have been observed by many researchers to increase soil pH (Ohno and Erich 1990; Unger and Fernandez 1990; Etiegni et al. 1991; Ohno 1992; Huang et al. 1992; Krejsl and Scanlon 1995; Muse and Mitchell 1995; Williams et al. 1996; Omil et al. 2007; Solla-Gullon et al. 2008; Odlare and Pell 2009).

2.5 Plant Tissue Nutrient Status and Biomass

Limited research has been conducted, pertaining to how wood ashes affect the nutrient status in plants. A study conducted by Bae Park et al. (2005) observed no significant change in foliar or stem tissue nutrient concentrations of *Salix purpurea* after the serial application of wood ashes at both rates of 10 and 20 t ha^{-1}. In this same study, plant biomass was also not significantly affected as a result of the treatment, however overall stem count reduced significantly as a result of wood ash application in comparison to the control (Bae Park et al. 2005). In a greenhouse study, Park et al. (2011) showed that there was no significant difference between *Avena sativa* and *Lolium perenne* plant tissue concentrations of Ca and Mg in comparison to a control after the application of ash at a rate of approximately 15 t ha^{-1}. However, there was a significant increase of plant tissue K in both plant species as a result of the wood ash treatment. In this same study, Park et al. (2011) also observed that wood ash caused a significant increase of Mo and Zn in both plant species and that the fly ash treatment significantly increased Cd and Hg concentrations in the tissues. Plant tissue P is an element that has been shown not to be significantly affected as a result of wood ash application (Voundie Nkana et al. 1998; Park et al. 2011). Voundie Nkana et al. (1998) showed that levels of Fe and Cu in plant tissues were not significantly affected as a result of wood ash applied according to its CCE value of 27.3 in order to reach a targeted pH of 5.5, 6 and 6.5. Levels of the trace elements; Al, Fe, Mn, Zn, Cr, Cu, Cd, As, Ni, Pb, Ti, V and Mo did not significantly increase in a number of forest berries and mushrooms in a forest soil after the application of wood ashes at rates ranging from 3 to 15 t ha^{-1} (Moilanen et al. 2006). Similarly, Ozolincius et al. (2007), observed no significant difference in Cd, Pb, Cr, Ni, Cu and Zn concentrations in the tissues of *Pleurozium schreberi* when wood ash was applied to a sandy soil at rates ranging from 1.25 – 5 t ha^{-1}.

2.6 Rate of Application

Just like any other soil amendment, the rate at which wood ash is applied is important for it determines just how effective the product is. Naylor and Schmidt (1989) determined that soil pH as well as available soil nutrients increased linearly as ash application rate increased. In Nova Scotia, wood ash is applied based on the lime requirements determined by soil tests and nutrient management plans. This is done by determining the calcium carbonate equivalency (CCE) of a particular wood ash. The CCE is a comparison to pure $CaCO_3$ (calcium carbonate) which has a CCE value of 100. Wood ash generally has a lower CCE than agricultural lime (Demeyer et al. 2001). Vance (1996) analyzed wood ashes from 18 different wood-fired boilers and found an average CCE of 48.1%, with a range from 13.2% - 92.4%. The research conducted by Vance (1996), therefore suggests that an average of two tonnes of wood ash is required to obtain the same neutralizing value as one tonne of lime.

Besides knowing the CCE of an amendment such as wood ash, it is important to know the particle size of the material. Amendments such as calcitic and dolomitic limestone must be of a particular fineness in order to be used as amendments. This is to ensure that the particle size is small enough so that the amendment will react quickly, and coarse enough so there is a sustained neutralizing effect (NCSU 2003). In Nova Scotia an agricultural lime must be of the following particle size: 100% of the material must pass through a 2 mm (10 mesh) screen, and 60% of the material must pass through a 0.15 mm (100 mesh) screen (HSP 2012). It has been shown that lime applied at the same application rates yet at different particle sizes reacted differently. Lime that passed through a 100 mesh screen increased soil pH up to a value of 6.7 in as little as two months, while lime which passed through a 40-50 mesh screen to as long as 15 months (NCSU 2003). In fact, when considering the particle size of wood ash, it has already been found that a finer textured ash will release nutrients more quickly than a coarser textured ash and, thus, reaction time in the soil will be shorter (Steenari et al. 1998).

Particle size and CCE are combined to determine the effective calcium carbonate equivalence (ECCE). ECCE calculations incorporate a numerical score for fineness (NCSU 2003).

2.7 The Benefits of Wood Ash

Wood ash had beneficial effects on crop yield when applied as an agricultural soil amendment. Legumes, including *Trifolium pratense* and *Medicago sativa*, showed overall yield increases as a result of wood ash application (Seekins et al. 1986). In another study wood ash increased *Medicago sativa* biomass more than lime when ash applications did not exceed rates of 45 t ha^{-1} (Meyers and Kopecky 1998). Biomass of *Phaseolus vulgaris*, increased by 64%, compared to control, following wood ash application to an acidic soil at a rate of 50 t ha^{-1}(Krejsl and Scanlon 1995).

Legumes are not the only plants that have been recorded to benefit as a result of wood ash application. A study conducted by Muse and Mitchell (1995) determined that wood ash tends to have an overall positive effect on plant growth. For example, yield of *Hordeum vulgare*, increased up to 83% following wood ash application compared to the control (Hébert and Breton 2008), however, in another study, wood ash increased *Hordeum vulgare* yield only from 6 to 12.5% (Patterson et al. 2004). Park et al. (2011) determined in a greenhouse experiment that wood fly ash caused a significant increase of plant biomass in *Avena sativa* of 36% in comparison to the control when ash was applied at a rate of approximately 15 t ha^{-1}. However, in the same experiment, no significant increase of biomass was observed in *Lolium perenne L.* (Park et al. 2011).

2.8 Cation Exchange Capacity (CEC)

The ability of a soil to hold and exchange positively charged molecules is referred to as a soil's Cation Exchange Capacity (CEC). Positively-charged ions including: K^+, H^+, Na^+, Ca^{2+}, Mg^{2+}, Al^{3+} and NH_4^+ are attracted to negatively-charged soil colloids. These cations remain attached to soil colloids until displaced from colloid exchange sites by more positively-charged cations (Plaster 2003). The CEC of a soil is measured in units of centimoles of charge per kilogram (cmolc kg^{-1}) of soil and according to Brady and Weil (2002), "a soil with a CEC of 15 cmolc kg^{-1} indicates that 1 kg of the soil can hold 15 cmolc of H^+ ions and can exchange this quantity of H+ ions with the same number of charges from any other cation". A CEC of 15 cmolc kg^{-1} is what would be expected from soil particles such as kaolinite or mica, however, humus particles in soil organic matter are known to have CECs as high as 250 cmolc kg^{-1} (Brady and Weil 2008).

2.9 Nutrient Cycling

Although the parent material and surrounding soil type determine what nutrients occur naturally in a soil, there are processes common to all soils that impact the source and cycling of nutrients in the environment. Typical processes which impact the level of nutrients in the environment include: decomposition, weathering, addition of amendments, atmospheric deposition and sediments (Bierman and Rosen 2005).

The process of decomposition is essentially the breakdown of organic substances into smaller components. Soil organisms break down the larger organic components so microbial activity can proceed to break down constituents such as proteins, lignin, cellulose and starch into smaller molecules, releasing elements into the soil (Brady and Weil 2008). The activity of these soil decomposers results in not only an increase in the soil nutrient status, but improvement in soil structure and enhanced soil nutrient holding capacity (Brady and Weil 2008).

Weathering, as the name suggests, involves the breakdown of naturally occurring parent materials such as rocks and minerals into finer particles through atmospheric processes such as wind, precipitation, freezing and thawing. As a result, over time, this causes the disintegration of rocks and minerals into their elemental constituents (Brady and Weil 2008).

The process of adding amendments to a soil can, of course, influence the nutrient composition of a soil. As mentioned earlier, organic amendments can be decomposed, and weathering will aid the breakdown of amendments such as agricultural lime. Chemical fertilizers when applied as amendments directly increase a soil's nutrient status and levels can be tailored to meet need. Ultimately all additions by amendments will impact natural pools for given elements.

One process that may not stand out as an obvious contributor to a soil's nutrient status is atmospheric deposition. Nitrogen in the forms of ammonia and nitrogen oxide and sulfur in the forms of carbonyl sulfide, hydrogen sulfide and sulfur dioxide can be significantly increased in soils through precipitation. In fact, it is believed that in North America, soils typically receive 8 to 10 kg S ha^{-1} annually through atmospheric deposition (Brady and Weil 2008). The addition of both nitrogen and sulfur through atmospheric deposition impact pH by acidifying the soil and thus contribute to altering nutrient availability.

The arrival of sediments into a soil that were carried by either wind or water can significantly increase the level of soil nutrients, by simply moving from one location to another. Conversely, this is also one way in which nutrients are lost from a soil.

As there are various processes that contribute to a soil's nutrient status, there are also processes which contribute to the loss of nutrients from the soil. The primary processes that occur that can remove nutrients from a soil are: runoff, erosion, leaching, gaseous losses and crop removal (Bierman and Rosen 2005).

Runoff is essentially caused by excess precipitation and can be classified as surface runoff if the water does not enter the soil and groundwater runoff if water enters the soil. Through this process, nutrients and sediments can be picked up and carried away from an area and deposited in another location. Increased runoff can, in turn, lead to erosion of the surrounding soils and leaching of elements.

Erosion is defined by Brady and Weil (2002) as the "detachment and movement of soil or rock by water, wind, ice or gravity". This process physically removes nutrients from a system through the displacement of rocks, soil and organic matter that contribute to and help hold nutrients. Many producers try to keep their soils covered with crops and avoid fall plowing that would leave soil exposed and vulnerable to heavy precipitation during the winter months. These practices help reduce soil erosion, thus limiting nutrient losses.

One way that nutrients are often lost through soils is by leaching. Leaching occurs when water carries dissolved elements and nutrients out of a soil and into groundwater and streams. The reason for this has to do with how strongly an element is adsorbed to soil colloids. Nitrogen and sulfur are two elements in particular that are susceptible to leaching, however any element can be leached from soils if present in excess and not adsorbed onto soil colloids. Sandy soils with low clay and organic matter content are the most susceptible to nutrient losses by leaching, while soils with high cation exchange capacities, such as those with high clay and/or organic matter content, are more resistant to leaching losses (Brady and Weil 2008).

Volatilization is another way that nutrients can leave a soil system; however this primarily pertains to nitrogen. Nitrogen is often lost from soils through a process known as denitrification when nitrate or nitrite reduces to nitrogen gas. Nitrogen is not considered to be one of the main components of wood ashes (Ohno and Erich, 1993), and thus, gaseous losses of elements will not be addressed in this study.

In agricultural systems, one of the greatest losses of nutrients can occur though crop uptake. Vital nutrients required by plants are taken up by plant roots and used by the plants to carry out vital life processes. Many of these nutrients are held in plant tissues, so when crops are harvested and removed, there is substantial removal of nutrients from the system (Brady and Weil 2008). For example, crops such as alfalfa, timothy, orchard grass and some clovers can remove P_2O_5 at a range of 5 to 7 kg t^{-1} and K_2O can be removed at rates ranging as high as 19 to 27 kg t^{-1} (PPI 2012). All elements that are required for plant growth will be removed at some level when a crop is harvested and moved off site.

2.10 Allowable Concentrations of Trace Elements in Soil Amendments

In order to ensure the health and sustainability of our soils, the Canadian Council of Ministers of the Environment (CCME) developed guidelines that stipulate the allowable concentrations of trace elements in soil amendments. According to CCME guidelines, soil amendments are placed in one of two categories: A or B. CCME guidelines for compost quality state that, " Category A amendments can be used in any application, such as for agricultural lands and residential gardens and that acceptable tolerances for trace elements are achievable using best source separated municipal solid waste feedstock, or municipal bio-solids, or pulp and paper mill biosolids or manure". Category B amendments have restricted use due to the possibility of them containing unwanted sharp foreign objects or undesirable levels of trace elements (CCME 2005).

In order to ensure the safety and sustainability of wood ash as a soil amendment, wood ash available in Nova Scotia is subject to random testing by the Nova Scotia Department of Environment, to make sure element levels are within acceptable ranges.

2.11 Botanical Composition in Perennial Forage Stands

The botanical species found in an area, often correlate to the condition of the surrounding soil (Bever et al. 1997). Botanical composition is particularly important in perennial forage stands due to the fact that some species, including legumes, not only have higher nutritional feed value, but can also improve soil structure and increase soil nutrient status (Bronick and Lal 2004). Some soils tend to favor the growth of particular species due to a variety of chemical and physical characteristics. Chemical characteristics may include pH, leading to nutrient availability as well as general element composition and concentration (Christensen et al. 1951; Jenne 1968). Physical characteristics include soil texture (eg. percent sand, silt and clay) and structure (Plaster 2003).

In terms of chemical characteristics, soils vary greatly. Soils in Nova Scotia generally have low pH values due to abundant precipitation and acidic soil parent materials (Shaw 1979). The majority of desirable forage plants prefer only slightly acidic pH, therefore, soils in the Atlantic region are often amended with lime. This, in turn, creates more favorable conditions for optimum nutrient availability and increased plant growth. A study conducted by Caddel et al. (2004) showed that yields of red clover (*Trifolium pratense*) and alfalfa (*Medicago sativa*) increased from 1.1 to 1.6 and from 1.8 to 2.0 t ha^{-1}, respectively, per unit of soil pH increase.

Soil physical characteristics including structure and texture, play a role in botanical composition. These factors regulate a soil's ability to retain moisture and nutrients as well as facilitate or restrict plant root growth (Passioura 1991). Many field crops are negatively affected when soil structure is impaired. A study conducted by Brereton et al. (1986), showed that brassica and legume species had reduced yields in compacted soils by as much as 59 and 26%, respectively, due to impaired root growth. Compaction can also decrease water use efficiency in several cereal species (Radford et al. 2001).

Forage legumes vary in their responses to various soil characteristics. For instance, Hall (2008) reported that red clover had low tolerance to drought and moderate tolerance to wet soils and low pH. White clover had low tolerance to drought, yet had a high tolerance to wet soils. Alfalfa required well-drained soils due to its low tolerance of wet conditions and low pH, yet it had a high tolerance to drought.

2.12 Pasture Condition Scores

One management tool used by producers in North America to determine the overall health and productivity of their pastures and perennial forage stands is the Pasture Condition Score (PCS) (USDA 2011). A PCS is derived from observing and scoring ten key indicators on a scale from 1 to 5 and is an effective method for quickly assessing a pasture's current condition. These ten indicators, as listed by the USDA (2011), are: percent desirable plants, live plant cover, plant density, plant residue, plant vigor, legume content, uniformity of grazing, livestock lounging areas, soil compaction and erosion (Cosgrove et al. 2001; USDA 2011). An example of the PCS card used in this study can be seen in the appendices (Appendix A-1).

For plant residue, the amount of dead material, as well as the amount of thatch that is present below the forage is assessed. Too much plant residue in the forage reduces forage quality and too much thatch impairs forage growth and provides habitat for disease. The rate of decomposition of plant residue is generally an indicator of how healthy the system is. A healthier system will break down residues quickly while in a less healthy system, residues will remain and possibly create problems (Cosgrove et al. 2001).

A PCS is a valuable tool for keeping track of the health and needs of particular pastures. Farmers can use pasture condition scoring throughout the season and can, in turn, make decisions related to rotational and fertility management (Cosgrove et al. 2001). Thus, pasture condition scoring is a more effective way of assessing the effectiveness of an applied amendment such wood ash, rather than just going by an initial greening up after application.

CHAPTER 3.0 SITE DESCRIPTIONS

Nine Nova Scotia farms participated in the study. Five of the farms were located in Lunenburg County, two in Richmond County, and one farm each in Guysborough and Inverness counties. Each farm supplied a field which was devoted to perennial forage or pasture production and had never received wood ash before. Individual sampling dates can be viewed in Appendix A-2.

Site 1, was located on Mr. Creighton Allen's farm, in Back Centre, Lunenburg Country, NS (Coordinates: N44.368517 W064.362041). The field was 1.6 ha, and has been used for perennial forage production for the past 20 years. The representative soil at the site is a well-drained, sandy loam, Orthic Humo-Ferric Podzol of the Bridgewater series (Appendix A-3 and A-4), and the plant rooting depth was 44 cm. The wood ash was obtained from Brooklyn Power Corporation in Liverpool, NS and was applied at the end of August, 2009 at the rate of 8.5 t ha^{-1}.

Site 2, was located on Mr. Clarence Crouse's farm, on Hwy 324 in Lunenburg County, NS (Coordinates: N44.41611 W064.37337). The field studied was 2.19 ha, and was used for both pasture and perennial forage production. The representative soil for the site is a well-drained, gravelly sandy loam, Orthic Humo-Ferric Podzol of the Bridgewater series (Appendix A-5 and A-6), and the plant rooting depth was 70 cm. The wood ash was obtained from Brooklyn Power Corporation in Liverpool, NS and was applied on August 28, 2009 at the rate of 5.2 t ha^{-1}.

Site 3, was located on Mr. Peter Falkenham's farm on Hwy 324 in Lunenburg County, NS (Coordinates: N44.39586 W064.34482). The field was 2.1 ha, and was used for perennial forage production. The representative soil for the site is an imperfectly-drained, loam, Fragic Humo-Ferric Podzol of the Wolfville series (Appendix A-7 and A-8) and the plant rooting depth was 38 cm. The wood ash was obtained from Brooklyn Power Corporation in Liverpool, NS and was applied at the end of August, 2009 at a rate of 4.5 t ha^{-1}.

Site 4, was located on Mr. Bill Fancy's farm, on Fancy Rd. in Colpton, Lunenburg County, NS (Coordinates: N44.45829 W064.84766). The field studied was 1.01 ha, and was used for both pasture and perennial forage production for >15 years. The representative soil for the site is a very poorly drained organic soil. It is classified as a Typic Mesisol belonging to the Rossignol series (Appendix A-9 and A-10) and the plant rooting depth was 65 cm. The wood ash was obtained from Brooklyn Power Corporation in Liverpool, NS and was applied at the end of August, 2009 at the rate of 13.5 t ha^{-1}.

Site 5, is farmed by Mr. Kevin Veinotte, and the field was located on Northfield Rd., Lunenburg County, NS (Coordinates: N44.48056 W064.57920). The study area was a 1.04 ha perennial forage stand that had been farmed for the past 10 years. The soil at the site is an imperfectly-drained, loam, Fragic Humo-Ferric Podzol of the Wolfville series (Appendix A-11 and A-12) and the plant rooting depth was 48 cm. The wood ash was obtained from Brooklyn Power Corporation in Liverpool, NS and was applied at the end of August, 2009 at the rate of 31.0 t ha^{-1}.

Site 6, was located on the farm of Mr. Kari Easthouse, on West Bay Hwy in Richmond County, NS (Coordinates: N45.762872 W060.919906). This study area was a 0.77 ha field which was used for pasture for the last 40 years. The soil at the site is an imperfectly-drained, gravelly loam, Gleyed Sombric Brunisol belonging to the Millbrook series (Appendix A-13 and A-14) and the plant rooting depth was 50 cm. The wood ash was obtained from NewPage Corporation in Port Hawkesbury and was applied on June 11, 2010 at the rate of 5.4 t ha^{-1}.

Site 7, was located on the farm of Mr. Andrew MacLennan, on Old Mull River Rd., Inverness Country, NS (Coordinates: N46.018959 W061.299427). The study area was a 3.86 ha field used for perennial forage production for the past 30 years. The representative soil at the site is an imperfectly-drained, loam, Gleyed Sombric Brunisol of the Queens series (Appendix A-15 and A-16) and the plant rooting depth was 55 cm. The wood ash was obtained from NewPage Corporation in Port Hawkesbury and was applied on May 15, 2010 at the rate of 6.9 t ha^{-1}.

Site 8, was situated on the farm of Mr. Bruce Sinclair, in Copper Lake, Antigonish County, NS (Coordinates: N45.413736 W061.976944). The study area was approximately 1 ha and was rotationally used for forage and cereal production. The moderately sloping (14%) field has suffered soil loss due to erosion over time and the B horizon has been incorporated into the plow layer (i.e. Ap horizon). The representative soil for the site is a moderately well-drained, very gravelly, silt loam, Orthic Humic Regosol of the Thom series (Appendix A-17 and A-18) and the plant rooting depth was 60 cm. The wood ash was obtained from NewPage Corporation in Port Hawkesbury and was applied in November, 2009 at the rate of 6.1 t ha^{-1}.

Site 9, was in Long Lake, Cape Breton, NS (Coordinates: N45.671824, W060.921249) and belonged to Mr. Edward Touesnard. The study area was a 2.86 ha perennial forage stand that had been in production for the past 15 years. The soil at the site is a poorly-drained, silt loam, Orthic Humic Gleysol belonging to a Kingsville series (Appendix A-19 and A-20). The plant rooting depth was 28 cm. The wood ash was obtained from NewPage Corporation in Port Hawkesbury and was applied on December 1, 2009 at the rate of 9.0 t ha^{-1}.

CHAPTER 4.0 MATERIALS AND METHODS

Fields at participating farms throughout Nova Scotia were evaluated for various aspects of their overall health and productivity before and after the application of wood ash. The variables evaluated included botanical composition and pasture condition scores. Soil samples were tested for soil quality aspects including pH, CEC, organic matter and plant-available nutrients via a Mehlich 3 extraction in conjunction with ICP-MS at the Prince Edward Island (PEI) soil, feed and water testing laboratory. Soil and plant tissues were also analyzed for total elemental concentrations at Agriculture and Agri-Food Canada's laboratory in PEI by means of Microwave-Assisted Acid Digestion (MAAD) followed by ICP-MS.

The data collected from each site were used along with general observations to produce a Pasture Condition Score (PCS).

Data from a growth chamber incubation experiment that tested the liming capacity of three wood ashes against two agricultural limes were analyzed to compare the overall liming effectiveness of these amendments over time. Data from a greenhouse study which used two different soils types and ashes at various application rates were also analyzed for plant nutrient uptake.

4.1 Soil Sampling

Soil sampling was performed at each site before and after wood ash application and samples were analyzed to determine soil pH, CEC and elemental concentrations. Two cm diameter soil core sub-samples were collected to a 20 cm depth using a stainless steel soil probe. The sampling points were randomly taken by traveling in a zig-zag pattern across each site. Every sub-sample core was combined with the other sub-samples, to produce a single composite sample. This procedure was repeated to provide one soil sample per site, per sampling date. There were five sampling dates for each site; the first sampling took place just before ash was applied and the final sampling took place one year after ash application, with three other samplings through the year (Appendix A-2).

On the final sampling date, soil cores were separated according to depth (0-5cm, 5-10cm, 10-20cm) and pH was measured for each increment.

All composite soil samples were air dried and subjected to a flail type grinder provided by Agriculture and Agri-Food Canada (AAFC). The flail grinder broke up soil clods and passed through a 2 mm mesh screen before being sent for analysis.

A representative soil profile was described and sampled at each site by an AAFC soil scientist. The soil characterization was vital in determining if key soil properties such as soil structure, texture or drainage played a role in interpreting the results. Three, 7.6 cm diameter x 7.6 cm long, soil core samples were also taken from the surface (Ap) horizon of each soil profile. The soil cores were analyzed for bulk density, saturated hydraulic conductivity and water holding capacity. Bulk soil was sampled from each major horizon in the soil profile and sent to the Soil, Feed and Water Chemistry Testing Laboratory in PEI. These samples were analyzed for pH (H_2O), total carbon and nitrogen, CEC, organic matter and Mehlich 3 extractable P, K, Ca, Mg, Fe, S, Mn, Na, Zn, B, Cu and Al. Particle size analysis with sand fraction separation was conducted using the pipet method (Sheldrick 1984).

4.2 Forage Sampling

Forty forage sub-samples were collected from each site by walking through the fields in a zig-zag pattern and collecting a “handful” of plant material located directly in front of one’s right foot after every 10 paces. Each sample was cut 2 cm above the soil using a pair of stainless steel hand pruners. Careful attention was made to not bias sample collection. This procedure was repeated to provide one composite sample per site, per sampling date. Once the forage samples were collected, they were dried at 55˚C for 48 hours. Following drying, samples were ground to < 1mm in a stainless steel Wiley Mill® (Arthur H. Thomas Co., Philadelphia, USA) and sent to Agriculture and Agri-Food Canada’s laboratory, Crops and Livestock research division in PEI for elemental analysis.

4.3 Sample Analysis

Analyses for total elements were performed at Agriculture and Agri-Food Canada’s laboratory, Crops and Livestock research division in PEI. Total elements were determined via microwave extraction method 3051a (Quimlab 2007) in which samples were dissolved in nitric and then hydrochloric acids in a laboratory microwave unit. Samples were then filtered, centrifuged and diluted to volume prior to ICP-MS (Quimlab 2007).

Plant-available concentrations were determined at the Soil and Feed Testing Laboratory in PEI, following Mehlich 3 extraction (Mehlich 1984). 2 g of each sample were mixed with 14 ml of Mehlich 3 extractant, sealed and shaken for five minutes. Samples were then filtered and analyzed via ICP-MS.

4.4 Botanical Composition

Fields at the nine participating farms were evaluated for various aspects of their overall health and productivity before and after the application of wood ash. The variable evaluated was botanical composition.

A step-point system devised by Owensby (1973), which involved sampling in a zig-zag pattern, was used to determine the botanical composition. Plants at three hundred random points in each field were identified. If at any point no plants were present, that information was recorded as well, to determine basal cover. This method of evaluation was performed at the pre-ash and one year post sampling periods (Appendix A-2). The data provided information on whether botanical composition changed ash application.

4.5 Pasture Condition Scores

Pasture condition scores were conducted at each site pre- and one year post-wood ash application, resulting in two pasture condition scores for each site. All information pertaining to the pasture condition score was recorded on a pasture condition score card that contained a short description of each of ten indicators (percent desirable plants, live plant cover, plant density, plant residue, plant vigour, legume content, uniformity of grazing, livestock lounging areas, soil compaction and erosion) and depicted how these indicators should be rated on a scale from 1 to 5. Three indicators; uniformity of grazing, livestock lounging areas and soil compaction were given a default score that remained constant for the pre- and post-ash PCS to prevent variables that would not have been altered as a result of the ash from affecting the final scores. An example of the pasture condition score card used in this study can be seen in the appendix (Appendix A-1).

4.6 Growth Chamber Incubation

Data from a growth chamber incubation experiment conducted by NSAC Nutrient Management Chair Dr. Mehdi Sharifi were analyzed to determine the pH adjusting properties of the wood ashes and two agricultural limes. Two different field soils with pH of 5.0 and 5.4 (Appendix A-21) were air dried and passed through a 2 mm sieve, and then equal portions (300 g) representing the top 20 cm of the soil profile were added to plastic containers that contained holes in the lids for air exchange. Wood ashes from NewPage, Brooklyn Power and JD Irving as well as two locally sourced agricultural limes from Mosher Limestone Ltd. and Antigonish Limestone Ltd. were tested plus a control. Application rates of amendments were determined based on the effective calcium carbonate equivalence (ECCE) values supplied by the suppliers and involved using the lime recommendation for each soil as reported by Laboratory Services, Nova Scotia Department of Agriculture.

Amendments were mixed into each of the two different soils and were stored in a growth chamber with 80% relative humidity at 25˚C. Soil pH was measured over time by removing 10 g samples and using a 1:1 soil: water ratio method with an IQ 150 handheld pH/mv/temperature meter, with ISFET (Ion Sensitive Field Effect Transistor) probe, manufactured by IQ Scientific Instruments.

4.7 Greenhouse Fertility Bioassay

One kg of a light-textured, field soil from Petite Riviere Vineyards, Crouse town, Nova Scotia (pH 7.4) representing the top 20 cm of the soil profile was dried, passed through a 4.75 mm sieve and placed into each of thirty three 12.7 cm diameter pots. Annual ryegrass (*Lolium multiflorum*) seedlings were transplanted into each pot at a density of twenty seedlings per pot. Pots were placed in a greenhouse at 18 to 22˚C, and were watered 2-3 times per week (based on pot weights), and were rotated weekly. The experiment was organized as a completely randomized design with eleven treatments and three replications. Application rate of wood ash was determined based on soil and wood ash nutrient analysis, with the assumption that 40% of the total K in the wood ash was plant available (Ohno and Erich 1990). Treatments consisted of both the NewPage and Brooklyn Power ashes as well as an ash from Irving, applied at 0.5x, 1x and 2x the recommended rate. A treatment of solely Mosher limestone and a control treatment of lime/fertilizer combination were also used. The annual ryegrass was harvested to 2.5 cm four times (27, 51, 81 and 115 days after transplanting) and plant material was dried for 48 hr at 65˚C, weighed (fresh and dry), ground to 2 mm and analyzed to determine total nutrients. Soil samples from each pot were collected after the experiment and were dried, ground through a 2mm sieve and analyzed for both plant-available and total elements at RPC Laboratory in Fredericton, NB.

4.8 Wood Ash Particle Size Distribution

Particle size distribution was conducted on the Brooklyn Power and NewPage wood ashes. Four samples from each of the ash sources were separated into various fractions by individually placing each of the samples into a metal sieve with 20, 60 and 100 mesh screens. The sieve was then sealed, and rigorously shaken in a soil shaking device for 10 minutes. Each of the separated fractions were weighed and divided against the mass of the sum of all the separated fractions to determine the percent of material that passed through each of the mesh screens.

4.9 Experimental Design

At the beginning of the study, wood ash sources in Nova Scotia included Brooklyn Power in Liverpool and NewPage Corporation in Port Hawkesbury. The sites/farms included in the study were determined based on information provided by L.P. Consulting. The two ash sources were analyzed separately. Data were analyzed using Proc Mixed of SAS v. 9.2 (SAS Institute Inc., Cary, NC). Sampling period (pre-ash, postdate 1, postdate 2, postdate 3 and postdate 4 was one year following ash application) was treated as a repeated effect and farm was treated as a random effect. Rate of application, pH, OM percent and CEC were included as covariates in the model. Means were compared, where appropriate (i.e., where $P \leq 0.05$), using Tukey's HSD test at $\alpha = 0.05$. Assumptions of analysis of variance were tested by Proc Univariate of SAS v. 9.2 for normal distribution of residuals. Proc Plot of SAS v. 9.2 was used to plot predicted (x) versus residual (y) values to test homogeneity of variance and independence of predicted and residual values. Outliers were removed from some data sets. Data that did not meet the assumptions of analysis of variance (i.e. pasture condition score as well as Cr and Pb plant tissue data) were tested using Proc Npar1way in SAS v. 9.2., with P-values determined by the Kruskal-Wallis test.

Model: $Yij = \mu + farmi + periodj + \beta 1\ ratei + \beta 2\ pHi + \beta 3\ OMi + \beta 4\ CECi + \varepsilon ij$

μ = overall mean

$farm_i$ = random effect of farm

$period_j$ = fixed effect of sampling period

$rate_i$ = rate of wood ash application covariate

pH_i = initial soil pH covariate

OM_i = initial percent soil organic matter covariate

CEC_i = initial cation exchange capacity covariate

ε_{ij} = residual error

Polynomial regression was conducted on the pH incubation experiment data using Proc Reg of SAS v. 9.2. Linear, quadratic and cubic regression models were tested. Best fit regression was usually quadratic ($Y=\beta_o + \beta_1 x + \beta_2 x^2$) but in two cases was cubic ($Y=\beta_o + \beta_1 x + \beta_2 x^2 + \beta_3 x^3$). The independent variable was square root of days post-application and the dependent variable was soil pH. First derivatives of the best fit regression equations (quadratic or cubic) were set to zero and solved for days to maximum pH.

Annual ryegrass data from the greenhouse experiment were analyzed using Proc Mixed of SAS v. 9.2 with amendment as a fixed effect.

Model: $Y_{ij} = \mu + treatment_i + \varepsilon_{ij}$

Contrast statements were used to test limestone plus fertilizer versus wood ashes and to test Brooklyn wood ash versus NewPage wood ash. Assumptions of analysis of variance and regression were tested by Proc Univariate of SAS v. 9.2 for normal distribution of residuals. Means were compared, where appropriate (i.e., where $P \leq 0.05$), using Tukey's HSD test at $\alpha = 0.05$.

Particle size distribution data was analyzed using Proc t-test in SAS v.9.3.

CHAPTER 5.0 RESULTS AND DISCUSSION

5.1 Soil pH

5.1.1 On-farm

Soil pH changed significantly over the course of a year following wood ash application for both wood ash sources (Table. 5.1). Soil pH rapidly and significantly increased by 0.69 units after Brooklyn Power ash application, (Fig. 5.1). Although the soil pH dropped slightly after the first sampling following ash application, a significant increase of soil pH remained up to one year post ash application.

Table 5.1. *P* values from analyses of plant-available nutrients in soil and total nutrients in soil and plant tissue for plant macronutrients and pH measured for both Brooklyn Power and NewPage ash sites.

	P > F					
	Brooklyn Power			NewPage		
Elements	Plant-available Soil	Total Soil	Total Plant	Plant-available Soil	Total Soil	Total Plant
Ca	**0.015**	0.0764	0.595	0.368	0.4088	0.693
K	**0.002**	**<0.0001**	0.296	0.473	**0.0068**	0.301
Mg	**0.052**	**0.0089**	**0.055**	0.620	0.6464	0.875
P	**0.0046**	**0.0040**	0.370	0.840	0.7428	0.363
S	**0.0014**	**-**	-	0.729	-	-
pH		**0.007**			**0.002**	

The NewPage sites behaved differently in terms of pH than the sites that received ash from the Brooklyn source. The pH at the NewPage sites rose more slowly (Fig. 5.1). Fig. 5.1 also shows that there was a significant increase from the pre-ash sampling on the second sampling post application. However, this increase was not maintained, and by the third and one year post samplings, there was no significant difference in soil pH compared to before the wood ash was applied.

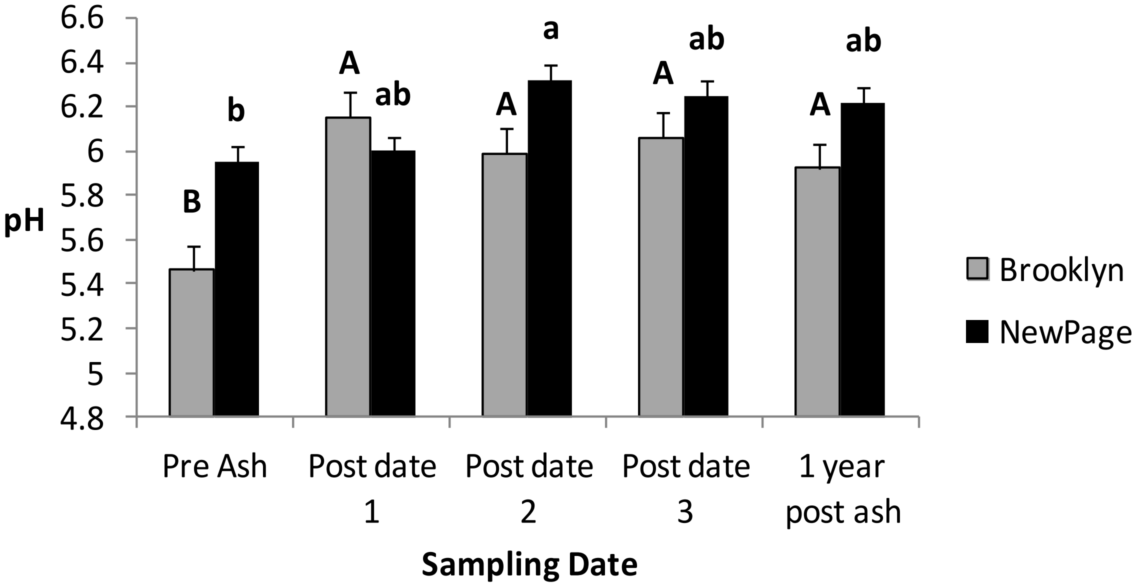


Fig. 5.1. Mean soil pH over time, for farms which received ash from Brooklyn Power and NewPage. Columns within ash source with different letter groupings differ significantly according to Tukey's HSD test ($P < 0.05$).

Incremental depth soil sampling from the final sampling date one year post ash application, are presented in Fig. 5.2. The incremental sampling essentially shows how quickly the neutralizing capacity of the ash may have moved down through the soil profile. The pH adjustment at the Brooklyn sites took place primarily in the upper 5 cm of the soil profile, with the mean pH of 6.25 being significantly higher than the lower depths (Fig 5.2). There was no significant difference among the three measured depths at the NewPage sites.

The difference in how the pH was affected after the application of either Nova Scotia ash source in field conditions could be explained by the individual pH values for each of the wood ashes. The mean pH of the Brooklyn Power ash was 10.8, while the mean pH of the NewPage ash was 8.9 (Table 5.2). The higher pH would be caused by the higher concentration of available Ca, K and Mg in the Brooklyn ash in comparison to the NewPage ash (Table 5.2).

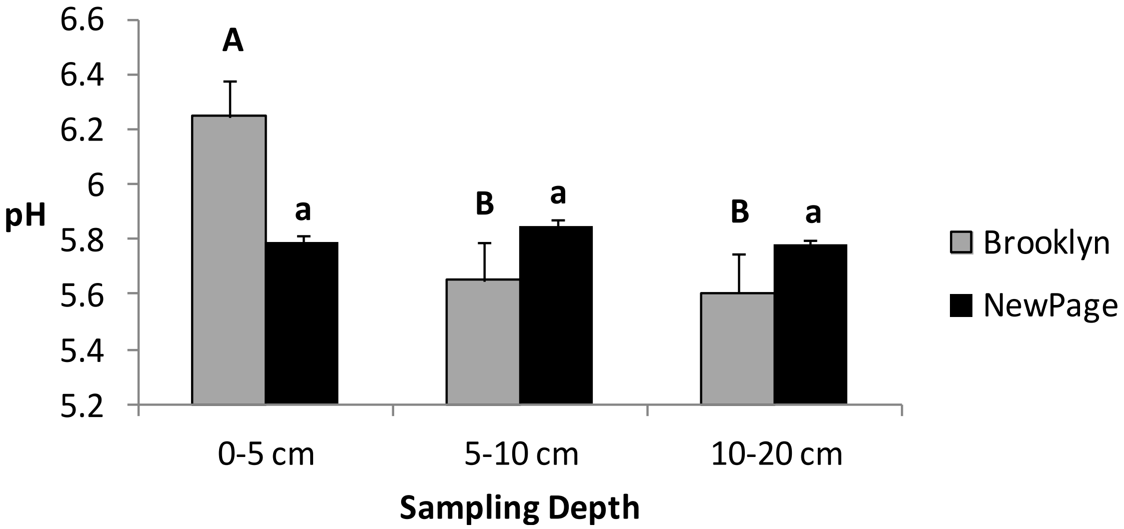


Fig. 5.2. Mean soil pH at three soil depths as a result of incremental soil sampling for soils which received the Brooklyn Power and NewPage wood ash. Columns within ash source not sharing a letter are significantly different according to Tukey's HSD test ($P < 0.05$).

It is possible that how these ashes affected pH in the field trials could also be explained by ash particle size and time of application. The NewPage ash had a significantly coarser texture than the Brooklyn ash (Table 5.3), which means that the Brooklyn ash would have had more surface area exposed to interact with the soil, enhancing pH adjusting reactions. The province of Nova Scotia stipulates that 60% of lime must fit through a 150 µm (100 mesh) sieve in order to ensure that pH adjusting reactions are not too prolonged. The two wood ashes available in this province do not meet that size requirement (Table 5.3). The coarser texture of the NewPage ash could explain the slower pH adjusting reaction in comparison to the Brooklyn ash yet does not fully explain why the overall pH increase over time was not as great. Steenari et al. (1998) also found that finer textured ash releases Ca and K faster than a coarser textured ash.

Table 5.2. Mean Mehlich 3 extractable (plant-available) element concentrations of NewPage and Brooklyn Power.

	NewPage		Brooklyn Power	
Element	Soil Analysis Report Mean Conc[z] (mg kg^{-1})	Std. Error	Soil Analysis Report Mean Conc[z] (mg kg^{-1})	Std. Error
Ca	22000	1900	34000	1900
Fe	80	1	130	4
K	1000	100	5000	20
Mg	1500	100	2000	16
Mn	600	9	200	15
Na	400	8	1000	200
P	60	33	10	1
S	1000	320	4000	250
Al	1000	60	N/A	N/A
B	50	3	60	4
C	65000	1200	49000	3120
Zn	200	26	200	7.4
pH	8.9	0.145	10.8	0.206

[z] Means derived from Mehlich 3 analyses performed on 3 ash samples from each ash source. Soil Analysis Report analyzed via Mehlich 3 extraction, representing plant available nutrients

Table 5.3. Results of a particle size distribution conducted on both the NewPage and Brooklyn Power wood ashes.

Fineness (µm)	NewPage (%)	Brooklyn (%)	*P>t*
Finer than 850 (20 mesh)	51	87	<0.0001
Finer than 250 (60 mesh)	26	46	0.0002
Finer than 150 (100 mesh)	14	36	0.0023

*Results based on four wood ash samples from each ash source.

In terms of application time, two of the sites which received NewPage ash, received it in late fall, meaning the first sampling post application happened during a time when soil temperatures were cooler, and thus, pH adjusting reactions may have taken longer to occur (Leiros et al. 1999). This may also explain the trend as to why the higher mean soil pH appears deeper in the soils that received the NewPage ash than that of the Brooklyn Power ash (Fig. 5.2). Over the winter, high precipitation may have caused leaching of the ash into the 5 to 10 cm depth, from which point the ash participated in pH adjusting reactions when soil temperatures increased during the spring of the year (Appendix A-22). Because the Brooklyn ash was applied during a warmer period of the year (Appendix A-2), it would have reacted immediately with the top 5 cm of the soil.

Another reason for the greater effectiveness of the Brooklyn Power ash may have been due to the rates at which the wood ash was applied. Farms that applied wood ash from Brooklyn Power generally applied at greater rates than the farms that applied NewPage ash (see Site Descriptions). These rates of application were based on nutrient management plans which took into account the lime recommendation provided by a soil analysis report, the CCE values reported by the ash distributor (Table 5.4), and the individual characteristics of the fields.

Table 5.4. The effective calcium carbonate equivalence (ECCE) values for the various amendments as reported by their distributors.

Amendment	ECCE
Mosher Lime	64
Antigonish Lime	54
NewPage Ash	30
Brooklyn Ash	33

Organic matter (OM) in the soils may have also affected how the pH changed in the soils. Brooklyn Power sites contained a higher mean percentage of OM than NewPage sites (Appendix A-3 to A-20). The higher OM would result in Brooklyn sites having higher buffering capacities, and thus more wood ash would be required to adjust pH and it would take longer for an adjusted pH to return back to unadjusted levels.

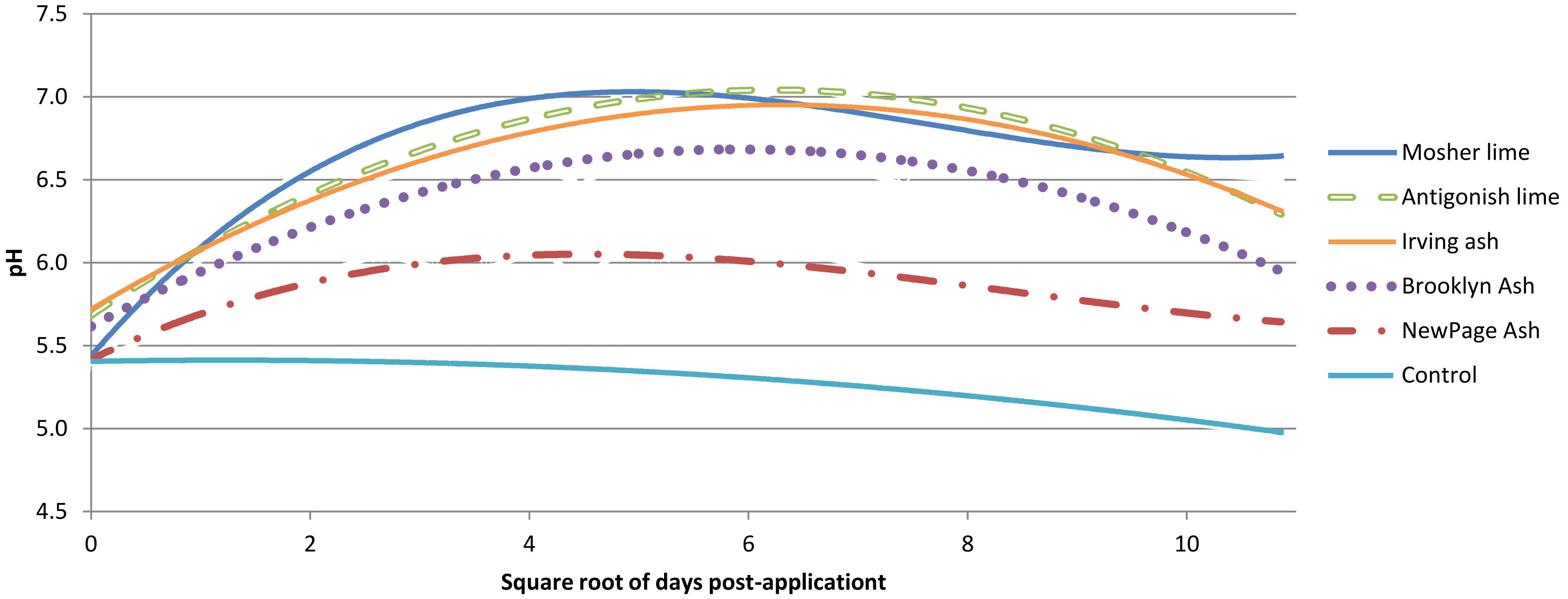
5.1.2 Incubation Experiment

Overall, pH changes in soils of the perennial forage stands was similar to pH changes observed in the incubation experiment. Figs. 5.3 and 5.4 show results of regression conducted on incubation derived pH data for two different soil types (Soil properties described in Appendix A-21). The figures show visually, that for each of the soil types, the effectiveness of the treatments at increasing and sustaining an increase of pH are represented by the higher and more sustained peaks in the graphs (Figs. 5.3 and 5.4). The regression equations show this numerically and show (Fig 5.3) that the Mosher and Antigonish limes were the most effective at increasing and sustaining pH on the H4 soil, followed closely by the Irving ash produced in New Brunswick. The results are similar for the Harvey soil, however, this time the Irving ash and Antigonish lime reacted the same (Fig. 5.4). It can be seen that for both soil types, Brooklyn Power ash acted more quickly in increasing soil pH, and raised the pH to a higher level than wood ash derived from NewPage (Figs. 5.3 and 5.4). However, both of these wood ashes produced in Nova Scotia were outperformed by the other treatments, yet performed better than the control.

The results from this controlled experiment are somewhat surprising considering the fact that the treatments were applied based on the ECCE values which took into account the fineness of the amendments. This being the case, one would have expected all treatments to affect pH similarly, and ideally all of the regression lines in Figs 5.3 and 5.4 would have been similar. Instead, the results support what was observed in the on-farm portion of the project; in that Brooklyn ash was more effective at raising pH than ash from NewPage. This may stand to reason that when it comes to comparing these two wood ashes to each other and to agricultural lime, there are chemical properties that are trumping physical properties of the ash when it comes to the ultimate effectiveness of the wood ashes as a soil amendment. The Brooklyn ash contained higher total concentration of Ca (Table 5.5) and higher plant-available Ca, K and Mg (Table 5.2) than the NewPage ash.

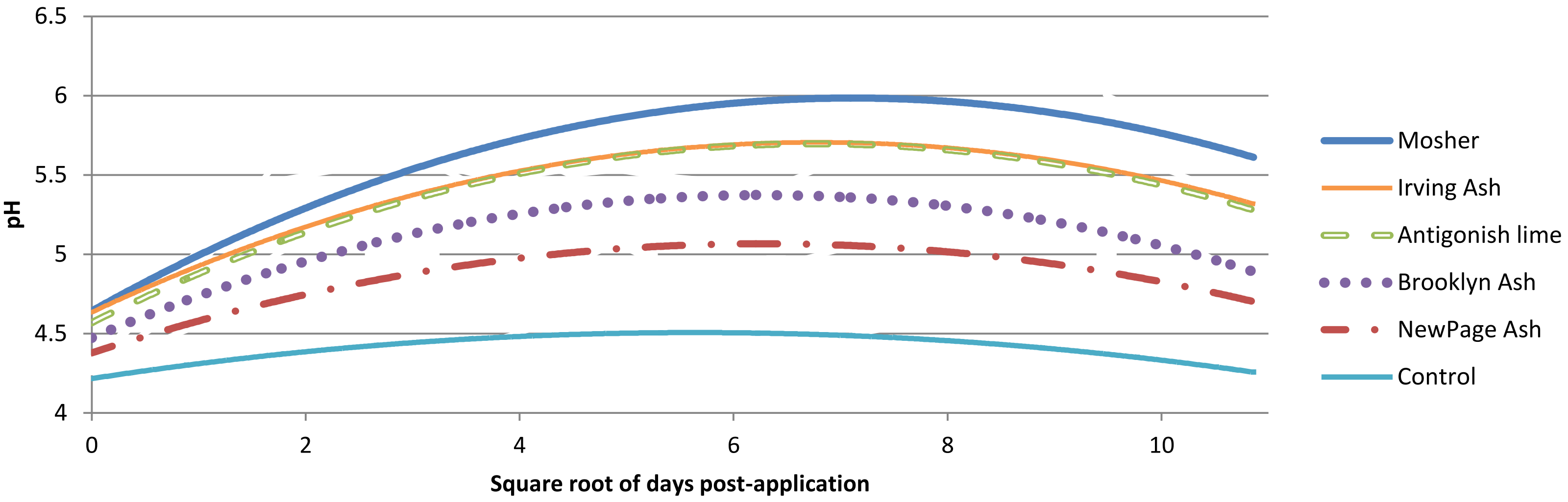
Despite these concentrations of elements there are chemical properties of the ash that were not measured in this study. It is known that how the elements are combined, primarily as carbonates, bicarbonates and oxides, determine how wood ash will affect pH (Meiwes 1995). Two factors that can largely influence the concentrations of these molecules are furnace temperature and storage time (Etiegni and Campbell 1991). Because the furnace temperature at which the two wood ashes were burned is not known, it is possible that Brooklyn ash resulted from a temperature that was more favorable for the formation or retention of carbonates, bicarbonates and oxides.

It is interesting to see that how the treatment behaved in the incubation experiment closely resemble the individual treatments ECCE values in order from greatest to least (Table 5.4). This, despite the fact that the application rates were adjusted to compensate for the variation of ECCE within treatments. Overall, with the exception of the Irving ash, the higher the ECCE value of the treatment, the better it performed at increasing soil pH.



Amendment	**Regression equation**	**R^2**	**Days to Max pH**	**Max pH**
Control	$pH = 5.41 + 0.0118\ day^{1/2} – 0.0047\ day$	0.83	2	5.4
NewPage Ash	$pH = 5.41 + 0.326\ day^{1/2} – 0.0487\ day + 0.00190\ day^{3/2}$	0.87	21	6.1
Brooklyn Ash	$pH = 5.60 + 0.361\ day^{1/2} – 0.0302\ day$	0.85	36	6.7
Mosher Lime	$pH = 5.44 + 0.766\ day^{1/2} – 0.114\ day^2 + 0.00497\ day^{3/2}$	0.90	25	7.0
Antigonish Lime	$pH = 5.64 + 0.440\ day^{1/2} – 0.0349\ day$	0.82	40	7.0
Irving Ash	$pH = 5.70 + 0.393\ day^{1/2} - 0.0309\ day$	0.79	40	6.9

Fig. 5.3. Regression lines, equations, R^2, days to maximum pH and maximum pH values as a result of applying amendments to H4 soil.



Amendment	**Regression equation**	**R^2**	**Days to Max pH**	**Max pH**
Control	$pH = 4.22 + 0.098\ day^{1/2} – 0.0087\ day$	0.54	32	4.5
NewPage Ash	$pH = 4.37 + 0.221\ day^{1/2} – 0.0175\ day$	0.77	40	5.1
Brooklyn Ash	$pH = 4.44 + 0.297\ day^{1/2} – 0.0238\ day$	0.83	39	5.4
Mosher Lime	$pH = 4.62 + 0.383\ day^{1/2} – 0.0275\ day$	0.78	49	6.0
Antigonish Lime	$pH = 4.57 + 0.335\ day^{1/2} – 0.0248\ day$	0.79	46	5.7
Irving Ash	$pH = 4.63 + 0.316\ day^{1/2} - 0.0233\ day$	0.68	46	5.7

Fig. 5.4. Regression lines, equations, R^2, days to maximum pH and maximum pH values as a result of applying amendments to Harvey soil.

Table 5.5. CCME maximum concentrations of total trace elements allowable in soil amendments compared to total wood ash and lime element concentrations.

	CCME Category A	**CCME Category B**	**NewPage Wood Ash**		**Brooklyn Power Wood Ash**		**Dolomitic Lime**
Chemical Name	**Conc. (mg kg^{-1})**	**Conc. (mg kg^{-1})**	**Mean[Z] Conc. (mg kg^{-1})**	**SE**	**Mean[Y] Conc. (mg kg^{-1})**	**SE**	**Conc.[X] (mg kg^{-1})**
Al	n/a	n/a	55500	4540	31500	3490	4150
As	13.0	75.0	8.30	2.30	**139**	18.3	10.5
B	n/a	n/a	214	27.1	168	13.1	38.0
Ca	n/a	n/a	79800	7720	80200	11500	202000
Cd	3.00	20.0	**3.80**	0.600	**5.80**	0.60	0.10
Co	34.0	150	7.00	0.500	10.0	0.90	3.40
Cr	210	1060	45.2	4.70	182	24.5	n/a
Cu	400	757	70.9	7.10	205	26.6	21.6
Fe	n/a	n/a	15500	2160	24800	2710	7000
K	n/a	n/a	19600	1940	21400	2780	711
Mg	n/a	n/a	10400	589	10300	874	80600
Mn	n/a	n/a	10400	1210	8740	1150	5030
Na	n/a	n/a	7870	1004	4120	230	198
Ni	62.0	180	33.3	10.4	23.1	3.50	8.70
P	n/a	n/a	10900	1430	11100	607	7610
Pb	150	500	33.8	10.6	**369**	52.3	137
Zn	700	1850	665	102.6	**1020**	77.1	11.8

[Z] Values are the means of four separate NewPage wood ash samples.

[Y] Values are the means of four separate Brooklyn Power wood ash samples.

[X] The result of the analysis of one lime sample from Mosher Limestone.

5.2 Plant-Bioassay Experiment

The results of the bioassay experiment on Annual Ryegrass (Table 5.6) showed that in comparison to the control (lime + fertilizer treatment), two out of the seven elements measured were present at concentrations significantly greater than those measured in control plants. Concentrations of K and Zn were significantly greater in plant tissues as a result of the Brooklyn 2x treatment and Zn concentrations were also significantly greater post the Brooklyn 1x treatment in comparison to control levels.

As a result of the lime only treatment, plant tissue concentrations after the application of all other treatments were significantly greater for all elements tested.

With the exception of K, the Brooklyn 2x treatment did not significantly alter plant tissue concentrations in comparison to the Brooklyn 1x treatment. And in comparison to the Brooklyn 0.5x treatment, the Brooklyn 2x treatment only caused higher concentrations of K and Zn in the plant tissues, while Mg concentrations were actually higher in the 0.5x treated plants than in the 2x treated plants.

The only significant difference between the NewPage 2x and 1x treatments in terms of plant tissue concentrations was the element Mg. As observed with the Brooklyn 2x and 0.5x treatments, the NewPage 1x and 0.5x treatments resulted in significantly greater concentrations of Mg in the plant tissues than the NewPage 2x treatment. The only other element that was significantly different in the plant tissues when comparing the NewPage 2x and 0.5x treatments was K. There was significantly greater K in the NewPage 2x treated plants than there was in the NewPage 0.5x plants.

Table 5.6. Bioassay results showing nutrient uptake and shoot dry weight of annual ryegrass after the application of wood ash at various rates as compared to agricultural lime.

	Element (mg kg^{-1})							
Treatment	**K**	**P**	**Ca**	**Mg**	**Cu**	**B**	**Zn**	**Shoot Dry Weight (g)**
Brooklyn 0.5x [Z]	181*d*	31.0*a*	126*ab*	50.9*ab*	0.284*a*	0.693*a*	0.536*bc*	11.8*ab*
Brooklyn 1x [Y]	244*b*	33*a*	114*b*	43.9*bc*	0.277*a*	0.686*a*	0.623*ab*	12.7*ab*
Brooklyn 2x [X]	340*a*	29.1*a*	121*ab*	40.5*c*	0.243*a*	0.683*a*	0.733*a*	13.6*a*
NewPage 0.5x [Z]	131*e*	27.9*a*	117*b*	54.6*a*	0.236*a*	0.687*a*	0.461*c*	11.3*b*
NewPage 1x [Y]	165*de*	28.7*a*	124*ab*	54.9*a*	0.274*a*	0.794*a*	0.484*c*	12.3*ab*
NewPage 2x [X]	194*cd*	28.4*a*	107*b*	42.7*bc*	0.243*a*	0.759*a*	0.524*bc*	11.5*b*
Lime NK [W]	229*bc*	27.7*a*	145*a*	59.3*a*	0.294*a*	0.699*a*	0.477*c*	12.6*ab*
Lime	53.1*f*	9.06*b*	24.9*c*	9.94*d*	0.052*b*	0.239*b*	0.085*d*	2.12*c*
Standard Error	9.81	1.57	5.35	2.03	0.015	0.041	0.025	0.38

[Z] represents half the recommended application rate as determined by the ECCE

[Y] represents the recommended application rate as determined by the ECCE

[X] represents two times the recommended application rate as determined by the ECCE

[W] Lime, nitrogen, potassium combination (Control) treatment

*Different letter groupings within columns differ significantly according to Tukey's HSD test ($P < 0.05$)

5.2.1 Bioassay Elements

The results of the bioassay experiment on Annual Ryegrass showed that the plants which received the control (lime + fertilizer treatment) experienced significantly greater uptake of Ca than the lime, NewPage 2x, NewPage 1x and Brooklyn 1x treatments (Table 5.6). Regardless of the wood ash application rates, there was no significant difference among treatments in terms of Ca plant uptake; however Ca plant uptake as a result of the wood ashes was higher than the lime only treatment (Table 5.6).

The greatest uptake of K by annual ryegrass was from the Brooklyn Power ash treatment applied at two times the recommend rate (Brooklyn 2x) (Table 5.6). Plant uptake as a result of the Brooklyn 2x treatment exceeds the control and resulted in almost twice the K uptake as observed with the NewPage 2x treatment (Table 5.6). This is likely due to the Brooklyn ash containing approximately five times more plant-available K than the NewPage ash (Table 5.2). It is interesting to see as part of the results of this experiment, the luxury consumption of K. As the rate of K application increases with the increasing ash application rates, there is a corresponding increase of K uptake by plant.

In the bioassay, the concentrations of the macronutrient P and of the micronutrients B and Cu, behaved similarly. All treatments resulted in significantly higher plant tissue concentrations of these three elements than that of the lime treatment; however none of these treatments resulted in plant tissue concentrations significantly different from each other (Table 5.6). This shows that regardless of soil concentrations for these elements, annual ryegrass did not take up P, B or Cu in excess of their need.

The control, NewPage 1x, and NewPage 0.5x treatments resulted in significantly greater Mg uptake by annual ryegrass than all of the other treatments with the exception of the Brooklyn 0.5x treatment (Table 5.6). The lowest uptake observed in the experiment was from the lime treatment in which levels were approximately four times lower than the next lowest treatment (Brooklyn 2x)(Table 5.6). The highest application rate of wood ash did not result in increased uptake of Mg (Table 5.6). For both ashes, the highest application rate resulted in significantly lower Mg uptake than the lowest ash application rate. The reason for this most likely has to do with higher concentrations of cations such as K being present at the higher application rates. A study conducted by Adams and Henderson (1961) showed that in soils that were not deficient in Mg, plant uptake of Mg was reduced as levels of K in the soil increased.

The bioassay of annual ryegrass showed Brooklyn Power ash supplying the most Zn to the plants. The Brooklyn 2x treatment resulted in significantly higher plant uptake of Zn than any of the other treatments with the exception of the Brooklyn 1x treatment (Table 5.6). At the nutrient management plans recommended (1x) rate, the Brooklyn ash significantly increased plant tissue Zn more than the NewPage recommended rate. The Brooklyn ash treatment contributing more Zn to the plant tissues would have been caused by the total concentration of Zn in Brooklyn ash, despite the two ashes containing the same quantity of plant-available Zn (Table 5.2), Brooklyn ash contained approximately twice the total concentration of Zn (Table 5.5). Both treatments resulted in greater Zn uptake compared to the lime control (Table 5.6). Overall, the findings of this bioassay agree with the findings of Wei-Hong et al. (1997) in which it was shown that Zn accumulation in annual ryegrass increases as soil concentrations increase.

5.3 Plant-Macronutrient Status – On Farm

Plant-available levels of all five of the plant macronutrients measured in this experiment significantly changed after the application of Brooklyn Power wood ash, however, plant-available levels of the macronutrients did not significantly change after the application of NewPage ash (Table 5.1).

Plant-available concentrations of Ca, K and S in the Brooklyn soils all significantly increased from pre-ash levels by the first sampling post application (Figs 5.5, 5.6 and 5.7). For each of these elements, levels returned to no longer being significantly different from pre-ash levels by the second sampling post application. For the macronutrients P and Mg, plant-available levels in the soil never significantly differed from pre-ash levels after Brooklyn ash application. Plant-available P and Mg only significantly changed among dates post application.

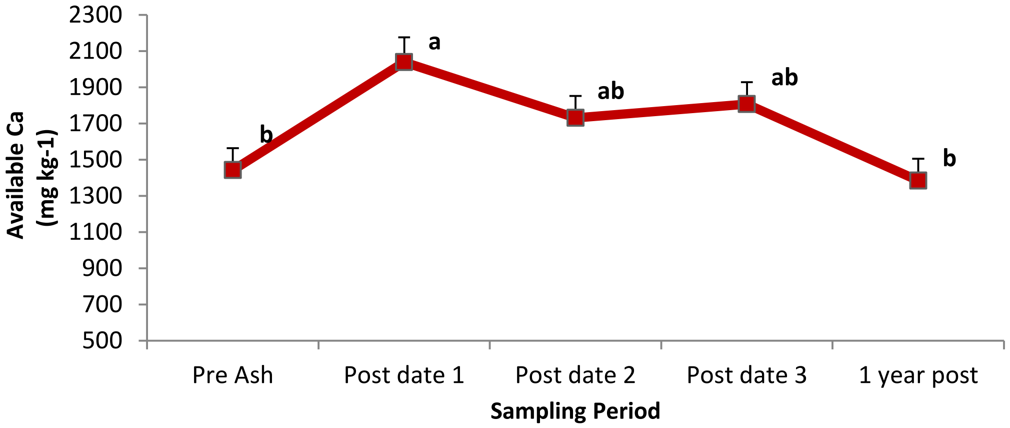


Fig. 5.5. Mean plant-available Ca concentrations for soils at Brooklyn Power sites. Points not sharing a letter differ significantly according to Tukey's HSD test (P < 0.05).

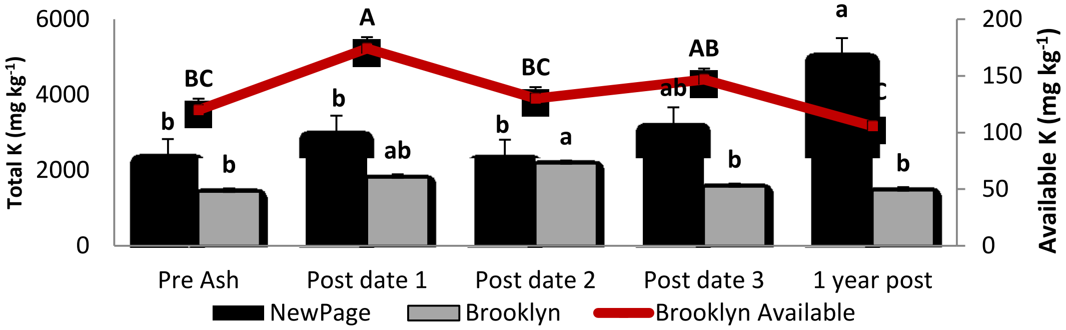


Fig. 5.6. Mean total soil K concentrations for sites that received NewPage and Brooklyn Power wood ashes and mean plant-available K for the Brooklyn sites. Columns and points within ash source not sharing a letter differ significantly according to Tukey's HSD test (P < 0.05).

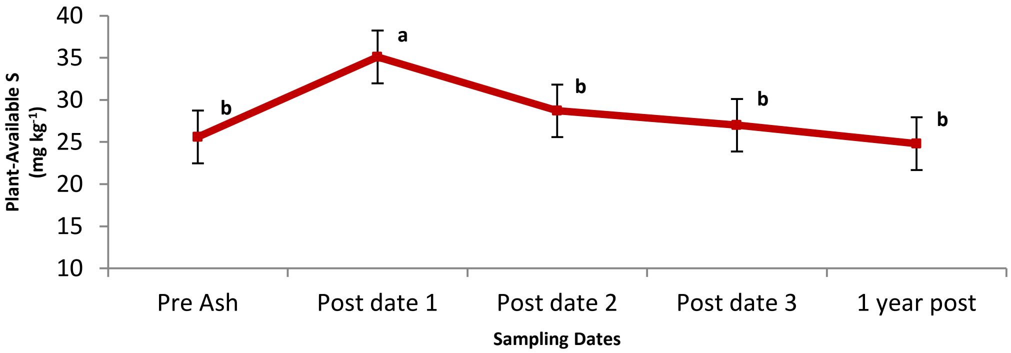


Fig. 5.7. Mean plant-available S concentrations for soils that received wood ash from Brooklyn Power. Points not sharing a letter differ significantly according to Tukey's HSD test (P < 0.05).

In terms of total concentrations of these elements in the soil, neither Brooklyn nor NewPage wood ashes significantly affected total concentrations of Ca (Table 5.1). Total concentrations of K were significantly altered after the application of NewPage ash, while total concentrations of K, Mg and P significantly changed after Brooklyn ash application (Table 5.1).

At the NewPage sites there was a flux in total soil K concentrations; however K levels were not significantly altered until the final sampling one year post application (Fig. 5.6). By this final sampling there was a 102% increase in total soil K compared to before the ash was applied. After the application of Brooklyn Power ash, total soil K was quicker to significantly increase, and by the second sampling post application, soil K had increased by 52% (Fig. 5.6). However, by the following sampling and for the remainder of the study, soil K concentrations no longer differed from before the ash was applied.

Total soil levels of Mg and P numerically increased by the first sampling post application. By the following sampling, total P significantly decreased and total Mg showed a trend of decreasing. Both elements then showed a trend of increasing total soil levels by the third sampling post application, however, by the final sampling, total soil Mg was significantly greater than pre-ash levels (Fig. 5.8) and total soil P concentrations became no different than pre-ash levels (Fig. 5.9).

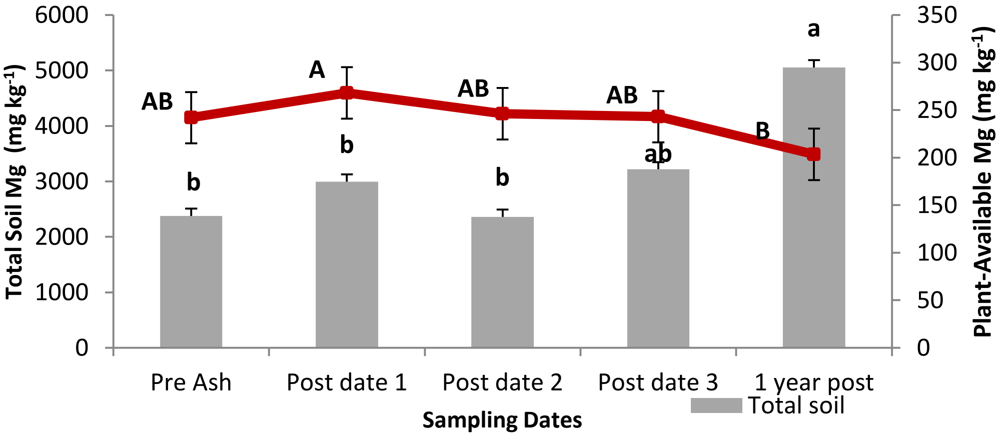


Fig. 5.8. Mean total and plant-available Mg concentrations for soils that received wood ash from Brooklyn Power. Columns and points not sharing a letter differ significantly according to Tukey's HSD test ($P < 0.05$).

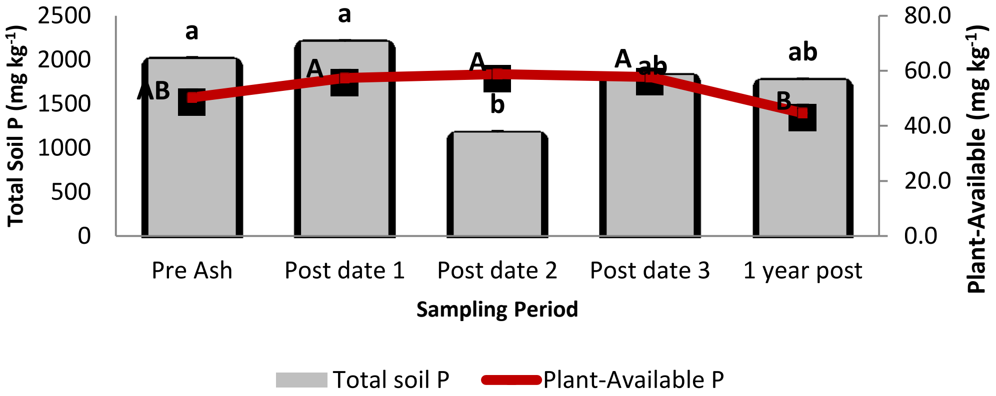


Fig. 5.9. Mean total and plant-available P concentrations for soils that received wood ash from Brooklyn Power. Columns and points with different letter groupings differ according to Tukey's HSD test ($P < 0.05$).

5.3.1 Plant-Available Macronutrient Concentrations

Plant-available concentrations of Ca did not significantly change at the NewPage sites, yet plant-available concentrations of Ca, K and S significantly increased at the Brooklyn sites (Table 5.1). One reason for this may be due to the rate of application. Based on the mean application rate (see Site Descriptions) and mean total concentration of Ca and K in the wood ash (Table 5.5), Brooklyn sites received approximately twice as much of these elements per ha^{-1} as NewPage sites. Also, Brooklyn Power ash contained higher concentrations of Mehlich 3 extractable Ca, K and S (Table 5.2), which in turn, would have increased available concentrations of these elements in the soil.

If the wood ash was responsible for the significant increase of these elements in plant-available form, it could be explained by the research conducted by Steenari et al. (1998), which states that elements such as Ca and K will be released faster in a fine textured ash than a coarse textured one. Since the Brooklyn Power ash was significantly finer in texture (Table 5.3), it may have released elements faster, which translated into increased pH (Fig. 5.1), and increased plant-available Ca, K and S (Figs. 5.5, 5.6 and 5.7).

The fact that NewPage sites did not increase in soil plant-available K is not surprising considering the fact that it contained approximately five times less extractable K than the Brooklyn ash (Table 5.2). Also, the bioassay revealed that NewPage ash resulted in reduced plant uptake of K compared to Brooklyn ash, corroborating the Mehlich 3 results (Table 5.2) suggesting that NewPage ash contains less plant-available K than Brooklyn ash. This fact may be somewhat surprising considering that both ashes contained similar quantities of total K (Table 5.5). These total concentrations of K in the two ashes are substantially less than total concentrations that can be as high as 100,000 mg kg^{-1} in wood ashes (Ohno and Erich, 1993) and even as high as 130,000 mg kg^{-1} K (Muse and Mitchell, 1995). However, levels reported by Pitman (2006) for paper mill ashes (25,700 mg kg^{-1}) are much closer to levels observed in this study.

One explanation for the significant decrease of available soil K after Brooklyn ash application between the second and third sampling could have been due to leaching. The period between the second and third samplings was winter. Since it is known that freezing, thawing and increased soil moisture affect the release of soil K (Brady and Weil 2008; Steenari et al. 1998), these processes would have caused a significant loss of K over the winter months. The adsorption of K by organic matter or clay does not seem a reasonable explanation for the decrease of available K, because total levels of K decreased as well (Fig. 5.6).

The lack of significant increase of soil plant-available P at the NewPage sites is not completely surprising despite the findings of other researchers (Unger and Fernandez 1990; Ohno and Erich 1990; Ohno 1992; Meiwes 1995; Kahl et al. 1996; Williams et al. 1996) who claim that wood ash is a significant source of P. Despite the two ashes containing similar total concentrations of P (Table 5.5), Brooklyn ash was applied at a higher average application rate (see Site descriptions), leading to Brooklyn sites receiving approximately twice as much P as the NewPage sites.

One reason for the drop of available Mg and P between dates post application at Brooklyn sites may be because this period corresponds to the months May through July (Appendix A-2), a time when forage is rapidly growing and Mg and P is being utilized for plant growth. Plant-available soil concentrations were below optimum Mg soil levels for Nova Scotia of approximately 420 mg kg^{-1} (Leblanc 2008), so plant uptake should have occurred. This is also true for available P, in which the optimum concentration of plant-available P for forage production in Nova Scotia soils is 72 mg kg^{-1} with adequate plant tissue concentrations being approximately 2000 mg kg^{-1}(AES 2012). The theory of loss through plant uptake is supported by the finding of the bioassay experiment that showed that wood ash increased plant tissue concentrations of Mg and P when compared to a lime only treatment (Table 5.6).

Another possible explanation for the significant change in available Mg levels post-application may be due to the mass ion effect. Essentially due to an influx of large amounts of Ca and the fact that Ca has a greater affinity for soil colloids, Mg would have been removed from exchange sites and then released into soil solution, increasing the possibility of Mg being leached from the soil (Brady and Weil 2008). This agrees with the findings of Williams et al. (1996) who showed that some leaching of Mg can occur as a result of wood ash application.

Although plant tissue S was not determined in this study, plant uptake could explain why soil levels dropped quickly after the initial increase immediately following ash application. The short-lived significant increase in soil S after Brooklyn Power ash application could be explained by the ash containing a higher percentage of available S than NewPage ash (Table 5.2). However, S is an element that is known to fluctuate greatly in soils due to its cycling through the environment that can resemble that of nitrogen (Brady and Weil 2008). What may have been measured in this study in terms of S, was the natural ups and downs of the S cycle. Castellano and Dick (1991) showed that available soil S will be at its peak around the months of September to November, after the warm summer months facilitate microbial breakdown of organic S into available S. Thus, there is an accumulation of available S by the end of the growing season, when plants require less S. Furthermore, available S is usually at its lowest naturally occurring concentration in the soil in early summer, because this is when rapidly growing plants uptake S to meet their needs (Castellano and Dick 1991).

5.3.2 Total Soil Macronutrient Concentrations

Total soil concentrations of Ca did not significantly change after wood ash application despite past studies that have reported increases of total soil Ca with the application of wood ash (Ohno and Erich 1993; Etiegni et al. 1991). The eight percent Ca present in the two ashes tested in this study (Table 5.5) was not enough of a contribution in relation to the amount of Ca already present in the soil to significantly alter levels.

In terms of total K the slower release over time into the soil at NewPage sites may have been due to the particle size of the ash (Table 5.3). As mentioned earlier in this chapter, Steenari et al. (1998) showed that K is released more slowly from coarser-textured ash than from finer textured ash. Wood ash from NewPage was significantly coarser-textured than the Brooklyn ash (Table 5.3), and would have released K into the soil more slowly. Particle size of the wood ash does not explain the slow but significant increase of total Mg concentrations in the soil at the Brooklyn Power sites by one year post application. The slow increase of total Mg at the Brooklyn sites may have been caused by the release of Mg from small piles of ash on the soil surface that were not included as part of the soil cores during soil sampling. These piles would have been caused by the relatively uneven distribution of the ash which is hard to avoid when applying such an amendment. The small piles and clumps of ash would have broken down and released Mg as well as K at each of the sites over time.

Total soil P at Brooklyn sites decreased between postdate 1 and 2, and total K decreased from its highest concentration at postdate 2 by the following sampling. The reason for the significant decrease of these two elements may have been due to increased plant uptake. Results of the bioassay show that compared to a lime only treatment, wood ash caused a significant increase of plant tissue P and K (Table 5.6). Also, as will be discussed later, no significant change in plant tissue concentrations of these two elements in the forage supports the theory of plant uptake.

The lack of significant increase of soil P at NewPage sites is not completely surprising despite the findings of other researchers (Unger and Fernandez 1990; Ohno and Erich 1990; Ohno 1992; Meiwes 1995; Kahl et al. 1996; Williams et al. 1996) who claim that wood ash is a significant source of P. Despite the two ashes containing similar total concentrations of P (Table 5.5), Brooklyn ash was applied at a higher average application rate (see. site descriptions), leading to Brooklyn sites receiving approximately twice as much P as the NewPage sites.

The reason for the generally lower percentage of some elements, particularly K, of the wood ashes examined in this study could be due to the fact that a large component of the ash derives from what is referred to as hog fuel. Hog fuel as described by NewPage Corp., is composed of wood bark, sawdust, hardwood and paper mill sludge (Personal communication, Sept 22, 2009). A study conducted by Someshwar (1996) showed that hog fuels can vary greatly in terms of elemental composition of ash due to the variability of what is being burned.

5.3.3 Plant Tissue Macronutrient Concentrations

The lack of statistical significance with respect to plant tissue concentrations (Table 5.1) of the macronutrients examined in this study is not surprising, and in fact, was expected. During the spring and summer months, plant species were growing and increasing biomass. Thus, the plants growing at the Brooklyn and NewPage sites were maintaining plant tissue concentrations of the macronutrients Ca, K, Mg, P and S. If plants were not taking up these elements, there would have been a significant decrease of tissue concentrations as plant biomass increased in proportion to the concentration of elements already present in the plants. A significant increase in the concentration of a particular element would mean that the element was being taken up in luxury consumption. Out of the macronutrients, only K would have been expected to have been taken up in such a fashion because plants are known to take up K in excess of their needs (Brady and Weil 2008). Despite this, there was no significant increase of plant tissue K. An explanation for this may be due to the fact that forage plants were not physiologically active in October when the plant-available concentrations were at their peak, thus, the plants were not capable of taking up the available K, and K would have been lost through leaching.

5.4 Plant-Micronutrient Status

After the application of Brooklyn Power wood ash, plant-available and total soil concentrations of B, Cu, Mn and Zn were significantly affected, while only plant-available B and Fe and total soil B significantly changed after NewPage wood ash application (Table 5.7).

Table 5.7. *P* values from analyses of plant-available nutrients in soil and total nutrients in soil and plant tissue for plant micronutrients measured for both Brooklyn Power and NewPage ash sites.

	P > F					
	Brooklyn Power			NewPage		
Elements	Plant-available Soil	Total Soil	Total Plant	Plant-available Soil	Total Soil	Total Plant
B	**0.0017**	**<0.0001**	0.86	**0.027**	**0.0022**	0.653
Co	**-**	0.373	0.390	-	0.546	0.205
Cu	**0.0009**	**0.033**	0.67	0.749	0.572	0.590
Fe	0.093	0.189	0.083	**0.001**	0.093	0.150
Mn	**0.0014**	**0.025**	0.470	0.553	0.8248	0.524
Zn	**0.0072**	**0.018**	**0.017**	0.480	0.3089	0.994
Ni	**-**	0.980	0.142	-	0.128	0.464

In terms of plant-available soil concentrations of micronutrients after Brooklyn ash application, all elements that were significantly affected behaved similarly. Plant-available levels of B, Cu, Zn and Mn all significantly increased after the ash application, however, these levels dropped to no longer being significantly different than pre-ash levels by one year post application (Figs 5.10, 5.11, 5.12, 5.13). After NewPage ash application, plant-available levels of B significantly increased in the soil by the third sampling post application, however B dropped back to no longer being significantly different than pre-ash levels by the end of the study (Fig 5.14). Plant-available Fe concentrations in the soil only changed between dates post application after the NewPage ash application, with Fe concentrations never significantly differing from pre-ash levels throughout the study (Fig 5.15).

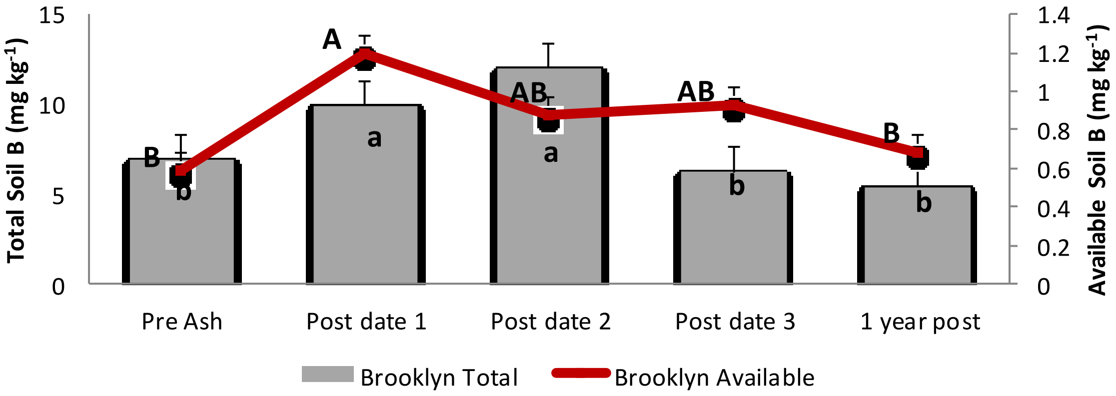


Fig. 5.10. Mean total and plant-available B concentrations for soils that received wood ash from Brooklyn Power. Columns and points with different letter groupings differ significantly according to Tukey's HSD test (P < 0.05).

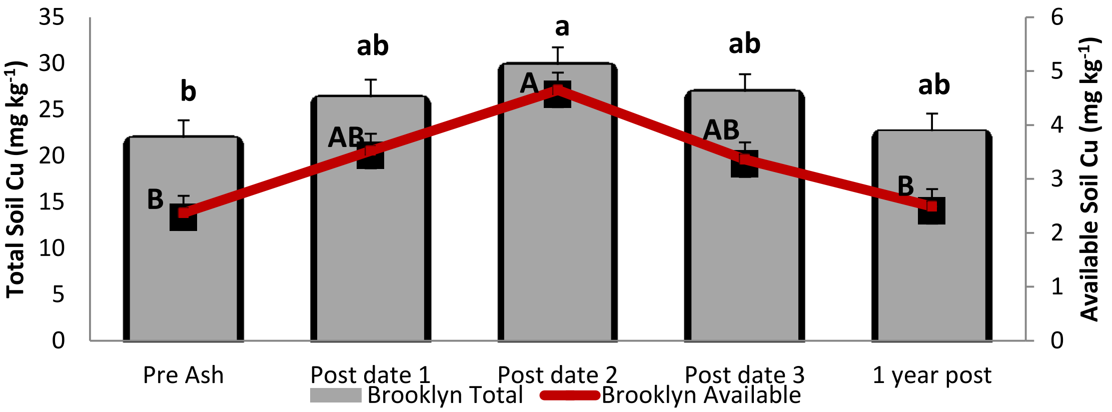


Fig. 5.11. Mean total and plant-available Cu concentrations for soils that received wood ash from Brooklyn Power. Columns and points with different letter groupings differ significantly according to Tukey's HSD test (P < 0.05).

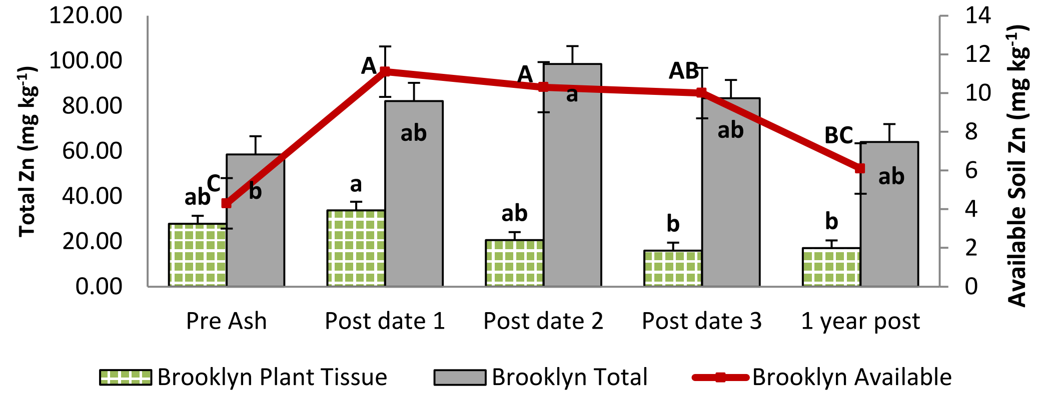


Fig. 5.12. Mean plant tissue, total and plant-available soil concentrations of Zn over time as a result of wood ash from Brooklyn Power. Columns in different categories and points not sharing a letter differ significantly according to Tukey's HSD test ($P < 0.05$).

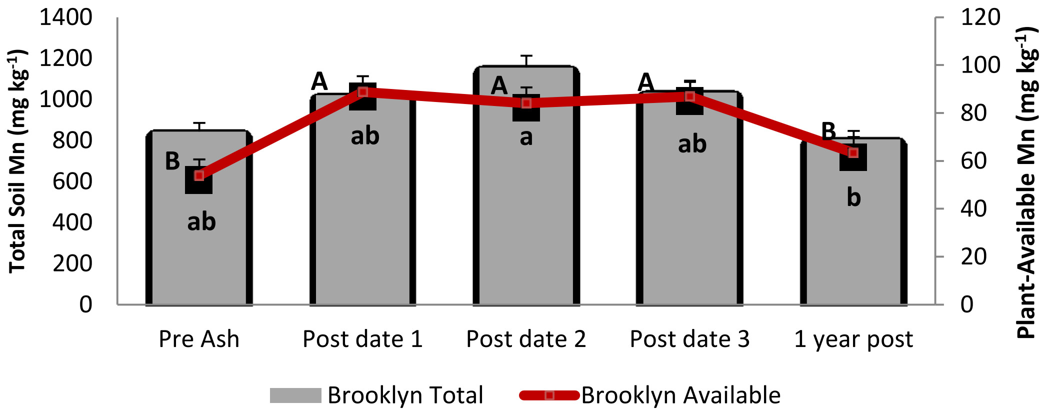


Fig. 5.13. Mean total and plant-available Mn concentrations for soils that received wood ash from Brooklyn Power. Columns and points with different letter groupings differ significantly according to Tukey's HSD test ($P < 0.05$).

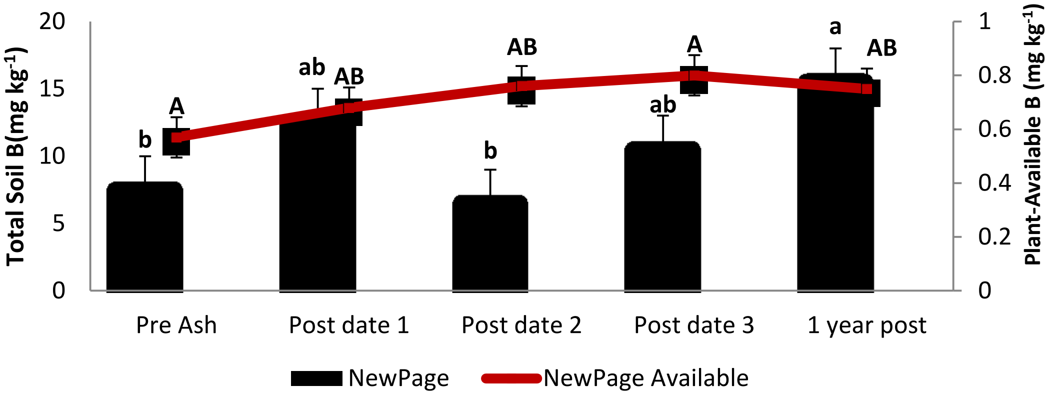


Fig. 5.14. Mean total and plant-available B concentrations for soils that received wood ash from NewPage. Columns and points with different letter groupings differ significantly according to Tukey's HSD test (P < 0.05).

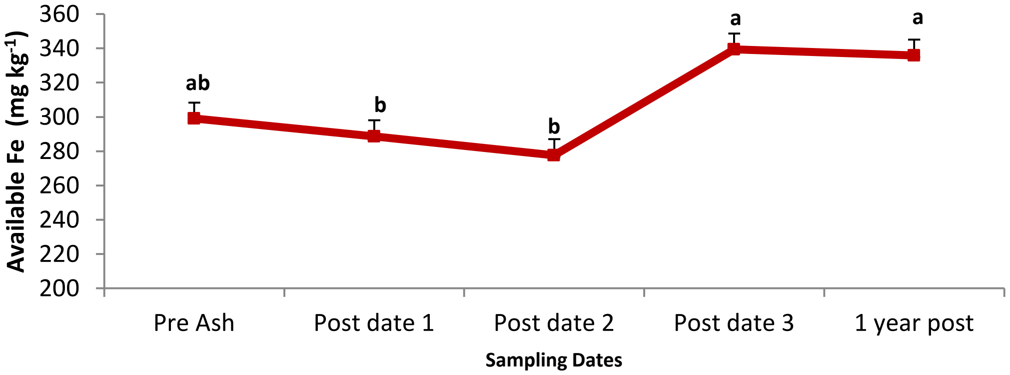


Fig. 5.15. Mean plant-available Fe concentrations for soils that received wood ash from NewPage. Points not sharing a letter differ significantly according to Tukey's HSD test (P < 0.05).

In terms of total soil concentrations of elements, after NewPage ash application, B significantly increased over time with levels slowly increasing, becoming significantly greater than pre-ash and second postdate levels by the final sampling (Fig 5.14).

As observed with soil plant-available levels, total soil concentrations of B, Cu, Mn and Zn all significantly changed post Brooklyn ash application. By the first sampling post application, total B was significantly greater than pre-ash levels (Fig 5.10), but was no longer significantly different from pre-ash levels by the following sampling and for the rest of the study. Total concentrations of Cu and Zn all took until the second sampling post ash application to become significantly greater than pre-ash levels. However, by the third and then final samplings, levels were no longer significantly different (Figs 5.11, 5.12). Total concentrations of Mn only changed between dates post application, with levels never significantly differing from pre-ash concentrations (Fig 5.13).

5.4.1 Plant-Available Soil Micronutrient Concentrations

B availability has been found to decrease as soil pH increases (Gupta et al. 1981; Peterson and Newman 1976). This is also true for the elements Cu (Zhou and Wong 1999; Krejsl and Scanlon 1995), Mn (Tisdale and Nelson 1975) and Zn (Giordano and Mortuedt 1980; Duquette and Hendershot 1990). Peterson and Newman (1976) showed that maximum availability of B occurs at soil pH 5.3 - 6.3 and that plant uptake of B decreases by 150% when soil pH increases from 6.3 to 7.4. Similarly, Cu and Mn availability begin to decrease after the pH has gone above 6.5 - 7.0 (Truog 1946). In terms of Zn, a study by Shuman (1975), showed that Zn sorption can begin at soil pH as low as 5.5, reaching maximum sorption at soil pH of 8.0. Considering this, and knowing that soil pH increases after the application of both ashes were not high enough to form complexes and prevent availability of these elements (Fig 5.1), the decrease of available B, Cu, Mn and Zn by the final sampling is, therefore, most likely the result of plant uptake. Although there was no significant change in concentration of these elements (with the exception of Zn), in the plant tissues (Table 5.7), as plants grew, these micronutrients were taken up by the plants. Any one of these elements can be a limiting factor in plant growth (Acquaah 2002; Sommer and Lipman 1926), thus, plants take up these elements when available. For instance, in Nova Scotia, B is commonly present in forage species at a concentration ranging from approximately 20 to 80 mg kg^{-1} (Leblanc 2008). In this study, forage from the NewPage and Brooklyn sites contained mean plant tissue B concentrations of 10.7 and 9.9 mg kg^{-1} before the ash was applied. So micronutrients in the wood ash would have been taken up to support growth and development. This is confirmed by the results of the bioassay experiment, which show that regardless of the wood ash application rate, there was a significant increase of B, Cu and Zn in plant tissues when compared to the lime treatment (Table 5.6).

Another possible explanation for the loss of plant-available B, Cu, Mn and Zn from the soil by the end of the study may have been leaching. Approximately 273 mm of precipitation fell at Brooklyn ash sites through the months of May to July (Appendix A-2). Because the pH was not high enough to cause total sorption of these elements (Fig. 5.1), allowing for increased plant-availability, increased precipitation had the potential to leach some of these elements from the soil. Also, incremental soil sampling showed that soil pH was greatest in the top 5 cm of soil at the Brooklyn sites, while the lower depths had significantly lower pH (Fig. 5.2). What may have happened is that Mn gradually moved down through the soil profile, being leached away at lower soil pH, where it would be increasingly mobile.

With the exception of plant-available Fe, NewPage sites did not experience a significant change following ash application to either soil or plant tissue concentrations of any of the micronutrients examined. This may be due to the mean application rates and the mean element concentrations in the ash (see Site descriptions and Table 5.5). Brooklyn ash sites received substantially more B, Cu, Mn and Zn per ha^{-1} than NewPage sites.

5.4.2 Total Soil Micronutrient Concentrations

Total soil concentrations of B, Cu, Mn and Zn behaved similarly at Brooklyn ash sites as did the plant-available concentrations. Similarly, the reasons as to why total concentrations of these elements significantly increased, and then decreased back to levels no longer different from pre-ash levels are the same. Primarily, total reserves of these elements in the soil were depleted through plant uptake, and secondly, leaching due to high precipitation. One difference from plant-available concentrations is that total concentrations of B after NewPage ash application were actually significantly greater one year post application than they were before the wood ash was applied (Fig 5.14). Considering that when measuring total concentrations of an element in the soil, plant-available and plant-unavailable forms of an element are being measured, one may have expected the immediate significant increase of soil B and not the gradual increase of this element over time (Fig. 5.14). The reason for the gradual increase of B could be explained by the particle size of the ash. In addition to NewPage ash having a larger particle size than the Brooklyn ash (Table 5.3), it generally contained more aggregate clumps in the ash, that remained on the surface and were not included in soil samples. At NewPage sites, B may have been released gradually from the larger particles of ash which were laying on the soil surface, at which point there was the gradual increase of total soil concentrations of B.

The significant contribution of B to the soil after the application of the ash treatments concurs with the findings of Ferm et al. (1992). Total B concentrations in the wood ash from both NewPage and Brooklyn Power sources are similar (Table 5.5). These concentrations tend to be somewhat lower than the B concentrations found in birch and spruce wood ashes evaluated by Reimann et al. (2008), where the ashes contained means ranging from 462 – 869 mg kg^{-1}.

In terms of Cu, the mean Cu concentration in both wood ashes is within the range of concentrations reported in various wood ashes (Hakkila 1989; Ohno and Erich 1993; Muse and Mitchell 1995). The concentrations of Cu in the soil after the application of Brooklyn ash increased to a maximum of 30 mg kg^{-1} (Fig. 5.11), which is greater than the provincial mean of 2.5 mg kg^{-1} (Leblanc 2008), but is well below the maximum acceptable limit of 400 mg kg^{-1} as defined by the CCME (Table 5.5).

The reason for no significant response in terms of total soil and plant tissue concentrations of Fe could be due to the already high concentrations that exist in Nova Scotia soils due to the fact that Fe is one of the most abundant elements present in the earth's crust (Chen and Barak 1982). The mean total soil concentrations of Fe for both

NewPage and Brooklyn soils before the ash was applied were 27,200 and 26,400 mg kg^{-1} respectively.

As it turns out, the MAAD extraction and analysis of the soil samples resulted in data for soil Fe that were not normally distributed. The reason for this could be due to naturally occurring variation of Fe in the soils, however it is most likely due to error in the ICP-MS analysis. Segura et al. (2003) determined that ICP-MS analysis for Fe results in erroneous Fe concentrations due to polyatomic interference from Ca and Ar, and that Fe determination is not accurate if using a hot Argon plasma (Segura et al. 2003). These researchers discovered, however, that Fe detection can be improved with the use of iron-specific chelating agents.

In terms of total soil Mn, it is unclear why total levels were significantly affected at the Brooklyn sites yet not at the NewPage sites despite the fact that Mn was present in the Brooklyn ash at a mean concentration of approximately 1700 mg kg^{-1} less than the total amount of Mn which was present in the NewPage ash (Table 5.5). However, the most likely explanation for this is the higher application rate. Mn is one of the most prominent plant micronutrients in soils across Canada, ranging in concentrations from 47 – 2900 mg kg^{-1} (Sheppard et al. 2007), and it is present in Nova Scotia soils at a mean concentration of 58 mg kg^{-1} (Leblanc 2008). It was interesting to see that after Brooklyn ash application, total and plant-available levels of Mn in the soils significantly increased to levels similar to the provincial mean (Fig. 5.13). It is also interesting that mean concentrations of this element were substantially higher in both ashes than in analyses conducted by others on pulp and paper ash (Ohno and Erich 1993; Muse and Mitchell 1995).

In this study, the significant increase of available Zn as a result of Brooklyn ash application goes against the findings of Krejsl and Scanlon (1995) who state that wood ash is not a significant contributor of Zn. Regardless, it is important to note that soil Zn concentrations measured in this study are below the maximum amount of Zn permitted in agricultural soils of 200 mg kg^{-1} (CCME 1999). Despite this, it is also important to note that the total concentration of Zn in the Brooklyn ash (Table 5.5) exceeds the maximum concentration of Zn allowable in soil amendments by approximately 300 mg kg^{-1}(Table 5.5). Zn concentrations this high in the Brooklyn ash means that according to CCME, the wood ash should not be unrestricted in use (CCME 1999).

5.4.3 Plant Tissue Micronutrient Concentrations

The lack of statistical significance with respect to plant tissue concentrations (Table 5.7) of the micronutrients examined in this study indicates that plants were taking up micronutrients from the soil. Plants growing at Brooklyn and NewPage sites were maintaining plant tissue concentrations of the micronutrients B, Cu, Mn and Fe. If plants were not taking up these elements, there would have been a significant decrease of tissue concentrations as plant biomass increased in proportion to the concentration of elements already present in the plants.

Of the micronutrients examined, the only one to be significantly affected in the plant tissues was Zn. There was a trend of increased plant tissue Zn by the first sampling post-application which corresponds to the significant increase of plant-available levels; however there was a significant decrease from this concentration by the third sampling post application (Fig. 5.12). Regardless of the significant fluctuation post-ash application, plant tissue Zn concentrations never significantly deviated from pre-ash levels throughout the study as a result of the Brooklyn Power ash.

It is interesting to see that while there was a significant increase of plant-available Zn immediately after the Brooklyn ash application, there was a corresponding trend of increased Zn in plant tissues (Figure 5.12). Yet, as total soil concentrations reached their maximum concentration at the second sampling post application, plant-available Zn stopped increasing, and plant concentration of Zn showed a decreasing trend (Fig. 5.12). In fact, plant tissue concentrations of Zn at this time were at one of the lowest means observed for Zn throughout the study. This would suggest that Zn was becoming bound in plant-unavailable form. Although the pH at the Brooklyn Power sites did not rise much greater than 6 (Fig 5.1), it is possible that soil sorption began to occur, but unlikely that it was high enough to prevent plant uptake. Research by Truog (1946) suggests that Zn availability should not begin to decrease until soil pH rises above 7.0.

5.5 Total Soil Concentrations of Selected Metals

Total soil concentrations of some selected metals changed significantly after the application of both the Brooklyn and NewPage wood ashes. After the application of Brooklyn ash, total As, Cd and Cr concentrations in the soil sites were significantly affected, while after the application of NewPage ash, total Al and Cr significantly changed (Table 5.8).

Table 5.8. *P* values from analyses of total selected metals in soil and plant tissue for both Brooklyn Power and NewPage ash sites.

	P > F					
	Brooklyn Power			NewPage		
Elements	Plant-available Soil	Total Soil	Total Plant	Plant-available Soil	Total Soil	Total Plant
Al	**-**	0.215	0.122	-	**0.016**	0.197
As	**-**	**0.043**	**0.035**	-	0.538	0.934
Cd	**-**	**0.005**	**0.050**	-	0.534	0.4825
Cr	**-**	**0.0002**	**0.011**	-	**0.0267**	0.207
Ni	**-**	0.980	0.142	-	0.128	0.464
Pb	**-**	0.085	**0.001**	-	0.777	0.458

At NewPage sites, total soil concentrations of Al and Cr significantly increased after wood ash application. Over time, Al and Cr levels slowly increased so that by one year post application, levels were significantly greater than they were at pre and second date post application levels (Figs. 5.16 and 5.17).

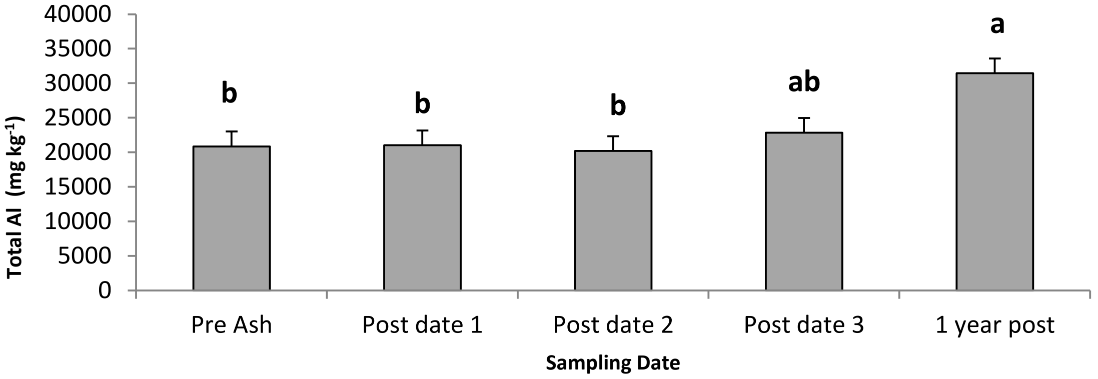


Fig 5.16. Mean total Al concentrations for soils that received wood ash from NewPage. Columns not sharing a letter differ significantly according to Tukey's HSD test (P < 0.05).

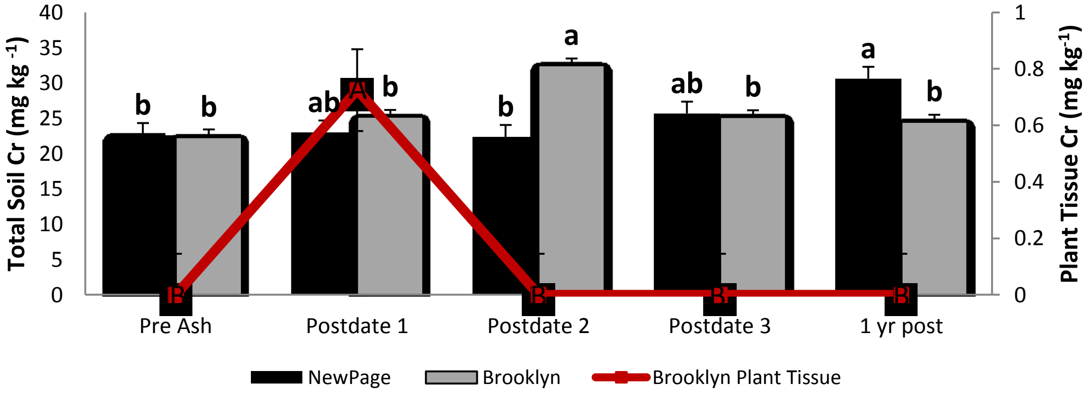


Fig. 5.17. Mean total soil Cr concentrations for sites that received both NewPage and Brooklyn Power wood ashes and mean plant tissue Cr for the Brooklyn sites. Columns within categories with different letter groupings differ significantly according to Tukey's HSD test (P < 0.05). For plant tissue concentrations points not sharing a letter are significantly different according to Kruskal Wallis test (P < 0.05).

The selected metals which were significantly affected at Brooklyn sites tended to behave similarly to what was observed with total concentrations of plant micronutrients. At the Brooklyn sites, total soil concentrations of Cr and Cd both significantly increased, becoming significantly greater than pre-ash levels by the second sampling post application. Levels then dropped to no longer being significantly different from pre ash levels by the third and then final samplings post application (Figs. 5.17 and 5.18).

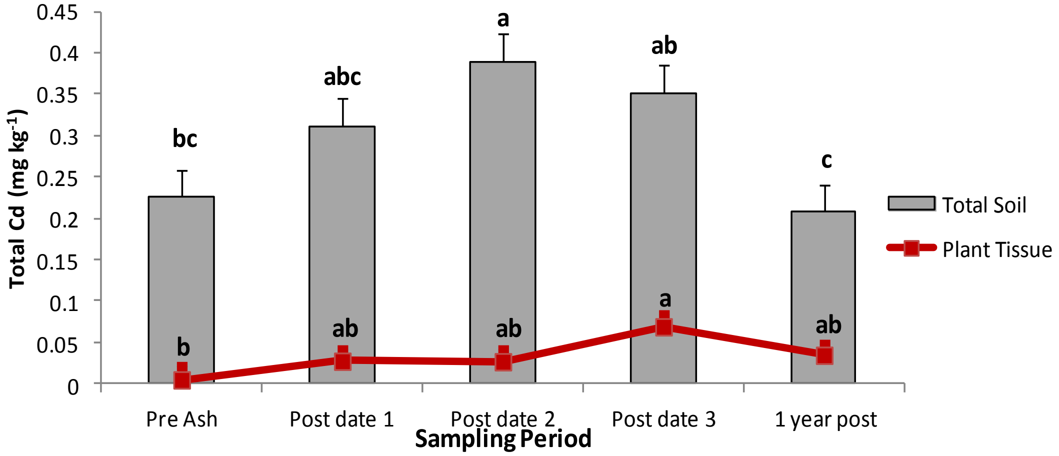


Fig 5.18. Mean total soil and plant tissue Cd concentrations for sites that received wood ash from Brooklyn Power. Columns and points within different categories not sharing a letter differ significantly according to Tukey's HSD test ($P < 0.05$).

A similar numerical trend was observed with total soil concentrations of As after Brooklyn ash application. Levels of total soil As numerically increased by the second sampling post application and then numerically decreased to being similar to pre-ash levels by the end of the study (Fig. 5.19). Although Table 8 shows that total soil concentrations of As were significantly affected (P=0.043), Fig. 5.19 shows that as a result of a Tukey's HSD means comparison, there were no actual differences among sampling dates for total soil As.

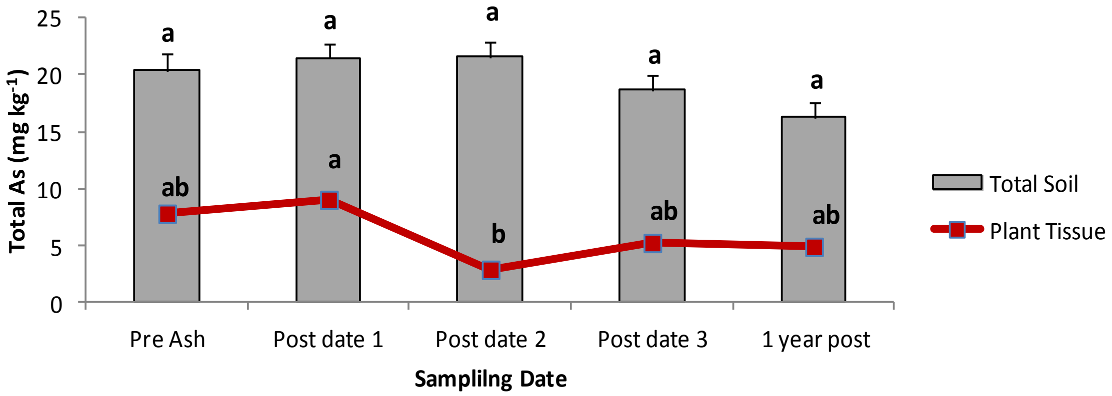


Fig. 5.19. Mean total soil and plant tissue As concentrations for sites that received wood ash from Brooklyn Power. Columns and points within the same category not sharing a letter are significantly different according to Tukey's HSD ($P < 0.05$).

It is interesting to see in Table 5.5 that NewPage ash contained a mean of approximately 5.5 percent Al, while Brooklyn ash contained approximately 3 percent Al. Based on the mean application rates and the concentration of Al in the individual wood ashes, each site should have received approximately the same amount of Al. NewPage sites received an average of 380 kg Al ha^{-1} while Brooklyn sites would have received approximately 390 kg Al ha^{-1}, on average. The reason why only NewPage sites significantly increased in terms of total soil Al is unclear. There was less mean organic matter in soils at NewPage sites (Appendix A-14 – A-20), meaning that if Al was bound to organic matter it would have happened at Brooklyn sites. Also, the pH was not low enough to have facilitated Al leaching at Brooklyn sites, so that does not explain why NewPage levels were higher.

The fact that NewPage ash contained a higher mean concentration of Al (Table 5.5) may be one explanation as to why a significant effect was observed. The gradual increase over time is likely due to the ash having a significantly coarser texture (Table 5.3), and thus taking longer to break down. It is interesting to note that Al is second to Ca in terms of element concentrations in the ash (Table 5.5). This is similar to the findings of Ohno and Erich (1993) in which their analysis of ashes from pulp and paper also contained Al in the largest quantity behind Ca.

The larger particle size of NewPage ash would also explain the gradual increase of Cr over time, however it doesn't explain why there was a Cr increase one year post application at NewPage sites and not Brooklyn sites despite Brooklyn ash containing approximately four times the amount of Cr (Table 5.5). Although levels of total Cr significantly increased at Brooklyn sites, it is not clear why there was a significant decrease of total soil Cr at these sites by the third sampling post application. pH was not above 8.5 which would have facilitated Cr leaching (CCME 1999) (Fig 5.1) and there were no detectable concentrations of Cr in the plant tissues at this sampling period (Fig 5.17).

One important fact is that the maximum spikes in soil Cr over the course of a year (Table 5.5) were below CCME defined maximum concentrations for this element on agricultural soils of 64 mg kg-1 (CCME 1999).

At Brooklyn sites, total soil concentrations of Cd followed a similar pattern as plant tissue concentrations (Fig. 5.18). As total levels of Cd began to decrease from their maximum on the second sampling post application, plant tissue concentrations began to increase, removing Cd from the soil. Another possible reason as to the loss of Cd from the soil after the second sampling post application could have been due to leaching. Because Cd is completely mobile at pH 4 and completely bound at pH 8, the mean pH at Brooklyn sites (Fig. 5.1) could have allowed for Cd leaching during increased precipitation at this period (Appendix A-22).

As is a carcinogenic trace element that, according to the CCME, causes cancers, arteriosclerosis and chronic liver disease (Wagner 1973), and because of this, As must not be present in soil amendments at concentrations above 75 mg kg^{-1} in order to be classified as Category B (CCME 2005). Category B amendments are those that are restricted in use. Table 5.5 shows that the mean total concentration of As present in the Brooklyn Power wood ash was approximately 140 mg kg^{-1}, which is almost twice the allowable level for Category B amendments, and more than 10 times the allowable concentration for Category A amendments. Category A amendments are those that are suitable for unrestricted use on agricultural land (CCME 2005).

In terms of As loading in soils and plant tissue, the CCME currently does not have guidelines for acceptable levels of As in plant tissues. The highest mean concentration of As observed in this study in soils treated with Brooklyn Power ash was on the first sampling post application (Fig. 5.17). In terms of tissue guidelines, the CCME only issues guidelines for acceptable As concentrations in fish and fish products and that value is 0.0035 mg As kg^{-1}. However, the CCME does issue soil quality guidelines for agricultural, residential, commercial and industrial usage. These guidelines state that soil As concentrations should be no greater than 12 mg kg^{-1} (CCME 2005). Although not shown to be statistically significant as a result of the wood ash application, the highest mean concentration of soil As post application for sites that received the Brooklyn Power ash was approximately 22 mg kg^{-1}, with a high of 40 mg kg^{-1} and a low of 7.3 mg kg^{-1}. Interestingly, soils from the Lunenburg County area that participated in this study contained a mean soil As concentration of 20.4 mg kg^{-1} before the wood ash was applied.

The reason for the soils and ultimately the wood ash from the Lunenburg county area containing high levels of As is due to geology. Soils in southern NS contain the sulphide mineral arsenopyrite due to southern NS being Meguma terrane (Goodwin et al. 2009). In fact, Goodwin et al. (2009) discovered through the North American soil geochemical landscapes project, which sampled soils from all over NS, that nine out of the ten highest soil As concentrations measured were from southern NS, with the highest concentration being 345.7 mg kg^{-1}. High soil concentrations of As in southern NS would translate to increased uptake by plant species (Jacobs et al. 1970) and storage around the pith and xylem tissue of trees (Martin et al. 2000). Increased As would be expected from wood ashes derived from southern NS.

Although soil levels of Pb were not significantly affected as a result of ash application over the course of one year, the amount of Pb in Brooklyn Power ash was quite high (Table 5.5). Pb concentration in Brooklyn Power ash was two times the amount of Pb allowed in a category A soil amendment and was much greater than the values of Pb found in the wood ashes reported by Huang et al. (1992), Ohno and Erich (1993) and Muse and Mitchell (1995).

5.6 Plant Tissue Concentrations of Selected Metals

Only the Brooklyn sites experienced significant changes in some of the selected metal concentrations (Table 8). Plant tissue concentrations of As, Cd, Cr and Pb all significantly changed after the application of Brooklyn ash. Total As only changed between dates post application, with levels on the first sampling post application being significantly higher than levels on the second sampling post application (Fig. 5.17). Total plant tissue concentrations of Cd, Cr and Pb significantly increased to greater than pre-ash levels for one of the samplings post ash application. Cd concentrations slowly increased over time, and became significantly greater than pre-ash levels by the third sampling post application, however, levels then dropped to no longer being different from pre-ash levels by the final sampling. Plant tissue concentrations of Cr and Pb acted similarly in that these elements were only detected in the plant tissues on the first sampling post application and were no longer detected in the plant tissues by the following sampling and for the remainder of the study (Figs. 5.19 and 5.20).

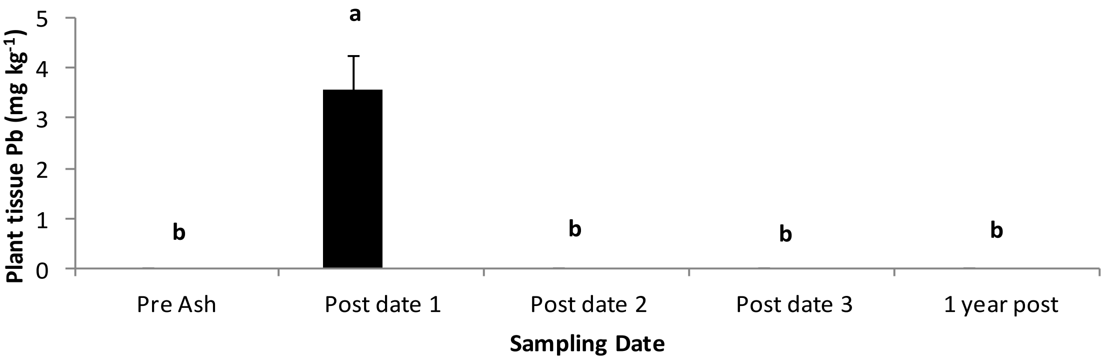


Fig. 5.20. Mean plant tissue concentrations of Pb at sites that received wood ash from Brooklyn Power. Columns not sharing a letter differ significantly according to Kruskal-Wallis ($P < 0.05$).

Although soil concentrations of As were not significantly affected in this study, according to Tukey's HSD, the significant decrease of As in plant tissues between postdates suggests decreased availability of soil As, which may be due to increased soil pH. Fig. 5.1 shows the immediate significant increase of soil pH after Brooklyn Power ash application. Reduced mobility of As as pH increases is supported by the findings of Mariner et al. (1996) who investigated As leaching in sandy soils.

In this study, concentrations of Cd in plant tissues significantly increased at Brooklyn sites (Fig 5.18), however, these levels fit into a range that are commonly measured in many plant species (Brooks 1998). It is interesting to see that despite the significant increase of soil pH, there was also increased plant uptake by the third sampling post application. This makes sense, because the increased pH, was not high enough to facilitate complete soil sorption, for at this pH (Fig. 5.1) Cd still would have been available (Christensen 1983).

As already mentioned, Cr and Pb measured in plant tissues at Brooklyn sites behaved similarly. Cr uptake into tissues on the first sampling post ash application (Fig. 5.17) corresponds to the sampling period when soil Cr concentrations at the Brooklyn sites were increasing. At this sampling, soil pH was at a level that could have facilitated plant uptake (Fig. 5.1).

Pb was also only detected in plant tissues on the first sampling post-application at Brooklyn sites with mean plant tissue concentrations at this time of 3.56 mg kg^{-1}. The significant increase of Cr and Pb on the first sampling date post-application could possibly be due to contamination of ash on the plant material. Because this was the first sampling, trace amounts of ash could have been on the plant tissue, and thus translated to higher Cr and Pb concentrations during the analysis. The drop of plant tissue Cr and Pb for the following samplings could have been due to there no longer being ash residue on the leaves; however it could have also been due to the increase of pH. Higher pH associated with the application of the Brooklyn Power ash (Fig. 5.1) may have caused decreased plant availability of these elements (MacLean et al. 1969).

The significant increase of Pb does not agree with the findings of Levula et al. (2000), or other researchers who found that wood ashes did not increase Pb in plant tissues (Levula et al. 2000; Perkiomaki et al. 2003).

Despite being a toxic non-essential element in plants (Huffman and Allaway 1973), Cr can be taken up by plant roots, however Cr uptake is usually low (Desmet et al. 1975; Cary et al. 1977), as was observed in this study.

For NewPage sites, the fact that Cr was not detected in the plant tissues despite there being significant spikes in Cr soil concentrations, means that the Cr may have been largely unavailable to plants. Considering the pH at the NewPage sites (Fig. 5.1), there should have been plant-available Cr present in either of the forms Cr (III) or Cr (VI) (Bartlett 1991). Because higher Cr concentrations in the soil do not necessarily translate to higher Cr concentrations in plant tissues (Cary and Kubota 1990), the lack of Cr in the plant tissues at NewPage sites, despite the significant increase in soil levels, is understandable. Despite this, a strong possibility as to why the selected metals were more prevalent in the plant tissues after Brooklyn ash application rather than after NewPage ash application has to do with the total mean concentration of these elements in each of the ashes. Brooklyn ash contained mean concentrations of these elements which were greater than the mean concentrations in the NewPage ash (Table 5.5). In Brooklyn ash, concentrations of Cr were approximately four times greater, As was approximately 17 times greater and Pb was approximately 10 times greater than concentrations found in the NewPage wood ash. This coupled with the mean application rate which was almost twice as great for Brooklyn ash is most likely the reason why the two ashes contributed elements differently.

5.7 Shoot Dry Weights

In the Bioassay experiment, shoot dry weights significantly differed as a result of the ash treatments at various rates in comparison to the lime treatment (Table 5.6). All of the wood ash treatment rates produced shoot dry weights which were significantly greater than the treatment of lime alone (Table 5.6). Brooklyn 2x ash treatment produced the greatest mean shoot dry weight and this mean was significantly greater than the NewPage

2x and NewPage 0.5x treatments. Shoot dry weights from the Brooklyn 2x treatment were not significantly greater than the Brooklyn 0.5x, 1x, nor the NewPage 1x or lime + fertilizer combination treatments (Table 5.6).

Overall, the results of the bioassay experiment, in terms of shoot dry weights, showed that wood ashes significantly increased crop biomass more so than agricultural lime alone. This agrees with the findings of other researchers who claimed increased crop yield as a result of wood ash application (Seekins et al. 1986; Krejsl and Scanlon 1995; Muse and Mitchell 1995; Hébert and Breton 2008; Patterson et al. 2004).

5.8 Botanical Composition

Although not statistically significant, Fig. 5.21 shows that there was a numerical decrease of grass (*P*=0.40) and broadleaves (*P*=0.98) in the fields, and a numerical increase of percent legume (*P*=0.11) following application of the Brooklyn ash. Over the course of the study grasses at the Brooklyn Power sites numerically decreased by approximately 5 percent one year after the ash was applied. In terms of the composition of broadleaf plants, there was a numerical decrease from over the course of a year and the percentage of plants in the fields that were legumes numerically increased by approximately 6 percent (Fig. 5.21).

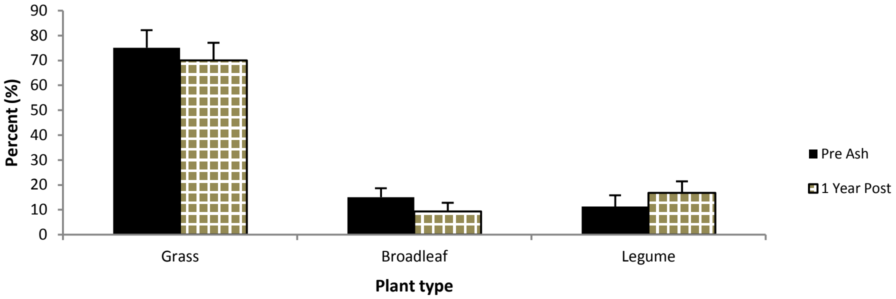


Fig. 5.21. The mean percentage of grasses, broadleaves and legumes present at the sites which received Brooklyn Power ash, pre-ash and 1 year post-ash application.

Following application of wood ash to the NewPage sites, the opposite of what happened at the Brooklyn Power sites occurred. Although not statistically significant, Fig. 5.22 shows that there was a mean numerical increase in grass (*P*=0.40) and broadleaf plants (*P*=0.07) and a numerical decrease in legume species (*P*=0.28).

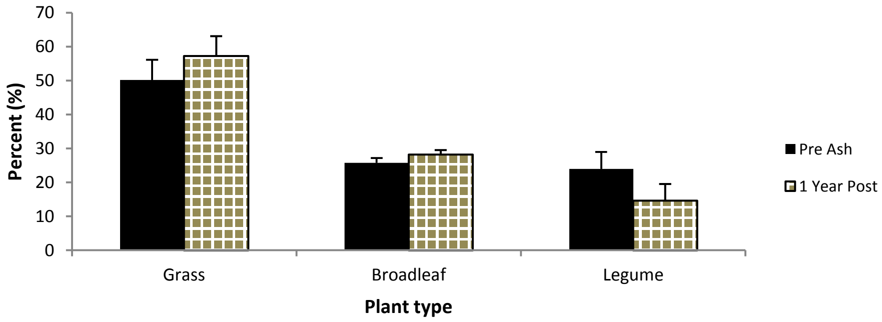


Fig. 5.22. The mean percentage of grasses, broadleaves and legumes present at the sites which received New Page ash, pre-ash and 1 year post-ash application.

The reason that neither of the wood ashes significantly affected botanical composition is likely due to soil pH. Although the pH significantly increased at the sites, the increase was not great enough to impact the type of plant species present (Fig 5.1).

5.9 Pasture Condition Score

There was no significant change in terms of pasture condition score following ash application at either Brooklyn Power or NewPage sites (Fig. 5.23). This was also true when statistically comparing the individual indicators which make up the total score. None of the indicators significantly changed as a result of the treatments over the course of a year.

There appeared to be a numerical increase of PCS one year post-ash application following Brooklyn ash (*P*=0.29) (Fig. 5.23). On the other hand, the NewPage treatment appeared to cause a numerical decrease in PCS (*P*=0.37) (Fig. 5.23).

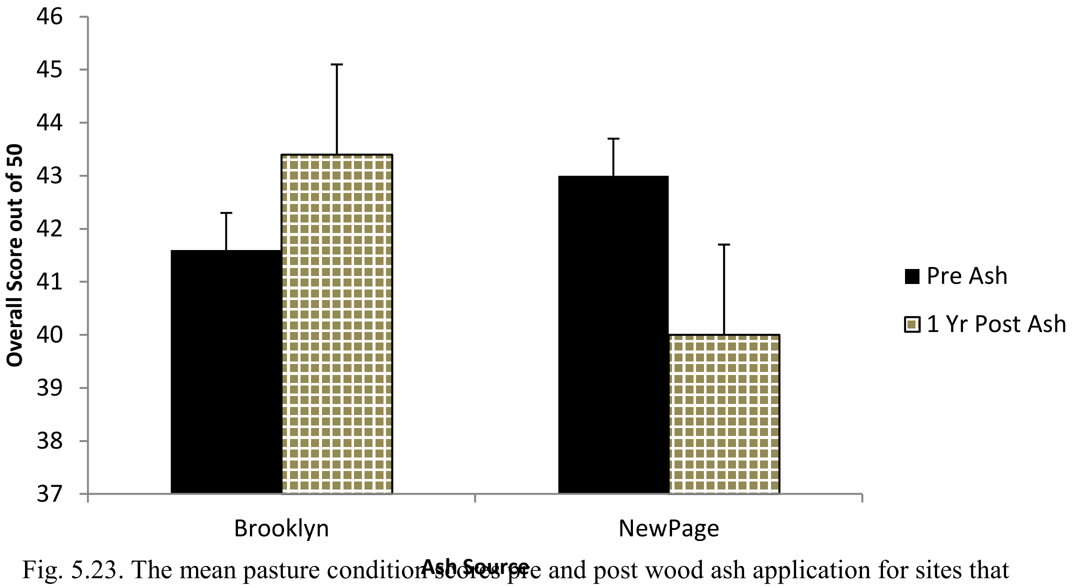


Fig. 5.23. The mean pasture condition scores pre and post wood ash application for sites that received the Brooklyn Power and NewPage ash.

The reason for the numerically increased score as a result of the Brooklyn ash and the numerically decreased score as a result of the NewPage ash treatment would principally be due to the numerical change in legume content. The numerical increases and decreases in pasture condition scores correlate with the numerical fluxes in percent legume content (Figs. 5.21 and 5.23). The numerical increase of legume content as a result of the Brooklyn ash corresponded to the numerically increased PCS. The numerically decreased legume content at the NewPage sites corresponded to the numerically decreased PCS. Because there was such little numerical difference observed between the indicators pre- and post-application, the numerical difference observed in terms of legume content would have been enough to cause the numerical difference in PCS for both ash treatments.

Generally, the pasture condition scores of the fields observed in this study were on par with the higher end of scores from research conducted on pastures in the Northeastern United States. In research conducted by Sanderson and Goslee (2005), 108 pastures were examined and assessed via the same pasture condition score card system used in this study. In the study by Sanderson and Goslee (2005), approximately 40% of the pastures had scores in the range of 36-45, 44% of the pastures had scores in the range of 26-35, and only about three pastures scored in the high 46-50 score range. Fig. 5.29 shows that the pastures examined in this study had mean scores which fit into the higher 36-45 score range for the pastures examined in the Sanderson and Goslee (2005) study. According to the suggested management for scores within this range, only minor changes would be required in order to obtain maximum production (Sanderson and Goslee 2005). When comparing the scores of the individual indicators to those from the study by Sanderson and Goslee (2005), it was interesting to see that the studies shared “plant diversity” and “percent legume” as the lowest scored indicators for the PCS. This indicates that botanical composition is a limiting factor in terms of pasture and perennial forage stand productivity. An example of the PCS card used in this study can be seen in Appendix A-1.

5.10 General Discussion

Although agricultural limes can vary in the amount of time they take to alter soil pH (Vanderwatt and Croft, 1993), agricultural lime generally is known as a reliable amendment to increase soil pH and maintain it over a wide variety of soil types (Tisdale and Nelson, 1975). Of the two wood ashes examined, Brooklyn Power ash was the only one that rapidly increased soil pH, and maintained that increase for a year after ash application, despite the two ashes containing similar total concentrations of possible carbonate forming cations Ca, K and Mg (Table 5.5). It is not unreasonable to conclude that the reason for the difference between how the two wood ashes behaved may have been due to the variation between the soils in which the on-farm study was conducted. It is interesting to see however, that some of the more basic properties of the soils (Appendix A-3 to A-20) in the upper soil horizons were somewhat similar. The majority of the soils were loam to silt loam soils with imperfect drainage and they were all of similar bulk density. In terms of CEC, the soils were all approximately 20 (with the exception of an organic soil) however NewPage sites contained lower mean organic matter in the Ap horizon, yet, higher base saturations. The fact that NewPage sites contained higher percentages of exchangeable cations (Appendix A-13 to A-20) may explain the differences in how the two ashes reacted in the soils.

Despite any differences between the soils, how the two wood ashes reacted at the on-farm sites resembles what was found as a result of the pH incubation experiment. The results of the regression conducted on the incubation data clearly show that Brooklyn ash acted faster and maintained a soil pH increase longer than NewPage ash (Figs. 5.3 and 5.4). It also shows that in comparison to agricultural limes available in Nova Scotia, NewPage ash acted more slowly in adjusting pH while Brooklyn ash took approximately the same amount of time to act on soil pH as the two agricultural limes examined. However, neither ash was able to increase soil pH as effectively as the two limes when applied at rates determined by the ECCE values (Figs. 5.3 and 5.4).

The overall results of this study show that wood ashes produced by Brooklyn Power in Liverpool, NS and NewPage Corporation in Port Hawkesbury, NS contain similar concentrations of the plant macronutrients Ca, K, P, and Mg. Based on the means for each element as derived from the analyses conducted in this study, it is interesting to see the total amounts of particular elements if applied at a rate of 1.0 t ha^{-1} (Table 5.9). Although the table shows values based on the total concentration of these elements in ashes, this does not equate to the amount of macronutrients that are actually plant-available. Despite the fact that Brooklyn Power ash tended to contain higher quantities of plant-available nutrients than NewPage ash, the proportion of the elements that could be utilized by plants as a result of a 1.0 t ha^{-1} application varied. Thus, based on the results of Mehlich 3 analyses of the ash (Table 5.2), NewPage and Brooklyn wood ashes contributed different amounts of plant-available elements when applied to a field at the rate of 1.0 t ha^{-1} (Table 5.9). Based on 2009 wood ash prices, the quantities of plant-available macronutrients shown in Table 5.9 are what could be obtained for \$9.00. This does not include the 2009 trucking cost for shipping the wood ash which ranged from \$2.30 – \$5.85 per km^{-1} depending on fuel costs. Government subsidies are now available to cover some of the wood ash trucking costs.

Table 5.9. Expected element contribution by the NewPage and Brooklyn Power wood ashes when applied at 1 t ha^{-1}.

	NewPage Ash		**Brooklyn Power Ash**	
Element	Total (kg ha^{-1})	Mehlich 3 Extractable (kg ha^{-1})	Total (kg ha^{-1})	Mehlich 3 Extractable (kg ha^{-1})
Ca	80	22	80	34
K	20	1	20	5
P	10	0.06	10	0.01
Mg	10	1.5	10	8

It is interesting to compare the results of the Mehlich 3 extractions conducted on the ash (Table 5.2) to the plant uptake data derived from the controlled bioassay experiment (Table 5.6). Similar to the Mehlich 3 extractions conducted on the wood ashes, the bioassay resulted in Brooklyn ash supplying significantly more available K and Zn than NewPage ash. This agrees with the findings of Park et al. (2011) in which it was shown that Mehlich 3 was an accurate predictor of available K and Zn on ash/soil mixtures when determining plant uptake. However, unlike the results of the Mehlich 3 extractions, higher levels of extractable P did not translate into higher P uptake by plants. This finding also concurs with the findings of Park et al. (2011) when using Mehlich 3 to test an ash/soil mixture. Plants which received the NewPage ash treatment contained higher concentrations of Mg than plants that received the Brooklyn Power treatment despite the fact that Brooklyn Power ash contained higher levels of Mehlich 3 extractable Mg. Although this may have been due to greater levels of K with increased application rate (Adams and Henderson 1961), it could mean that Mehlich 3 is not the most accurate predictor of nutrient availability when used on highly alkaline wood ashes. Despite this, Mehlich 3 has been used by a number of other researchers as an extraction method for determining plant-availability of elements in wood ash (Omil et al. 2007; Solla-Gullon et al. 2008; Park et al. 2011; Pousada-Ferradás et al. 2011).

Despite the relatively low cost of wood ash, the levels of P, K, Mg and Ca present in NewPage ash as determined by the separate analyses conducted in this study, were less than the amounts of these elements reported by the ash supplier (Table 5.10). According to a Research and Productivity Council (RPC) laboratory analysis (the source of the results that have been relayed to northern Nova Scotia producers) the wood ash when analyzed via ICP-MS contained approximately 220 to 330% more P, 69 to 110% more K, 30 to 80% more Mg and 28 to 57% more Ca than the highest values obtained from the separate analyses in this study (Table 5.10).

Table 5.10. Range of nutrient levels in wood ash based on test analysis from RPC Fredericton, 2007-2009, compared to two separate analyses conducted in this study.

Nutrient	RPC Laboratory Ash Analysis Range (kg tonne^{-1})	NewPage Ash		Brooklyn Power Ash	
		PEI Analytical Laboratories (kg tonne^{-1})	PEI Provincial Lab, Mehlich 3 Plant available nutrients	PEI Analytical Laboratories (kg tonne^{-1})	PEI Prov. Lab, Mehlich 3 Plant available nutrients
	Total	Total	Plant Available	Total	Plant Available
P	32-43	10	0.06	11	0.01
K	33-41	19.5	1	21	5
Mg	13-18	10	1.5	10	2
Ca	101-124	79	22	80	34

While results of this study show that the wood ashes available to Nova Scotia producers generally contain lower macronutrient concentrations than what they are promoted to contain, the analyses also found that the wood ashes contained higher levels of some trace elements than expected. As already discussed, wood ash from NewPage contributed the least to the soil nutrient status out of the two ashes in terms of both total and plant-available nutrients. This was also true for some undesirable trace elements. NewPage wood ash contained only one element (Cd) that was higher than the permissible concentration for an element in a category A soil amendment. Table 5.5 shows that the wood ashes from NewPage contained a mean of 0.8 mg Cd kg^{-1} more than the maximum amount allowable in a soil amendment that is to be unrestricted in use. Although the mean concentration of Cd in the ash does not greatly exceed the threshold (Table 5.5), technically this amendment cannot be unrestricted in its application to agricultural lands. Concern arises when confronting the results of Brooklyn Power ash analyses. Four elements in Brooklyn ash exceeded the CCME thresholds for category A amendments (Table 5.5). Zn was 46% greater than the threshold for category A amendments, while Cd was 93% greater, Pb was 146% greater and finally, As was 970% greater than allowable As concentrations for soil amendments that are to be unrestricted in use. In fact, Table 5.5 also shows that the levels of As in Brooklyn ash exceeded the permissible threshold for category B amendments by 85%. At the very least, wood ash from Brooklyn Power should not be used as a soil amendment on agricultural lands, and according to the CCME, must be disposed of appropriately (CCME 2005). As noted in Chapter 5, wood ash is likely high in As due to southern NS being made up of Meguma terrane, that contains the sulphide mineral arsenopyrite (Goodwin et al. 2009). It is not defined by the CCME what the proper disposal method for a product that exceeds category B criteria should be.

CHAPTER 6.0 CONCLUSION

Soil pH levels increased following application of both Brooklyn Power and NewPage wood ash (Fig. 5.1), however, the pH of soils that received NewPage ash was not significantly higher than pre-ash levels by one year post-ash application. A pH incubation experiment showed that the two agricultural limes were the most effective liming agents, followed by the Brooklyn, then NewPage wood ashes (Figs 5.3 and 5.4). The results of the incubation experiment support what was observed on-farm.

For the Mehlich 3 analyses which determined plant-available element concentrations, after the application of the Brooklyn Power ash, all elements, with the exception of Fe and Na, increased initially, then dropped to pre-ash levels within one year. Fe was not significantly affected and Na levels did not significantly increase. None of the Mehlich 3 extracted elements, except boron, increased significantly following application of NewPage wood ash.

Mean element concentrations of wood ash from the two ash sources were determined by MAAD extraction (total elements) and a soil analysis report (Mehlich 3 extractable levels). Mehlich 3 extractable levels for all elements were substantially lower than total levels, as expected. While total levels for individual elements were generally similar for NewPage and Brooklyn Power, Mehlich 3 results were lower for B, Ca, Fe, K, Mg, Na, and S in NewPage compared to Brooklyn Power ash. NewPage ash also had a lower pH which helps to explain the reduced ability of the New Page ash to produce a sustained pH increase. Generally, wood ash available to producers in Nova Scotia had lower total levels of Ca, K and Mg but higher or equal levels of P, Fe and Mn than those reported by authors including Pitman (2006).

Wood ash from NewPage Corporation and Brooklyn Power, behaved quite differently in terms of how they affected soil and plant tissue concentrations of the elements tested. MAAD extraction and analysis determined that after the application of wood ash from NewPage, the only elements that significantly changed in terms of plant tissue and soil concentrations were Al, B, Cr, K and Na. After the application of Brooklyn Power ash, As, B, Cd, Cr, Cu, K, Mg, Mn, Na, P, Pb and Zn soil and plant tissue concentrations significantly changed.

In terms of plant tissue concentrations, at NewPage sites only Na was significantly affected after wood ash application. Brooklyn Power ash significantly altered plant tissue concentrations of As, Cd, Cr, Pb and Zn. As and Zn concentrations only fluctuated among dates post-application but never significantly deviated from pre-ash levels. Cd increased initially but then dropped back to pre-ash levels by the end of the study. Interestingly, plant tissue concentrations of Cr and Pb were only detected on the second sampling but then dropped back to undetectable levels by the following sampling, implying immediate plant uptake or contamination on plant tissue.

Levels of elements in plant tissues varied in terms of ash application rate, as determined by the bioassay experiment. Plant uptake of Ca, Cu, B and P did not significantly differ regardless of ash source or application rate, yet levels were all greater than the control. Mg uptake significantly decreased as application rate increased, while K and Zn levels increased as application rate increased. There was no significant difference for shoot dry weights among the individual wood ashes. The Brooklyn 2x treatment resulted in significantly greater shoot dry weights than the NewPage 0.5x and 2x treatments and all treatments resulted in significantly greater dry weights compared to the control.

MAAD extraction and analysis determined that NewPage sites were changed in total soil concentrations of Al, B, Cr, K and Na. All of these elements behaved similarly, slowly increasing throughout the study until they were significantly higher than pre-ash levels one year post-application.

Total soil concentrations of As B, Cd, Cr, Cu, K, Mg, Mn, Na, P and Zn were significantly affected following Brooklyn Power ash application. All of these elements, with the exception of Mg, Na and P, significantly increased as a result of the Brooklyn Power ash but then dropped back down to levels no longer significantly different than pre-ash levels by one year post-application. Total P behaved differently in the soil by decreasing after the treatment, but then increasing back to pre-ash concentrations by the end of the study. Total soil Na also decreased at the Brooklyn Power sites, but just between dates post-application, with levels at the final sampling being no different than before the ash was applied. Mg was the only element in which total soil levels were significantly higher one year post application.

Wood ashes from Brooklyn Power and NewPage did not significantly affect the botanical composition of perennial forage stands.

Over the course of one year, neither of the wood ash treatments significantly changed PCS or significantly altered individual visible indicators such as; percent desirable plants, live plant cover, plant diversity, plant residue, plant vigor or legume content.

In general, wood ashes from Brooklyn Power in Liverpool, NS and NewPage Corporation in Port Hawkesbury, NS., are different products, with different chemical characteristics. This resulted in two wood ashes which behaved quite differently when applied to perennial forage stands and when examined in the incubation and bioassay experiments. Brooklyn Power ash consistently outperformed NewPage wood ash in terms of soil pH adjusting capacity and nutrient contributions. In my opinion, wood ash from NewPage is a safer but less effective product than Brooklyn Power ash, as it was not able to contribute to increasing soil pH or soil nutrient status as well as the Brooklyn Power ash. Unfortunately, considering the levels of trace elements in the Brooklyn Power ash, most notably the element arsenic (As), Brooklyn ash should not be used on agricultural lands due to its potential to contaminate soils and cause harm to human health.

Because wood ashes produced by pulp and paper mills are so variable in terms of their physical and chemical characteristics (Tables 5.2, 5.3 and 5.4), other researchers have suggested that regular testing of wood ashes should be in place if they are to be used as soil amendments (Lerner and Utzinger 1986; Ohno and Erich 1990). Thus my recommendation is that a regular sampling and analysis of wood ash be conducted and that the results be made public to ensure the safe use of these materials as soil amendments in the future.

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APPENDICES

Appendix A-1: Example of the Pasture Condition Score Sheet Used in the Study

Farm or ranch site:______________________________________ Date______________

	Pasture Unit Description									
Indicators										
Percent desirable plants1/ Percent plant cover by weight that is desirable forage: 1 2 3 4 5 <20 20-40 40-60 60-80 >80										
Plant cover1/ 2/ Percent live, leafy canopy cover of desirables and intermediates is: 1 2 3 4 5 <50 50-70 70-90 90-95 95-100 Percent live basal area cover of desirables and intermediates is: <15 15-25 25-35 35-50 >50										
Plant diversity1/ The diversity of well-represented forage species is: 1 2 3 4 5 (Read criteria and select appropriate number)										
Plant residue1/ Ground cover, standing dead forage, or thatch is: 1 2 3 4 5 (Read criteria and select appropriate number)										
Plant vigor (Read criteria and select appropriate number) Degree of stress of plant community is: 1 2 3 4 5 (If less than 4, see Causative factors table. Rate those factors)										
Percent legume1/ 3/ Percentage of legume present as total air dry weight: 1 2 3 4 5 <10, or >60 bloating legume; 10-19, or 40-60 spreading legume; 20-29; 30-39; 40-60 no grass loss										
Uniformity of use Degree of spot grazing is: 1 2 3 4 5 >50% ungrazed; 25-50% ungrazed; 10-25% ungrazed; Minor species rejection; Urine and dung spots ungrazed										
Livestock concentration areas Presence of livestock conc. areas and proximity to surface water: 1 2 3 4 5 (Read criteria and select appropriate number)										
Soil compaction Degree of soil compaction is: 1 2 3 4 5 (Read criteria and select appropriate number)										
Erosion (Always rate sheet and rill; others only if present) Sheet and rill, and gully, streambank, shoreline, or wind erosion is: 1 2 3 4 5 Very severe Severe Moderate Slight No visible										
Pasture condition score										

Appendix A-2. Sampling and Ash Application Dates for all Farms that Participated in the Wood Ash Study.

Farm	Pre-ash Sampling Date	Wood Ash Application Date	Postdate 1	Postdate 2	Postdate 3	Final Sampling 1 year post application
Allen	20-Aug-09	24-Aug-09	05-Oct-09	27-May-10	26-Jul-10	01-Sept-10
Crouse	20-Aug-09	30-Aug-09	05-Oct-09	27-May-10	26-Jul-10	01-Sept-10
Falkenham	20-Aug-09	30-Aug-09	05-Oct-09	27-May-10	26-Jul-10	01-Sept-10
Fancy	20-Aug-09	21-Aug-09	05-Oct-09	27-May-10	26-Jul-10	01-Sept-10
Veinotte	20-Aug-09	31-Aug-09	05-Oct-09	27-May-10	26-Jul-10	01-Sept-10
Easthouse	11-May-10	11-June-10	11-Jul-10	20-Sept-10	19-Nov-10	11-June-11
MacLennan	12-May-10	15-May-10	15-Jun-10	20-Sept-10	18-Nov-10	11-June-11
Sinclair	7-Nov-09	03-Dec-09	11-May-10	30-Jul-10	20-Sept-10	18-Nov-10
Touesnard	16-Nov-09	01-Dec-09	11-May-10	30-Jul-10	20-Sept-10	18-Nov-10

Appendix A-3: Soil Core and Bulk Sample Analysis for Site 1

Horizon	Depth (cm)	pH (H_2O)	Total C (%)	Org. Matter (%)	Total N (%)	Exchangeable cations (%)					% Base saturation	CEC (cmol/kg)
						Ca	Mg	K	Na	H		
Ap	0-22	5.7	4.87	8.41	0.34	30.6	6.6	0.8	0.8	61.2	38.0	16
Bf1	22-44	6.2	1.08	1.86	-	18.3	5.4	0.5	0.6	75.3	24.2	6
Bf2	44-65	5.7	0.52	0.89	-	31.0	11.7	1.1	1.0	55.2	43.8	4
BC	65-80	5.8	0.40	0.69	-	28.6	11.9	1.3	2.1	56.0	41.8	4
C	80-100	5.5	0.30	0.51	-	38.3	18.5	2.2	0.9	40.3	59.0	3

Horizon	Soil test (mg/kg)											
	P	K	Ca	Mg	Fe	S	Mn	Na	Zn	B	Cu	Al
Ap	26	50	960	125	251	32	96	29	2.4	0.7	4.2	1470
Bf1	13	13	233	41	141	23	34	9	0.6	0.4	0.6	1841
Bf2	12	19	270	61	301	25	68	10	0.5	0.3	0.8	1158
BC	11	23	245	61	341	23	53	21	0.8	0.2	0.7	1026
C	11	25	228	66	394	21	32	6	0.4	0.2	0.5	1032

Horizon	Particle Size Distribution (%)								C.F (% wt)
	VCS	CS	MS	FS	VFS	Sand	Silt	Clay	
Ap	4.1	10.1	12.5	15.4	0.8	42.8	47.4	9.8	8.9
Bf1	9.3	11.3	12.9	18.2	7.5	59.2	31.1	9.8	14.5
Bf2	11.7	13.8	14.4	20.6	13.5	73.9	18.3	7.8	15.5
BC	10.1	15.1	17.8	19.9	8.1	70.9	18.2	10.9	14.7
C	7.3	11.9	17.6	20.1	11.1	67.9	26.2	5.9	20.7

Horizon	Depth (cm)	Moisture Retention (%)							AWC (% vol.)	Air cap (% vol.)	Ksat (cm/h)	Bulk den. (g/cm^3)
		0 kPa	5 kPa	10 kPa	33 kPa	100 kPa	300 kPa	1500 kPa				
Ap	0-22	68.8	54.5	47.0	39.9	34.4	16.0	11.9	42.5	14.3	288	0.86

Appendix A-4: Soil Description for Site 1

Soil name:	**Bridgewater series (BWT)**
Site ID:	**2010 - Wood Ash Pedon 7**
Location & Date:	Back Centre, Lunenburg County, 27 May 2010
Land owner:	Creighton Allen
Coordinates:	20T 391530E, 4913713N
Slope; position; aspect:	3%; lower; NNE43
Land use - Vegetation:	Forage - wood ash research site
Parent material:	Till derived from slate rocks
Underlying bedrock:	Cambrian-Ordivician Halifax Formation slate
Stoniness; rockiness:	nonstony; nonrocky
Drainage:	Well drained
Soil classification:	Orthic Humo-Ferric Podzol
Rooting depth (cm):	44
Rooting restriction:	none present
Watertable depth (cm):	none present
Sampled by:	K.T. Webb

Horizon	***Depth***	***Description***
Ap	0-22	Dark yellowish brown (10YR 3/4 m); loam; weak, medium and coarse, subangular blocky breaking to weak, fine granular (with crumb structure), very friable; abundant, very fine and fine roots; 5% gravel; clear, smooth boundary, 20-22 cm thick; medium acid (pH 5.7).
Bf1	22-44	Strong brown (7.5YR 4/6 m); sandy loam; moderate, fine granular; very friable; few, fine and very fine roots; 10% gravel; diffuse, wavy boundary, 18-23 cm thick; slightly acid (pH 6.2).
Bf2	44-65	Strong brown (7.5YR 4/6 m); sandy loam; moderate, fine and medium, subangular blocky breaking to moderatte, fine granular; very friable; no roots; 10% gravel; diffuse, wavy boundary; medium acid (pH 5.7).
BC	65-80	Dark yellowish brown (10YR 4/6 m); gravelly sandy loam; weak, coarse, subangular blocky breaking to weak fine granular; friable; no roots; 15% gravel and stones; diffuse wavy boundary; medium acid (pH 5.8).
C	80-100	Dark yellowish brown (10YR 4/6 m); gravelly sandy loam; weak, coarse, subangular blocky breaking to weak, fine, subangular blocky; friable; no roots; 20% gravel and stones; strongly acid (pH 5.5).

Appendix A-5: Soil Core and Bulk Sample Analysis Site 2

Horizon	Depth (cm)	pH (H_2O)	Total C (%)	Org. Matter (%)	Total N (%)	Exchangeable cations (%)					% Base saturation	CEC (cmol/kg)
						Ca	Mg	K	Na	H		
Ap	0-22	5.7	5.09	8.79	0.35	33.7	8.4	0.8	0.3	56.8	42.9	19
Bf1	22-44	5.6	1.42	2.45	-	12.8	3.8	1.0	1.6	80.8	17.6	9
Bf2	44-70	5.6	1.37	2.37	-	9.4	2.7	0.8	0.8	86.3	12.9	8
C	70-100	5.6	0.39	0.67	-	27.6	12.8	2.4	1.5	55.7	42.8	6

Horizon	Soil test (mg/kg)											
	P	K	Ca	Mg	Fe	S	Mn	Na	Zn	B	Cu	Al
Ap	35	61	1282	192	145	43	108	14	4.0	0.6	2.0	1703
Bf1	13	34	228	41	183	27	64	32	0.9	0.3	1.1	2041
Bf2	14	28	157	27	163	24	28	15	0.4	0.2	0.7	2231
C	13	61	357	99	212	19	31	23	0.6	0.2	0.4	1929

Horizon	Particle Size Distribution (%)								C.F (% wt)
	VCS	CS	MS	FS	VFS	Sand	Silt	Clay	
Ap	5.5	11.3	13.2	18.5	1.7	50.1	42.1	7.8	12.3
Bf1	10.8	12.4	13.9	18.6	7.9	63.5	33.6	2.9	32.3
Bf2	7.4	10.2	12.4	17.4	8.4	55.8	38.4	5.8	32.1
C	7.1	11.0	12.4	17.6	10.6	58.7	31.6	9.8	21.9

Horizon	Depth (cm)	Moisture Retention (%)							AWC (% vol.)	Air cap (% vol.)	Ksat (cm/h)	Bulk den. (g/cm^3)
		0 kPa	5 kPa	10 kPa	33 kPa	100 kPa	300 kPa	1500 kPa				
Ap	0-22	59.9	47.6	42.7	36.8	32.2	17.5	15.4	32.3	12.3	136	1.01

Appendix A-6: Soil Description for Site 2

Soil name:	**Bridgewater series (BWT)**
Site ID:	**2010 - Wood Ash Pedon 9**
Location & Date:	Northwest, Lunenburg County, May 27, 2010
Land owner:	Clarence Crouse
Coordinates:	20T 390583E, 4918832N
Slope; position; aspect:	9%; mid; NNE60
Land use - Vegetation:	Forage - wood ash research site
Parent material:	Till derived from slate rocks
Underlying bedrock:	Cambrian-Ordivician slates of the Halifax Formation
Stoniness; rockiness:	nonstony; nonrocky
Drainage:	Well drained
Soil classification:	Orthic Humo-Ferric Podzol
Rooting depth (cm):	70
Rooting restriction:	none present
Watertable depth (cm):	none present
Sampled by:	K.T. Webb

Horizon	***Depth***	***Description***
Ap	0-22	Dark brown (10YR 3/3 m); loam; moderate, fine, subangular blocky breaking to moderate, fine, granular (with crumb structure); very friable; plentiful, very fine and few, medium, roots; 8% gravel; clear, smooth, boundary, 20-22 cm thick; medium acid (pH 5.7).
Bf1	22-44	Dark yellowish brown (10YR 4/6 m); gravelly sandy loam; weak, fine, granular breaking to crumb; very friable; plentiful, very fine roots; 20% gravel; diffuse wavy boundary; medium acid (pH 5.6).
Bf2	44-70	Strong brown (7.5YR 4/6 m); gravelly sandy loam; weak, fine and medium, subangular blocky breaking to weak, fine, granular; very friable; few, very fine, roots; 20% gravel; gradual wavy boundary; medium acid (pH 5.6).
C	70-100	Reddish brown (5YR 4/4 m); gravelly sandy loam; weak, coarse, subangular blocky breaking to weak, fine and medium, subangular blocky; friable; no roots; 15% gravel; medium acid (pH 5.6).

Appendix A-7: Soil Core and Bulk Sample Analysis for Site 3

Horizon	Depth (cm)	pH (H_2O)	Total C (%)	Org. Matter (%)	Total N (%)	Exchangeable cations (%)					% Base saturation	CEC (cmol/kg)
						Ca	Mg	K	Na	H		
Ap	0-26	6.1	4.65	8.04	0.34	41.6	11.8	0.7	0.5	45.4	54.1	19
Bfgj	26-38	6.0	0.71	1.22	-	34.9	15.9	1.6	1.3	46.3	52.4	5
BCxgj	38-62	5.8	0.21	0.36	-	48.6	30.7	2.5	2.2	15.9	81.8	8
Cgj	62-100	5.9	0.10	0.18	-	57.4	38.4	2.9	1.3	0.0	98.7	9

Horizon	Soil test (mg/kg)											
	P	K	Ca	Mg	Fe	S	Mn	Na	Zn	B	Cu	Al
Ap	23	53	1541	262	217	29	206	22	2.5	0.9	2.1	1409
Bfgj	14	33	362	99	366	15	78	16	0.8	0.3	0.7	1425
BCxgj	13	74	733	278	273	9	54	38	1.1	0.3	0.8	1124
Cgj	34	103	1055	424	315	6	56	28	0.8	0.3	0.7	1016

Horizon	Particle Size Distribution (%)								C.F (% wt)
	VCS	CS	MS	FS	VFS	Sand	Silt	Clay	
Ap	6.6	8.6	10.6	15.4	8.7	49.8	42.4	7.8	14.8
Bfgj	8.7	11.6	15.0	21.0	11.8	68.1	26.1	5.8	14.6
BCxgj	4.9	7.2	9.9	14.8	7.1	43.9	48.3	7.8	16.3
Cgj	5.5	7.3	9.4	13.7	5.9	41.9	42.3	15.8	17.5

Horizon	Depth (cm)	Moisture Retention (%)							AWC (% vol.)	Air cap (% vol.)	Ksat (cm/h)	Bulk den. (g/cm^3)
		0 kPa	5 kPa	10 kPa	33 kPa	100 kPa	300 kPa	1500 kPa				
Ap	0-26	65.9	47.1	44.9	40.0	34.5	18.7	16.0	31.2	18.8	162	0.91

Appendix A-8: Soil Description for Site 3

Soil name: **Wolfville series (WFV)**

Site ID: **2010 - Wood Ash Pedon 8**
Location & Date: Lilydale, Lunenburg County, May 27, 2010
Land owner: Peter Falkenham
Coordinates: 20T 392937E, 4916725N
Slope; position; aspect: 9%; upper; NNE60
Land use - Vegetation: Forage - wood ash research site
Parent material: Till derived from sedimentary and slate rocks
Underlying bedrock: Cambrian-Ordivician slates of the Halifax Formation
Stoniness; rockiness: nonstony; nonrocky
Drainage: Imperfectly drained
Soil classification: Fragic Humo-Ferric Podzol
Rooting depth (cm): 38
Rooting restriction: fragic compact till subsoil
Watertable depth (cm): none present
Sampled by: K.T. Webb

Horizon	*Depth*	*Description*
Ap	0-26	Dark brown (7.5YR 3/2 m); loam; moderate, medium and coarse, subangular blocky breaking to moderate, fine, granular; very friable; plentiful, very fine and fine roots; 5% gravel; clear, smooth boundary, 25-27 cm thick; slightly acid (pH 6.1).
Bfgj	26-38	Dark yellowish brown (10YR 3/4 m); sandy loam; few, fine, faint dark yellowish brown (10YR 4/6 m) mottles; moderate, fine and medium, subangular blocky breaking to moderate, fine and medium, granular; very friable; few, fine roots; 7% gravel; clear, wavy boundary, 12-14 cm thick; medium acid (pH 6.0).
BCxgj	38-62	Dark reddish brown (5YR 3/3 m); loam; common, medium, disctinct, yellowish red (5YR 4/6 m) mottles, yellowish red (10YR 4.5/4 m) fracture planes; weak, coarse, prismatic breaking to weak, coarse, platy; firm; no roots; 10% gravel; diffuse, wavy boundary; medium acid (pH 5.8).
Cgj	62-100	Dark reddish brown (5YR 3/3 m); loam; few, medium, faint, yellowish red (5YR 4/6 m) mottles; structureless, massive; very firm; no roots; 14% gravel; medium acid (pH 5.9).

Appendix A-9: Soil Core and Bulk Sample Analysis for Site 4

Horizon	Depth (cm)	pH (H_2O)	Total C (%)	Org. Matter (%)	Exchangeable cations (%)					% Base saturation	CEC (cmol/kg)
					Ca	Mg	K	Na	H		
Omp	0-13	4.8	42.5	73.5	18.5	8.1	1.3	0.3	71.7	27.9	30
Oh1	13-33	4.2	35.8	61.8	7.4	3.3	0.3	0.2	88.8	11.0	27
Oh2	33-45	3.9	44.9	77.6	11.3	4.1	0.3	0.4	83.8	15.7	24
Om	45-65	3.7	31.1	53.7	10.7	2.9	0.2	0.4	85.7	13.8	24

	Soil test (mg/kg)											
Horizon	P	K	Ca	Mg	Fe	S	Mn	Na	Zn	B	Cu	Al
Omp	85	157	1115	292	303	47	9	22	1.1	0.3	0.7	611
Oh1	20	31	400	108	284	18	15	13	0.4	0.1	0.6	707
Oh2	9	24	552	121	507	207	35	23	0.8	0.2	1.0	1255
Om	8	20	510	84	515	551	43	22	1.3	0.4	1.5	1161

*Particle Size Distribution – N/A

*Moisture Retention – N/A

Appendix A-10: Soil Description for Site 4

Soil name:	**Rossignol series (RGO)**
Site ID:	**2010 - Wood Ash Pedon 6**
Location & Date:	Fancy Lake/Colpton, Lunenburg County, May 26, 2010
Land owner:	Bill Fancy
Coordinates:	20T 352938E, 4924551N
Slope; position; aspect:	0%; level; all
Land use - Vegetation:	Pasture-forage - wood ash research site
Parent material:	Sedge-fen peat veneer over slate bedrock
Underlying bedrock:	Cambrian-Ordovician Halifax formation slate
Stoniness; rockiness:	nonstony; nonrocky
Drainage:	very poorly
Soil classification:	Typic Mesisol
Rooting depth (cm):	65
Rooting restriction:	bedrock
Watertable depth (cm):	65 (very dry spring)
Sampled by:	K.T. Webb

Horizon	*Depth*	*Description*
Omp	0-13	Reddish black (10R 2.5/1 m); moderately decomposed grasses and shrubs (von Post 5); abundant, very fine and fine, and plentiful, medium roots; 2% wood; clear smooth boundary; 13-14 cm thick; very strongly acid (pH 4.8).
Oh1	13-33	Black (10YR 2/1 m); highly decomposed peat (von Post 7); moderate, fine and medium granular; friable; plentiful, fine and medium roots; clear, smooth boundary; 20-22 cm thick; extremely acid (pH 4.2).
Oh2	33-45	Very dark brown (10YR 2/2 m); highly decomposed sedge and moss peat (von Post 7); few, medium, roots; clear, smooth boundary; 12-14 cm thick; extremely acid (pH 3.9).
Om	45-65	Dark brown (7.5YR 3/3 m); moderately decomposed sedge peat (von Post 4-5); 3% gravel; few, medium, roots; clear, wavy boundary; extremely acid (pH 3.7).
R	65+	fractured slate bedrock

Appendix A-11: Soil Core and Bulk Sample Analysis for Site 5

Horizon	Depth (cm)	pH (H_2O)	Total C (%)	Org. Matter (%)	Total N (%)	Exchangeable cations (%) Ca	Mg	K	Na	H	% Base saturation	CEC (cmol/kg)
Ap	0-22	6.1	4.90	8.47	0.32	50.3	10.9	1.0	0.6	37.2	62.2	19
Bf	22-36	5.6	1.55	2.68	-	19.9	5.6	0.6	1.3	72.6	26.1	13
Bmgj	36-48	5.4	0.30	0.52	-	41.5	18.7	1.9	1.5	36.3	62.1	10
BCxgj	48-70	5.4	0.16	0.27	-	53.8	25.5	2.6	0.9	17.2	81.9	14
Cgj	70- 100	6.1	0.09	0.15	-	64.9	31.8	2.2	1.2	0.0	98.9	16

Horizon	Soil test (mg/kg) P	K	Ca	Mg	Fe	S	Mn	Na	Zn	B	Cu	Al
Ap	34	73	1943	253	259	36	70	28	4.3	0.9	2.3	1672
Bf	14	31	527	89	246	30	18	39	1.3	0.3	0.7	2429
Bmgj	9	75	822	222	457	16	20	35	1.1	0.3	0.7	1462
BCxgj	12	142	1498	426	491	13	44	30	0.8	0.3	0.7	1312
Cgj	8	139	2136	628	458	5	109	45	1.1	0.3	1.1	1062

Horizon	Particle Size Distribution (%) VCS	CS	MS	FS	VFS	Sand	Silt	Clay	C.F (% wt)
Ap	3.6	8.1	9.6	13.8	8.1	43.0	43.2	13.8	9.1
Bf	5.7	7.7	10.1	15.2	10.5	49.1	39.2	11.8	18.0
Bmgj	5.6	8.1	10.2	15.6	8.0	47.5	36.8	15.8	17.6
BCxgj	4.6	7.5	9.1	13.5	8.9	43.6	42.5	14.0	13.7
Cgj	5.1	7.5	9.6	14.1	9.1	45.4	40.7	13.9	14.6

Horizon	Depth (cm)	Moisture Retention (%) 0 kPa	5 kPa	10 kPa	33 kPa	100 kPa	300 kPa	1500 kPa	AWC (% vol.)	Air cap (% vol.)	Ksat (cm/h)	Bulk den. (g/cm^3)
Ap	0-22	67.3	48.5	46.6	42.3	37.1	18.9	15.4	33.1	18.8	190	0.93
Cgj	70- 100	34.4	29.0	28.4	26.9	24.1	31.6	21.2	7.8	5.4	0.4	1.84

Appendix A-12: Soil Description for Site 5

Soil name:	**Wolfville series (WFV)**
Site ID:	**2010 - Wood Ash Pedon 5**
Location & Date:	Lower Northfield, Lunenburg County, May 26, 2010
Land owner:	Kevin Veinotte
Coordinates:	20T 374408E, 4926578N
Slope; position; aspect:	18%; mid to lower; N
Land use - Vegetation:	Forage - wood ash research site
Parent material:	Till derived from sedimentary and slate rocks
Underlying bedrock:	Cambrian-Ordivician Halifax Formation slates
Stoniness; rockiness:	nonstony; nonrocky
Drainage:	Imperfectly drained
Soil classification:	Fragic Humo-Ferric Podzol
Rooting depth (cm):	48
Rooting restriction:	fragic compact till subsoil
Watertable depth (cm):	none present
Sampled by:	K.T. Webb

Horizon	*Depth*	*Description*
Ap	0-22	Dark brown (10YR 3/3 m); loam; moderately, fine, subangular blocky breaking to moderately, fine and medium, granular; very friable; plentiful very fine and fine roots; 5% gravel; clear smooth boundary; 20-22 cm thick; slightly acid (pH 6.1).
Bf	22-36	Brown (7.5YR 4/4 m); loam; moderate, fine and medium subangular blocky breaking to weak, fine and medium granular; very friable; plentiful, very fine and fine roots; 10% gravel; gradual wavy boundary; 12-20 cm thick; medium acid (pH 5.6).
Bmgj	36-48	Yellowish brown (10YR 4.5/4 m); loam; common, fine, distinct, strong brown (7.5YR 4/6 m) mottles; weak, fine and medium subangular blocky; friable; few, fine roots; 10% gravel; gradual, wavy boundary; 12-16 cm thick; strongly acid (pH 5.4).
BCxgj	48-70	Dark reddish brown (5YR 3/3 m); loam; coarse, fine, distinct yellowish red (5YR 4/6 m) mottles; weak, coarse, prismatic breaking to weak, coarse, platy; firm; few, fine, verticle, exped roots in fracture planes; 11% gravel; diffuse wavy boundary; 23-27 cm thick; strongly acid (pH 5.4).
Cgj	70- 100	Dark reddish brown (5YR 3/3 m); loam; few, fine, faint reddish brown (5YR 4/4 m) mottles; structureless, massive; very firm; no roots; 12% gravel; slightly acid (pH 6.1).

Appendix A-13: Soil Core and Bulk Sample Analysis for Site 6

Horizon	Depth (cm)	pH (H_2O)	Total C (%)	Org. Matter (%)	Total N (%)	Exchangeable cations (%)					% Base saturation	CEC (cmol/kg)
						Ca	Mg	K	Na	H		
Ap	0-18	6.1	4.52	7.81	0.29	48.5	22.8	1.6	0.7	26.4	72.9	18
Bmgj	18-40	6.0	0.65	1.11	-	40.6	24.5	2.1	1.1	31.6	67.2	8
BCgj	40-60	6.3	0.23	0.40	-	65.8	30.6	2.5	1.1	0.0	98.9	8
Cgj	60-100	6.8	0.17	0.30	-	58.2	22.6	1.7	0.8	16.7	82.5	14

	Soil test (mg/kg)											
Horizon	P	K	Ca	Mg	Fe	S	Mn	Na	Zn	B	Cu	Al
Ap	36	117	1765	498	449	37	251	30	3.2	0.8	2.3	1074
Bmgj	6	63	616	223	542	11	64	20	1.2	0.3	0.2	1347
BCgj	13	82	1086	303	470	8	210	21	1.8	0.3	1.5	1249
Cgj	8	89	1604	374	526	6	231	26	4.2	0.4	2.5	1032

Horizon	Particle Size Distribution (%)								C.F (% wt)
	VCS	CS	MS	FS	VFS	Sand	Silt	Clay	
Ap	2.8	5.4	7.0	10.2	0.7	26.1	52.1	21.8	14.5
Bmgj	5.2	6.1	7.4	10.8	8.9	38.4	39.8	21.8	21.2
BCgj	6.3	7.2	7.6	11.3	8.5	40.8	39.4	19.8	25.2
Cgj	6.3	6.8	7.5	11.0	8.5	40.1	40.2	19.8	28.7

Horizon	Depth (cm)	Moisture Retention (%)							AWC (% vol.)	Air cap (% vol.)	Ksat (cm/h)	Bulk den. (g/cm^3)
		0 kPa	5 kPa	10 kPa	33 kPa	100 kPa	300 kPa	1500 kPa				
Ap	0-18	64.1	53.5	51.5	47.8	42.6	24.8	20.3	33.2	10.5	235	1.01

Appendix A-14: Soil Description for Site 6

Soil name:	**Millbrook series (MLO)**
Site ID:	**2010 - Wood Ash Pedon 1**
Location & Date:	Poor Point, Cape Breton - 11-May-2010
Land owner:	Kari Easthouse
UTM Coordinates:	20T 5069818N; 661760E
Slope; position; aspect:	14%; Mid; N
Land use - Vegetation:	Old pasture - Forage-wood ash research site
Parent material:	Till derived from sedimentary rocks
Underlying bedrock:	Early Carboniferous - Windsor Group sedimentary rocks
Stoniness; rockiness:	Nonstony; nonrocky
Drainage:	Imperfectly drained
Soil classification:	Gleyed Sombric Brunisol
Rooting depth (cm):	50
Rooting restriction:	Compact till subsoil
Watertable depth (cm):	none present
Sampled by:	K.T. Webb

Horizon	*Depth*	*Description*
Ap	0-18	Dark brown (7.5YR 3/2 m); gravelly silt loam; weak, medium and coarse, subangular blocky breaking to moderate, fine and medium granular; friable; plentiful fine, very fine and medium roots; 15% gravel; clear, smooth boundary, 17-19 cm thick; slightly acid (pH 6.1).
Bmgj	18-40	Brown (7.5YR 4/3 m); gravelly loam; common, fine and medium, distinct, strong brown (7.5YR 5/8 m) mottles; moderate, fine and medium, subangular blocky; firm; few, very fine, fine and medium roots; 20% gravels and cobbles; clear, wavy boundary, 17-24 cm thick; medium acid (pH 6.0).
BCgj	40-60	Dark reddish brown (5YR 3/3 m); gravelly loam; few, medium, faint, yellowish red (5YR 4/6 m) and common, fine, distinct, black (5YR 2.5/1 m) mottles; very weak, very coarse platy; very firm; very few, very fine and fine roots; 25% gravels and cobbles; diffuse, wavy boundary, 18-25 cm thick; slightly acid (pH 6.3).
Cgj	60-100	Dark reddish brown (5YR 3/3 m); gravelly loam; few, medium, faint, reddish brown (5YR 4/4 m) mottles; structureless, massive; very firm; no roots; 25% gravels and cobbles; neutral (pH 6.8).

Appendix A-15: Soil Core and Bulk Sample Analysis for Site 7

Horizon	Depth (cm)	pH (H_2O)	Total C (%)	Org. Matter (%)	Total N (%)	Exchangeable cations (%)					% Base saturation	CEC (cmol/kg)
						Ca	Mg	K	Na	H		
Ap	0-16	6.0	3.48	6.02	0.25	50.2	25.0	1.1	0.6	23.2	76.3	21
Btjgj	16-28	5.1	0.45	0.77	-	25.1	17.9	1.7	1.3	54.0	44.7	13
BCgj	28-52	4.8	0.08	0.14	-	21.6	11.4	1.6	0.6	64.8	34.6	19
Cgj	52-100	5.0	0.07	0.12	-	29.7	12.6	1.5	0.7	55.5	43.8	17

	Soil test (mg/kg)											
Horizon	P	K	Ca	Mg	Fe	S	Mn	Na	Zn	B	Cu	Al
Ap	21	86	2081	621	465	21	135	0.6	1.3	0.6	0.7	1221
Btjgj	7	89	671	286	515	18	24	1.3	1.5	0.3	0.4	1472
BCgj	52	113	801	253	389	8	85	0.6	1.1	0.3	0.6	1626
Cgj	61	103	1029	261	400	6	201	0.7	0.9	0.3	0.7	1374

Horizon	Particle Size Distribution (%)								C.F (% wt)
	VCS	CS	MS	FS	VFS	Sand	Silt	Clay	
Ap	3.5	5.2	5.6	6.0	2.9	23.3	53.8	22.9	14.0
Btjgj	3.5	5.9	6.0	6.7	7.1	29.3	42.9	27.8	12.0
BCgj	4.6	6.2	5.9	6.6	9.8	33.2	51.0	15.8	7.6
Cgj	4.5	6.5	6.9	7.5	5.9	31.3	42.9	25.8	3.0

		Moisture Retention (%)										
Horizon	Depth (cm)	0 kPa	5 kPa	10 kPa	33 kPa	100 kPa	300 kPa	1500 kPa	AWC (% vol.)	Air cap (% vol.)	Ksat (cm/h)	Bulk den. (g/cm^3)
Ap	0-16	59.2	49.8	47.9	44.5	39.8	32.1	21.3	28.5	9.3	222	1.11
Cgj	52-100	34.3	31.0	30.5	28.9	25.9	22.5	19.7	11.3	3.3	1.0	1.79

Appendix A-16: Soil Description for Site 7

Soil name: **Queens series (QUE)**

Site ID: **2010 - Wood Ash Pedon 3**
Location & Date: Miramichi, Inverness Co., Cape Breton; May 12, 2010
Land owner: Andrew MacLennan
Coordinates: 20T 631641E, 5097568N
Slope; position; aspect: 9%; mid; S160
Land use - Vegetation: Grass/alfalfa forage-wood ash research site
Parent material: Till derived from sedimentary rocks
Underlying bedrock: Early Carboniferous Horton Group sedimentary rocks
Stoniness; rockiness: Nonstony; nonrocky
Drainage: Imperfect
Soil classification: Gleyed Sombric Brunisol
Rooting depth (cm): 55
Rooting restriction: Compact till subsoil
Watertable depth (cm): none present (>100)
Sampled by: K.T. Webb

Horizon	*Depth*	*Description*
Ap	0-16	Dark brown (7.5YR 3/3 m); loam; moderate, fine to medium subangular blocky breaking to weak medium granular; friable, slightly sticky; plentiful, very fine exped roots; 10% gravel; clear, wavy boundary; 14-18 cm thick; medium acid (pH 6.0).
Btjgj	16-28	Brown (7.5YR 4/3 m); clay loam; many fine and medium, distinct strong brown (7.5YR 5/6 m) mottles; moderate, very coarse, subangular blocky breaking to weak, coarse, subangular blocky; very firm, slightly sticky; few, thin, clay films on ped faces; plentiful, very fine exped roots; 10% gravel; clear, wavy boundary; 11-16 cm thick; strongly acid (pH 5.1).
BCgj	28-52	Dark reddish brown (5YR 3/3 m); loam; few, coarse, distinct, yellowish red (5YR 4/6 m) mottles; weak, coarse prismatic breaking to weak, medium to coarse, subangular blocky, very firm; few, very fine, exped roots; 5% gravel; diffuse wavy boundary; very strongly acid (pH 4.8).
Cgj	52-100	Dark reddish brown (5YR 3/3 m); loam; few, fine, faint mottles; weak, very coarse, platy breaking to weak, coarse, subangular blocky; firm; few, very fine, exped roots; 5% gravel; very strongly acid (pH 5.0).

Appendix A-17: Soil Core and Bulk Sample Analysis for Site 8

Horizon	Depth (cm)	pH (H_2O)	Total C (%)	Org. Matter (%)	Total N (%)	Exchangeable cations (%)					% Base saturation	CEC (cmol/kg)
						Ca	Mg	K	Na	H		
Ap	0-20	5.8	2.61	4.50	0.17	31.9	9.7	2.6	0.6	55.1	44.2	11
C1	20-60	5.8	0.28	0.48	-	35.4	23.0	5.2	2.7	33.7	63.6	4
C2	60-100	7.2	0.17	0.29	-	48.6	35.1	9.3	2.2	4.8	93.0	3

Horizon	Soil test (mg/kg)											
	P	K	Ca	Mg	Fe	S	Mn	Na	Zn	B	Cu	Al
Ap	63	113	696	127	413	20	116	0.6	2.9	0.5	2.6	1711
C1	91	73	252	98	345	9	114	2.7	1.6	0.2	2.2	1441
C2	65	95	254	110	405	6	257	2.2	1.5	0.2	2.1	1233

Horizon	Particle Size Distribution (%)								C.F (% wt)
	VCS	CS	MS	FS	VFS	Sand	Silt	Clay	
Ap	8.8	7.4	6.4	8.2	1.4	32.2	58.9	8.9	29.7
C1	8.8	7.9	7.0	9.0	0.5	33.2	53.0	13.8	39.6
C2	7.5	5.9	5.6	7.8	6.3	33.1	53.1	13.8	35.0

*Moisture Retention – N/A

Appendix A-18: Soil Description for Site 8

Soil name:	**Thom series (THM)**
Site ID:	**2010 - Wood Ash Pedon 4**
Location & Date:	Copper Lake, Antigonish County; May 12, 2010
Land owner:	Bruce Sinclair
Coordinates:	20T 580076E; 5029409N
Slope; position; aspect:	14%; upper; S190
Land use - Vegetation:	Plowed cropland - Forage-wood ash research site
Parent material:	Till derived from meta-sedimentary rocks
Underlying bedrock:	Early Carboniferous Horton Group sedimentary rocks
Stoniness; rockiness:	Slightly stony; nonrocky
Water erosion:	moderate
Drainage:	Moderately well
Soil classification:	Orthic Humic Regosol
Rooting depth (cm):	60
Rooting restriction:	Compact till subsoil
Watertable depth (cm):	none present (>100)
Sampled by:	K.T. Webb

Horizon	***Depth***	***Description***
Ap	0-20	Dark yellowish brown (10YR 3/4 m); gravelly silt loam; weak, fine to medium, subangular blocky; very friable; plentiful, very fine, fine and medium roots; 25% gravel; clear, smooth boundary; 18-22 cm thick; medium acid (pH 5.8).
C1	20-60	Brown (7.5YR 4/3 m); very gravelly silt loam; weak, medium, subangular blocky; friable to firm, slightly sticky; few, fine to medium roots; 35% gravel; diffuse, wavy boundary; medium acid (pH 5.8).
C2	60-100	Brown (10YR 4/3 m); very gravelly silt loam; weak, medium to coarse, subangular blocky; friable to firm; no roots; 35% gravel; neutral (pH 7.2).

Appendix A-19: Soil Core and Bulk Sample Analysis for Site 9

Horizon	Depth (cm)	pH (H_2O)	Total C (%)	Org. Matter (%)	Total N (%)	Exchangeable cations (%)					% Base saturation	CEC (cmol/kg)
						Ca	Mg	K	Na	H		
Ap	0-16	7.0	5.23	9.09	0.27	64.2	22.0	0.5	0.4	12.9	86.7	24
Aheg	16-21	5.3	0.78	1.34	-	28.6	13.2	0.4	0.3	57.4	42.2	21
Bg	21-32	4.7	0.33	0.56	-	8.8	5.3	0.6	0.2	85.2	14.7	15
BCxjgj	32-44	4.9	0.20	0.35	-	18.5	7.4	1.6	0.5	72.0	27.5	12
Cgj	44-100	6.6	0.19	0.32	-	62.1	15.6	1.5	0.8	20.0	79.2	13

	Soil test (mg/kg)											
Horizon	P	K	Ca	Mg	Fe	S	Mn	Na	Zn	B	Cu	Al
Ap	31	44	3074	631	508	33	107	20	2.1	1.4	0.4	834
Aheg	6	35	1195	332	413	12	17	14	0.5	0.2	0.3	1449
Bg	3	36	272	98	482	10	6	7	0.7	0.2	0.5	1422
BCxjgj	12	72	432	103	417	12	84	13	1.1	0.2	1.8	1389
Cgj	9	73	1577	238	374	4	262	24	2.4	0.3	2.0	911

Horizon	Particle Size Distribution (%)								C.F (% wt)
	VCS	CS	MS	FS	VFS	Sand	Silt	Clay	
Ap	4.9	3.8	5.3	14.2	10.8	39.0	47.2	13.8	15.9
Aheg	3.3	3.7	4.2	7.9	5.0	24.1	60.0	15.9	13.9
Bg	1.5	0.0	3.4	14.3	10.9	30.1	54.1	15.8	10.2
BCxjgj	6.0	5.6	5.6	9.6	6.0	32.9	51.3	15.8	20.2
Cgj	2.3	2.5	4.0	8.8	8.1	25.7	46.5	27.8	13.8

		Moisture Retention (%)										
Horizon	Depth (cm)	0 kPa	5 kPa	10 kPa	33 kPa	100 kPa	300 kPa	1500 kPa	AWC (% vol.)	Air cap (% vol.)	Ksat (cm/h)	Bulk den. (g/cm^3)
Ap	0-16	60.9	46.7	44.4	39.2	33.5	23.8	19.0	27.7	14.2	78	1.11

Appendix A-20: Soil Description for Site 9

Soil name:	**Kingsville series (KSV)**
Site ID:	**2010 - Wood Ash Pedon 2**
Location & Date:	Long Lake, Cape Breton - May 11, 2010
Land owner:	Edward Touesnard
UTM Coordinates:	20T 661762E, 5059642N
Slope; position; aspect:	0%; Level; all
Land use - Vegetation:	Grass forage/pasture - Forage-wood ash research site
Parent material:	Till derived from sedimentary rocks
Underlying bedrock:	Late Carboniferous Riversdale Group sedimentary rocks
Stoniness; rockiness:	Nonstony; nonrocky
Drainage:	Poorly drained
Soil classification:	Orthic Humic Gleysol
Rooting depth (cm):	28
Rooting restriction:	Compact till
Watertable depth (cm):	10 - perched watertable
Sampled by:	K.T. Webb

Horizon	***Depth***	***Description***
Apg	0-16	Very dark grayish brown (10YR 3/2 m); loam; few, medium to coarse, prominent, yellowish brown (10YR 5/6 m) mottles; moderate, medium and coarse, subangular blocky breaking to moderate, medium to coarse, granular; friable; plentiful, very fine and fine roots; 5% gravel; abrupt, smooth boundary, 14-18 cm thick; neutral (pH 7.0).
Aeg	16-21	Light brownish gray (10YR 6/2 m); silt loam; many, fine, medium and coarse, prominent, strong brown (7.5YR 5/8 m) mottles; weak, coarse subangular blocky breaking to weak, fine to medium subangular blocky; firm; few, very fine, fine and medium roots; 5% gravel; clear, wavy boundary, 4-7 cm thick; strongly acid (pH 5.3).
Bg	21-32	Pinkish gray (7.5YR 6/2 m); silt loam; many, coarse, prominent, strong brown (7.5YR 5/8 m) mottles; moderate, fine and medium, subangular blocky; firm; few very fine and fine roots; 5% gravel; clear, wavy boundary; very strongly acid (pH 4.7).
BCgj	32-44	Dark brown (7.5YR 3/3 m); silt loam; common, medium to coarse, distinct, strong brown (7.5YR 5/8 m) mottles; weak, coarse, prismatic breaking to very weak, coarse, subangular blocky; very firm; no roots; 14% gravel; diffuse, wavy, boundary; very strongly acid (pH 4.9).
C	44-100	Dark brown (7.5YR 3/3 m); clay loam; structureless; massive; very firm; no roots; 10% gravel; neutral (pH 6.6).

Appendix A-21. Soil Properties of Soils 1 and 2 used in the Greenhouse Incubation Experiment to Determine the Liming Effectiveness of Wood Ash.

	OM	pH	P	K	Ca	Mg	Na	S
	(%)		-------------------(%)----------------				--------(mg kg^{-1})--------	
Soil 1	7.60	5.00	.005	.02	.01	.03	57.5	50.5
Soil 2	3.00	5.40	.008	.01	.05	.01	23.5	13.0
	Fe	**Mn**	**Cu**	**Zn**	**B**	**Al**	**CEC**	**Lime req.**
	----------------------------(mg kg^{-1})-----------------------						Meq/100g	Mg ha^{-1}
Soil 1	555	14	0.65	2.3	0.63	-	15	11
Soil 2	321	92	2.18	1.8	0.28	965	7	5

Appendix A-22. Monthly Data Reports for the Years 2009 and 2010 from the Halifax Weather Station.

	2009		**2010**	
Month	**Precipitation (mm)**	**Temperature (˚C)**	**Precipitation (mm)**	**Temperature (˚C)**
January	128.1	-7.7	92.4	-4.1
February	92.1	-4.5	72	-3.2
March	156.2	-1.7	93	2.1
April	158.8	5.4	39.9	7.3
May	88.6	10.8	48	11.1
June	n/a	n/a	99.6	15.2
July	71	17.6	125.2	19.8
August	179.6	19.9	65.3	19.4
September	73	13.7	117.5	16.3
October	166.9	6.9	153.6	9.2
November	95.1	5.6	226.3	4.1
December	149.6	-2.5	191	0.7

(Environment Canada 2012)