Early effects of helicopter liming on soil and vegetation in two acidified forest stands in Nova Scotia, Canada

By

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Abstract

Fossil fuel burning from increased industrial practices in the 1900's caused high levels of acid deposition in northeastern North America. Acid deposition depletes base cations (Ca^{2+}, Mg^{2+}, K^{+}) and increases toxic aluminum (Al^{3+}) concentrations in forest soil and drainage waters. Base cation depletion impairs forest growth, regeneration, and ecosystem health. Despite decreases in acid deposition after the enactment of the Clean Air Act and Clean Air Act Amendments, little to no improvement in soil base cation concentrations over the last 30 years has been reported in Nova Scotia. The application of calcium-containing soil amendments such as dolomitic limestone ($CaMgCO_3$), known as liming, can increase base cation concentrations in terrestrial ecosystems and help restore forest health. Terrestrial liming studies in Europe and northeastern North America have shown variable but promising results; however, gaps exist in our knowledge of terrestrial liming such as the short-term (one-year) effects of terrestrial liming on soil and plant tissue chemistry on acidified forests in Nova Scotia (NS). This study conducted a terrestrial liming trial at the Otter Ponds Demonstration Forest in Mooseland, NS, where 10 t ha^{-1} of dolomitic limestone was deposited via helicopter over mature acidic hardwood and softwood forests and assessed one year after liming using a before-after-control-impact experimental design with six and five plots at the hardwood and softwood sites, respectively. Lime collection boxes distributed throughout the treatment sites evaluated the lime distribution. Collection of soil, foliage, and ground vegetation samples before and after liming in the softwood and hardwood stands was conducted and assessed for chemical analysis. Chemical analysis of the samples focused on acid-indicating properties such as pH, base saturation, calcium (Ca^{2+}), magnesium (Mg^{2+}), and aluminum (Al^{3+}) concentrations. A limited cost-benefit of liming forest stands in NS was conducted to determine its feasibility.

The results show that despite a non-uniform distribution of lime over the treatment sites, soil Ca^{2+}, Mg^{2+}, percent base saturation (%BS), and pH increased, and total acidity decreased in the forest floor in response to liming. Upper mineral soil pH, %BS, Ca^{2+}, and Mg^{2+} increased significantly at the hardwood site, and %BS and Mg^{2+} increased significantly at the softwood site. No significant increases or decreases in Al^{3+} were observed in any soil horizons at either site; however, a non-significant decrease was observed in the upper forest floor of the softwood site. Foliar Ca increased in red spruce and sugar maple trees but not red maple. Ground vegetation Ca, and Al increased while potassium (K) decreased in the ground vegetation at the softwood and hardwood sites. First-year results indicate that liming initiated the restoration of depleted base cations in forest soil and increased important tree species' nutritional status in NS acidified forests. Helicopter liming can potentially offset economic losses or increase economic gains from the timber, maple syrup and fall foliage tourism industries. The initial response from liming acidified forest stands in NS indicates that helicopter liming can promote recovery from soil acidification and increase the value of currently acidified forests in NS.

List of Abbreviations Used

Abbreviation	**Full name**
%BS	Percent base saturation
AIC	Akaike Information Criterion
$Al(OH)_3$	Aluminum hydroxide
Al^{3+}/Al	Aluminum ion/Aluminum
ANC	Acid neutralizing capacity
BACI	Before-after-control-impact
BAI	Basal area increment
BCD	Base cation depletion
BF	Balsam fir
C	Carbon
Ca^{2+}/Ca	Calcium ion/Calcium
$CaCO_3$	Calcium carbonate
CEC	Cation exchange capacity
CES	Cation exchange sites
cmol	Centimole
Co-dom	Co-dominant
CV	Coefficient of Variation
Db	Bulk Density
DBH	Diameter at breast height
DRIS	Diagnosis and Recommendation Integrated System
EA	Exchangeable acidity
Fe^{3+}/Fe	Iron ion/Iron
GLMM	General linear effects mixed model
H^+	Hydrogen ion
H_2SO_4	Sulphuric acid
Ha	Hectare
HBEF	Hubbard Brook Experimental Forest
HCO_3^-	Bicarbonate ion
HNO_3	Nitric acid
HWC	Hardwood control
HWT	Hardwood treatment
ICP-MS	Inductively coupled plasma mass spectrometry
IDW	Inverse distance weighting
Int.	Intermediate

K^+/K	Potassium ion/Potassium
KCl	Potassium chloride
LCR	Live Crown Ratio
LMM	Linear mixed effects model
LOOCV	Leave one out method
M1	Upper mineral horizon
M2	Lower mineral horizon
Mg^{2+}/Mg	Magnesium ion/Magnesium
$MgCO_3$	Magnesium carbonate
Mn^{2+}/Mn	Manganese ion/Manganese
MNF	Monongahela National Forest
MPANS	Maple Producers Association of Nova Scotia
N	Nitrogen
Na^+	Sodium ion
NBI	Nutrient balance index
NBM-NS	Nutrient budget model of Nova Scotia
NH_3	Ammonia
NO_3^-	Nitrate ion
NO_X	Nitous oxides
NPV	Net present value
NS	Nova Scotia
OPDF	Otter Ponds Demonstration Forest
P	Phosphorous
PSP	Permanent sample plot
RM	Red maple
RMSE	Root-mean-square-error
RS	Red spruce
S	Sulphur
SchM	Schreber’s moss
SE	Standard error
SM	Sugar maple
SO_2	Sulphur dioxide
SO_4^{2-}	Sulphate ion
SOM	Soil organic matter
SusMAI	Sustainable mean annual increment
SWC	Softwood control
SWT	Softwood treatment

US	United States
WB	White Birch
WP	White Pine
WF	Wood fern
YB	Yellow Birch

Glossary

Acid deposition	Commonly referred to as acid rain, acidic emissions from fossil fuel combustion such as SO2 and NOx which can be transported and deposited in other locations. Pollutants can be deposited as dry deposition or wet deposition, undergoing hydrolysis with water to form H2SO4 and HNO3.
Adsorption	The process in which ions bind to the surface of solids through chemical and physical processes.
Basal area	The cross-sectional area of a tree, taken at diameter at breast height.
Base cation depletion	The loss of exchangeable base cation from soil, usually through leaching.
Buffering capacity	The capacity of the soil to maintain a stable pH when confronted with acidifying or alkalinizing agents.
Canopy closure	The proportion of sky covered by the tree canopy when looking upwards from a single point.
Cation exchange	The process by which cations held on the cation exchange complex are exchanged with cations in soil solution.
Cation exchange capacity	The ability of soil to retain exchangeable cations, dependent on the number of negatively charge surfaces on soil organic matter and clay particles.
Cold tolerance	The ability of plants to withstand cold temperatures without sustaining damage.
Critical loads	The amount of deposition a system can withstand without experiencing deleterious effects
Horizon (soil)	A soil layer, relatively parallel to the land surface, which is distinct from other horizons by physical or chemical properties such as, texture, colour, consistence, pH, etc.
Humus	The highly decomposed portion of soil organic matter that remains after the removal of dissolved organic matter and larger organic matter.
Leaching	Loss of soluble ions from the soil through water movement.
Lime	A soil amendment which contains calcium used to neutralize soil acidity.
Mineralization	The process by which organic substances are converted to inorganic substances usually through microbial decomposition.
Net present value	The value of future cash flow within a defined time period.

Percent base saturation	The percent of the cation exchange complex which is occupied by basic cations (Ca2+, Mg2+, K+, Na+).
Soil acidification	An overabundance of H+ in soil leading to a reduction in pH.
Soil amendment	Materials added to the soil to improve chemical, physical, or biological soil properties.
Soil organic matter	The portion of soil that contains decomposed plant and animal matter at different stages of decomposition.
Soil texture	The relative abundance of sand, silt, and clay particles in mineral soil.
Sustainable mean annual increment	An estimate of the sustainable growth rate of a stand (m^3/ha/yr) based on the calculated nutrient demand of the vegetation type found and the estimated nutrient supply rate of the site.
Terrestrial liming	The addition of Ca^{2+}-containing rock dust to a natural upland ecosystem such as a forest

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Chapter 1 – Introduction

1.1 Background

1.1.1 Soil Acidification and Anthropogenic Acid Deposition

Increases in industrial fertilizer use and emissions from power plants, factories, and vehicles have increased airborne pollutants such as sulphur dioxide (SO_2), nitrous oxides (NO_x), and ammonia (NH_3), which are the main pollutants in acid deposition. Acid deposition increased in the United States (US) and Canada in the 1850s and peaked in the 1970s (Smith et al., 2011). The airborne pollutants undergo oxidation to form sulfuric acid (H_2SO_4) and nitric acid (HNO_3), which can be transported by wind over thousands of kilometres and deposited onto forest soils and aquatic ecosystems (Shaw, 1979). Acid deposition in forests in northeastern North America has resulted in increased soil acidification (Driscoll et al., 2001; Likens et al., 1996), decreased forest productivity (Driscoll et al., 2001), and loss of aquatic species (Clair & Hindar, 2005). After the peak in acid deposition emissions in North America, legislation known as the Clean Air Act (1970), the Clean Air Act Amendments (1990), and the Air Quality Accord (1991) were enacted, leading to significant reductions in these emissions. Despite substantial decreases in acid deposition throughout northeastern North America, limited or slow recovery in soil acidification status (Lawrence et al., 2015) and little to no recovery in forest productivity has occurred (Warby et al., 2009; Lawrence et al., 2012).

Soil acidification can cause severe declines in forested ecosystems (Driscoll et al., 2001; Reuss & Johnson, 1986; Tomlinson, 1990). Soil acidification occurs where there is an overabundance of acidic cations, particularly hydrogen (H^+), on the negatively charged cation exchange complex of soil, leading to reduced pH. Soil acidification is further increased by a reduction of base cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+) (Reuss &

Johnson, 1986). Soil acidification occurs naturally from acidic bedrock material, plant uptake, and organic matter decomposition (Clair & Hindar, 2005). The acceleration of soil acidification can be caused by anthropogenic sources such as harvest, fertilizer use, and acid deposition (Reuss & Johnson, 1986).

This thesis examines liming as a potential tool to initiate forest recovery from lingering impacts of acid deposition. I examine the background on the mechanisms of soil acidification and its effects on forest ecosystems. I assess the potential of dolomitic limestone to accelerate the recovery of base cations and improve forest productivity from studies in northeastern North America and Europe (Chapter 1). I evaluate the short-term (1-year) effects of a long-term helicopter liming trial in two acidified forest stands in Nova Scotia (NS), Canada. The evaluation of the helicopter liming trial includes an assessment of the method (Chapter 2), the initial response of soil and plant tissue chemistry (Chapter 3), and a review of the economic impact of using helicopter liming in acidified forest stands in NS (Chapter 4).

1.1.2 Mechanisms of Soil Acidification

1.1.2.1 Base Cation Depletion

Increased levels of acid deposition in acidified forests can lead to the depletion of plant essential base cations, particularly Ca^{2+} and Mg^{2+} (Tomlinson, 1990). Many studies have attributed leaching as the primary mechanism of base cation depletion (BCD) (Bailey et al., 2005; Hanson et al., 1982; Johnson et al., 1994; Ouimet et al., 2008). Dissolution of strong acids (H_2SO_4 and HNO_3) in soil solution increases the abundance of H^+, sulphate (SO_4^{2-}) (Equation 1), and nitrate (NO_3^-) concentrations.

$$H_2SO_4(aq) \leftrightarrow 2H^+(aq) + SO_4^{2-}(aq) \tag{1}$$

$$HNO_3(aq) \leftrightarrow H^+(aq) + NO_3^-(aq) \qquad (2)$$

The products from the dissolution reaction promote soil acidification through different mechanisms. First, the increase of H^+ in soil solution leads to a decrease in pH which helps dictate chemical buffering in soil (Driscoll et al., 2001; Reuss & Johnson, 1986; Tomlinson, 1990). The availability of base cations in soil solution largely depends on the pH buffering range (Driscoll & Schecher, 1990; Reuss and Johnson, 1986). Naturally acidic soils with a pH range of approximately 4.2 to 5.5 are mainly buffered by cation exchange because base cations are abundant in soil solution (Ross et al., 2008). The cation exchange buffering mechanism replaces adsorbed base cations with acidic cations such as H^+ and aluminum (Al^{3+}) on the cation exchange complex to maintain electro-neutrality with the soil solution (Equation 2; Figure 1). Cation exchange occurs at the negatively charged sites on clay particles and soil organic matter (SOM) (Driscoll & Schecher, 1990; Tomlinson, 1990).

$$BC^{n+}_{(abs)} + nH^+ \leftrightarrow nH^+_{(abs)} + BC^{n+} \qquad (2)$$

Second, excess NO_3^- and SO_4^{-2} not taken up by plants or, in the case of SO_4^{-2}, adsorbed by mineral soil combine with available cations (mainly base cations) and are lost from the system through leaching. The resulting compounds are no longer available for plant uptake or adsorption and are lost from the system through leaching. Leaching can result in the depletion of base cations from soils and can lead to nutrient deficiencies in forest stands (Driscoll et al., 2001; Reuss & Johnson, 1986). The degree of BCD in soil is often represented by percent base saturation (%BS) (Cronan & Grigal, 1995; Ross et al., 2008). If %BS levels decrease to approximately 15-20% or below, Al^{3+} can become readily available for plant and organism uptake, leading to Al^{3+} stress and potentially Al^{3+} toxicity (Cronan & Grigal, 1995; Reuss & Johnson, 1986).

1.1.2.2 Aluminum Mobilization in Soil

The behaviour of Al^{3+} in acidified soils is complicated and highly dependent on pH (Oulehle et al., 2011). Once soil pH levels decline below approximately 4.2, dissolution of aluminum hydroxide ($Al(OH)_3$) becomes the dominant acid buffering mechanism through releasing Al^{3+} in soil solution to maintain electro-neutrality (Ross et al., 2008). Aluminum hydroxide solubility increases at low pHs from hydrolyzation of Al^{3+} complexes by H^+; exchangeable Al^{3+} is then released into soil solution (Equation 3) (Li & Johnson, 2016; Reuss, 1983).

$$Al(OH)_n{}^{3-n} + nH^+ \leftrightarrow Al^{3-n} + H_2O \tag{3}$$

Exchangeable Al^{3+} has a higher affinity for organic binding sites than base cations and can be retained more effectively on the cation exchange complex, often replacing base cations (Gruba & Mulder, 2015; Reuss & Johnson, 1986; Scheel et al., 2007) (Figure 1). As acidification progresses, the overabundance of H^+ can release Al^{3+} into soil solution. High availability of Al^{3+} in soil solution can interfere with base cation plant uptake and promote Al^{3+} toxicity (de Wit et al., 2010; Lawrence et al., 2005; Ouimet & Camiré, 1995) (Figure 1). Exchangeable Al^{3+} can also bind with available anions and be leached into surface waters, causing damage to aquatic ecosystems (Clair & Hindar, 2005) (Figure 1).

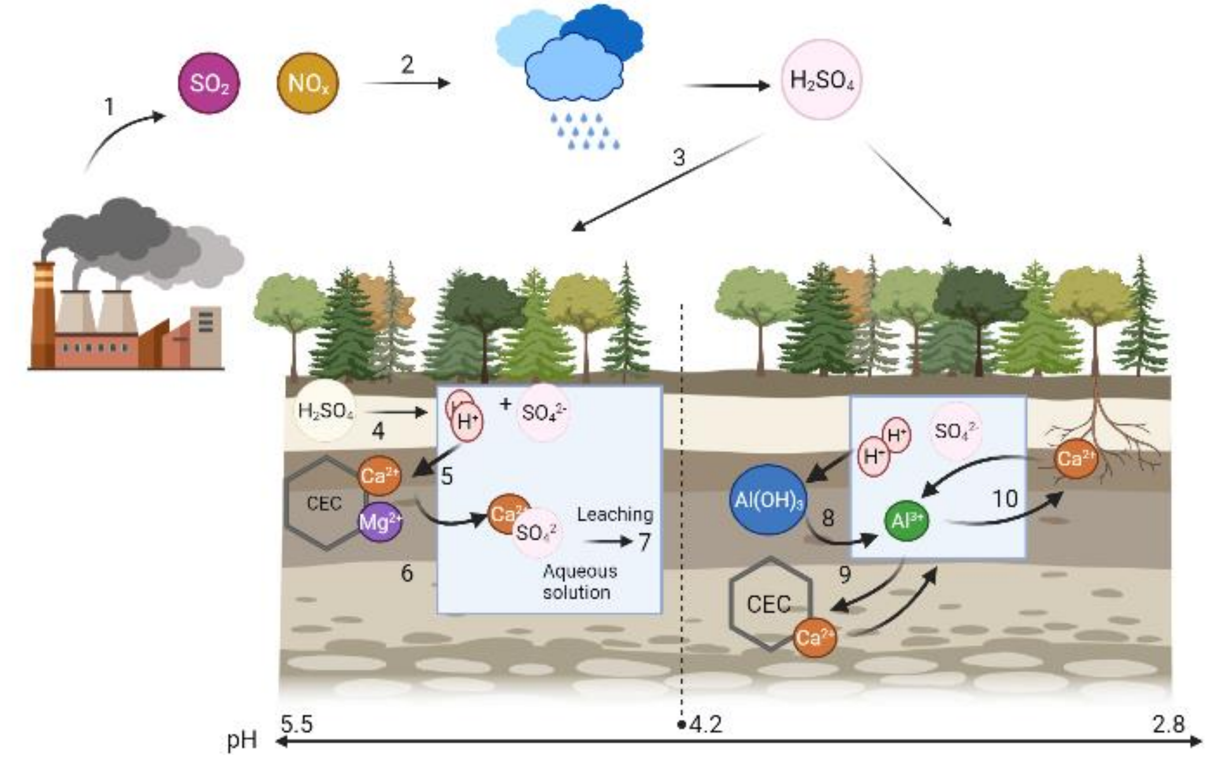


Figure 1. Acid deposition in a forest and the soil acidification mechanisms at different pHs. The dotted line represents the estimated pH by which the acid buffering mechanism switches from cation exchange to Al^{3+} *buffering. 1. Emission of sulphur dioxide (*SO_2*) from industrial practices; 2. Hydrolysis of* SO_2 *with rainwater forms sulfuric acid (*H_2SO_4*); 3. Deposition of* H_2SO_4*; 4. Dissolution of sulfuric acid in soil solution; 5. Replacement of hydrogen ions (H+) with base cations (*Ca^{2+}*,* Mg^{2+}*,*K^{+}*,* Na^{+}*) on the cation exchange complex; 6. Displacement of base cations into soil solution; 7. Leaching of base cations and other ions; 8. Continued decreases in pH increases the mobilization of aluminum (*Al^{3+}*) from hydroxide minerals (*$Al(OH)_3$*) and releases* Al^{3+} *into soil solution; 9. Replacement of base cations with* Al^{3+} *on the CEC because* Al^{3+} *has a higher affinity and can bind more efficiently to the CEC; 10.* Al^{3+} *can also impede the uptake of base cations in roots. (Note: chemical equations are not balanced, and soil processes may change depending on climate, soil physical characteristics, and disturbance. This figure displays the reactions for sulphuric acid; similar reactions occur for* HNO_3 *and* NH_3*.).*

1.1.3 Indicators of Soil Acidification in Northeastern North America

Retrospective studies have shown significant reductions in pH and increases in BCD throughout northeastern North America. Significant decreases in pH and increases in BCD were observed from 1967 to 1997 in Pennsylvania soils, likely caused by accelerated leaching of base cations (Bailey et al., 2005). Base cation depletion occurred from 1930 to 1984 in the Adirondack region (Johnson et al., 1994). Additionally, median extractable Ca^{2+} decreased by 64% from 1932 to 2005/6 throughout the soil profile in the Adirondack region (Bedison & Johnson, 2010). Similar results were found throughout the northeastern US (Fenn et al., 2006; Lawrence et al., 1995; Warby et al., 2009).

While retrospective studies were not performed in NS, studies which examined acid deposition gradients, experimental acidification, and an assessment of critical loads provided evidence that acid deposition led to accelerated soil acidification in the region. Base cation depletion increased along a decreasing pH gradient (Hanson et al.,1982), and declines in Ca^{2+} and increases in Al^{3+} were associated with greater SO_4^{2-} deposition rates (Lawrence et al., 1999). Significant decreases in base cations and increases in mobile Al^{3+} were observed in experimental acidification studies in which sulphur (S) or nitrogen (N) containing fertilizers were applied and compared with control sites (Fernandez et al., 2003; Gilliam et al., 2020; Ouimet et al., 2008).

Indicators of soil acidification are still present in NS despite a significant decrease in acid deposition between 1990 and 2010 (NEG-ECP, 2007). Despite decreases in acid deposition, many areas of NS still exceeded critical loads (NEG-ECP, 2007). Exceedance of critical loads was evaluated in eastern Canada to help determine the extent of acidification in the region. Critical loads are the amount of deposition a system can withstand without experiencing deleterious effects (NEG-ECP, 2007). Exceedance of critical loads of SO_4^{2-} and NO_3^- in 52% of the eastern Canadian provinces (Ontario, Quebec, New Brunswick, Prince Edward Island, NS, and Newfoundland) was reported; however, these results were reported in 2006 (Ouimet et al., 2006). Southeastern NS was one of the locations most impacted by acid deposition (Ouimet et al., 2006). Despite decreases in SO_4^{2-} and NO_3^- loading by approximately 40-50% from 1990 to 2010, median critical load exceedance in NS was 81 eq ha^{-1} $yr^{-1,}$ and some parts of NS exceedances were upwards of 500 eq ha^{-1} yr^{-1} (NEG-ECP, 2007).

1.1.4 Forest Decline from Acid Deposition

Acid deposition, through BCD in soils, Al^{3+} toxicity, and direct foliar leaching has negatively impacted many forests (Moore et al., 2015; Schaberg et al., 2011; Tomlinson, 1990). Calcium is important for plant cell wall stability, environmental stress response, reproduction, growth, and development (Schaberg et al., 2011). Root uptake of H^+ can replace Ca^{2+} on the cell wall membrane, destabilizing the membranes and promoting Ca^{2+} leaching from foliage (DeHayes et al., 1999). During plant response to environmental stress, such as climate or pests, Ca^{2+} moves from areas of high concentration in organelles and extra-cellular sites to the cytoplasm and binds to protein complexes. These protein complexes can interact with other cellular components and alter the physiological stress response. Decreased Ca^{2+} levels can modify this response and disrupt plant stress signalling (Schaberg et al., 2001). Suppression of appropriate responses could make affected trees more susceptible to pests, diseases, and/or other pressures. Calcium stress has translated to decreased growth and health, reduced cold tolerance, and increased susceptibility to pests and diseases in forest stands (DeHayes et al., 1999; Schaberg et al., 2011; Schaberg & DeHayes, 2000).

Red spruce and sugar maple forest stands are most sensitive to acid deposition (Driscoll et al., 2001). Additionally, they are species of high value in northeastern North America (Lawrence et al., 2016). Declines in the health and growth of red spruce trees have been recorded throughout the northeastern US and are often associated with reduced cold tolerance (Borer et al., 2004; DeHayes et al., 1999; Duarte et al., 2013; Halman et al., 2008; Schaberg et al., 2011; Shortle &

Smith, 1988). Northern hardwood studies have indicated decreased sugar maple growth (Bigelow & Canham, 2007; Duchesne et al., 2002; Long et al., 2009; Ouimet et al., 2008), decreased health (Bailey et al., 2005; Duchesne et al., 2002; Ouimet et al., 2008; Schaberg et al., 2006; Wilmot et al., 1995), increased mortality, and decreased regeneration (Moore et al., 2008; Sullivan et al., 2013).

Increased levels of soil Al^{3+} have been linked with sugar maple seedling mortality (Bigelow & Canham, 2010), decreased growth and vigour of mature sugar maple (Schaberg et al., 2006), increased oxidative stress (St. Clair et al., 2005), reallocation of carbon sources from growth and reproduction to defence mechanisms, and severe root damage (Halman et al., 2013). Hindrance of root growth from Al^{3+} stress was also evident in red spruce and balsam fir seedlings (Schier, 1985). Exchangeable Al^{3+} can interfere with Ca^{2+} on the root-soil interface and promote further Ca^{2+} deficiencies (Andersson, 1988). In addition, foliar Al competes with Ca and can inhibit Ca uptake, leading to calcium deficiencies (Cronan & Grigal, 1995). Calcium deficiency can elicit oxidative stress (St. Clair et al., 2005), alter stomata opening and closing (Ridolfi et al., 1994), and weaken cell wall stability (Schaberg et al., 2010).

In addition to tree species and forest soil impacts, acid deposition can affect soil flora and fauna through decreased pH. Increases in soil acidity have altered the abundance and species composition of the soil microbial community. For example, Clivot et al. (2012) showed an increase in the abundance of proteobacteria and a decrease in the abundance of acidobacteria in response to liming. Rousk et al. (2010) showed that the abundance and diversity of soil bacteria increased along an increasing pH gradient. Ground vegetation also changes in response to variations in soil pH. Vascular plant species composition changed along an acid cation scale in soil, showing that plant communities varied along an acid gradient (Horsley et al., 2008).

1.1.5 Forest Recovery from Acid Deposition

Despite significant decreases in SO_2 and NO_x emissions since the 1990s, there has been little to no recovery or a lag time between emission reductions and soil recovery in many areas of northeastern North America and Europe (Johnson et al., 2018; Lawrence et al., 2016). Indicators of soil recovery include increases in Ca^{2+} and Mg^{2+} in soil solution, increases in %BS (Cronan & Grigal, 1995; Driscoll et al., 2001), decreases in Al^{3+} concentrations (Lawrence et al., 2012), and increases in soil pH (Lawrence et al., 2015). Re-sampling studies from before and after the enactment of emissions-reducing policies provided evidence that the indicators of soil recovery were not improved or improved very little. There was little change in pH, exchangeable Ca^{2+}, Mg^{2+}, and K^+ in the Oa horizon and the upper B horizon in the northeastern US from 1992/3-2003/4; however, there were decreases in Al^{3+} in the Oa horizon at some sites (Lawrence et al., 2012). There were variable changes in base cation concentrations in the forest floor over several plots in the Adirondack region from 1980 to 1990; however, the average change in base cation concentrations over ten years was not significant (Yanai et al., 1999). Similarly, there were minimal changes in Ca^{2+}, pH, and Al^{3+} from 1986 to 2003 and 2005 throughout the entire soil profile at the Turkey Lakes Watershed in Ontario (Hazlett et al., 2011). Few studies in northeastern North America demonstrated an increase in soil base cation concentrations; however, base cation concentrations have not shown a continuous decrease and have remained relatively stable.

Where soils have started to recover after the decrease in acid deposition emissions, recovery has been slower than expected (Figure 2), and amendments to encourage recovery still may be helpful (Fernandez et al., 2003; Lawrence et al., 2016). Little change in Ca^{2+} and Al^{3+} were found in the B horizon in forest sites in the Alleghany plateau after sampling in 1997 and 2017.

However, increases in Ca^{2+}, Mg^{2+}, and Al^{3+} were observed in the organic horizons (Bailey et al., 2021). More recent samples collected in 2009 and 2019 in the Monongahela National Forest (MNF) suggested a slight improvement in pH following declining acid deposition (Fowler et al., 2022).

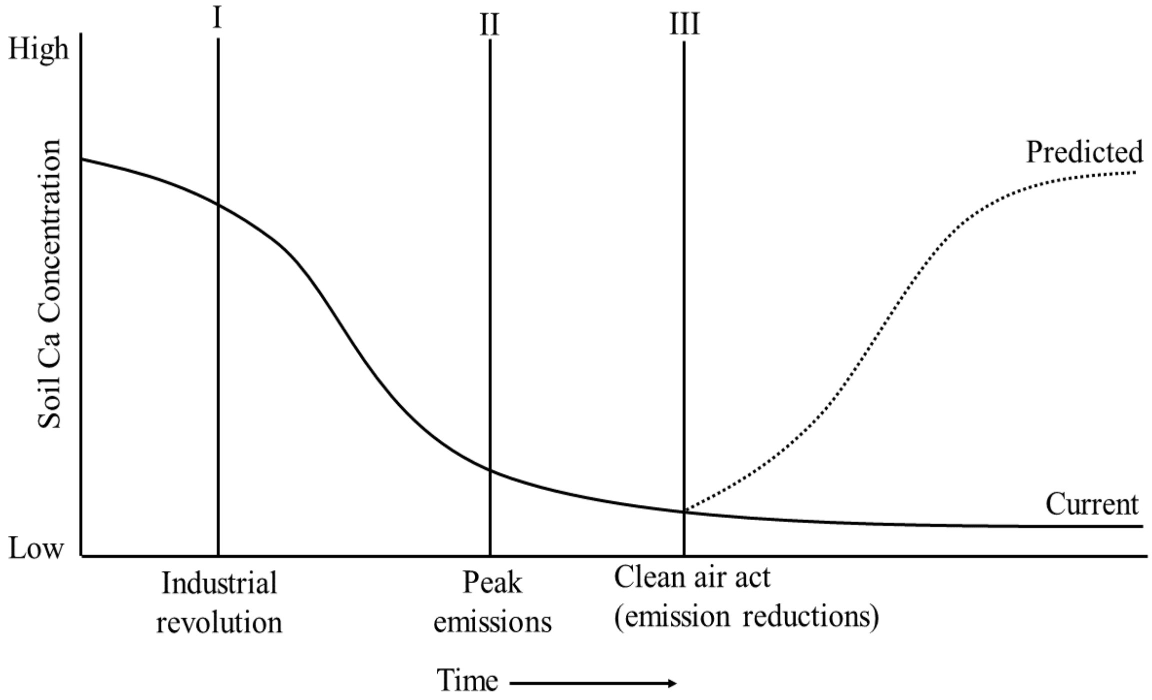


Figure 2. The conceptual model of forest soil calcium (Ca^{2+}) concentration evolution over time where I is the beginning of SO_2 and NO_x emissions from increased industrial practices, and II is at peak emissions. The dotted line represents the expected or predicted recovery from reduced emissions after the enactment of the Clean Air Act and Clean Air Act Amendments (III). The solid line represents the actual recovery of soil calcium since the reduction in emissions (adapted from Fernandez et al., 2003 and Lawrence et al., 2016).

The timeline for natural recovery from acid deposition is still unclear. Decreases in exchangeable Al^{3+} measured in re-sampling trials over 8-24 years could be the first sign of soil acidification reversal, followed by an increase in pH in the forest floor; however, not all sites showed the same results (Lawrence et al., 2015). The likely sequence of events for the organic horizon is (1) BCD halts, (2) Al^{3+} concentration decreases, and (3) pH increases. Recovery from acidification in the B horizon is much less clear and may depend on the upper layers of soil and other factors. For example, Al^{3+} increased in several B horizons at some re-sampled sites 8-24 years after initial sampling due to the downward leaching of organic matter associated Al^{3+} from upper horizons because of increased mobility of organic matter from pH increases (Lawrence et al., 2015).

Recovery from soil acidification depends on soil and site characteristics. Forest soil more affected by acidification had the greatest recovery after re-sampling 8-24 years later (Hazlett et al., 2020). Recovery in the organic horizons was greatest when pH was below 3.5, and recovery in the B horizon was greatest when pH was below 5.0. In addition to initial pH, time intervals played a large role in recovery from soil acidification, and soils recovered more from acidification over greater periods (Hazlett et al., 2020). Overall, natural recovery from soil acidification is possible; however, it is slow and largely depends on site-specific characteristics. The uncertainty of natural recovery and the delay of recovery from emission decreases supports the need for liming to accelerate the recovery of base cations in soil.

1.1.6 Terrestrial Liming

Terrestrial liming is a solution to help encourage forest recovery from soil acidification by restoring depleted base cations and increasing soil pH. Terrestrial liming is defined here as the addition of Ca^{2+}-containing rock dust to a natural upland ecosystem such as a forest. Large-scale terrestrial liming has been performed in Europe with variable responses (Court et al., 2018; Jansone et al., 2020; Nilsson et al., 2001; Tomlinson et al., 1990).

1.1.6.1 Liming Methods

Several different methods have been used to apply lime to forests. Lime can be applied by hand, tractors, spreaders, or helicopters (Table 1). Each method has advantages and disadvantages. While manual application can be cheaper and easier to target specific areas (Moore et al., 2000), it does not guarantee a uniform lime distribution and is difficult to perform over large areas (Sterling et al., 2014). Tractors and spreaders can be used for lime distribution but require the use of trails throughout the forest. Spreaders were used in a trial in Pennsylvania; however, they only limed the interior 0.2 ha of established study plots (Long et al., 1997). Helicopter application can spread lime over large areas; however, it is expensive and requires access to various machinery. The most suitable application method depends on the accessibility of materials, the location, and the purpose of liming (i.e., academic research or operational application).

1.1.6.2 Soil Mechanisms of Liming

Lime has a high acid neutralizing capacity (ANC) which is the ability of a product to neutralize protons (Moore et al., 2008). The dissolution of lime in acidified soils and subsequent H^+ buffering occurs in two steps: (1) liming materials dissolve in soil solution and releases base cations, and bicarbonate (Equation 4), and (2) bicarbonate ions (HCO_3^-) neutralize H^+ (Equation 5) (Kreutzer, 1995).

$$CaMg(CO_3)_2 + 2H^+ \rightarrow Ca^{2+} + Mg^{2+} + 2HCO_3^-{}_2 \qquad (4)$$

$$2HCO_3^- + 2H^+ \rightarrow 2CO_2 + 2H_2O \qquad (5)$$

Liming can help to reverse and/or slow down the effects of soil acidification by (1) restoring base cations, (2) increasing soil pH, and (3) decreasing toxic mobile Al^{3+}.

(1) Base cation restoration

A surplus of base cations in soil solution become available for plant uptake or replace acidic cations on the cation exchange complex (Lawrence et al., 2016). Calcium saturation in soil solution can decrease acidity directly by replacing Al^{3+} and H^+ on soil organic matter and clay particle exchange sites, thus increasing base saturation (Gu et al., 2017). Replacing acidic cations with basic cations may increase the base saturation but not necessarily increase pH.

(2) pH Increases

pH increases occur through the replacement of H^+ by base cations on the cation exchange complex and the deprotonation of organic acid functional groups in the forest floor (Kreutzer, 1995). Released H^+ binds with available bicarbonate in solution, neutralizing the acidic H^+.

(3) Decreases in Al^{3+}

pH increases to above 4.2 promote the complexation of Al^{3+} to organic functional groups, aluminum hydroxides (such as gibbsite), or secondary alumino-silicate minerals, making Al^{3+} less available for leaching and root uptake (Berggren & Mulder, 1995; Kreutzer, 1995; Li & Johnson, 2016; Ross et al., 2008). Decreases in exchangeable Al^{3+} in the forest floor and the upper mineral soil were directly related to organically bound Al^{3+} (Driscoll & Schecher, 1990; Gu et al., 2017). However, decreases in Al^{3+} in the forest floor are also related to increased SOM mineralization, complexation and subsequent leaching, and decreased Al^{3+} mobility to lower horizons (Lawrence et al., 2016). Changes in Al^{3+} may be constrained by increases in dissolved organic carbon (DOC) which can increase the solubility of Al^{3+} (Jansen et al., 2003).

Positive responses of soil from liming have been shown in numerous studies in Europe and North America (Table 1). The response of soil to liming can vary based on (1) soil properties, (2) stand type, (3) time since application, (4) application rate, and (5) amendment type (Reid & Watmough, 2014).

(1) Soil Properties

Different soil properties, such as soil texture, drainage, and pH, help determine how soils respond to liming. The response of soil pH from liming is different in the mineral and organic horizons (Reid & Watmough, 2014). Initial Ca^{2+} pools are greatest in the forest floor after liming (Melvin et al., 2013), and there is often a declining concentration with increasing depth (Jansone et al., 2020). Soil texture can also play a role in the response from liming as pH increases more in sandier soils than soils with higher clay content in agricultural production systems (Li et al., 2018). Clay-dominated soils have a greater cation exchange capacity (CEC) and buffering capacity (Ross et al., 2008) and are less susceptible to changes in soil acidity. Significant differences from liming in different forest stands can be attributed to different soil texture; however, other factors may affect the response (Jansone et al., 2020). Greater response of soil pH from liming occurred in soils with an initial pH < 4.5 (Reid & Watmough, 2014), potentially due to the increased dissolution of lime in more acidified soils (Jansone et al., 2020).

(2) Stand Type

Tree species composition affects the liming response, and stands dominated by hardwood may behave differently than those dominated by softwood. Different stand types may respond differently to lime addition; for example, in softwood stands, %BS had the greatest increase in mineral soils with ≥ 10-year response time, whereas, in hardwood stands, %BS had the greatest increase with larger application rates (Reid & Watmough, 2014).

Sugar maple is a calcium sensitive species (Sullivan et al., 2013; Wilmot et al., 1995) and will often respond more positively than less Ca^{2+} sensitive tree species such as black cherry or American beech (Long et al., 2011).

(3) Time Since Application

It can take several years for significant changes in soil chemistry in response to liming to occur; however, some studies have found increases in soil pH in the upper forest floor horizons or top 5 cm of soil after one-year (Eriksson et al., 1998; Fowler et al., 2022; Long et al., 1997). The timing of the peak effect following liming is variable. For example, Johnson et al. (2014) indicated that peak forest floor Ca^{2+} levels occurred three years after treatment. At some sites, pH increased in the upper mineral soil three years after lime application (Cho et al., 2010; Moore et al., 2008), but peak Ca^{2+} levels likely did not occur until 7-10 years after liming (Court et al., 2018; Johnson et al., 2014). The dissolution rate of lime is the likely cause of differences in peak effect timing.

(4) Application Rate

Changes in pH are often directly related to lime application rates in which greater lime doses have resulted in longer-lasting effects on forest soil (Li et al., 2016; Moore et al., 2012). After 15 years, higher doses of 10, 20, and 50 t ha^{-1} nearly doubled the amount of foliar Ca^{2+} compared with lower doses of 0.5, 1, 2, and 5 t ha^{-1}, and pH remained < 5 for the lower doses while soil pH was > 5 for higher dose rates (Moore et al., 2012).

(5) Amendment Type

The types of Ca^{2+} amendments often used in forest liming trials include calcite ($CaCO_3$), dolomite ($CaMgCO_3$), wollastonite ($CaSiO_3$), calcium chloride ($CaCl_2$), and wood ash. Calcite and dolomite are commonly used, and dolomite has a slightly greater acid neutralizing capacity but weathers slower than calcite (Clair & Hindar, 2005). Calcium chloride was applied over four years at the Hubbard Brook Experimental Forest (HBEF) until replaced by wollastonite, a silicate mineral that weathers slower than calcite and dolomite (Huggett et al., 2007). Selection of liming materials is often based on availability and the overall purpose of the trial. For example, calcitic limestone may be best suited if soils contain low concentrations of Ca^{2+} but sufficient Mg^{2+}. In addition to treatment type, smaller particle sizes dissolve faster because of their higher surface area (Huang et al., 2007), and smaller particle size distribution will likely increase the response rate of soil to lime.

Table 1. Summary of soil chemical changes after liming and the length of the study. Studies are from different locations and use varying liming materials and doses.

Years Since Liming	Event
≤1	Decreases in ionic Al^{3+} in the soil solution of upper soil horizons (Long et al., 1997; Shao et al., 2015)
	Increases in soil pH in the upper forest floor horizons (Long et al., 1997).
	Increases in Ca^{2+} (Cho et al., 2010; Long et al., 1997) and Mg^{2+}at a depth of 0-5 cm (Long et al., 1997).
	Decreases in total acidity in the upper mineral soil (Cho et al., 2010).
	Increase in forest floor Ca^{2+}, pH, and decrease in Al^{3+} (Fowler et al., 2022)
2	Increases in pH, CEC, and %BS, and decreases in exchangeable acidity (Blette & Newton, 1996)
3	Increases in exchangeable Ca^{2+} in the forest floor and upper mineral soils (Cho et al., 2010; Long et al., 1997; Shao et al., 2015).
	Decreases in acidity and Al^{3+} in forest floor and upper mineral soil (Cho et al., 2010).
	Peak increase in Ca^{2+} in forest floor horizon (Johnson et al., 2014).
	Increases in exchangeable Ca^{2+}, Mg^{2+}, %BS and greater ANC in the forest floor (Moore et al., 2008).
	Increases in Mg^{2+} and pH at depths up to 15 cm (Long et al., 1997).
5	Increases in Ca^{2+}, Mg^{2+}, pH, CEC and decrease in Fe^{3+} in forest floor and increases in Ca^{2+}, Mg^{2+}, and Mn^{2+} in mineral horizons (Houle et al., 2002)
7	The peak increase in Ca^{2+} and a significant increase in %BS in upper mineral soil. Decrease in SOM content (Johnson et al., 2014).
8	Increases in Ca^{2+} and Mg^{2+} up to 45cm deep and increases in %BS, pH, and CEC in upper horizons (Ingerslev, 1997)
10	Effects of lime (increased pH and Ca^{2+}) peak at 10 years and begin to decline thereafter (Court et al., 2018)
	Increases in exchangeable Ca^{2+}, Mg^{2+}, and %BS with greater ANC in forest floor and mineral horizons (Moore et al., 2008)
11	Increases in Ca^{2+} concentrations in soil (Traaen et al., 1997)
	Maintenance of significant increase in %BS in upper mineral soil (Johnson et al., 2014)
12	Increases in soil solution Ca^{2+} and decrease in soil solution ionic Al^{3+} throughout soil profile (Shao et al., 2015).
15	Continued shift from exchangeable to organically bound Al^{3+} in forest floor and upper mineral soil (Gu et al., 2017)
	Increases in pH, Ca^{2+}, Mg^{2+}, and %BS while carbon (C), SOM, N, K^{+}, and Na^{+} decreased (Moore et al., 2012).
16	Increases in pH, CEC, Ca^{2+}, and %BS and decrease in total acidity and Al^{3+} in forest floor and upper mineral soil (Lofgren et al., 2009)

Table 2 Con't.

Years Since Liming	Event
19	Elevated Ca^{2+}, pH, C, and N and decreased soil respiration and mineralization (Melvin et al., 2013)
21	Increases in Ca^{2+}, Mg^{2+}, pH and decreases in Al^{3+}, Mn^{2+} persisted in the top 0 - 15 cm, and increases in Ca^{2+}, Mg^{2+}, and pH were evident in the 15-45 cm horizons (Long et al., 2015)
	Increases in pH, Ca^{2+}, and Mg^{2+} in forest floor and upper mineral soil (Saarsalmi et al., 2011)
25	Increases in Ca^{2+} and reduced Al^{3+} persists. Decrease in C and N pools throughout soil profile (Persson et al., 1995). Restored buffering capacity of soil, increased pH, and decomposition of OM (Siepel et al., 2019).
30	Sustained increases in Ca^{2+} and Mg^{2+} in the top 45-55 cm of soil (Long et al., 2022)

1.1.6.3 Tree Species Response to Liming

Soil chemical changes in response to liming have often been accompanied by improvements in tree growth, health, and productivity. Long-term terrestrial liming studies at the HBEF in New Hampshire, US, the Duchesnay Experimental Forest in Quebec, CA, and the Alleghany Plateau in Pennsylvania, US, provide some insight into the effects of liming on forests in the region (Table 2). These sites were emphasized here because the impact from acid deposition and stand characteristics may be similar to those in Nova Scotia because of similarities in climate and soil formation

Table 3. Summary of significant findings for forest liming trials at three different locations in northeastern North America. All percent increases are relative to a control unless otherwise stated. All findings are for sugar maple stands unless otherwise stated.

Studies	Location	Treatment	Significant Findings
Moore et al., 2000; Moore & Ouimet, 2006; Moore et al., 2012 Moore & Ouimet, 2010; Moore & Ouimet, 2014 Ouimet et al., 2008; Duchesne et al., 2013 ; Moore & Ouimet, 2021	Duchesnay Experimental Forest, Quebec	Dolomite was applied manually at 0, 0.5, 1, 2, 5, 10, 20, and 50 t/ha.	- Basal area increment (BAI) increased by approximately 40-95% across all application rates 10 years after treatment. - BAI mean over all treatments was approximately 80% ten years after treatment. - Mortality decreased, and foliar Ca and Mg and BAI increased 20 years after liming. BAI increased from 93-144% over 20 years, 127% greater than the control (low doses).
		Calcite and $CaSO_4$*$H_2$0 were applied manually at rates of 1, 2, and 4 t/ha.	- BAI increased by 37%, 52%, and 56% compared to untreated sites 3 years after treatment. - BAI increased 25%-36% 7 years after treatment. - Forest dieback decreased in treated sites.
		Calcite was applied manually at 0.4 and 0.8 t/ha and K_2SO_4 X $CaMgCO_3$ at a rate of 0.886 t/ha.	- BAI more than doubled ten years after treatment.
		Calcite was applied manually at 3 t/ha.	- Saplings increased in growth by 38%.
Juice et al., 2006; Battles et al., 2014; Shao et al., 2015; Fahey et al., 2016	Hubbard Brook Experimental Forest, New Hampshire	Wollastonite was applied at a rate of approximately 1 t/ha by helicopter.	- Tree dieback decreased. - Aboveground forest biomass recovered. - Crown health improved. - Fine root biomass decreased due to resource allocation to above ground biomass.
Huggett et al., 2007; Halman et al., 2013		Calcium chloride was applied each year for 4 years for a total of 0.2 t/ha in addition to the $CaSiO_3$ application.	- Tree growth increased significantly 2 years after treatment. - Fine root concentration increased in Ca^{2+} treated sites, - Flowering increased in Ca^{2+} treated sites.
Long et al., 1997; Long et al., 2011; Long et al., 2015; Long et al., 2022	Alleghany Plateau, Pennsylvania	Calcite was applied at a rate of 22.4 t/ha by conventional tractors and spreaders.	- BAI increased by 11% compared to only 4% at control sites. - BAI more than doubled after 20 years. - Increased BAI in sugar maple was sustained after 30 years.

1.1.6.4 Ground Vegetation Response to Liming

Liming can increase ground vegetation species abundance and richness and change the understory community. Following liming, species richness often increased with increasing pH (Dulière et al., 1999; Zarfos et al., 2019) and Ca^{2+} concentrations and biomass in forbs in the herb layer increased (Pabian et al., 2012). Additionally, changes in ground vegetation communities along an acidity gradient were observed in a northern hardwood forest (Zarfos et al., 2019), often associated with a decrease in the abundance of acidophilic species (Duliere et al., 1999). Studies in Europe have linked increases in pH and Ca^{2+} concentrations with increased abundance of grass and vascular plant species (Rodenkirchen, 1992; Hallbacken & Zhang, 1998). Some moss species, such as Schreber's moss, have a wide habitat range (Wyatt & Stoneburner, 1982) and has been referred to as an acidic soil indicator by Crum & Anderson (1981). Other common vegetation, such as wood fern, has been experiencing decreases in Ca since the 1990s at the HBEF (Likens et al. 1998).

1.1.6.5 Potential Risks of Liming

Despite improvements in tree health, sugar maple growth, and red spruce growth, liming may not positively affect all forest ecosystems. No improvements in BAI of American beech and decreases in BAI of black cherry were observed in Pennsylvania 23 (Long et al. 2011) and 30 years after treatment (Long et al., 2022) Pennsylvania. The decrease in BAI may be due to insect pressure. Similarly, American beech had little response to liming in Quebec, likely because this species is less acid sensitive than sugar maple (Duchesne et al. 2013). No significant increases in tree growth were observed in a Scots pine forest in Norway 35 years after lime treatment despite increases in Ca^{2+} and decreases in Al^{3+} concentrations in needles. However, changes in tree growth may not have been detectable due to a lack of replicates (Borja & Nilsen, 2009). No significant increases in Norway spruce and Scots pine occurred six years after liming (Hindar et al. 2003). However, these studies were conducted on commercial tree species, and there was no negative impact on the tree species. The lack of effect may result from different site conditions and/or limiting nutrients (e.g., N). Despite the lack of evidence of increased growth in all tree species, increases in tree BAI for sugar maple have been observed (Long et al., 2022; Moore et al., 2021). In addition, tree growth may not be an indicator of improved overall ecosystem health.

Negative impacts of liming in acidophilic environments such as wetlands and lakes have been observed. Stunted growth and decreased abundance of Sphagnum species in Sweden occurred four years after liming (Eriksson et al., 1983). Adding lime to wetlands in Sudbury, Ontario, increased pH, base cations, and mortality of hair-cap moss species (Gunn et al., 2001). In Norway, damage to Sphagnum species and a lichen species was observed (Traaen et al.,1997). Stem elongation of clubmoss species was reduced after liming (Brach & Raynal, 1992). However, the effect of lime on vascular plant species such as wood sorrel (*Oxalis acetosella*) and some weed species has been positive or negligible (Brach & Raynal, 1992).

Decreases in K concentration in tree tissue have been observed in response to Ca and Mg additions. Comparison of nutrient ratios using the diagnostic and recommendation integrated system (DRIS) for sugar maple have shown reductions in K foliar concentration, potentially leading to K deficiencies (Côté et al., 1995; Long et al., 1997; Moore et al., 2012). The authors of these studies have attributed the K deficiencies to the antagonistic relationship between Ca and K and/or Mg and K.

Carbon and N pools in forest soil can be reduced from liming. For example, in spruce and beech stands in Sweden, C and N pools decreased significantly, mainly in the litter layer, 40 years after liming 9 – 10 t ha^{-1} of $CaCO_3$ (Persson et al., 1995). The authors attributed this loss of C and N to increased mineralization and movement of organic matter to lower horizons. Likewise, Kreutzer (1995) found significant decreases in C cycling in response to lime and increased nitrification, leading to increased rates of NO_3^- leaching. In contrast, forest liming in Adirondack Park, New York, had the opposite effects in which C and N stocks increased (Melvin et al., 2013). Significant increases, decreases, and no significant differences in forest floor C were observed in forested sites in Sweden 40 years after liming (Persson et al., 2021), indicating high variability of C dynamics in the forest floor in response to liming. Variability of C and N stocks response to liming suggests that the response may depend on individual site characteristics, the specifics of which are not well understood.

Micro and macro biological communities can also shift in response to liming. The abundance and richness of microbiological species decreased four years after liming with 2.5 t ha^{-1} in France (Clivot et al., 2012). The decrease was attributed to declines in acidophilic bacteria. Similarly, declines in soil decomposers were found in hardwood forests in Quebec two years after liming (Chagnon et al., 2001). Improved %BS and pH of soils in Quebec have resulted in an increased abundance of invasive earthworm species, leading to increased SOM turnover and soil carbon dynamics (Moore et al., 2013). However, initial decreases in species richness and abundance of macro and microflora and fauna may not necessarily be a negative impact. Shifts in species composition could be interpreted as a positive response if the shift returned to pre-acidified conditions. Pre-acidified conditions were unknown; therefore, whether these changes are positive or negative is not conclusive.

Many potential risks from forest liming can be mitigated if site selection is strategic and avoids wetland habitats (Moore et al., 2015). The benefits of liming often outweigh the risks, and the adverse effects of liming are often smaller than natural variation (Foster et al., 1995). Risks of liming may differ based on the site; therefore, long-term liming studies which evaluate different physical, biological, and chemical parameters are valuable to help predict long-term responses to liming across different site types.

Table 4. Some benefits and risks associated with liming forest stands.

	Benefits	**Risks**
Overstory	• Increase in health and growth of sugar maple • Increase in cold tolerance of red spruce • Decrease in mortality • Decrease in crown dieback of sugar maple • Decrease in susceptibility to pests and diseases	• Decrease in the abundance of Black cherry • Antagonistic relationship between Mg^{2+} and K^+ and Ca^{2+} and K^+ in foliage.
Understory	• Increase of Ca in grazing shrubs • Increased seedling survival • Potential shift to pre-acidified conditions	• Decrease in abundance and health of acidophilic moss species such as sphagnum • Antagonistic relationship between Mg^{2+} and K^+ and Ca^{2+} and K^+
Soil Chemistry	• Increase in Ca^{2+} and Mg^{2+} • Increase in soil pH • Increase in Base saturation • Decrease in toxic mobile Al^{3+}	• Decrease in SOM through increased mineralization
Soil Biology	• Increase in microbial productivity	• Increase in invasive earthworm species. • Decrease in abundance and richness of microbial community

1.1.6.6 Liming Costs

Decreased forest productivity from terrestrial acidification has negatively impacted economies, such as the forest industry, the maple syrup industry, and tourism. Survey studies in the 1980s suggested an overall 5% productivity decline in Canadian forests likely associated with acidic emissions (Fraser et al., n.d.; Phillips & Forster, 1987). Crocker & Forster (1986) estimated that a 5% decline in forest productivity would equal a loss of CAD 197 million in wood products and an additional CAD 1.3 billion loss for wildlife habitat and recreation. A more recent report from Smith & McDougal (2017) emphasized the difficulty of estimating the economic impact of acid deposition on forests because of the many variables; however, they identified that there were hundreds of billions of dollars of assets at risk.

Studies in North America evaluated the costs associated with losses from acidic pollution in forests in the Adirondack region by comparing the value of hardwood forest stands on well-buffered and poorly buffered soils (Beier et al., 2017; Caputo et al., 2016). Hardwood forests on poorly buffered soils were worth approximately half that of forests on well-buffered soils (Beier et al., 2017). Similarly, decreases in forest production were found at %BS < 12% (Caputo et al., 2016). Ouimet et al. (2018) estimated the value of liming on timber and sugarbushes in Quebec and showed that liming was not profitable for lumber production, with a discount rate (the interest rate used to calculate the net present value) greater than 0%; however, liming was profitable for maple syrup production after 20 years at a discount rate of up to 4%.

1.1.7 Potential for Liming in Nova Scotia

Slow recovery from acid deposition and the continued negative impacts of BCD is widespread across northeastern North America, and forest liming has benefited many of those areas. Nova Scotia, Canada, is a good location to study forest liming because:

- Nova Scotia has been highly impacted by acid deposition, with approximately 8-20 kg ha^{-1} yr^{-1} of SO_4^{2-} wet deposition and 6 – 15 kg ha^{-1} yr^{-1} of NO_3^- wet deposition recorded in 1990 (CCME, 2013). Exceedance of N and S critical loads was evident in many areas of the province even 10 years after legislated reductions in acid-causing emissions (NEG-ECP 2007) (Figure 3).

- Nova Scotia has naturally acidic soils with a low buffering capacity. The average base saturation of the two most dominant soil series in NS (Halifax and Gibraltar) is below 10% (Whitfield et al., 2006).
- Improvements in soil acidification status have been negligible in NS. A recent study in Kejimkujik National Park suggested that there have been little to no improvements in base cation or Al^{3+} chemistry over the last 20 years (Keys, 2018).
- Calcium is often the limiting nutrient in red spruce and sugar maple stands in Nova Scotia (Keys et al., 2016).
- Low base saturation levels are predicted throughout eastern, western, and southern NS (Figure 3).

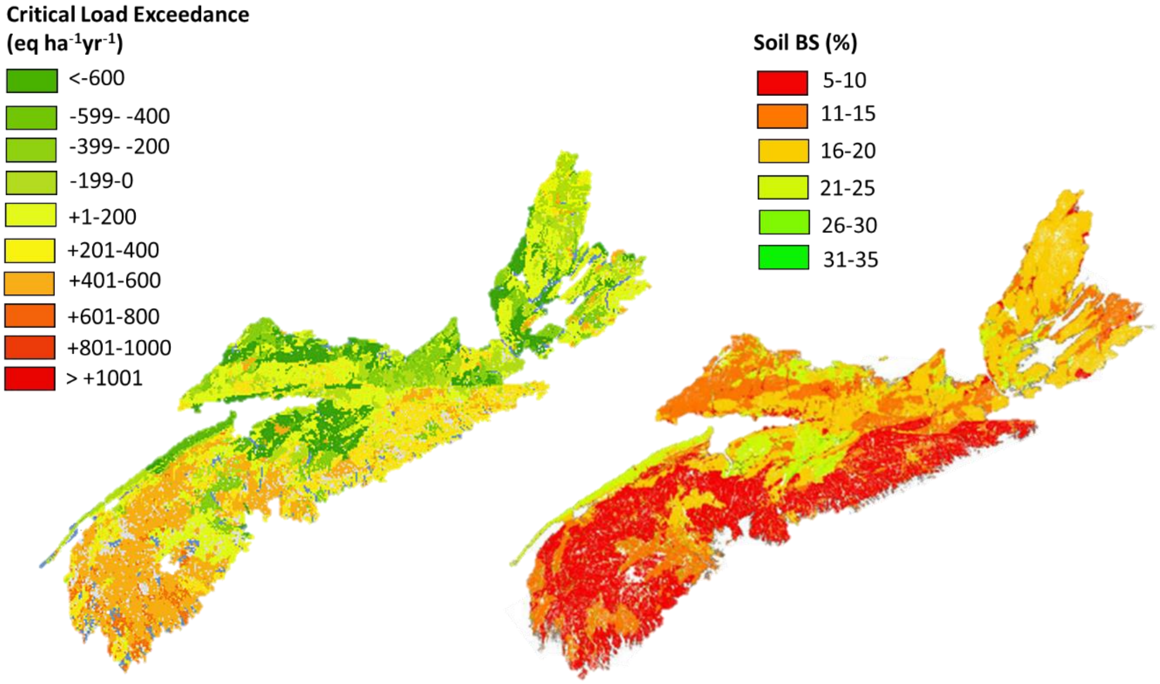


Figure 3. Critical load exceedances (left) for Nova Scotia derived from deposition data in 2002. Positive values indicate an exceedance of critical loads, and negative values indicate loading below critical loads. Critical loads are the amount an ecosystem can withstand N and S deposition before harmful effects are detected (CCME, 2013). Soil base saturation (%) (right) for Nova Scotia derived from recent forest soil assessments published in 2016 (Keys et al., 2016).

Previous liming trials in NS using hand application of lime in forests have monitored the impact on surface water (Sterling et al., 2014). Still, the effects of lime on terrestrial forested ecosystems have not been assessed in Nova Scotia. In-stream and helicopter liming are currently being conducted to evaluate the impact on acidified surface waters; however, the results are only preliminary.

1.2 Knowledge Gaps and Research Objectives

Terrestrial liming is a tool that could help initiate the reversal of soil acidification in Nova Scotia; however, there remain key gaps in our knowledge of forest liming, such as the distribution of liming via helicopter, the evaluation of impacts of terrestrial liming in Nova Scotia, specifically, the short-term (one-year) and longer-term response of soil chemistry under Nova Scotia conditions, and the feasibility of helicopter liming. Here, I aim to increase knowledge on terrestrial liming through establishing and analyzing the pretreatment conditions and the first year after treatment of a long-term research trial with the Nova Scotia Department of Natural Resources and Renewables that added 10 t ha^{-1} of dolomitic limestone by helicopter to an acidified red spruce stand and northern hardwood stand. The data collected in this project can be used as potential predictors for longer-term trends in response to liming. I consider different aspects of helicopter liming such as the method, the response, and the potential economic benefits, to provide insight on the use of liming as a forest management tool. My research aims to address terrestrial liming knowledge gaps in Nova Scotia by answering the following research questions:

RQ1. What are the main factors affecting helicopter application of 10 t ha^{-1} of dolomitic limestone and the uniformity of application? This question is addressed in chapter 2.

RQ2: Does terrestrial liming improve soil acidification status, such as increased soil %BS, Ca^{2+}, Mg^{2+}, and decreased mobile Al^{3+}, in two mature acidified forest stands in Nova Scotia? This question is addressed in chapter 3.

RQ3: Does terrestrial liming increase Ca and Mg concentrations, decrease Al concentration, and improve overall nutrient status in red spruce, sugar maple, red maple, and ground vegetation in two mature acidified forest stands in Nova Scotia? This question is addressed in chapter 3.

RQ4: Do the potential increases in growth and health in red spruce and sugar maple trees from liming outweigh the operational costs of helicopter liming in Nova Scotia? This question is addressed in chapter 4.

To answer these research questions, four forest research sites were established at the Otter Ponds Demonstration Forest (OPDF) in Mooseland, NS. The sites were established with the Nova Scotia Department of Natural Resources and Renewables. We established one treatment and control site with multiple plots at two forest types and used a before-after-control-impact (BACI) experimental design. Data and samples were collected before treatment and approximately one year after treatment. Research questions 1 and 4 focus on the operational use of helicopter liming in NS, while research questions 2 and 3 aim to increase our scientific understanding of the effects of terrestrial liming in acidified forests.

1.3 Outline and Interrelationship of Chapters

This thesis has three research chapters and three appendices. Chapters 2, 3, and 4 address one or more of the research questions and objectives listed above.

Chapter 2: *An Assessment of Helicopter Liming Methods in an Acidified Forest Site in Nova Scotia.* This chapter discusses my research on the distribution of dolomitic limestone by helicopter over two acidified forest stands in Nova Scotia and the factors contributing to the uniformity of lime distribution.

Chapter 3: *Early Effects of Helicopter Liming on Soil and Vegetation in Two Acidified Forest Stands in Nova Scotia, Canada.* This chapter discusses my research on soil chemical and plant tissue changes in two acidified forest stands one year after liming.

Chapter 4: *Helicopter liming value in Nova Scotia red spruce and sugar maple dominated stands on acid-sensitive soils.* This chapter discusses my research on the cost of helicopter application of dolomitic limestone in acidified forest stands and the potential value of liming in red spruce and sugar maple stands in Nova Scotia.

Appendix 1: *Supplementary Information for Chapter 2.*

Appendix 2: *Supplementary Information for Chapter 3.*

Appendix 3: *Supplementary Information for Chapter 4.*

Appendix 4: Stand characteristics at the Otter Ponds Demonstration Forest and baseline forest health growth, and regeneration results

The methods described in the following sections are for chapters 2, 3, and 4 of this thesis. Additional methods are described in each chapter.

1.31 Study Sites

The study sites are located in the OPDF in Mooseland, NS (44°56’18.68”, 62°46’15.16”), approximately 74 km east of Halifax (Figure 4). The mean annual temperature (1981-2010) is approximately 6.4°C, and the mean annual precipitation (1981-2010) is approximately 1,360 mm year $^{-1}$ (Environment Canada, 2021).

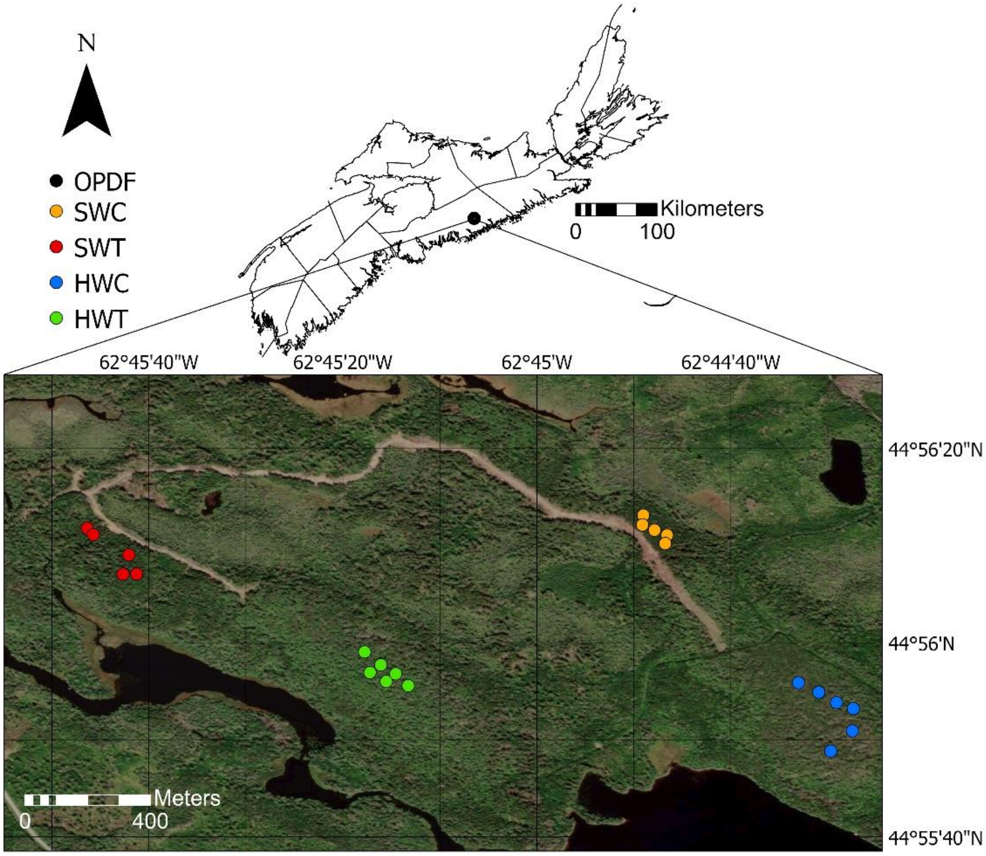


Figure 4. Location of the Otter Ponds Demonstration Forest (OPDF) in Mooseland, NS, with the control and treatment plots in which SWC is the softwood control site, SWT is the softwood treatment site, HWC is the hardwood control site, and HWT is the hardwood treatment site. Circles represent plot locations within each site.

1.3.2 Experimental Design

This study had a BACI design with one control and one treatment site in two different forest cover types. The two forest cover types selected were (1) a softwood stand dominated by red spruce and (2) a northern hardwood stand dominated by red maple and sugar maple. These stands were selected because they were accessible and contained red spruce and sugar maple, two commercially important tree species in Nova Scotia that can be strongly impacted by acid deposition (Driscoll et al., 2001). Control and treatment sites within each cover type were chosen for similarities in geographic features, forest cover, and soil type.

Growth plots were established at each site using the Nova Scotia Forest Inventory Permanent Sample Plot (PSP) protocol (NSDNR, 2006). Circular growth plots were used to measure tree growth, mortality, and health over time. Plot centers were randomly selected using ArcGIS software. Six growth plots were established at each hardwood site with a plot radius of 11.3 m, and five growth plots were established at each softwood site with a plot radius of 10.3 m (Table 4). The number of plots and plot sizes varied depending on the size of the site and tree density. The hardwood sites were larger and had a lower tree density; therefore, greater plot size and plot number were selected. Living trees within each growth plot with a diameter at breast height (DBH) ≥ 8.1 cm were labelled in numeric order using spray paint (Figure 5). A one-time treatment of dolomitic limestone was applied at a target rate of 10 t ha^{-1} via helicopter in October 2018 (Figure 6).

Table 5. Summary of the number of plots, plot radius, area, and tree count at each site at the Otter Ponds Demonstration Forest in which SWC is the softwood control site, SWT is the softwood treatment site, HWC is the hardwood control site, and HWT is the hardwood treatment site.

Site	**Number of plots**	**Radius**	**Area (ha)**	**Number of trees within plots**
SWC	5	10.3	0.037	413
SWT	5	10.3	0.037	327
HWC	6	11.3	0.040	263
HWT	6	11.3	0.040	269

Figure 5. Typical softwood stand dominated by red spruce (left) and hardwood stand dominated by red maple and sugar maple (right) at the Otter Ponds Demonstration Forest.

Figure 6. Loading lime from a front-end loader into a lime hopper (left) and lime deposition by helicopter over a red spruce stand (right) at the Otter Ponds Demonstration Forest in October 2018.

Chapter 2 – An Assessment of Helicopter Liming Methods in Acidified Forests in Nova Scotia.

2.1 Introduction

Acidified forest soils have not recovered as expected following the reduction of acid deposition (Driscoll et al., 2001; Lawrence et al., 2016). Therefore, intervention via the addition of base cations is needed to encourage ecosystem recovery (Lawrence et al., 2016). One method to rapidly apply base cations to remote forested areas is helicopter applications. The application of limestone products via helicopters, aka catchment liming, has been commonly used to de-acidify surface waters (Clair & Hindar, 2005) and recover soils from BCD (Lawrence et al., 2016). The advantages of liming via helicopter include access to remote locations, rapid widespread coverage without additional disturbances to forests, such as felling for access trails, the use of less liming materials, and a lower application frequency (Clair & Hindar, 2005). Despite the advantages of helicopter liming, the high upfront capital costs can be prohibitive. Other application methods, such as manual application (Moore et al., 2000; Sterling et al., 2014) and tractor and spreader application (Long et al., 1997) have been used in terrestrial liming research trials (Section 1.1.6).

Helicopter liming of whole catchments has been extensively conducted in Sweden (Henrikson & Bodin, 1995; Lofgren et al., 2009) and Norway (Hindar et al., 1996; Traaen et al., 1997). In northeastern North America, helicopter liming trials have been less common; however, projects have been conducted at the Woods Lake Watershed in New York in 1989 (Melvin et al., 2013) and the HBEF in New Hampshire in 1999 (Battles et al., 2014; Juice et al., 2006; Shao et al., 2015).

Although projects usually endeavour to distribute lime over the target area as uniformly as possible, the distribution of lime after helicopter liming can be variable. For example, studies in Sweden indicated that 70-80% and 50-60% of lime landed where it was targeted (Henrikson & Bodin, 1995). Similarly, Driscoll et al. (1996) indicated that actual loading rates varied from 3.42 t ha^{-1} to 7.85 t ha^{-1} despite a 10 t ha^{-1} anticipated application rate. Environmental factors, mainly wind, often cause a non-uniform lime application (Driscoll et al., 1996; Henrikson & Bodin, 1995). A more recent large-scale trial at the HBEF applied 4.6 metric tons ha^{-1} of wollastonite by helicopter (Peters et al., 2004; Fiorentino et al., 2003). This study suggested a uniform distribution (Fiorentino et al., 2003); however, no data on distribution uniformity was available.

Helicopter liming provides an opportunity to carry out large-scale restoration of acidified forests (Battles et al., 2014; Huggett et al., 2007; Juice et al., 2006); however, there is a gap in knowledge of the uniformity of lime distribution of this application method. Here we answer RQ1: What are the main factors affecting helicopter application of 10 t ha^{-1} of dolomitic limestone and the uniformity of application?

2.2 Methods

Uniformity of lime distribution was estimated using 12 collection boxes (approximately 91 cm x 61 cm) throughout each site; one near each growth plot center and a second randomly distributed within a 15 m radius around the plot. Each box was levelled to the ground, and the lime within each box was collected immediately after application (Figure 7). A picture of the canopy at each box location was taken, and percent crown closure was estimated using MATLAB for canopy image analysis and code developed by Korhonen and Heikkinen (2009). Percent crown closure estimates were used to estimate any lime that may have been trapped in the canopy after application.

Figure 7. Lime collection box being levelled at the hardwood treatment site in the Otter Ponds Demonstration Forest in Mooseland, NS.

2.2.1 Chemical and Physical Analysis of Lime

Lime samples from each collection box were dried and weighed to obtain the approximate amounts deposited at each location. Lime samples from the collection boxes were analyzed at AGAT Laboratories in Dartmouth, NS. Base cations and available metals were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) (AGAT Laboratories, n.d.). Additional lime samples from before helicopter application were collected to help provide insight on the lime particle sizes that reached the forest floor immediately after liming. Particle size distribution of lime before and after deposition was determined using sieve analysis.

The lime collection method was subject to variability because liming occurred over several days, rain impacted the collection, and leaves and needles impacted the weights of the lime. As a result, the absolute lime distributions may not be accurate; however, because all the samples were collected at a similar time and with the same method, the relative values provide a good indication of the total amount deposited after liming.

2.2.2 Spatial Interpolation

Spatial interpolation of lime distribution was performed to estimate the amount of lime deposited throughout each treatment site. Several interpolation methods were considered for analyzing the helicopter spatial data, and cross-validation was performed using the Leave One Out Method (LOOCV) to determine the best method. Spline and inverse distance weighting (IDW) spatial interpolation methods had the lowest root-mean-square error (RMSE). Inverse distance weighting and spline are common methods used in ecology and can detect changes within small sample sizes (Bronowicka-Mielniczuk et al., 2019; Simpson & Wu, 2014). A study on sedimentation found that spline was the most accurate interpolation method compared to IDW when n = >70. However, when the sample size was reduced to approximately n = 17, IDW was the most accurate (Simpson & Wu, 2014). Inverse Distance Weighting was used in this study because it works well with smaller samples sizes, is easy to use, and uses neighbouring points to calculate values which is likely the most accurate in the case of helicopter liming (Bronowicka-Mielniczuk et al., 2019). In addition, IDW can perform better when using selective sampling techniques instead of grid sampling (Zhang et al., 2015) and is commonly used for sparse data and irregularly spaced samples (Li & Heap, 2008).

Inverse Distance Weighting uses the principle that points closer together have more weight in determining the missing values than points further away (Li & Heap, 2008; Simpson & Wu, 2014; Isaaks & Srivastava, 1989; Johnston et al., 2001). The values in between known points are estimated using equation 6.

$$v = \frac{\sum_{i-1}^{n}\frac{1}{d_i}v_i}{\sum_{i=1}^{n}\frac{1}{d_i}} \qquad (6)$$

Where d_1, …, d_n represents the distance from each sample point n, and v_1,…, v_n are the estimated points (Isaaks & Srivastava, 1989). The IDW method was conducted using ArcGIS Pro version 2.5. Uniformity of lime distribution was analyzed on the lime raw data using the Chi-square test in RStudio version 3.6.1.

2.3 Results

2.3.1 Lime distribution

Lime deposition on the forest floor immediately after helicopter liming varied from 2.5 to 12.7 t ha^{-1} at the HWT site and 1.3 to 15.1 t ha^{-1} at the SWT site. The average lime dose between the two sites (n = 24) was 6.6 ± 0.7 t ha^{-1} (mean ± SE). Two boxes in each site exceeded the target of 10 t ha^{-1}, and four boxes in each site were below 5 t ha^{-1}.

Inverse distance weighting spatial interpolation model indicated that the distribution was variable throughout each site. Lime deposition at the HWT was not uniformly distributed throughout the site, with greater amounts in the northeastern part of the site (Figure 8). However, the chi-square test indicated that the differences in lime deposition were not significant (P = 0.11). Mean percent crown closure at the HWT site was 88 ± 1% (mean ± SE) (Figure 9) and did not differ significantly throughout the entire site (chi-square test, P = 0.997). There was no correlation between percent crown closure and lime distribution (correlation test, r = 0.10).

Lime deposition at the SWT site was not uniformly distributed throughout, with greater amounts in the southern part of the site (Figure 8). The differences in lime deposition were significant throughout the site (chi-square test, P = 0.004). Mean percent crown closure at the SWT site was

83 ± 1% (mean ± SE) (Figure 9) and did not differ significantly throughout the entire site (chi-square test, P = 0.998). There was no correlation between percent crown closure and lime distribution (correlation test, r = 0.18).

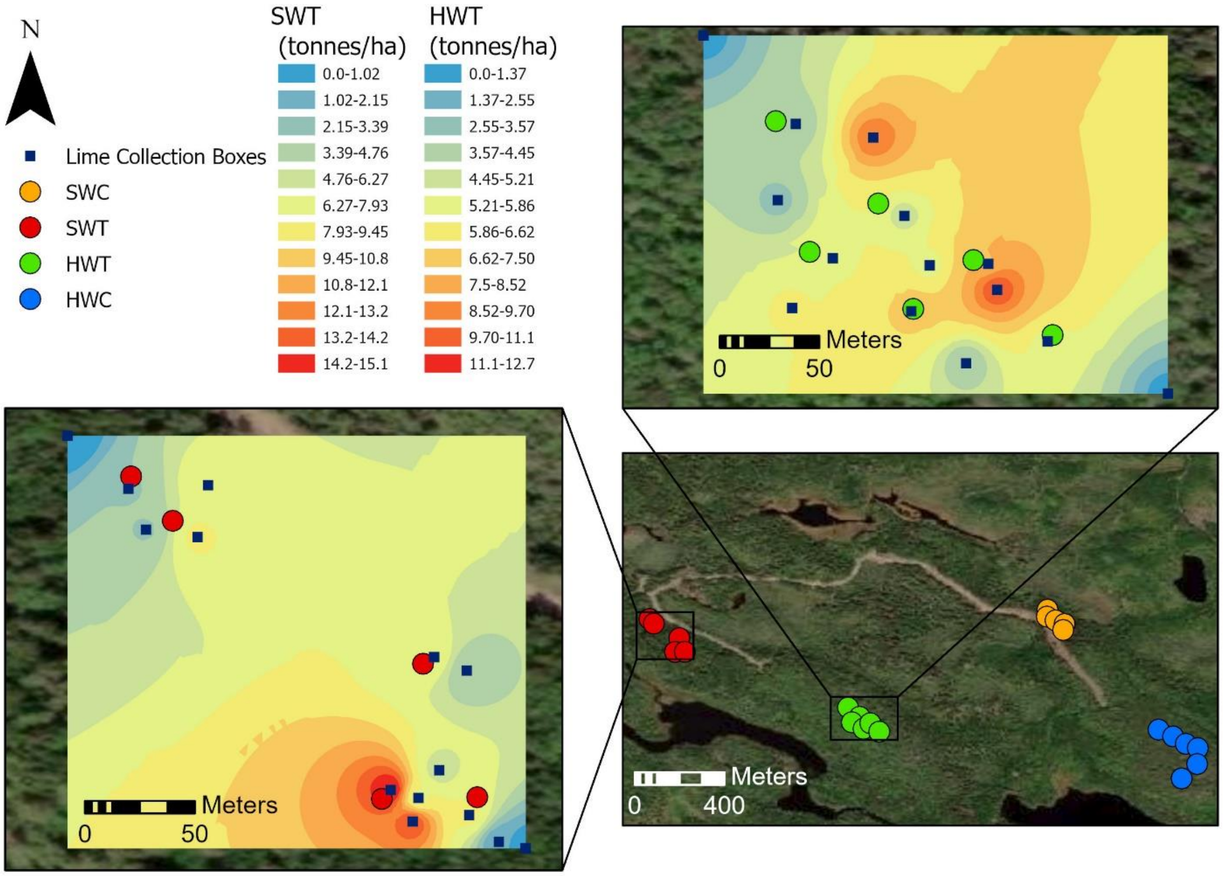


Figure 8. Estimated distribution of lime across treatment sites based on lime collection amounts in 24 collection boxes. Distribution was analyzed using inverse distance weighting spatial interpolation.

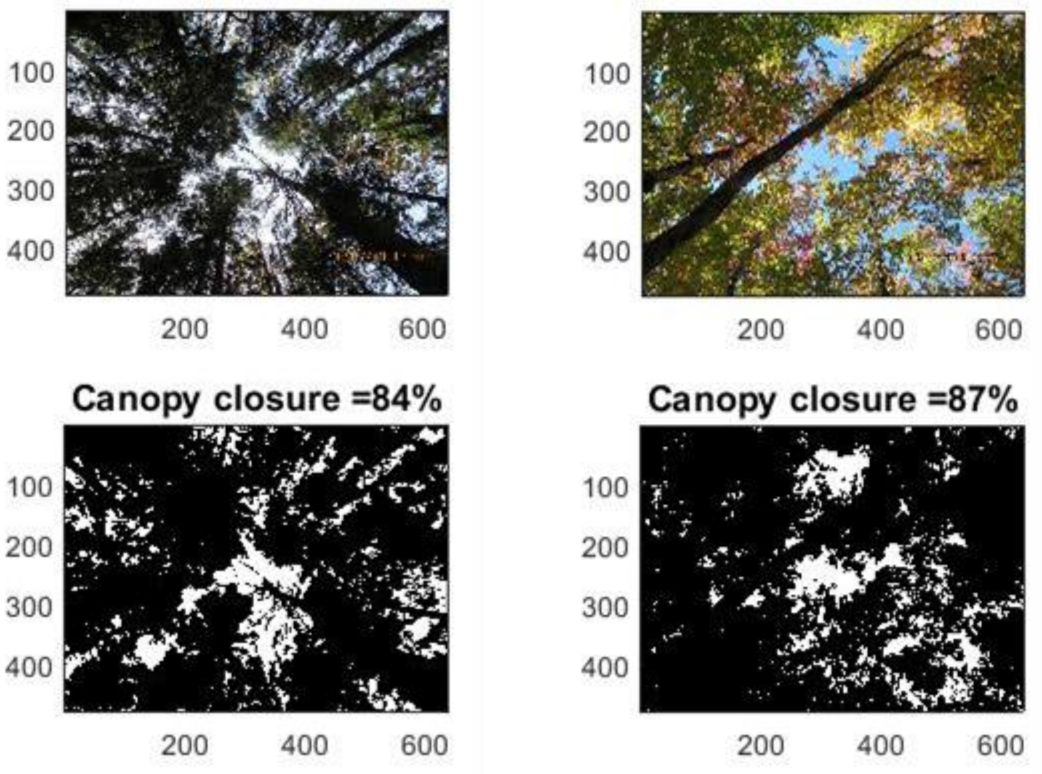


Figure 9. *Typical canopy closure at the SWT site (left) and the HWT site (right). Pictures were taken at the center of each lime box, and canopy closures were calculated with MATLAB codes developed by Korhonen and Heikkinen (2009).*

2.3.2 Chemical and Physical Analysis of Lime

The concentration of $CaCO_3$ in the powdered limestone amendment was approximately 39.4 ± 0.3% (mean ± SE), and the concentration of Ca^{2+} was approximately 15.7 ± 0.1%. The concentration of magnesium carbonate ($MgCO_3$) was approximately 32.8 ± 0.3% (mean ± SE), and the concentration of Mg^{2+} was approximately 9.4 ± 0.1%. The remaining constituents were a combination of sodium, potassium, carbon, and metals.

Table 6. Percent Ca^{2+}, $CaCO_3$, Mg^{2+}, and $MgCO_3$ concentrations at each lime box collected after liming at the OPDF. Assuming all Ca and Mg in dolomitic limestone is derived from $CaCO_3$ and $MgCO_3$, respectively.

Box	**%Ca^{2+}**	**%$CaCO_3$**	**% Mg^{2+}**	**%$MgCO_3$**
HWT 1A	16.0	40.0	9.45	32.8
HWT 2A	16.2	40.5	9.47	32.9
HWT 3A	16.1	40.3	9.82	34.1
HWT 4A	15.5	38.8	9.29	32.3
HWT 5A	15.7	39.3	9.15	31.8
HWT 6A	16.0	40.0	9.76	33.9
SWT 1A	15.7	39.3	9.61	33.4
SWT 2A	16.0	40.0	9.65	33.5
SWT 3A	15.0	37.5	8.82	30.6
SWT 4A	16.2	40.5	9.76	33.9
SWT 5A	15.8	39.5	9.38	32.6
SWT 5C	14.9	37.3	9.15	31.8

Based on the concentrations and distribution patterns described above, mean Ca^{2+} loading after application was approximately 705 ± 78 kg ha^{-1} and mean Mg loading was approximately 605 ± 98 kg ha^{-1}. The lime also had small amounts of $Al^{3+,}$ resulting in a mean loading of 8.1 ± 1.3 kg ha^{-1} across both treatment sites (Table 6).

Table 7. Lime collection box number and corresponding collection amount, cation concentration and relative cation distribution across the hardwood treatment (HWT) site and the softwood treatment (SWT) site.

Box	**Collection amount (t ha^{-1})**	**Cation Concentrations (kg t^{-1})**					**Cation Loading (kg ha^{-1})**				
		Ca^{2+}	Mg^{2+}	K^+	Na^+	Al^{3+}	Ca^{2+}	Mg^{2+}	K^+	Na^+	Al^{3+}
HWT 1A	3.2	160	94.5	1.68	0.5	1.26	512	302	5.4	1.8	4.0
HWT 2A	4.5	162	94.7	1.4	0.4	1.2	729	426	6.3	1.8	5.4
HWT 3A	5.5	161	98.2	1.22	0.4	1.23	886	540	6.7	2.2	6.8
HWT 4A	7.6	155	92.9	1.09	0.4	1.39	1178	706	8.3	2.8	10.6
HWT 5A	7.2	157	91.5	0.93	0.3	1.33	1130	659	6.7	2.4	9.6
HWT 6A	5.4	160	97.6	0.77	0.4	1.26	864	527	4.2	1.9	6.8
SWT 1A	3.3	157	96.1	0.65	0.3	1.09	518	317	2.1	1.0	3.6
SWT 2A	8.1	160	96.5	0.52	0.4	1.31	1296	782	4.2	3.3	10.6
SWT 3A	7.4	150	88.2	0.47	0.3	1.19	1110	653	3.5	2.2	8.8
SWT 4A	15.1	162	97.6	0.43	0.3	1.28	2446	1474	6.6	4.8	19.3
SWT 5A	8.1	158	93.8	0.37	0.3	1.21	1280	760	3.0	2.6	9.8
SWT 5C	1.3	149	91.5	0.37	0.3	1.2	194	119	0.5	0.4	1.6

Particle size distribution analysis of lime deposited on the forest floor and fresh lime (as delivered from the supplier) indicated that lime deposited on the forest floor at the HWT site did not contain any particles greater than 2 mm, while lime deposited on the forest floor at the SWT site did not contain any particles greater than 4 mm. By contrast, fresh lime samples contained particle sizes up to 16 mm (Figure 10).

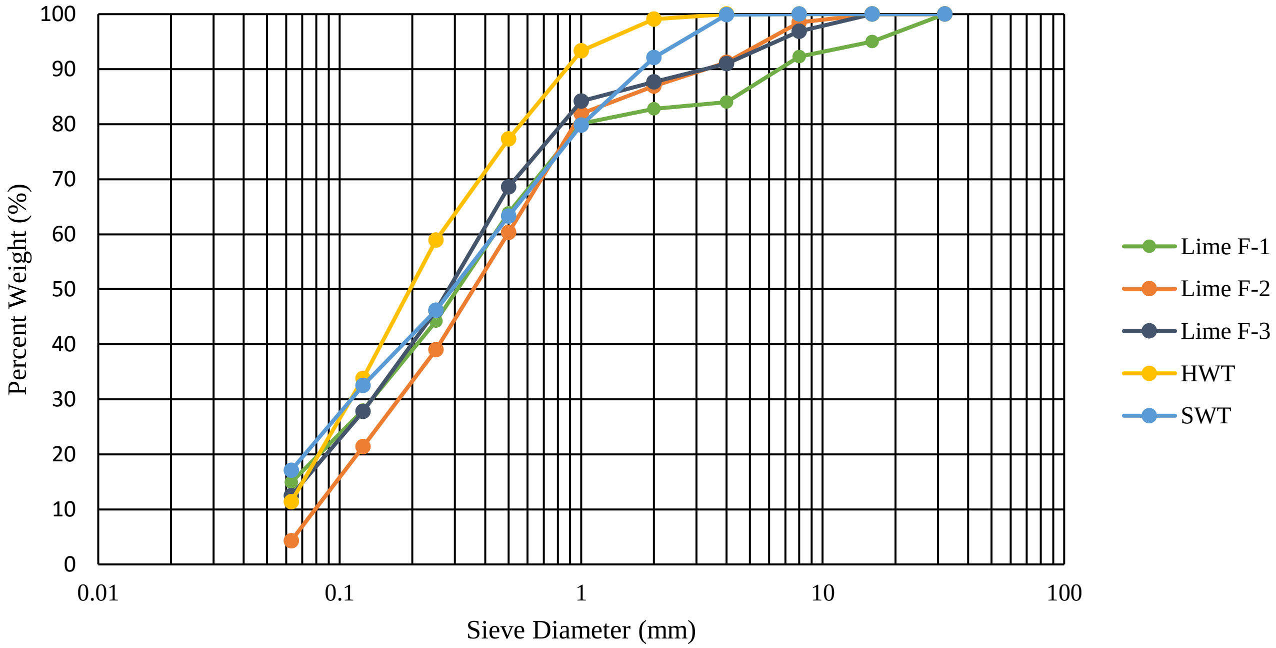


Figure 10. Particle size distribution of each lime sample in which HWT and SWT are the lime collected after deposition at the hardwood treatment and softwood treatment sites, respectively, and Lime F-1, F-2, and F-3 are fresh lime samples before deposition.

2.4 Discussion

Assessing the assumptions of aerial limestone treatment is important because it can help guide future liming studies or practical applications in forestry. Both the chemical composition of limestone and its distribution were different from expected, which may affect the response of forested ecosystems to liming. Typical dolomitic limestone samples contain 50-95% $CaCO_3$ and 4-40% $MgCO_3$ (Agricultural Limestone and Dolomite, 2015). Assuming that all Ca^{2+} is derived from $CaCO_3$ and all Mg^{2+} is derived from $MgCO_3$, Mg^{2+} concentrations are within range, but Ca^{2+} concentrations are lower than expected. The HWT and SWT samples did not have particles as large as the fresh lime samples. This indicates that larger particle sizes might have been caught up in the forest canopy, which is the reverse of what is expected as the larger and heavier particles were expected to retain more kinetic energy and thus penetrate the canopy further than smaller particles. Larger particle sizes may contain a higher concentration of Ca^{2+} and could explain the lower Ca^{2+} concentration found in throughfall samples. However, this intercepted lime should eventually reach the forest floor through litterfall, wind action, wet deposition after rain events, and stemflow.

The lime distribution at the SWT site was less uniform than that at the HWT site, which was contrary to what was expected since the SWT site had a more uniform canopy distribution (one dominant canopy class). The uneven distribution at the SWT site may result from the plot layout. Plots 1 and 2 are spaced further out from plots 3, 4, and 5 (Figure 4) because the area between them was a different aged stand. The target location for helicopter application was over two areas instead of one (like at the HWT site), potentially increasing application inaccuracy. In addition, IDW interpolation restricts analysis to the upper and lower ranges recorded; therefore, there may have been areas of higher dosage which were not recorded.

The lime distribution at the OPDF was not uniform, particularly at the SWT site. Few studies have looked directly at helicopter application of liming materials; however, Henrikson and Bodin (1995) and Driscoll et al. (1996) also indicated non-uniform distributions. There are several reasons why distribution may not be uniform: (1) difference in canopy closure, (2) high winds, and (3) operational efficiency. Canopy closure at both treatment sites was uniform, and no correlation was found between lime distribution and canopy closure. High winds ranging from approximately 10 to 27 km h^{-1} during liming may cause unwanted drift of liming materials; however, this would generally be avoided since liming was only performed in low winds. Therefore, the operational efficiency of the helicopters may have played a role in the non-uniformity of liming. The flight paths indicate overlap in the application areas between loads. The flight paths of the helicopters were relatively consistent, and lime was often unloaded as soon as the helicopters reached the treatment sites; therefore, much of the loading was in the same area, and a heavier loading near plots 4 and 5 in the SWT site and plots 2 and 5 in the HWT site was evident (Figure 11). In contrast, liming at Hubbard Brook indicated a “remarkably uniform” distribution (M. Martin, personal communication, October 8, 2021), although the data were not available to quantify the distribution. Additionally, helicopter liming in the MNF showed that the desired rate of 10 t ha^{-1} was attained (Fowler et al., 2022). Uniform distribution at the HBEF and the MNF suggests that it is possible to achieve uniformity of liming via helicopter. However, some key differences exist between the OPDF, HBEF and MNF research trials. First, the study at the HBEF used pelletized wollastonite which had a greater particle size and, therefore, may have been less impacted by wind. The study at MNF reported that 50% of particles were larger than 2 mm, while an average of approximately 10% were larger than 2 mm at the OPDF. Second, the trial scale at the HBEF and MNF was much larger; therefore, a better widespread distribution could have been achieved. Third, the application rate was much smaller at the HBEF; therefore, there may have been less opportunity for high levels of variation. The target application rate at the MNF forest was the same as OPDF. Due to limited information and differences between the OPDF and HBEF, it is difficult to compare directly. Given the similarities in application methods between the OPDF and the MNF trials, they are more easily compared. The particle size was slightly different, but Mizel et al., (2015) found that differences in particle sizes of liming materials did not change soil response in pH and Ca^{2+} significantly. The target rate was the same; therefore, the study's scale is likely the cause of differences in liming uniformity.

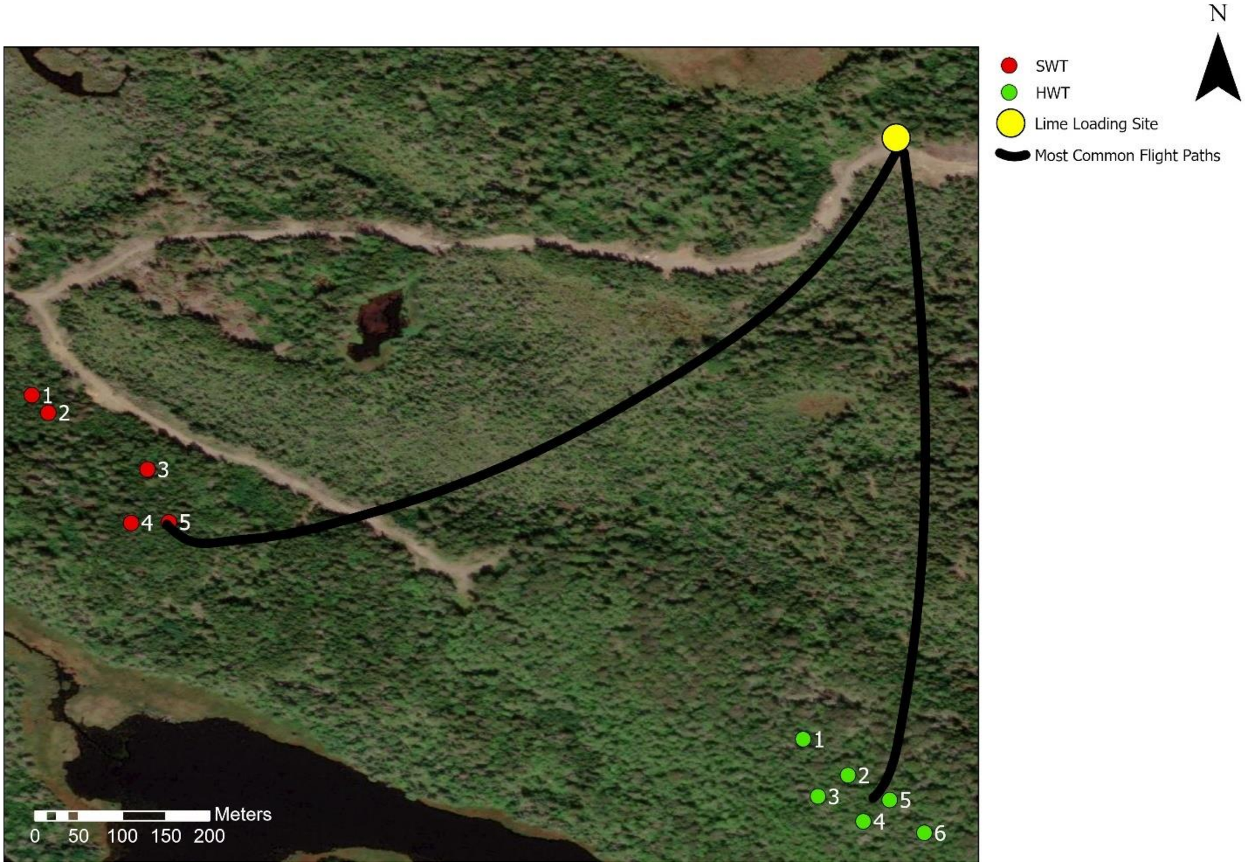


Figure 11. The most common flight path of the helicopter at the HWT and SWT sites. Lime was deposited at the end of the flight paths.

Improvements to the application and assessment of helicopter liming would be helpful for future research and potential industry applications. The application method could be improved by avoiding overlap of lime by keeping track of flight paths and the location of lime release. If application occurs over several days, collection of lime distribution boxes in-between days will help locate areas that need more lime, and those areas could be targeted. Using multiple smaller target areas instead of an entire stand may help avoid overlap. Assessment could be improved by increasing the sample size of lime boxes for more precise spatial interpolation.

The non-uniformity of lime distribution will likely not compromise the overall purpose of liming. Knowing micro-scale plot data is important for this research to help interpret soil and plant tissue chemistry differences. Despite non-uniformity, there weren't any areas recorded within the treatment site that received no lime. Therefore, areas with less lime will likely still show a response; however, it may be to a lesser degree than areas that received more lime. Also, the microscale distribution may be less important if liming was conducted at a whole-catchment level. Overall ecosystem health will likely still be improved through increased tree growth and health, improved soil health, and trickle-down effects on lakes and streams despite a non-uniform distribution.

2.5 Conclusion

Dolomitic limestone at a target rate of 10 t ha^{-1} was applied by helicopter over two acidified forest stands in Mooseland, NS. The uniformity of lime application was measured using collection boxes and showed that lime distribution was not uniform across the sites. In addition, Ca^{2+} levels in lime samples were lower than expected. Particle size distribution indicated that larger lime particles may have been held up in the tree canopy; however, lime distribution did not correlate with canopy closure.

This research may help guide future research at the OPDF and potential liming trials. Future sampling at the OPDF would benefit from targeting areas of high and low lime dose rates to evaluate differences in response. Response variation would provide more insight into lime dose rate, i.e. if responses in ecosystem parameters such as soil chemistry show similar results at lime dose rates of 2 t ha^{-1} and 10 t ha^{-1}, then perhaps the dose rate can be decreased. In addition, these results can increase the efficiency of helicopter application of lime to forests in the future.

Chapter 3 - Early Effects of Helicopter Liming on Soil and Vegetation in Two Acidified Forest Stands in Nova Scotia, Canada

3.1 Introduction

Many forests continue to show signs of soil acidification, BCD, and poor tree health and growth despite reductions in S and N deposition as soil Ca^{2+} has shown little recovery (Driscoll et al., 2001; Fernandez et al., 2003; Lawrence et al., 2012; Lawrence et al., 2015). The response of forests to liming amendments has been well documented in Europe and northeastern North America; however, it is unclear whether the results of these studies are broadly transferable as the geographic scope of this work is localized to the study sites. Despite Nova Scotia having highly acidified soil (Whitfield et al., 2006) and Ca often being the predicted limiting nutrient for sugar maple and red spruce species (Keys et al., 2016), no upland liming trials have been performed in NS. Few studies have looked at soil and plant tissue chemistry changes in the short-term (one year) in response to lime.

This chapter evaluates the short-term (one-year) response of an acidified softwood and acidified hardwood stand in NS to helicopter liming. This chapter addresses RQ2: Does helicopter application of 10 t ha^{-1} of dolomitic limestone improve soil acidification status, such as increased soil base cation concentrations and decreased mobile Al^{3+} in two mature acidified forest stands in Nova Scotia one year after treatment? This chapter also addresses RQ3: Does helicopter application of 10 t ha^{-1} of dolomitic limestone increase Ca and Mg, decrease Al, and improve overall nutrient status in red spruce, sugar maple, red maple, and ground vegetation in two mature acidified forest stands in Nova Scotia one year after treatment? The results focus on soil chemical parameters which indicate the acidification status of the soil, such as pH, total acidity, and base cations and plant tissue elements such as Ca, Mg, K, and Al.

3.2 Methods

3.2.1 Site Description

3.2.1.1 Softwood Sites

The softwood control (SWC) and softwood treatment (SWT) sites were dominated by co-dominant red spruce with total mean basal areas of 42.0 m^2 ha^{-1} (SWC) and 38.6 m^2 ha^{-1} (SWT).

The Nova Scotia Soil Survey Report for Halifax County classified the softwood sites’ soil as well-drained Orthic Humo-Ferric Podzols, derived from glacial till, high in quartzite (MacDougall et al., 1963). Soils in this region often have low fertility and are acidic throughout the profile. The humus form is hemimor in which F and H horizons are > 2 cm, fungal mycelia are dominant, there are low amounts of decaying wood, and the F horizon is > 50% of the forest floor thickness (Green et al., 1993; Neily et al., 2011).

Table 8. Description of the soil profiles at pits dug at the SWC sites based on the Canadian System of Soil Classification (Soil Classification Working Group, 1998) and humus classification from Green et al. (1993). All values are in cm and indicate the depth and thickness of each soil horizon. Zero centimeters indicates the beginning of the mineral soil.

Horizon	**Description**	**SWC 1**	**SWC2**	**SWC3**	**SWC4**	**SWC5**
L	Leaf litter.	Moss	Moss	Moss	Moss	Moss
Fm	Dark brown, semi-decomposed, fibrous layer, average pH 2.56.	12-2	15-3	13-4	14-3	12-3
Hh	Black, mostly decomposed layer, often greasy, average pH (F/H transitions) 2.39.	2-0	3-0	4-0	3-0	3-0
Ae	Light coloured, sandy loam eluviated horizon.	0-7	0-7	0-5	0-6	0-3
Bf1	Yellowish brown (10YR 4/6 or 7.5YR 4/6), sandy loam or loam, enriched, average pH 3.42.	7-19	7-19	5-17	6-18	3-15
Bf2	Yellowish brown (10YR 3/6 or 10YR 3/4), sandy loam or loam, average pH 3.79.	19-33	19-33	17-30	18-38	15-25
BC	BC transition horizon, olive colour (2.5Y 4/4), higher clay content.	33-40+	33-40+	30-40+	38-40+	26-40+

Table 9. Description of the soil profiles at pits dug at the SWT sites based on the Canadian System of Soil Classification (Soil Classification Working Group, 1998) and humus classification from Green et al. (1993). All values are in cm and indicate the depth and thickness of each soil horizon. Zero centimeters indicates the beginning of the mineral soil.

Horizon	Description	SWT 1	SWT 2	SWT 3	SWT 4	SWT 5
L	Leaf litter.	Moss	Moss	Moss	Moss	Moss
Fm	Dark brown, semi-decomposed, fibrous layer, average pH 2.58.	10-2	11-5	13-5	13-3	12-3
Hh	Black, mostly decomposed layer, often greasy, average pH (F/H transitions) 2.38.	2-0	5-0	5-0	3-0	3-0
Ae	Light coloured, sandy loam eluviated horizon.	0-7	0-7	0-5	0-12	0-10
Bf1	Yellowish brown (10YR 4/6 or 7.5YR 4/6), sandy loam, average pH 3.51.	7-17	7-17	5-22	12-23	10-20
Bf2	Yellowish brown (10YR 4/4 or 10YR 3/4), sandy loam, average pH of 3.97.	17-37	17-40+	22-40+	23-38	20-38
BC	BC transition horizon, olive colour (2.5Y 4/4), higher clay content.	37+			38+	38+

3.2.1.2 Hardwood Sites

The hardwood control (HWC) and hardwood treatment (HWT) sites were dominated by co-dominant and intermediate red maple and sugar maple with total mean basal areas of 27.8 m^2 ha^{-1} (HWC) and 35.8 m^2 ha^{-1} (HWT).

The hardwood sites reside on somewhat finer-textured drumlins. The Nova Scotia Soil Survey Report for Halifax County classified the hardwood sites' as moderately well to imperfectly drained Orthic Humo-Ferric Podzols (MacDougall et al., 1963). The humus form is typically mormoder in which F and H horizons are > 2 cm, both fungal mycelia and soil fauna are involved in decomposition, there are low amounts of decaying wood and the F horizon is > 50% of the forest floor (Green et al., 1993; Neily et al., 2011).

Table 10. Description of the soil profiles at pits dug at the HWC site based on the Canadian System of Soil Classification (Soil Classification Working Group, 1998) and humus classification from Green et al. (1993). All values are in cm and indicate the depth and thickness of each soil horizon. Zero centimeters indicates the beginning of the mineral soil.

Horizon	**Description**	**HWC 1**	**HWC2**	**HWC3**	**HWC4**	**HWC5**	**HWC6**
L	Leaf litter	7-3	6-3	6-4	9-7	7-5	6-4
Fa	Dark brown, semi-decomposed, fibrous layer, average pH 2.87.	3-0	3-0	4-1	7-3	5-0	4-0
Hh	Black, mostly decomposed layer, often greasy.	Trace	0	0-1	3-0	Pocket	Trace
Ah	Dark colour, organically enriched horizon, the colour value is lower than underlying horizons.		0-3	0-4		0-5	
Ae	Light coloured, sandy loam eluviated horizon.	0-9			0-4		0-6
AB	Transition horizon between the A and B horizons (10YR 4/6).		3-20				
Bf1	Yellowish brown (10YR 4/6, 10YR 4/4, or 10YR 3/6), loam or sandy loam, average pH 3.55.	9-15		4-18	4-16	5-16	6-17
Bf2	Yellowish brown (10YR 3/6 or 10YR 3/4), loam or silt loam, average pH 3.48.	15-30	20-30	18-27	16-31	16-24	17-31
BCgj	BC transition horizon, olive colour (2.5Y 4/4), higher clay content, faint mottling present.	30+	30+	27-40+	31-50+	24-40+	21-40+

Table 11. Description of the soil profiles at pits dug at the HWT site based on the Canadian System of Soil Classification (Soil Classification Working Group, 1998) and humus classification from Green et al. (1993). All values are in cm and indicate the depth and thickness of each soil horizon. Zero centimeters indicates the beginning of the mineral soil.

Horizon	**Description**	**HWT 1**	**HWT2**	**HWT3**	**HWT4**	**HWT5**	**HWT6**
L	Leaf litter	8-6	8-6	8-6	8-6	8-6	7-5
Fa	Dark brown, semi decomposed, fibrous layer, average pH 2.84.	6-0	6-1	6-0	6-1	6-0	5-0
Hh	Black, mostly decomposed layer, often greasy.	Trace	1-0	Trace	1-0	Trace	Trace
Ahe	Light coloured with streaks or pockets of black			0-5			
Ae	Light coloured, sandy loam eluviated horizon	0-5	0-4		0-7	0-5	
Bhf	Dark reddish colour						0-6
Bf1	Yellowish brown (10YR 3/6 or 7.5YR 4/4), loam or sandy loam, average pH 3.41.	5-11	4-14	5-16	7-18	5-21	6-16
Bf2	Yellowish brown (10YR 3/4), loam or silt loam, average pH 3.87.	11-25	14-34	16-35	18-38	21-39	16-28
BCgj	BC transition horizon, olive colour (2.5Y 4/4), higher clay content, faint mottling present.	25-40+	34-40+		38-50+	39-50+	28-30+
BC	BC transition horizon, olive colour (2.5Y 4/4), higher clay content.			35-40+			

3.2.2 Soil Sampling

The experimental design and plot numbers and locations are described in section 1.3. Mineral and organic soil horizons were sampled at all four sites for chemical analysis. Soil pits approximately 48 cm wide and 60 cm deep were dug and sampled. Soil pits were located outside each growth plot (six at the hardwood sites and five at the softwood sites) in areas representative of the site. In late August to early September 2018 (year 1), one soil pit per site was sampled and described in. In late August to early September 2019 (year 2), three pits were sampled at each site at random bearings around the growth plots. The increase in sample size was to help offset potential variability in treatment responses caused by uneven lime distribution.

The soil profile at each pit was described using the Canadian System of Soil Classification (Soil Classification Working Group, 1998). The most chemically active horizons in the forest floor and mineral soil were targeted for sample collection. The upper F horizon and F/H transition horizon of the forest floor were sampled at the softwood sites because the forest floor thickness was greater than 10 cm. Only the F horizon was sampled at the hardwood sites because the forest floor thickness was less than 10 cm. The upper mineral horizon (M1) and lower mineral horizon (M2) were sampled at both the hardwood and softwood sites (Figure 12; Table 11). Sampling depths ranged from 10-15 cm for M1 and 25-30 cm for M2. Consistent sampling depths and soil colour were used to decrease variability by ensuring samples came from the same horizons.

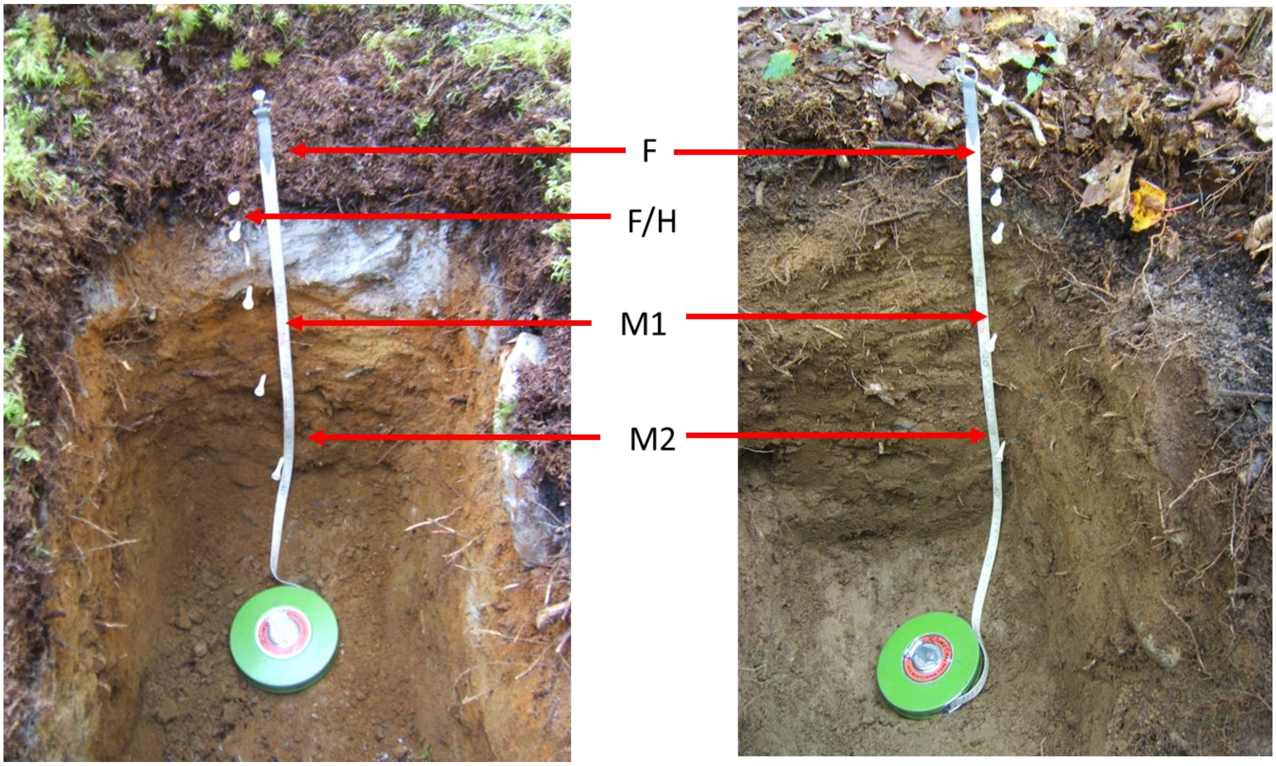


Figure 12. Representative soil profiles in the softwood (left) and the hardwood (right) sites. The red arrows are in reference to the sampled horizons at each site.

Table 12. Number of soil samples collected for each horizon at the hardwood control (HWC) site, hardwood treatment (HWT) site, softwood control (SWC) site, and softwood treatment (SWC) site before and after liming.

Site	**HWC**			**HWT**			**SWC**				**SWT**				**Total**
Soil Horizon	F	M1	M2	F	M1	M2	F	F/H	M1	M2	F	F/H	M1	M2	
Before	6	6	6	6	6	6	5	5	5	5	5	5	5	5	76
After	18	18	18	18	18	18	15	15	15	15	15	15	15	15	228

3.2.3 Tissue Sampling

Foliage and ground vegetation samples were collected for chemical analysis in late August to early September. The most dominant species and canopy classes were sampled at each site. Sample trees were randomly selected within the site boundary following an initial screening to ensure that trees were not visibly damaged and that the trees were either co-dominant red spruce (softwood sites) or co-dominant and intermediate red maple and sugar maple (hardwood sites). Foliage in the hardwood sites was sampled using pole pruners and/or a pole saw for intermediate trees and by climbing for co-dominant trees. Foliage in the softwood sites was sampled by felling selected trees and pruning the new shoots from upper canopy positions (Table 12). Co-dominant foliage at the hardwood sites could not be sampled in 2018 due to a lack of trained climbers and equipment to reach upper canopy positions. Two ground vegetation samples within each plot were sampled. Evergreen wood fern was sampled at the hardwood site, and Schreber’s moss was sampled at the softwood site because they were the dominant ground vegetation species.

Table 13. Summary of the number of tree tissue samples taken at each site for each species, red maple, sugar maple, and red spruce for the intermediate (Int.) and co-dominant (Co-dom) canopy classes.

Year	**HWC**				**HWT**				**SWC**	**SWT**	**Total**
	rM Int.	rM Co-dom	sM Int.	sM Co-dom	rM Int.	rM Co-dom	sM Int.	sM Co-dom	rS Co-dom	rS Co-dom	
2018	12	0	12	0	12	0	12	0	10	10	68
2019	12	12	12	12	12	12	12	12	10	10	116

3.2.4 Laboratory Analysis

Soil samples were air-dried, and coarse fragments were removed from mineral soils using a 2 mm sieve. Soil samples were analyzed at the Laboratory for Forest and Soils and Environmental Quality in Fredericton, New Brunswick and the Dalhousie Soil Health Laboratory in Truro, NS. Soil samples were analyzed for exchangeable acidity and Al^{3+} using potassium chloride (KCL) titration method (Hendershot et al., 2008; Thomas, 1982). Soil samples were analyzed for pH

(1:1) in 0.01 $CaCl_2$ solution and exchangeable base cations via Mehlich III extraction, followed by AAS analysis (Hendershot et al., 2008; Ziada & Sen Tran, 2008).

Tissue samples air-dried in paper bags were sent to the Laurentian Forestry Centre in Quebec City, Quebec, in addition to soil subsamples. Tissue and soil samples were analyzed for total C, N, and S using a LECO induction furnace. Total Ca, Mg, K, Na, phosphorus (P), Al, and manganese (Mn) in tissue samples were analyzed using acid digestion and ICP-MS analysis (Kalra, 1998).

3.2.5 Statistical Analysis

3.2.5.1 Calculations (%BS/CEC)

Cation exchange capacity (Equation 7) and percent base saturation (Equation 8) were calculated to help evaluate soil health, using the equation described by Hendershot et al. (2008) where:

$$CEC\ cmol_c\ kg^{-1} = \sum cmol_c\ (Ca, Mg, K, Na, Al, H)\ kg^{-1} \tag{7}$$

$$\%BS = \frac{\sum cmol_c\ (Ca,Mg,K,Na) kg^{-1}}{CEC\ cmol_c\ kg^{-1}}\ X100 \tag{8}$$

3.2.5.2 GLMM/LMM

General Linear Mixed Effects Model (GLMM) and Linear Mixed Effects Model (LMM) were used to analyze the difference between limed and un-limed sites before (year 1) and after (year 2) treatment for soil and tissue samples. This model was considered appropriate because the experimental design in this study used repeated measures at each sampling site. The GLMM includes random effect terms that help account for each site's spatial variability. Unlike a traditional repeated measures ANOVA, the GLMM can be used for non-normal data and is effective with small sample sizes (Bolker et al., 2009; Agresti, 2007).

The GLMM terms used were “Treatment” (Treatment vs. Control), Before.After (Before vs. After Liming), and an interaction term (Treatment*Before.After) as fixed effects for the model, and “Plot” as the random effect to help account for spatial variability. The models were evaluated using Akaike Information Criterion (AIC) to estimate prediction error and verify which model was the best fit and using the R^2_c (fixed and random effects) and R^2_m (fixed effects) to determine the fit of the model. Tukey multiple comparisons was used to determine differences between limed and un-limed sites. Analysis was conducted using RStudio Desktop 1.3.1093.

Change in mean soil Ca^{2+} concentrations, ground vegetation Ca concentration, and foliar Ca concentrations at each plot were compared with calcium loading in lime (Table 6) using Pearson correlation to determine if higher Ca^{2+} loading rates were correlated with higher lime dosing in the forest floor.

3.2.5.3 Diagnosis and Recommendation Integrated System

Diagnosis and Recommendation Integrated System, created by Beaufils (1973), is a tool used to interpret foliar nutritional data. DRIS was used to interpret the nutritional status of sugar maple foliage in the study sites. DRIS compares nutrient ratios with standard ratios for healthy trees called “norms” and develops an index for each nutrient. DRIS norms for sugar maple were created by Lozano & Hyunh (1989) and have been used in several studies (Long et al., 1997; Masson et al., 2019; Moore et al., 2000; Moore & Ouimet, 2006; Moore & Houle, 2009; Ouimet et al., 2008). Lozano & Hyunh (1989) developed the norms using a reference population from Ontario. Each tree was classified as healthy or declined, and foliage samples were collected from the upper, middle, and lower crown sections. The mean, coefficient of variation (CV), and variance (significant at the 5% level) were calculated for each ratio and inverse ratio. If the parameters achieved a significant variance ratio, they were kept, and the mean and coefficient of variation were used as DRIS norms. Nutrient indexes can be calculated from DRIS values and should sum to zero. DRIS calculates nutrient indexes (Equations 9, 10, 11, 12, 13) as the mean of the functions for all the ratios which contain a specific nutrient. The CV indicates the weight each ratio contributes to the index. Larger CVs indicate that the ratio can be within a larger range from its optimum mean value, while smaller CVs indicate that the ratio is more critically related to the plant's health because the ratio must be more closely related to the norm.

DRIS is a more effective method for evaluating tree nutritional status than nutrient thresholds because it is less dependent on growth stage, plant part, and sample location (Serra et al., 2013; Walworth & Sumner, 1987). DRIS presents the information on a continuous scale, classifying deficient nutrients from most deficient to most excessive (Lozano & Hyunh, 1989; Mourao Filho, 2004).

Only sugar maple foliage results were analyzed using DRIS because no DRIS norms were developed for red spruce or red maple. The DRIS nutrient indices were calculated using equations derived from Beaufils (1973) and described by Walworth & Sumner (1987) and Serra et al. (2013).

$$A\ index = \frac{[f(A/B)+f(A/C)+f(A/D)\ldots+f(A/N)]}{z} \tag{9}$$

$$B\ index = \frac{[-f(A/B)+f(B/C)+f(B/D)\ldots+f(B/N)]}{z} \tag{10}$$

$$N\ index = \frac{[-f(A/N)-f(B/N)-f(C/N)\ldots-f(M/N)]}{z} \tag{11}$$

When A/B ≥ a/b

$$f\left(\frac{A}{B}\right) = \left(\left(\frac{A/B}{a/b}\right) - 1\right) * \left(\frac{1000}{CV}\right) \tag{12}$$

When A/B < a/b

$$f\left(\frac{A}{B}\right) = \left(1 - \left(\frac{a/b}{A/B}\right)\right) * \left(\frac{1000}{CV}\right) \tag{13}$$

Where A/B is the observed nutrient ratio, a/b is the “norm” ratio, CV is the coefficient of variation for the “norm”, and z is the number of ratios comprising the nutrient index.

Analysis of DRIS was conducted using R code developed in RStudio version 1.3.1093 (R. Ouimet, personal communication, February 24, 2021).

A nutrient balance index (NBI) is used to estimate the overall nutritional status of the tree. The NBI is the sum of the absolute values of each nutrient index (equation 14). The higher the NBI value the greater the nutrient imbalance is in the plant.

$$NBI = |A\ index| + |B\ index| + \cdots + |N\ index| \tag{14}$$

3.2.5.4 Outliers

Due to low sample sizes, possible outliers were removed with caution following the conceptual framework developed by Benhadi-Marin (2018). Potential outliers were initially identified using visualization methods, with any suspected outliers then identified using the quartile method (Benhadi-Marin, 2018). These were then assessed to determine whether they were significant to the study, whether their cause could be detected, or if there were errors in sampling and analysis. Outliers were retained if the outlier represented relevant information to the study, for example, if the value was from a less represented area or if similar values were recorded nearby. Based on this assessment, several outliers were removed from each horizon and are described in Appendix 2.

3.3 Softwood Results

3.3.1 Pre-Treatment Conditions

There were few differences in soil conditions between the treatment and control sites in year 1. Exceptions include a significantly greater CEC at the control site in the F/H horizon and significantly greater K^+ concentration at the control site in the M1 and M2 horizons (Table 13).

*Table 14. Mean and standard error (SE) of pH, base saturation (BS), cation exchange capacity (CEC), exchangeable base cations (Ca^{2+}, Mg^{2+}, K^{+}), exchangeable acidity (EA), exchangeable Al^{3+}, and exchangeable Mn^{2+} in each soil horizon at the softwood control (SWC) and softwood treatment (SWT) sites in year 1. * Indicates a significant differences between the SWT and SWC sites ($P < 0.05$).*

Site	**pH**	**%**	**Exchangeable Ions (cmol kg^{-1})**						
		BS	**CEC**	**Ca^{2+}**	**Mg^{2+}**	**K^{+}**	**EA**	**Al^{3+}**	**Mn^{2+}**
F									
SWC	2.56 (0.03)	15.04 (0.87)	7.41 (0.21)	0.30 (0.04)	0.48 (0.02)	0.21 (0.01)	6.30 (0.23)	0.30 (0.04)	0.031 (0.004)
SWT	2.58 (0.04)	16.68 (1.81)	7.38 (0.45)	0.37 (0.06)	0.56 (0.01)	0.20 (0.02)	6.18 (0.50)	0.24 (0.05)	0.034 (0.005)
F/H									
SWC	2.39 (0.04)	5.04 (0.69)	16.25 (1.22)	0.040 (0.006)	0.46 (0.06)	0.14 (0.01)	15.46 (1.28)	1.41 (0.13)	0.034 (0.001)
SWT	2.38 (0.02)	7.51 (1.22)	13.60* (0.89)	0.077 (0.019)	0.64 (0.08)	0.12 (0.01)	12.62 (0.98)	1.05 (0.19)	0.010 (0.000)
M1									
SWC	3.42 (0.06)	1.01 (0.18)	4.30 (0.32)	0.003 (0.001)	0.012 (0.000)	0.017 (0.002)	4.26 (0.32)	3.26 (0.33)	0.001 (0.0001)
SWT	3.51 (0.04)	0.67 (0.05)	4.21 (0.19)	0.003 (0.000)	0.009 (0.001)	0.002* (0.000)	4.18 (0.19)	3.18 (0.19)	0.003 (0.001)
M2									
SWC	3.79 (0.06)	0.90 (0.13)	2.52 (0.26)	0.003 (0.000)	0.006 (0.000)	0.008 (0.002)	2.50 (0.26)	3.70 (0.32)	0.001 (0.000)
SWT	3.97 (0.05)	0.70 (0.13)	1.65 (0.13)	0.002 (0.000)	0.003 (0.000)	0.002* (0.000)	1.64 (0.13)	4.12 (0.09)	0.004 (0.000)

There were few differences in tissue chemistry between the treatment and control site in year 1. Exceptions include significantly greater N concentration at the treatment site for both Schreber's moss and red spruce foliage and significantly greater K concentration at the treatment site for Schreber's moss (Table 14).

*Table 15. Mean and standard error (SE) of elements for Schreber's moss (SchM) and red spruce foliage (RS) in year 1 at the softwood control (SWC) and softwood treatment (SWT) sites. * Indicates a significant difference between the SWT and SWC sites ($P < 0.05$).*

Site	**Elements (g kg^{-1})**							
	N	**P**	**K**	**Ca**	**Mg**	**Al**	**Fe**	**Mn**
SchM								
SWC	0.65 (0.01)	1.56 (0.04)	6.49 (0.15)	2.02 (0.08)	1.25 (0.02)	0.13 (0.005)	0.11 (0.004)	0.39 (0.02)
SWT	0.73* (0.02)	1.44 (0.04)	7.26* (0.15)	1.88 (0.06)	1.27 (0.03)	0.13 (0.02)	0.11 (0.004)	0.40 (0.01)
RS								
SWC	0.91 (0.02)	1.36 (0.05)	6.46 (0.27)	1.83 (0.14)	1.41 (0.03)	0.09 (0.005)	0.02 (0.001)	0.71 (0.03)
SWT	0.97* (0.02)	1.34 (0.05)	6.88 (0.28)	1.64 (0.12)	1.28 (0.05)	0.07 (0.008)	0.02 (0.002)	0.61 (0.02)

3.3.2 Soil Response to Liming

Softwood F Horizon

Slight changes were observed in some of the soil chemical properties in the upper forest floor horizon at the SWC site from year 1 to year 2; however, none were significant. The upper forest floor horizon pH, %BS, Ca^{2+}, Mg^{2+}, and Mn^{2+} significantly increased at the SWT site one year after treatment (Figure 13). The pH increased from 2.58 ± 0.04 to 3.96 ± 0.15 (mean ± SE), %BS increased from 16.7 ± 1.8 to 71.9 ± 3.7%, Ca^{2+} increased from 0.37 ± 0.07 to 1.65 ± 0.11 cmol kg^{-1}, Mg^{2+} increased from 0.56 ± 0.01 to 2.19 ± 0.13 cmol kg^{-1}, and Mn^{2+} increased from 0.034 ± 0.005 to 0.070 ± 0.006 cmol kg^{-1}. Cation exchange capacity and exchangeable acidity decreased significantly one year after treatment, while K^+ and Al^{3+} decreased, but not significantly (Figure 13). Cation exchange capacity decreased from 7.38 ± 0.45 to 5.72 ± 0.16 cmol kg^{-1} and exchangeable acidity decreased from 6.18 ± 0.50 to 1.64 ± 0.27 cmol kg^{-1}. The mean change in pH, %BS, Ca^{2+}, Mg^{2+}, Mn^{2+}, CEC, and exchangeable acidity significantly differed between the SWT and SWC sites (Table 15).

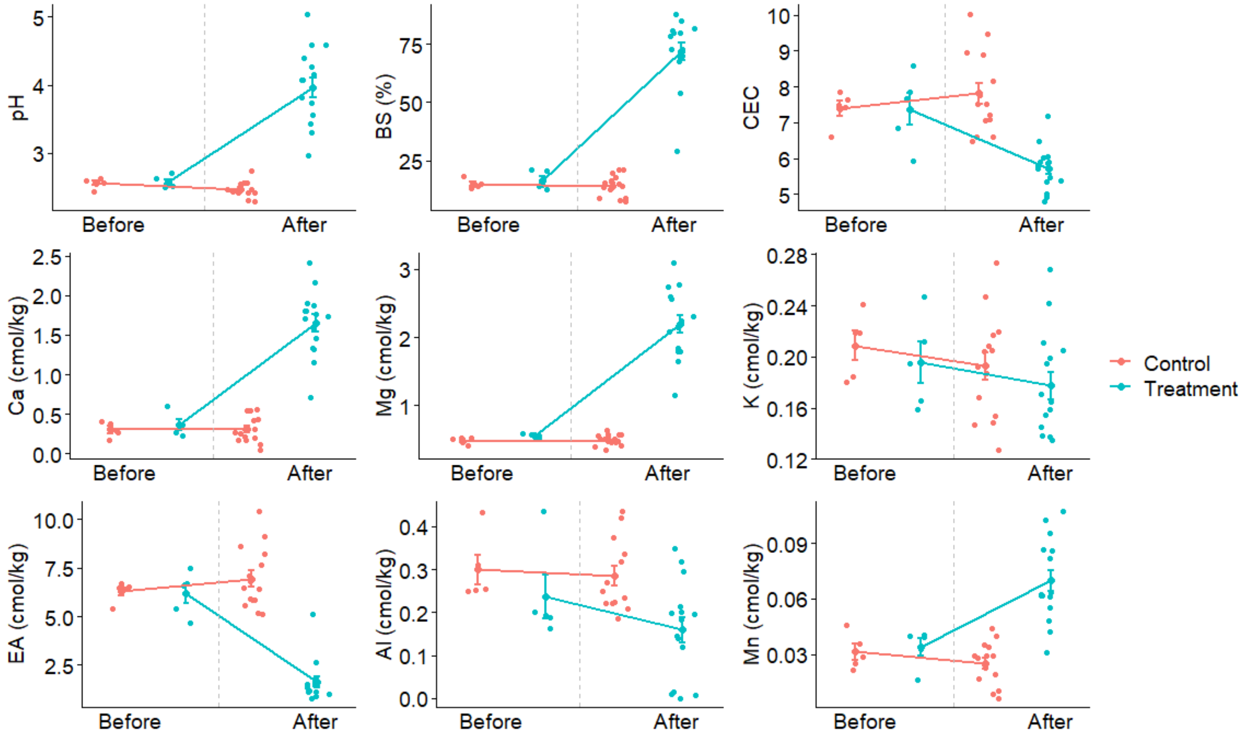


Figure 13. F horizon pH, percent base saturation (%BS), cation exchange capacity (CEC), base cation concentrations (Ca^{2+}, Mg^{2+}, K^{+}), exchangeable acidity (EA), Al^{3+} concentration, Mn^{2+} concentration, plot data at the softwood control (SWC) and treatment (SWT) sites. Error bars indicate the mean ± 1 SE. The x-axis shows a categorical timescale before and after lime application, and the dotted grey line indicates the lime application.

Table 16. Mean change (SE) from year 1 to year 2 for all soil parameters at the softwood control (SWC) and softwood treatment (SWT) sites upper forest floor horizon (F horizon) and the P-values showing the mean change at each site from year 1 to year 2 and the differences between the change in means between the SWC and SWT site.

Soil Chemical Properties	SWC	P-Value (Year 1 to year 2 at SWC site)	SWT	P-Value (Year 1 to year 2 at SWT site)	P-Value (Change in means between sites)
pH	-0.095 (0.041)	0.935	1.38 (0.21)	<.0001	0.002
%BS	-0.76 (0.96)	0.998	55.2 (4.8)	<.0001	0.000
CEC	0.50 (0.42)	0.520	-1.66 (0.42)	0.006	0.009
Ca^{2+}	0.001 (0.072)	1.00	1.28 (0.18)	<.0001	0.001
Mg^{2+}	0.017 (0.034)	0.999	1.64 (0.21)	<.0001	0.002
K^{+}	-0.014 (0.017)	0.997	-0.018 (0.028)	0.843	0.893
EA	0.65 (0.53)	0.673	-4.54 (0.59)	<.0001	0.000
Al^{3+}	0.005 (0.048)	0.993	-0.077 (0.037)	0.435	0.216
Mn^{2+}	-0.006 (0.003)	0.817	0.0036 (0.0060)	0.0001	0.001

Softwood F/H Horizon

Significant decreases in exchangeable acidity, Al^{3+}, and CEC were observed in the lower forest floor horizon at the SWC site from year 1 to year 2 (Table 16). The lower forest floor horizon pH, %BS, Ca^{2+}, Mg^{2+}, and Mn^{2+} significantly increased at the SWT site one year after treatment (Figure 14). The pH increased from 2.38 ± 0.01 to 2.75 ± 0.09 (mean ± SE), %BS increased from 7.51 ± 1.22 to 38.2 ± 5.2%, Ca^{2+} increased from 0.08 ± 0.02 to 0.71 ± 0.10 cmol kg^{-1}, Mg^{2+} increased from 0.64 ± 0.08 to 1.44 ± 0.12 cmol kg^{-1}, and Mn^{2+} increased from 0.01 ± 0.00 to 0.02 ± 0.00 cmol kg^{-1}. However, the change in means between the SWT and SWC sites for pH and Mn^{2+} was not significant ($P > 0.05$) (Table 16). Cation exchange capacity, exchangeable acidity, and Al^{3+} decreased significantly at the SWT site after treatment; however, the decreases were similar to those observed at the SWC site, and the difference in the change in means between sites was not significant (Table 16).

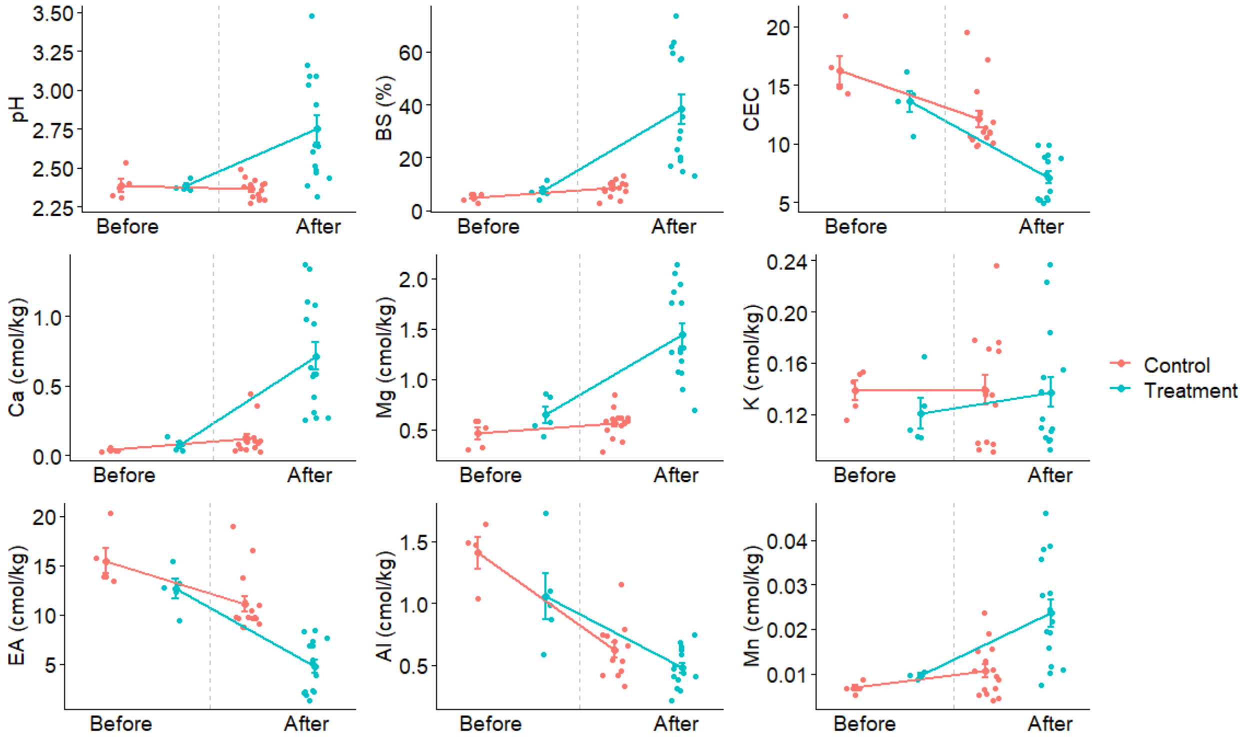


Figure 14. F/H horizon pH, percent base saturation (%BS), cation exchange capacity (CEC), base cation concentrations (Ca^{2+}, Mg^{2+}, K^{+}), exchangeable acidity (EA), Al^{3+} concentration, Mn^{2+} concentration, plot data at the softwood control (SWC) and treatment (SWT) sites. Error bars indicate the mean ± 1 SE. The x-axis shows a categorical timescale before and after lime application, and the dotted grey line indicates the lime application.

Table 17. Mean change (SE) from year 1 to year 2 for all soil parameters at the softwood control (SWC) and softwood treatment (SWT) sites lower forest floor horizon (F/H horizon) and the P-values showing the mean change at each site from year 1 to year 2 and the differences between the change in means between the SWC and SWT site.

Soil Chemical Properties	SWC	P-Value (Year 1 to year 2 at SWC site)	SWT	P-Value (Year 1 to year 2 at SWT site)	P-Value (Change in means between sites)
pH	-0.023 (0.050)	0.994	0.367 (0.140)	0.002	0.058
%BS	3.46 (1.10)	0.910	30.7 (8.6)	<.0001	0.035
CEC	-4.18 (1.90)	<.0001	-6.49 (0.80)	<.0001	0.311
Ca^{2+}	0.085 (0.016)	0.870	0.636 (0.160)	<.0001	0.028
Mg^{2+}	0.102 (0.093)	0.863	0.796 (0.200)	<.0001	0.026
K^{+}	0.002 (0.010)	0.831	0.016 (0.026)	0.902	0.641
EA	-4.35 (2.00)	0.007	-7.87 (1.00)	<.0001	0.165
Al^{3+}	-1.01 (0.23)	<0.0001	-0.575 (0.150)	<0.0001	0.160
Mn^{2+}	0.004 (0.002)	0.734	0.014 (0.004)	0.003	0.081

Softwood M1 Horizon

Slight changes were observed in some of the soil chemical properties in the upper B (M1) horizon at the SWC site from year 1 to year 2; however, none were significant at $P = 0.05$, but a decrease in K^+ was significant at $P < 0.1$. The M1 horizon %BS, Ca^{2+}, and Mg^{2+} significantly increased at the SWT site one year after treatment (Figure 15). Percent base saturation increased from 0.67 ± 0.05 to 1.66 ± 0.28%, Ca^{2+} increased from 0.003 ± 0.000 to 0.021 ± 0.003 cmol kg^{-1}, and Mg^{2+} increased from 0.009 ± 0.001 to 0.030 ± 0.004 cmol kg^{-1}. Potassium decreased non-significantly; however, the difference in the change in means between sites was significant (Table 17). No other soil chemical parameters showed significant changes at or between the SWC and SWT sites.

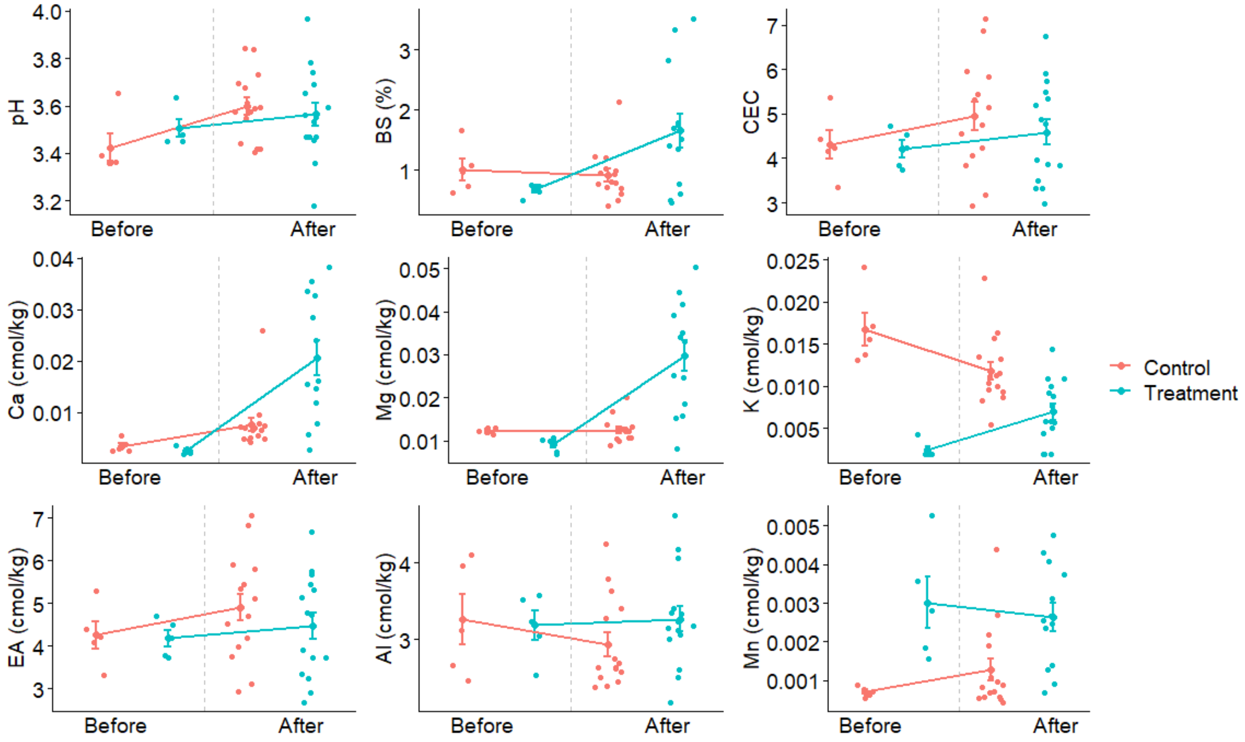


Figure 15. M1 horizon pH, percent base saturation (%BS), cation exchange capacity (CEC), base cation concentrations (Ca^{2+}, Mg^{2+}, K^{+}), exchangeable acidity (EA), Al^{3+} concentration, Mn^{2+} concentration, plot data at the softwood control (SWC) and treatment (SWT) sites. Error bars indicate the mean ± 1 SE. The x-axis shows a categorical timescale before and after lime application, and the dotted grey line indicates the lime application.

Table 18. Mean change (SE) from year 1 to year 2 for all soil parameters at the softwood control (SWC) and softwood treatment (SWT) sites upper B horizon (M1 horizon) and the P-values showing the mean change at each site from year 1 to year 2 and the differences between the change in means between the SWC and SWT site.

Soil Chemical Properties	SWC	P-Value (Year 1 to year 2 at SWC site)	SWT	P-Value (Year 1 to year 2 at SWT site)	P-Value (Change in means between sites)
pH	0.173 (0.037)	0.117	0.059 (0.051)	0.859	0.116
%BS	-0.095 (0.170)	0.983	0.971 (0.360)	0.001	0.043
CEC	0.640 (0.350)	0.621	0.379 (0.210)	0.884	0.545
Ca^{2+}	0.004 (0.002)	0.683	0.018 (0.005)	0.0004	0.055
Mg^{2+}	0.000 (0.000)	1.00	0.020 (0.004)	0.0001	0.008
K^{+}	-0.005 (0.002)	0.051	0.005 (0.002)	0.081	0.012
EA	0.640 (0.350)	0.643	0.280 (0.230)	0.954	0.427
Al^{3+}	-0.331 (0.210)	0.662	0.082 (0.30)	0.992	0.295
Mn^{2+}	0.001 (0.000)	0.995	-0.000 (0.001)	0.995	0.468

Softwood M2 Horizon

Slight changes were observed in some of the soil chemical properties in the lower B (M2) horizon at the SWC site from year 1 to year 2; however, only CEC, exchangeable acidity, and Mn^{2+} increased significantly. The M2 horizon %BS, CEC, Ca^{2+}, Mg^{2+}, exchangeable acidity, and Mn^{2+} significantly increased at the SWT site one year after treatment (Figure 16). Percent base saturation increased from 0.70 ± 0.13 to 2.42 ± 0.64%, CEC increased from 1.65 ± 0.13 to 2.56 ± 0.73 cmol kg^{-1}, Ca^{2+} increased from 0.002 ± 0.000 to 0.021 ± 0.006 cmol kg^{-1}, Mg^{2+} increased from 0.003 ± 0.000 to 0.025 ± 0.006 cmol kg^{-1}, exchangeable acidity increased from 1.64 ± 0.13 to 2.47 ± 0.77 cmol kg^{-1}, and Mn^{2+} increased from 0.004 ± 0.000 to 0.005 ± 0.001 cmol kg^{-1}. Despite increases at the SWT site, similar increases in these soil chemical parameters were observed at the SWC site. Only the change in means between sites for Mg^{2+} was significant (Table 18).

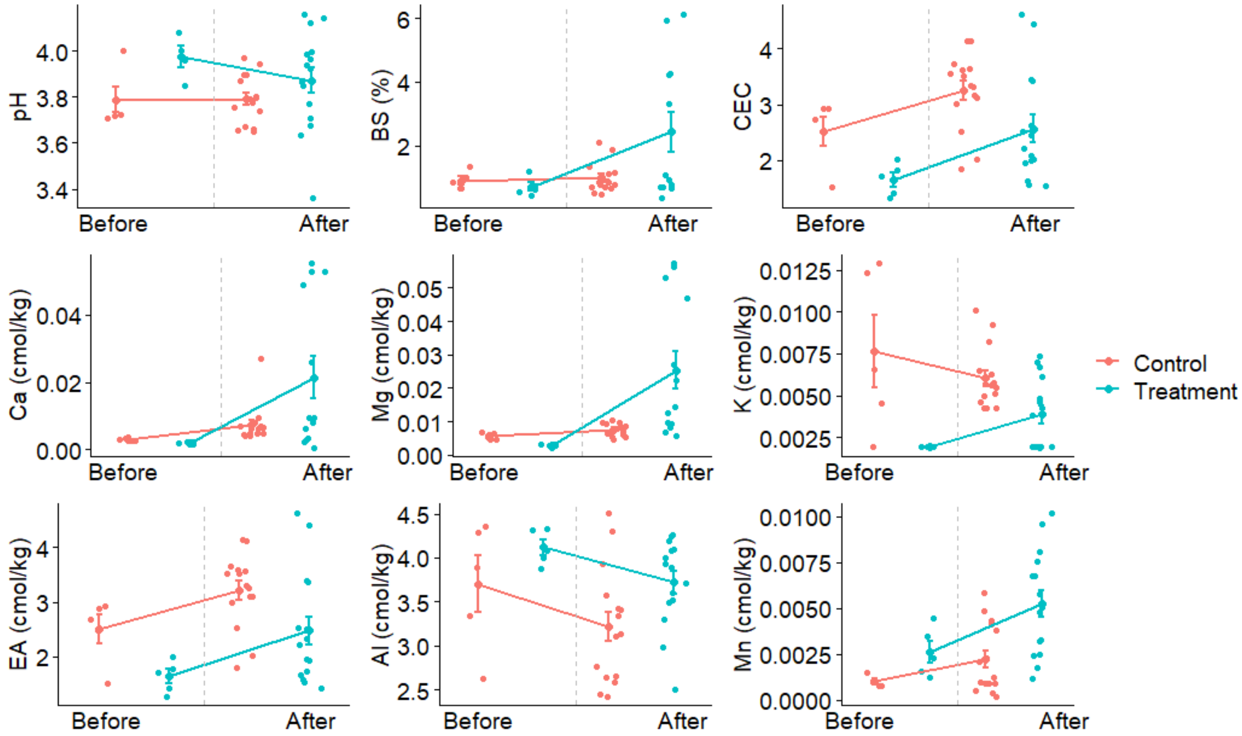


Figure 16. M2 horizon pH, percent base saturation (%BS), cation exchange capacity (CEC), base cation concentrations (Ca^{2+}, Mg^{2+}, K^{+}), exchangeable acidity (EA), Al^{3+} concentration, Mn^{2+} concentration, plot data at the softwood control (SWC) and treatment (SWT) sites. Error bars indicate the mean ± 1 SE. The x-axis shows a categorical timescale before and after lime application, and the dotted grey line indicates the lime application.

Table 19. Mean change (SE) from year 1 to year 2 for all soil parameters at the softwood control (SWC) and softwood treatment (SWT) sites lower B horizon (M2 horizon) and the P-values showing the mean change at each site from year 1 to year 2 and the differences between the change in means between the SWC and SWT site.

Soil Chemical Properties	SWC	P-Value (Year 1 to year 2 at SWC site)	SWT	P-Value (Year 1 to year 2 at SWT site)	P-Value (Change in means between sites)
pH	0.003 (0.039)	1.00	-0.036 (0.037)	0.760	0.496
%BS	0.084 (0.110)	0.999	1.94 (0.93)	0.019	0.119
CEC	0.722 (0.300)	0.021	0.913 (0.270)	0.021	0.648
Ca^{2+}	0.004 (0.002)	0.918	0.019 (0.008)	0.033	0.135
Mg^{2+}	0.002 (0.000)	0.986	0.022 (0.006)	0.006	0.033
K^{+}	-0.002 (0.003)	0.550	0.002 (0.001)	0.394	0.244
EA	0.713 (0.300)	0.035	0.833 (0.270)	0.035	0.774
Al^{3+}	-0.487 (0.180)	0.171	-0.399 (0.190)	0.324	0.744
Mn^{2+}	0.001 (0.001)	0.028	0.003 (0.001)	0.028	0.261

3.3.3 Plant Tissue Response to Liming

Softwood Schreber’s Moss

Schreber’s moss tissue P and Al increased, and K decreased significantly at the SWC site from year 1 to year 2. Potassium also decreased at the SWT site, but the change in means between sites was not significant. Plant tissue Ca, Mg, Al, Fe, and Mn all increased significantly at the SWT site one year after liming, and the change in means between the sites was significant for all properties (Figure 17, Table 19). Calcium increased from 1.88 ± 0.06 to 15.6 ± 0.8 g kg^{-1}, Mg increased from 1.27 ± 0.03 to 6.06 ± 0.31 g kg^{-1}, Al increased from 0.13 ± 0.02 to 0.48 ± 0.03 g kg^{-1}, Fe increased from 0.11 ± 0.00 to 1.00 ± 0.07, and Mn increased from 0.40 ± 0.01 to 0.54 ± 0.03. Nitrogen did not change significantly in response to the lime treatment.

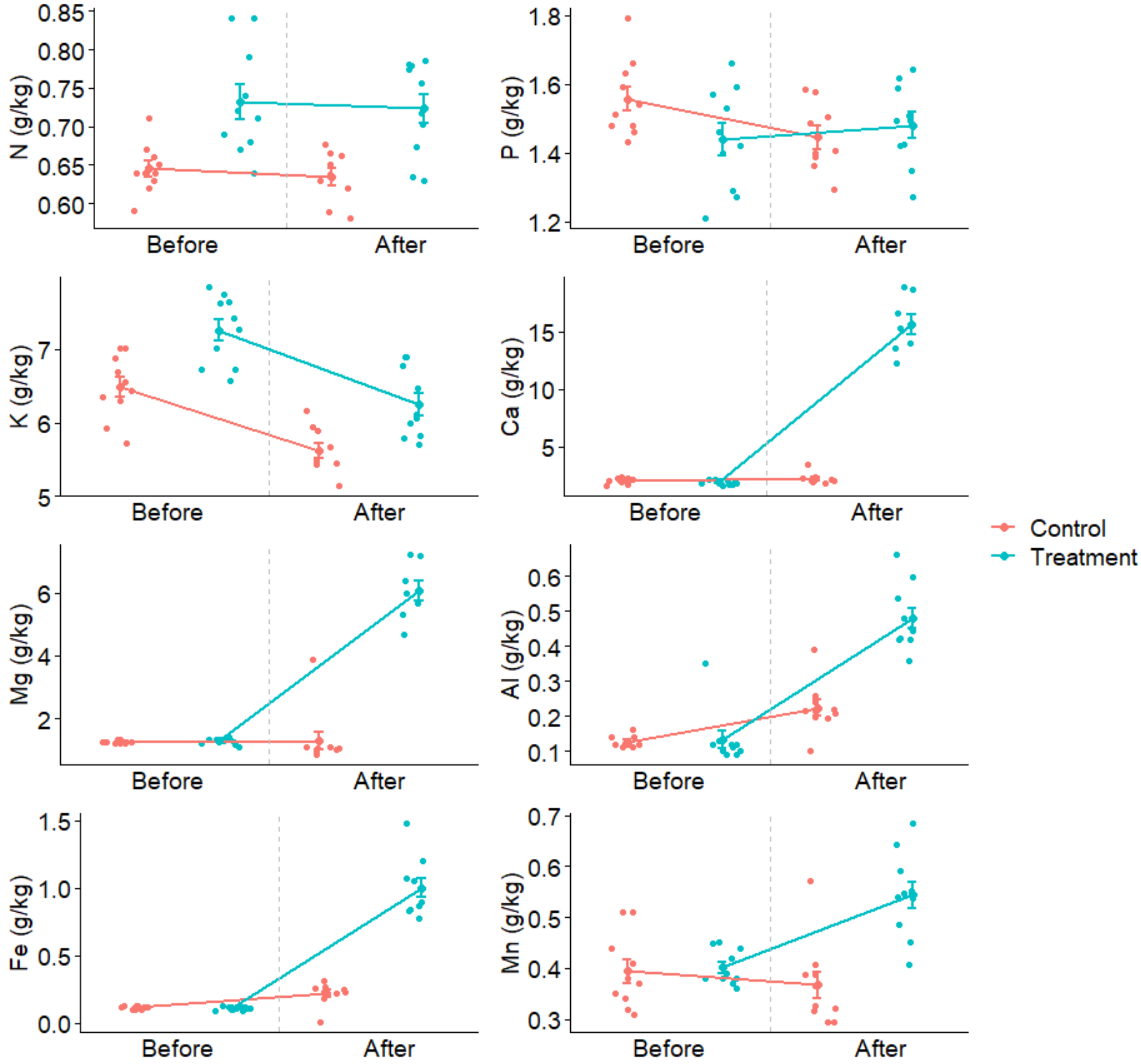


Figure 17. Schreber's moss tissue total element concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), iron (Fe), and manganese (Mn) at the softwood control (SWC) and treatment (SWT) sites before and after lime application. Error bars indicate the mean ± 1 SE. The x-axis indicates the categorical timescale before and after lime application, and the grey line indicates the lime application.

Table 20. Mean change (SE) from year 1 to year 2 for Schreber's moss tissue chemical properties at the softwood control (SWC) and softwood treatment (SWT) sites and the P-values showing the mean change at each site from year 1 to year 2 and the differences between the change in means between the SWC and SWT sites.

Plant Tissue Properties	**SWC**	**P-Value (Year 1 to year 2 at SWC site)**	**SWT**	**P-Value (Year 1 to year 2 at SWT site)**	**P-Value (Change in means between sites)**
N	-0.006 (0.019)	0.876	-0.009 (0.019)	0.876	0.922
P	-0.108 (0.044)	0.036	0.041 (0.039)	0.723	0.039
K	-0.853 (0.190)	<.0001	-1.01 (0.09)	<.0001	0.456
Ca	0.191 (0.220)	0.980	14.4 (1.1)	<.0001	0.000
Mg	0.028 (0.290)	1.00	5.02 (0.39)	<.0001	0.000
Al	0.097 (0.029)	0.024	0.346 (0.052)	<.0001	0.006
Fe	0.103 (0.027)	0.166	0.890 (0.080)	<.0001	0.001
Mn	-0.027 (0.032)	0.754	0.142 (0.047)	0.0001	0.021

Softwood Red Spruce Foliage

Red spruce foliar Mg, Fe, and Mn decreased significantly at the SWC site from year 1 to year 2; however, the change in means between sites was only significant for Mg. Manganese and Fe decreased similarly at the SWT site after treatment. Foliar Mg did not increase significantly at the SWT site; however, the change in means between sites was significant, suggesting an effect from liming. Foliar Ca increased significantly from 1.64 ± 0.12 to 2.65 ± 0.16 g kg^{-1} at the SWT site one year after treatment; however, the change in means between sites is not significant as a non-significant increase was observed at the SWC site (Figure 18, Table 20).

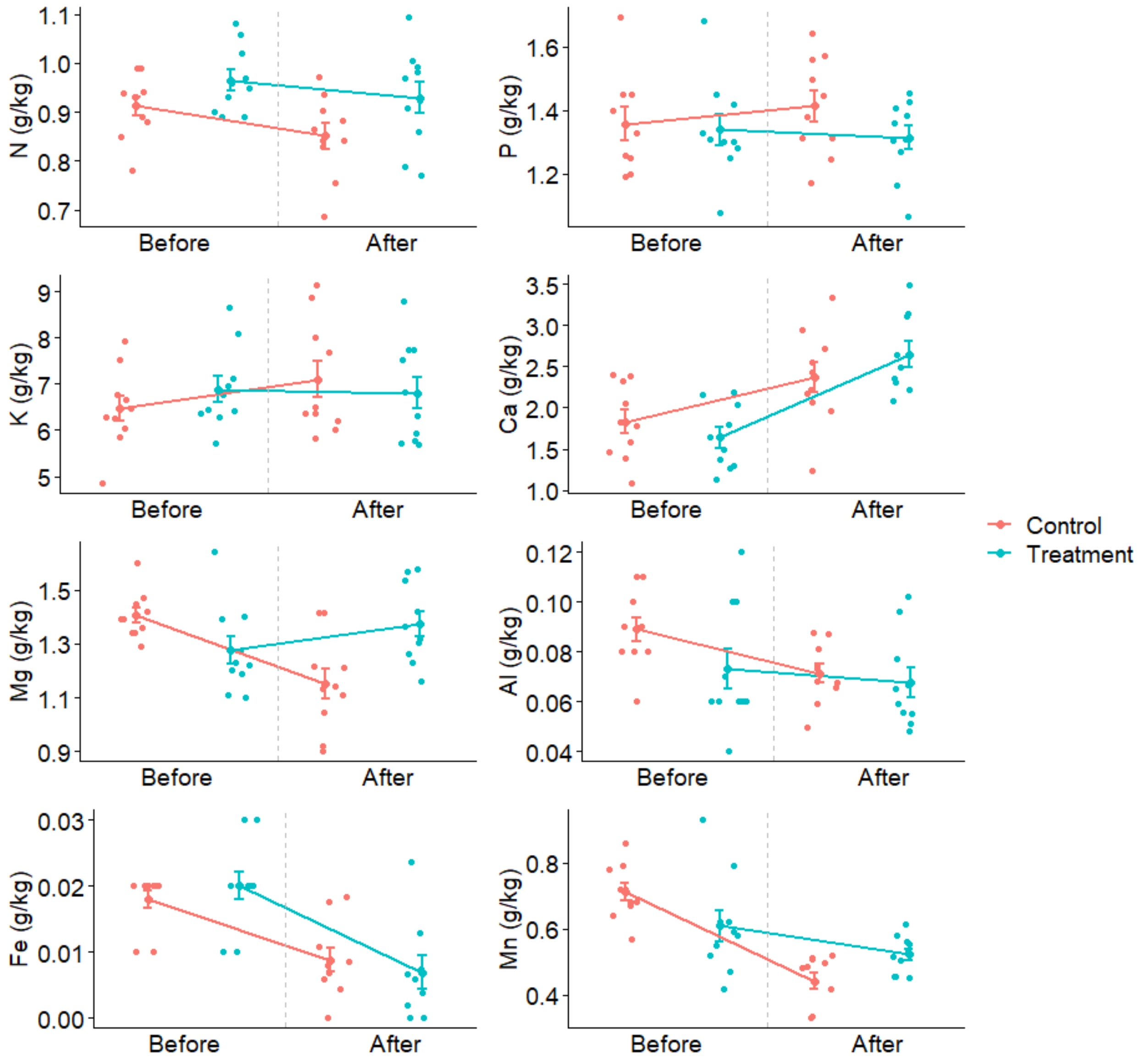


Figure 18. Red spruce foliage total element concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), iron (Fe), and manganese (Mn) at the softwood control (SWC) and treatment (SWT) sites before and after lime application. Error bars indicate mean ± 1 SE. The x-axis indicates the categorical timescale before and after lime application, and the grey line indicates the lime application.

Table 21. Mean change (SE) from year 1 to year 2 for red spruce foliar chemical properties at the softwood control (SWC) and softwood treatment (SWT) sites and the P-values showing the mean change at each site from year 1 to year 2 and the differences between the change in means between the SWC and SWT site.

Plant Tissue Properties	SWC	P-Value (Year 1 to year 2 at SWC site)	SWT	P-Value (Year 1 to year 2 at SWT site)	P-Value (Change in means between sites)
N	-0.061 (0.024)	0.223	-0.036 (0.039)	0.223	0.608
P	0.047 (0.082)	1.00	-0.025 (0.053)	0.989	0.489
K	0.63 (0.810)	0.512	-0.074 (0.350)	0.999	0.457
Ca	0.536 (0.180)	0.062	0.973 (0.180)	<0.0001	0.129
Mg	-0.254 (0.071)	0.001	0.099 (0.086)	0.433	0.016
Al	-0.018 (0.010)	0.134	-0.006 (0.010)	0.908	0.418
Fe	-0.009 (0.002)	0.004	-0.013 (0.005)	<0.0001	0.533
Mn	-0.269 (0.032)	<.0001	-0.087 (0.027)	0.200	0.003

3.3.4 Lime-Plant-Soil Relationship

Calcium and Mg concentration increased in the soil, ground vegetation, and foliage at the SWT site one year after liming (Figure 24). Correlations between the lime loading rate and change in Ca and Mg from year 1 to year 2 at the plot level were further investigated here. There was a positive correlation between lime loading rates and Ca^{2+} concentration increase (r = 0.63), as well as a positive correlation between lime loading rates and Mg^{2+} concentration increase in the F horizon (r = 0.54) (Figure 19). There was a positive correlation between lime loading rates and Ca concentration increase (r = 0.76) as well as a positive correlation between lime loading rates and Mg concentration increase (r = 0.78) in Schreber's moss at the SWT treatment site after liming (Figure 20). However, there was no correlation between lime loading and red spruce foliar Ca concentration (r = 0.00) and a weak positive correlation between lime loading and red spruce foliar Mg (r = 0.21) (Figure 21). There was little to no correlation between the change in

F horizon Ca^{2+} and Schreber's moss Ca (r = 0.29) (Figure 22) or F horizon Mg^{2+} and Schreber's moss Mg (r = 0.03) (Figure 23) at the plot level.

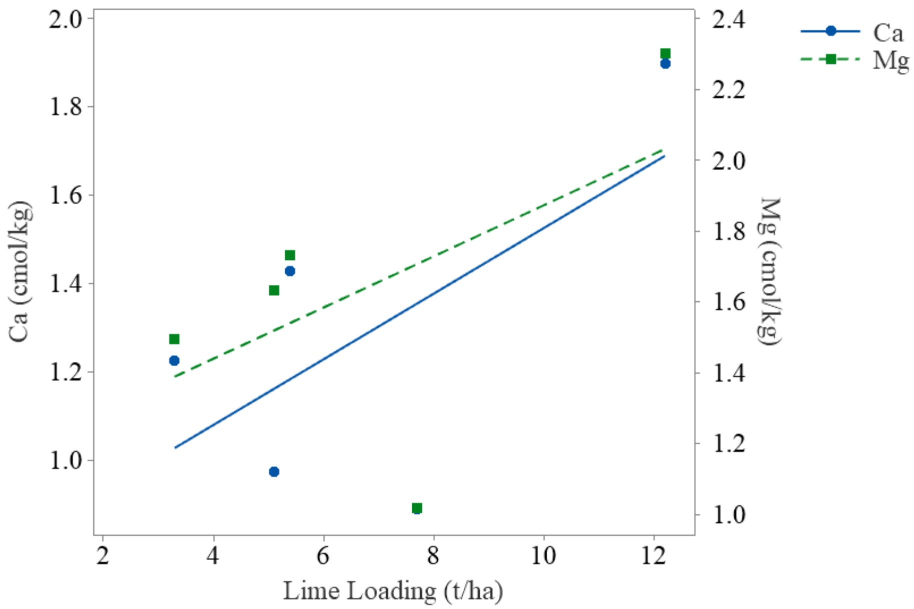


Figure 19. Correlation between lime loading rates and soil Ca^{2+} concentration (Ca) and lime loading rates and soil Mg^{2+} concentration (Mg) in the upper forest floor horizon after liming. Values represent the change in Ca and Mg concentrations from year 1 to year 2 at each plot at the softwood treatment site.

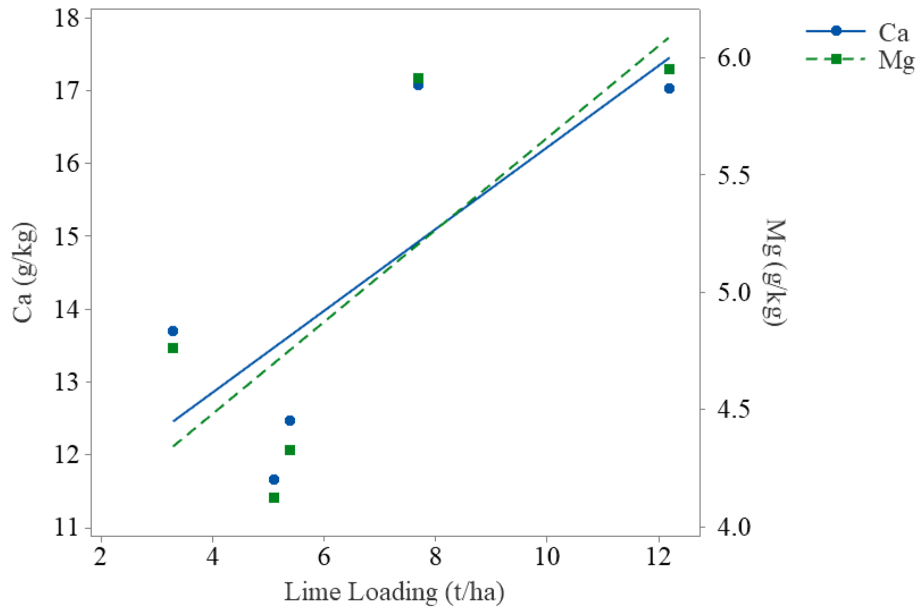


Figure 20. Correlation between lime loading rates and Schreber's Moss Ca concentration and lime loading rates and Schreber's Moss Mg concentration after liming. Values represent the change in Ca and Mg concentrations from year 1 to year 2 at each plot at the softwood treatment site.

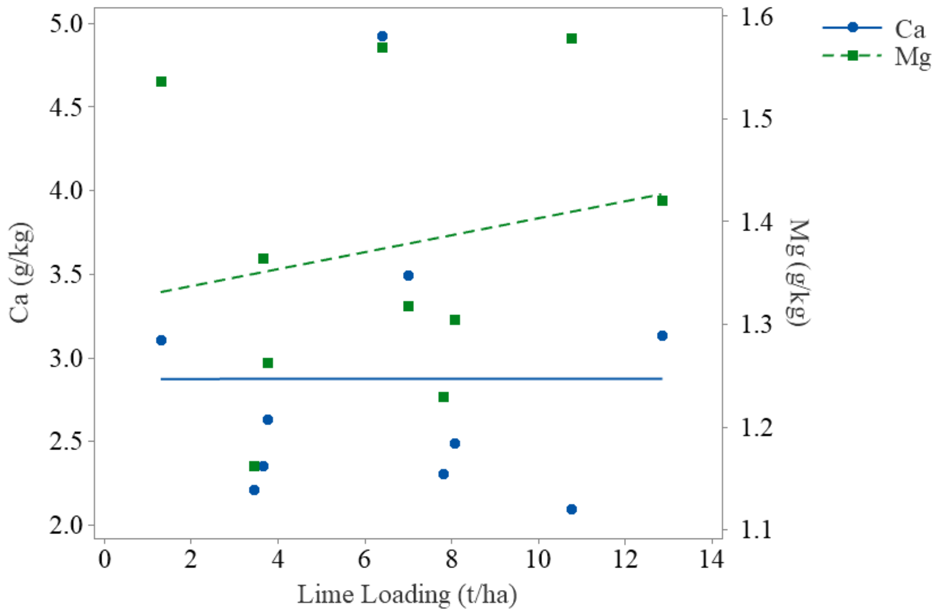


Figure 21. Correlation between lime loading rates and calcium (Ca) and lime loading rates and magnesium (Mg) concentrations of red spruce foliage at the softwood treatment site after liming.

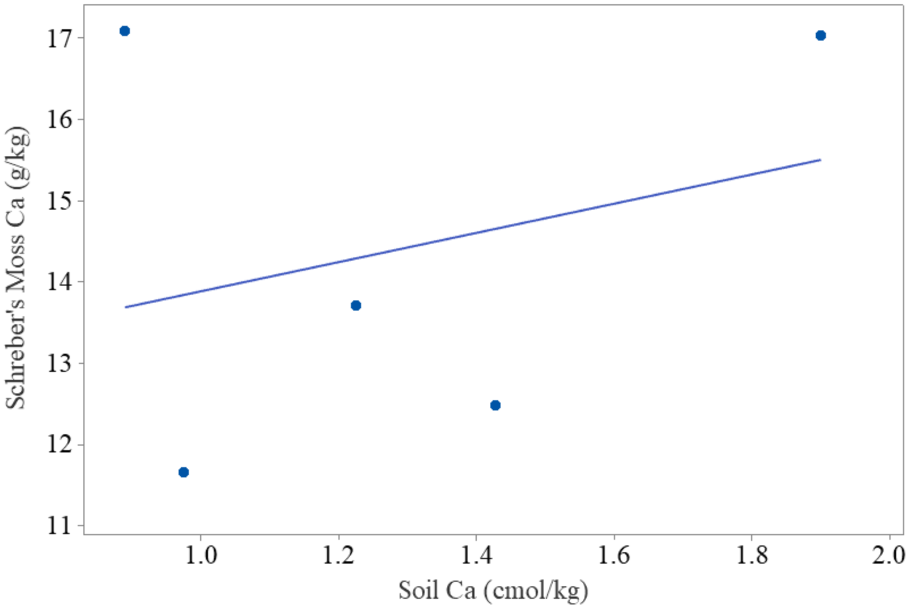


Figure 22. Correlation between soil Ca2+ and Schreber's moss calcium (Ca) at the softwood treatment site after liming.

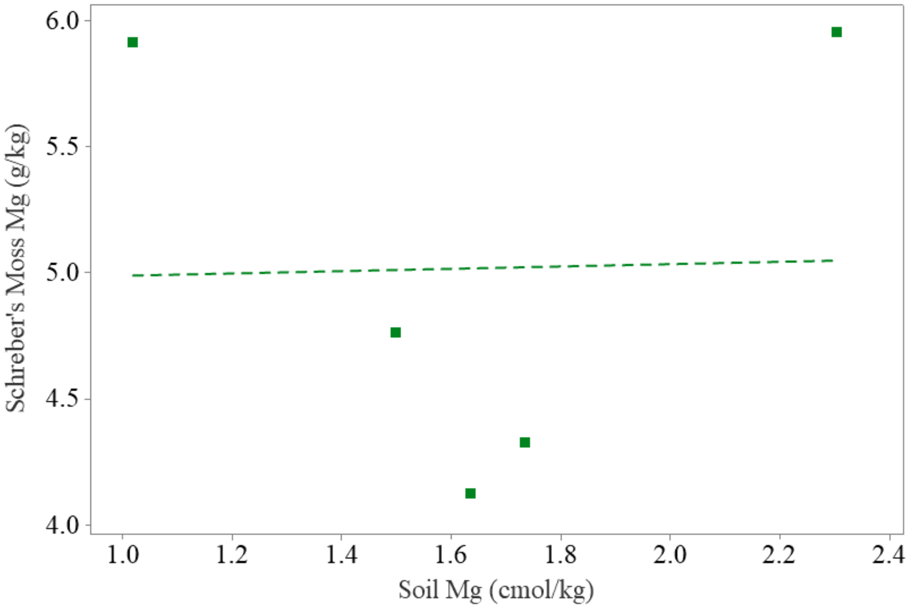
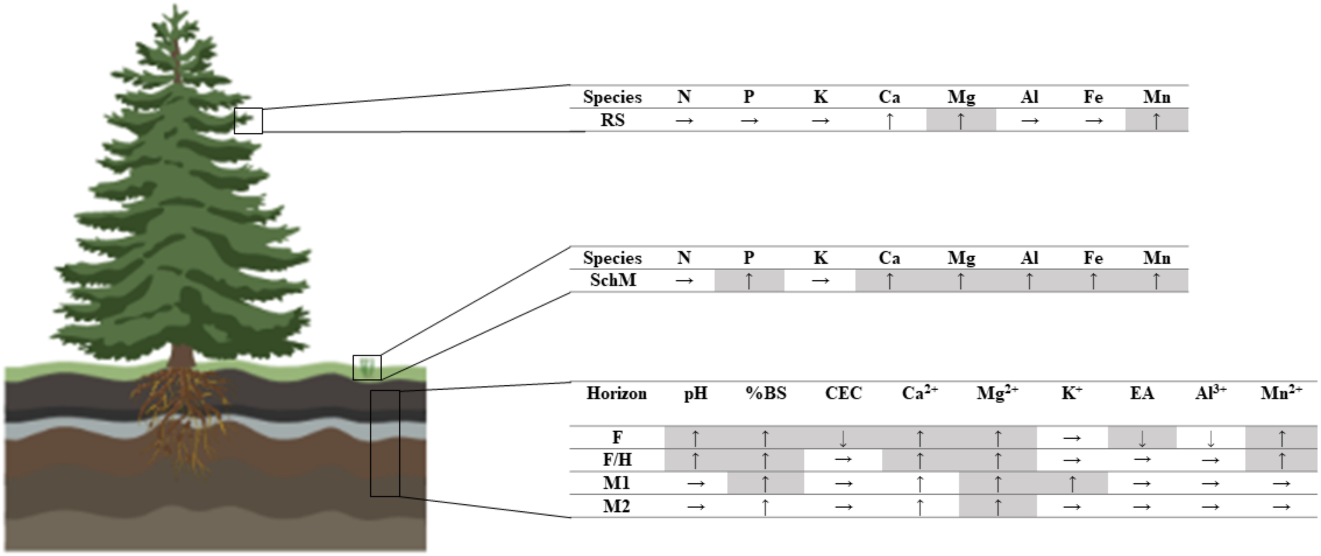


Figure 23. Correlation between soil Mg2+ and Schreber's moss magnesium (Mg) at the softwood treatment site after liming.



Species	N	P	K	Ca	Mg	Al	Fe	Mn
RS	→	→	→	↑	↑	→	→	↑

Species	N	P	K	Ca	Mg	Al	Fe	Mn
SchM	→	↑	→	↑	↑	↑	↑	↑

Horizon	pH	%BS	CEC	Ca^{2+}	Mg^{2+}	K^+	EA	Al^{3+}	Mn^{2+}
F	↑	↑	↓	↑	↑	→	↓	↓	↑
F/H	↑	↑	→	↑	↑	→	→	→	↑
M1	→	↑	→	↑	↑	↑	→	→	→
M2	→	↑	→	↑	↑	→	→	→	→

Figure 24. Summary of chemical changes in all sampled soil horizons (F, F/H, M1, M2), Schreber's moss (SchM), and red spruce foliage (RS) at the softwood treatment (SWT) site after liming. The arrows indicate trends, and shaded arrows indicate a significant difference ($P < 0.05$). Trends may indicate an increase or decrease at the SWT site in direct response to lime or lack of increase or decrease at the SWT site compared with the softwood control (SWC). If similar trends were shown at the SWT and SWC sites, they were not considered a response to liming.

3.4 Hardwood Results

3.4.1 Pre-Treatment Conditions

Differences in means for most soil chemical properties between the HWC and HWT sites in year 1 were not statistically significant, except K^+ was greater at the HWT site in the F horizon, and pH was greater at the HWT site in the M2 horizon (Table 21).

Table 22. Mean and standard error (SE) of pH, base saturation (BS), cation exchange capacity (CEC), exchangeable base cations (Ca^{2+}, Mg^{2+}, K^{+}), exchangeable acidity (EA), exchangeable Al^{3+}, and exchangeable Mn^{2+} in each soil horizon at the hardwood control (HWC) and hardwood treatment (HWT) sites in year 1. Indicates a significant difference between the HWT and HWC sites ($P < 0.05$).*

Site	**pH**	**%**	**Exchangeable Ions (cmol kg^{-1})**						
		BS	**CEC**	**Ca^{2+}**	**Mg^{2+}**	**K^{+}**	**EA**	**Al^{3+}**	**Mn^{2+}**
F									
HWC	2.87 ± 0.09	30.1 ± 3.6	6.82 ± 0.56	0.98 ± 0.10	0.70 ± 0.05	0.22 ± 0.02	4.85 ± 0.67	0.67 ± 0.32	0.18 ± 0.03
HWT	2.84 ± 0.06	32.5 ± 2.2	6.93 ± 0.30	1.08 ± 0.11	0.75 ± 0.02	0.29* ± 0.02	4.70 ± 0.33	0.64 ± 0.15	0.19 ± 0.03
M1									
HWC	3.55 ± 0.04	0.64 ± 0.05	3.79 ± 0.29	0.003 ± 0.001	0.011 ± 0.001	0.008 ± 0.001	3.77 ± 0.29	2.32 ± 0.03	0.023 ± 0.003
HWT	3.48 ± 0.05	0.97 ± 0.15	3.50 ± 0.24	0.005 ± 0.001	0.012 ± 0.001	0.014 ± 0.004	3.47 ± 0.24	2.45 ± 0.02	0.014 ± 0.001
M2									
HWC	3.48 ± 0.04	0.59 ± 0.06	2.20 ± 0.17	0.00096 ± 0.00069	0.008 ± 0.001	0.005 ± 0.001	2.18 ± 0.16	2.30 ± 0.18	0.017 ± 0.001
HWT	3.87* ± 0.03	1.24 ± 0.14	1.97 ± 0.15	0.0037 ± 0.0005	0.0060 ± 0.0004	0.0045 ± 0.0003	1.95 ± 0.15	2.89 ± 0.13	0.009 ± 0.002

There were few differences in tissue chemistry between the HWT and HWC sites in year 1. Exceptions include significantly lower N at the treatment site for both wood fern and sugar maple foliage, significantly lower Al at the treatment site for wood fern, significantly greater Ca at the treatment site for sugar maple foliage and significantly lower Fe at the treatment site for sugar maple foliage (Table 22).

*Table 23. Mean and standard error (SE) of elements for Evergreen wood fern (WF), red maple foliage (RM), and sugar maple foliage (SM) in year 1 at the hardwood control (HWC) and hardwood treatment (HWT) sites. * Indicates a significant difference between the HWT and HWC sites ($P < 0.05$).*

Site	g kg^{-1}							
	N	**P**	**K**	**Ca**	**Mg**	**Al**	**Fe**	**Mn**
WF								
HWC	2.31 ± 0.07	2.18 ± 0.14	16.3 ± 0.5	3.31 ± 0.14	5.70 ± 0.09	0.13 ± 0.04	0.022 ± 0.002	0.91 ± 0.04
HWT	1.99* ± 0.03	2.30 ± 0.14	17.0 ± 0.4	3.40 ± 0.07	5.59 ± 0.09	0.064* ± 0.007	0.013* ± 0.001	0.99 ± 0.06
RM								
HWC	1.76 ± 0.06	1.60 ± 0.05	6.67 ± 0.38	4.00 ± 0.20	1.23 ± 0.06	0.033 ± 0.004	0.028 ± 0.002	0.65 ± 0.03
HWT	1.59 ± 0.04	1.46 ± 0.04	6.42 ± 0.25	5.15 ± 0.19	1.51 ± 0.05	0.032 ± 0.004	0.024 ± 0.003	0.74 ± 0.06
SM								
HWC	1.90 ± 0.06	1.52 ± 0.06	8.18 ± 0.36	2.88 ± 0.20	1.70 ± 0.07	0.040 ± 0.004	0.037 ± 0.002	0.67 ± 0.04
HWT	1.64* ± 0.05	1.40 ± 0.04	7.34 ± 0.25	3.84* ± 0.31	1.65 ± 0.11	0.049 ± 0.003	0.020* ± 0.002	0.80 ± 0.05

3.4.2 Soil Response to Liming

Hardwood F Horizon

Slight changes were observed in some of the soil chemical properties in the forest floor (F) horizon at the HWC site from year 1 to year 2; however, K^{+} increased non-significantly. The forest floor horizon pH, %BS, Ca^{2+}, and Mg^{2+} significantly increased, while exchangeable acidity significantly decreased at the HWT site one year after treatment (Figure 25). The pH increased from 2.84 ± 0.06 to 4.39 ± 0.12, the %BS increased from 32.5 ± 2.2 to 76.9 ± 1.0%, Ca^{2+} increased from 1.08 ± 0.11 to 1.89 ± 0.05 cmol kg^{-1}, Mg^{2+} increased from 0.75 ± 0.02 to 2.33 ± 0.06 cmol kg^{-1}, and exchangeable acidity decreased from 4.70 ± 0.33 to 1.37 ± 0.06 cmol kg^{-1}. The change in means between sites was significant for pH, %BS, Ca^{2+}, Mg^{2+}, exchangeable acidity, and K^+, which decreased non-significantly at the HWT site after treatment. Exchangeable Al^{3+} increased non-significantly at the HWC site and decreased non-significantly at the HWT site. The change in means for Al^{3+} was significant when P = 0.1 (Table 23). No significant changes were observed for CEC or Mn^{2+}.

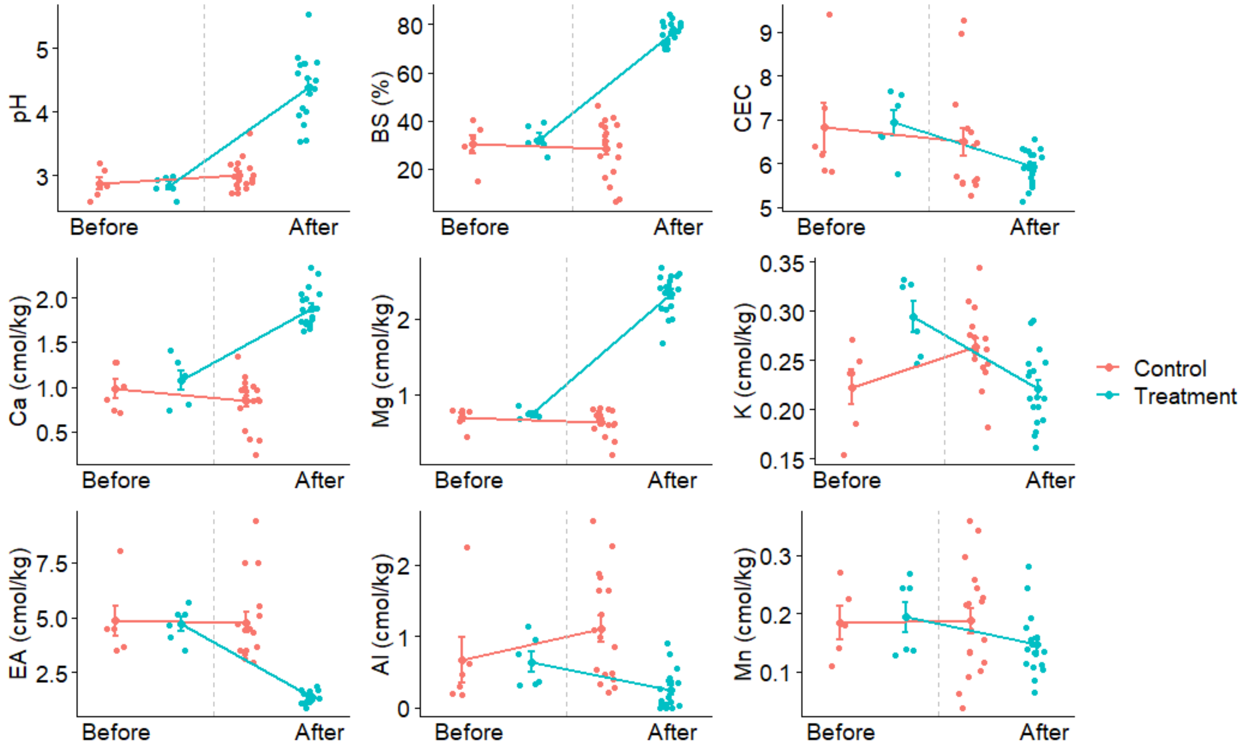


Figure 25. Forest floor (F) horizon pH, percent base saturation (%BS), cation exchange capacity (CEC), base cation concentrations (Ca^{2+}, Mg^{2+}, K^+), exchangeable acidity (EA), Al^{3+} concentration, and Mn^{2+} concentration plot data at the hardwood control (HWC) and treatment (HWT) sites. Error bars indicate the mean ± 1 SE. The x-axis shows a categorical timescale before and after lime application, and the dotted grey line indicates the lime application.

Table 24. Mean change (SE) from year 1 to year 2 for all soil properties at the hardwood control (HWC) and hardwood treatment (HWT) sites forest floor (F) horizon, the P-values showing the mean change at each site from year 1 to year 2, and the differences between the change in means between the HWC and HWT site.

Soil Chemical Properties	HWC	P-Value (Year 1 to year 2 at HWC site)	HWT	P-Value (Year 1 to year 2 at HWT site)	P-Value (Change in means between sites)
pH	0.132 (0.14)	0.804	1.55 (0.21)	<.0001	0.001
%BS	-1.6 (3.8)	0.978	44.4 (2.6)	<.0001	0.000
CEC	-0.40 (0.59)	0.974	-1.01 (0.35)	0.072	0.400
Ca^{2+}	-0.14 (0.10)	0.617	0.807 (0.16)	<.0001	0.001
Mg^{2+}	-0.059 (0.067)	0.882	1.58 (0.094)	<.0001	0.000
K^{+}	0.041 (0.015)	0.093	-0.073 (0.021)	0.001	0.002
EA	-0.05 (0.86)	0.829	-3.33 (0.33)	0.009	0.012
Al^{3+}	0.452 (0.36)	0.286	-0.391 (0.16)	0.613	0.069
Mn^{2+}	0.003 (0.059)	1.00	-0.047 (0.035)	0.529	0.833

Hardwood M1 Horizon

Few changes were observed in some of the soil chemical properties in the upper B (M1) horizon at the HWC site from year 1 to year 2; however, pH increased significantly. The M1 horizon pH, %BS, Ca^{2+}, and Mg^{2+} significantly increased at the HWT site one year after treatment (Figure 26). The pH increased from 3.48 ± 0.05 to 3.73 ± 0.04 at the HWT site, and despite similar changes observed at the HWC, the change in means between the two sites was significantly different, indicating that pH increased more at the HWT site. Percent base saturation increased from 0.97 ± 0.15 to 3.03 ± 0.17%, Ca^{2+} increased from 0.005 ± 0.001 to 0.039 ± 0.004 cmol kg^{-1}, and Mg^{2+} increased from 0.012 ± 0.001 to 0.038 ± 0.005 cmol kg^{-1}. The change in means between sites was significant for %BS, Ca^{2+}, and Mg^{2+}. No significant changes were observed for CEC, exchangeable acidity, Al^{3+}, or Mn^{2+} (Table 24).

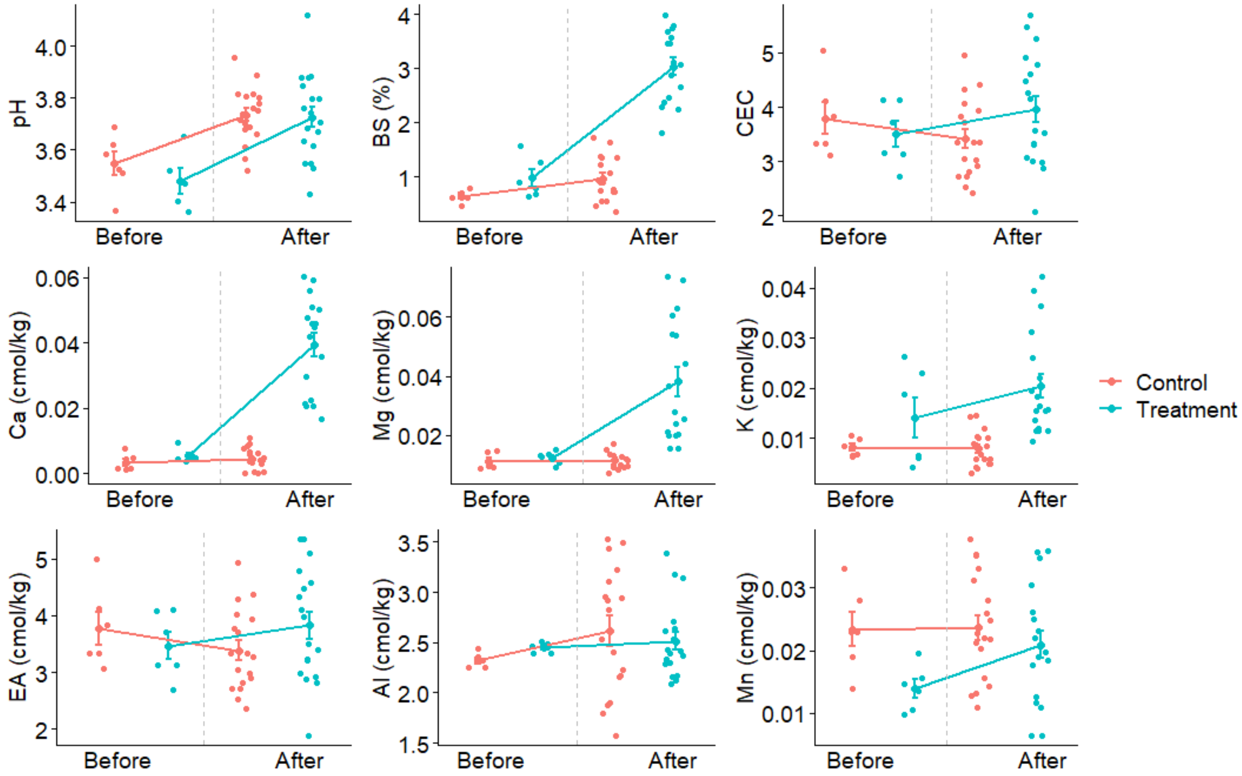


Figure 26. Upper B horizon (M1) pH, percent base saturation (%BS), cation exchange capacity (CEC), base cation concentrations (Ca^{2+}, Mg^{2+}, K^{+}), exchangeable acidity (EA), Al^{3+} concentration, and Mn^{2+} concentration plot data at the hardwood control (HWC) and treatment (HWT) sites. Error bars indicate the mean ± 1 SE. The x-axis shows a categorical timescale before and after lime application, and the dotted grey line indicates the lime application.

Table 25. Mean change (SE) from year 1 to year 2 for all soil parameters at the hardwood control (HWC) and hardwood treatment (HWT) sites upper B horizon (M1 horizon), the P-values showing the mean change at each site from year 1 to year 2, and the differences between the change in means between the HWC and HWT sites.

Soil Chemical Properties	HWC	P-Value (Year 1 to year 2 at HWC site)	HWT	P-Value (Year 1 to year 2 at HWT site)	P-Value (Change in means between sites)
pH	0.187 (0.034)	0.002	0.321 (0.040)	<0.0001	0.032
%BS	0.331 (0.150)	0.460	2.01 (0.22)	<0.0001	0.000
CEC	-0.375 (0.39)	0.771	0.432 (0.22)	0.640	0.114
Ca^{2+}	0.001 (0.002)	0.994	0.033 (0.004)	<0.0001	0.000
Mg^{2+}	0.000 (0.002)	0.996	0.024 (0.005)	<0.0001	0.008
K^{+}	-0.000 (0.001)	1.00	0.006 (0.007)	0.2493	0.407
EA	-0.383 (0.39)	0.742	0.328 (0.20)	0.783	0.146
Al^{3+}	0.296 (0.22)	0.441	0.065 (0.09)	0.988	0.372
Mn^{2+}	0.000(0.003)	1.00	0.006 (0.003)	0.288	0.216

Hardwood M2 Horizon

Few changes were observed in some of the soil chemical properties in the lower B (M2) horizon at the HWC site from year 1 to year 2; however, pH increased significantly. The change in pH means between sites was significantly different; however, the increase was observed at the HWC site and, therefore, not a response from liming. The M2 horizon pH, %BS, Ca^{2+}, Mg^{2+}, K^{+}, and Mn^{2+} significantly increased at the HWT site one year after treatment (Figure 27); however, the change in means between sites was not significantly different for K^{+} or Mn^{2+}. Percent base saturation increased from 1.24 ± 0.14 to 3.76 ± 0.33%, Ca^{2+} increased from 0.0037 ± 0.0005 to 0.029 ± 0.004 cmol kg^{-1}, and Mg^{2+} increased from 0.0060 ± 0.0004 to 0.025 ± 0.004 cmol kg^{-1}. The change in means between sites was significant for %BS, Ca^{2+}, and Mg^{2+}. No significant changes were observed for CEC, exchangeable acidity, Al^{3+}, or Mn^{2+} (Table 25).

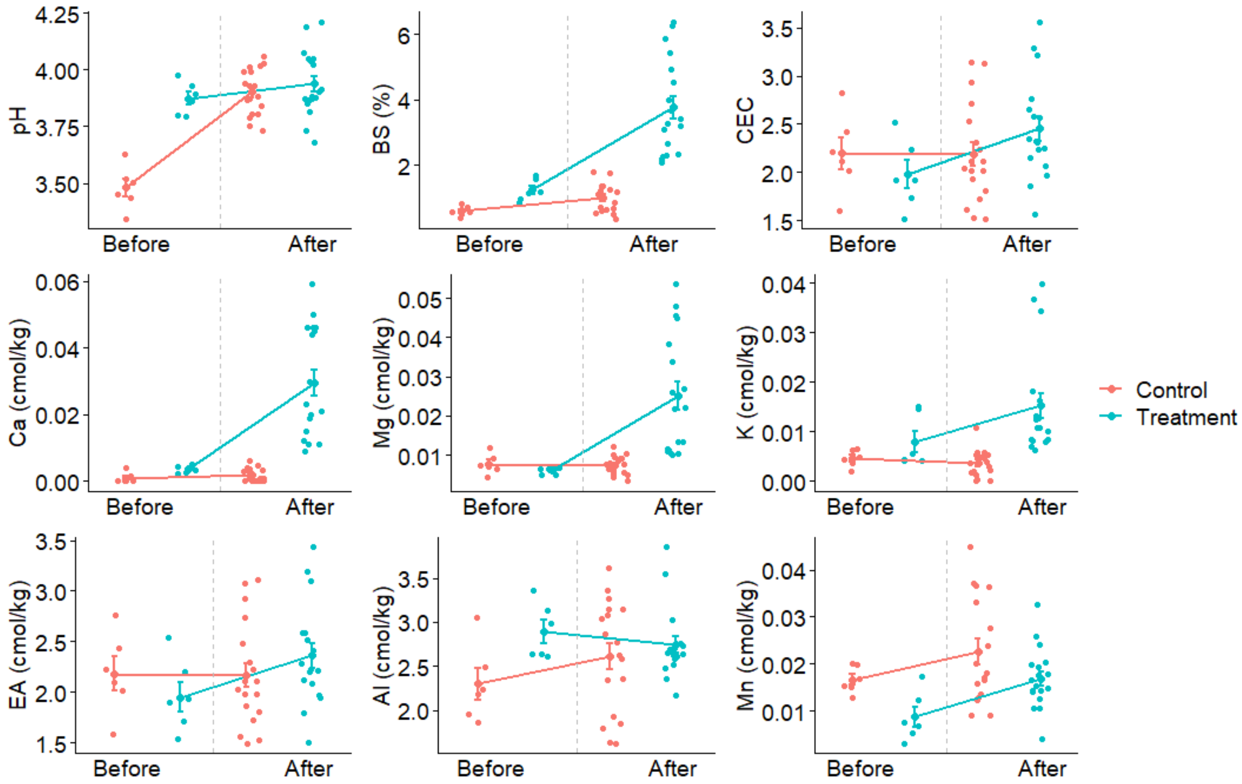


Figure 27. Lower B horizon (M2) pH, percent base saturation (%BS), cation exchange capacity (CEC), base cation concentrations (Ca^{2+}, Mg^{2+}, K^{+}), exchangeable acidity (EA), Al^{3+} concentration and Mn^{2+} concentration plot data at the hardwood control (HWC) and treatment (HWT) sites. Error bars indicate the mean ± 1 SE. The x-axis shows a categorical timescale before and after lime application, and the dotted grey line indicates the lime application.

Table 26. Mean change (SE) from year 1 to year 2 for all soil properties at the hardwood control (HWC) and hardwood treatment (HWT) sites lower B (M2) horizon, the P-values showing the mean change at each site from year 1 to year 2, and the differences between the change in means between the HWC and HWT site.

Soil Chemical Properties	HWC	P-Value (Year 1 to year 2 at HWC site)	HWT	P-Value (Year 1 to year 2 at HWT site)	P-Value (Change in means between sites)
pH	0.422 (0.044)	<0.0001	0.064(0.045)	0.556	0.000
%BS	0.415 (0.15)	0.693	2.52(0.51)	<0.0001	0.011
CEC	-0.008(0.19)	1.00	0.466(0.28)	0.095	0.198
Ca^{2+}	0.001(0.001)	0.993	0.026(0.006)	<0.0001	0.008
Mg^{2+}	-0.000(0.001)	1.00	0.019(0.005)	0.0001	0.014
K^{+}	-0.001(0.001)	0.976	0.007(0.005)	0.024	0.192
EA	-0.017(0.19)	1.00	0.397(0.26)	0.207	0.235
Al^{3+}	0.316(0.34)	0.504	-0.154(0.14)	0.902	0.246
Mn^{2+}	0.007(0.003)	0.274	0.008(0.002)	0.087	0.643

3.4.3 Plant Tissue Response to Liming

Hardwood Wood Fern

Wood fern tissue K and Fe increased, and Mg and Al decreased significantly at the HWC site from year 1 to year 2. Iron similarly increased at the HWT site, and the change in means between sites was not significant. Plant tissue Ca increased significantly at the HWT site from 3.40 ± 0.07 to 4.60 ± 0.09 g kg^{-1}, and the change in means between sites was significant. Plant tissue Mg decreased significantly at the HWT site after treatment; however, the decrease was significantly less than at the HWC site, and the change in means between sites was significant. Potassium also decreased significantly at the HWT site, and the change in means between sites was significant. Aluminum decreased non-significantly at the HWT site one year after treatment; the decrease was significantly less than at the HWC site. Nitrogen and Mn showed no significant changes from lime treatment (Figure 28, Table 26).

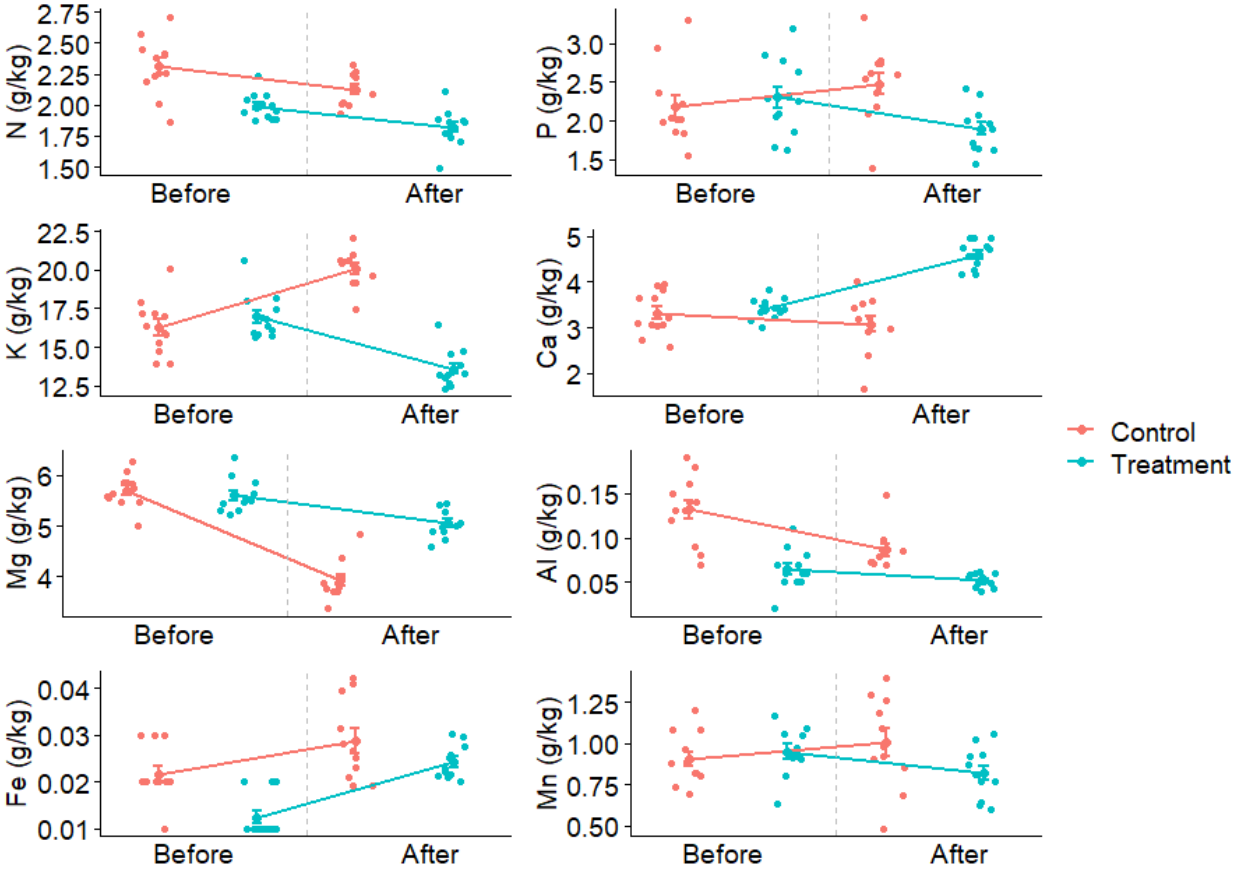


Figure 28. Wood fern tissue total element concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), iron (Fe), and manganese (Mn) at the hardwood control (HWC) and treatment (HWT) sites before and after lime application. Error bars indicate mean ± 1 SE. The x-axis indicates the categorical timescale before and after lime application, and the grey line indicates the lime application.

Table 27. Mean change (SE) from year 1 to year 2 for wood fern tissue chemical properties at the hardwood control (HWC) and hardwood treatment (HWT) sites, the P-values showing the mean change at each site from year 1 to year 2, and the differences between the change in means between the HWC and HWT site.

Plant Tissue Properties	HWC	P-Value (Year 1 to year 2 at HWC site)	HWT	P-Value (Year 1 to year 2 at HWT site)	P-Value (Change in means between sites)
N	-0.197 (0.12)	0.041	-0.170 (0.053)	0.063	0.838
P	0.300 (0.22)	0.197	-0.402 (0.12)	0.047	0.025
K	3.85 (0.73)	<0.0001	-3.39 (0.56)	<0.0001	0.000
Ca	-0.242 (0.32)	0.505	1.197 (0.18)	<0.0001	0.005
Mg	-1.786 (0.11)	<0.0001	-0.536 (0.16)	0.001	0.000
Al	-0.046 (0.011)	0.0002	-0.012 (0.008)	0.596	0.028
Fe	0.006 (0.003)	0.020	0.012 (0.002)	<0.0001	0.118
Mn	0.055 (0.10)	0.952	-0.174 (0.09)	0.147	0.127

Hardwood Red Maple Foliage

Red maple foliar chemical properties did not change significantly at the HWC or HWT site one year after treatment (Figure 29). The change in means between the sites did not differ significantly (Table 27). Calcium and Mg increased non-significantly at the HWT site; however, it was not enough to justify an effect from the liming treatment.

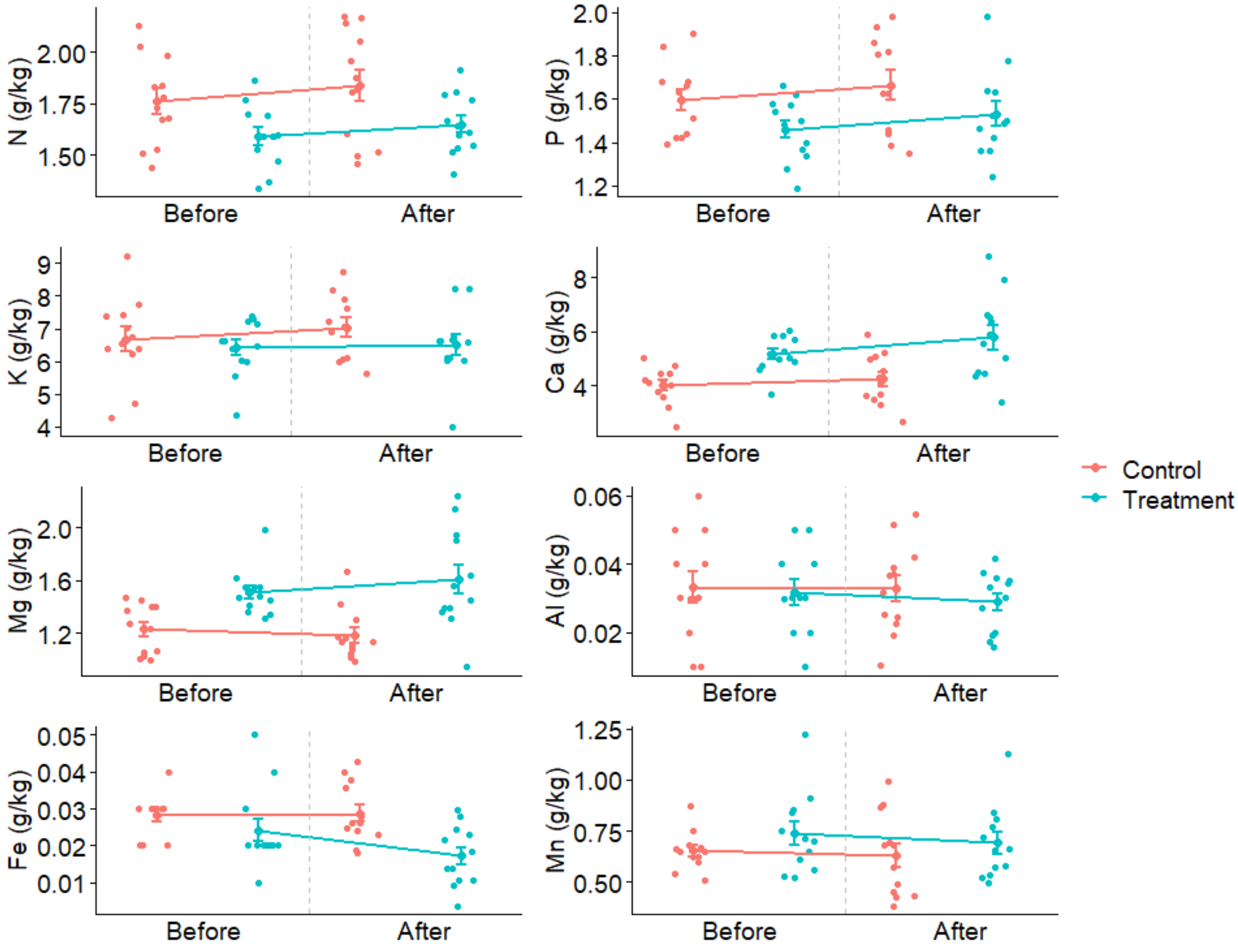


Figure 29. Red maple foliar total element concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), iron (Fe), and manganese (Mn) at the hardwood control (HWC) and treatment (HWT) sites before and after lime application. Error bars indicate mean ± 1 SE. The x-axis indicates the categorical timescale before and after lime application, and the grey line indicates the lime application.

Table 28. Mean change (SE) from year 1 to year 2 for red maple foliar chemical properties at the hardwood control (HWC) and hardwood treatment (HWT) sites, the P-values showing the mean change at each site from year 1 to year 2, and the differences between the change in means between the HWC and HWT sites.

Plant Tissue Properties	**HWC**	**P-Value (Year 1 to year 2 at HWC site)**	**HWT**	**P-Value (Year 1 to year 2 at HWT site)**	**P-Value (Change in means between sites)**
N	0.076 (0.068)	0.604	0.058 (0.065)	0.777	0.856
P	0.043 (0.047)	0.756	0.071 (0.045)	0.499	0.677
K	0.29 (0.53)	0.845	0.075 (0.22)	0.998	0.715
Ca	0.232 (0.25)	0.946	0.619 (0.24)	0.467	0.295
Mg	-0.045 (0.047)	0.968	0.101 (0.11)	0.744	0.279
Al	-0.001 (0.010)	0.999	-0.002 (0.004)	0.476	0.899
Fe	0.000 (0.004)	0.999	-0.007 (0.004)	0.202	0.183
Mn	-0.023 (0.095)	0.988	-0.048 (0.061)	0.902	0.832

Hardwood Sugar Maple Foliage

Sugar maple foliar Mg and K decreased significantly at the HWC site from year 1 to year 2; however, the change in means between sites was only significant for Mg because K showed similar decreases at the SWT site after treatment. Foliar N, Ca, and Mn increased significantly at the HWT site one year after treatment, and the change in means between sites was significant. Foliar Ca increased from 3.84 ± 0.31 to 5.19 ± 0.28 g kg^{-1}. Magnesium increased non-significantly at the HWT site one year after treatment; however, the change in means between sites was significant, suggesting an effect from liming. Phosphorous and Fe showed no significant changes from lime treatment (Figure 30, Table 28).

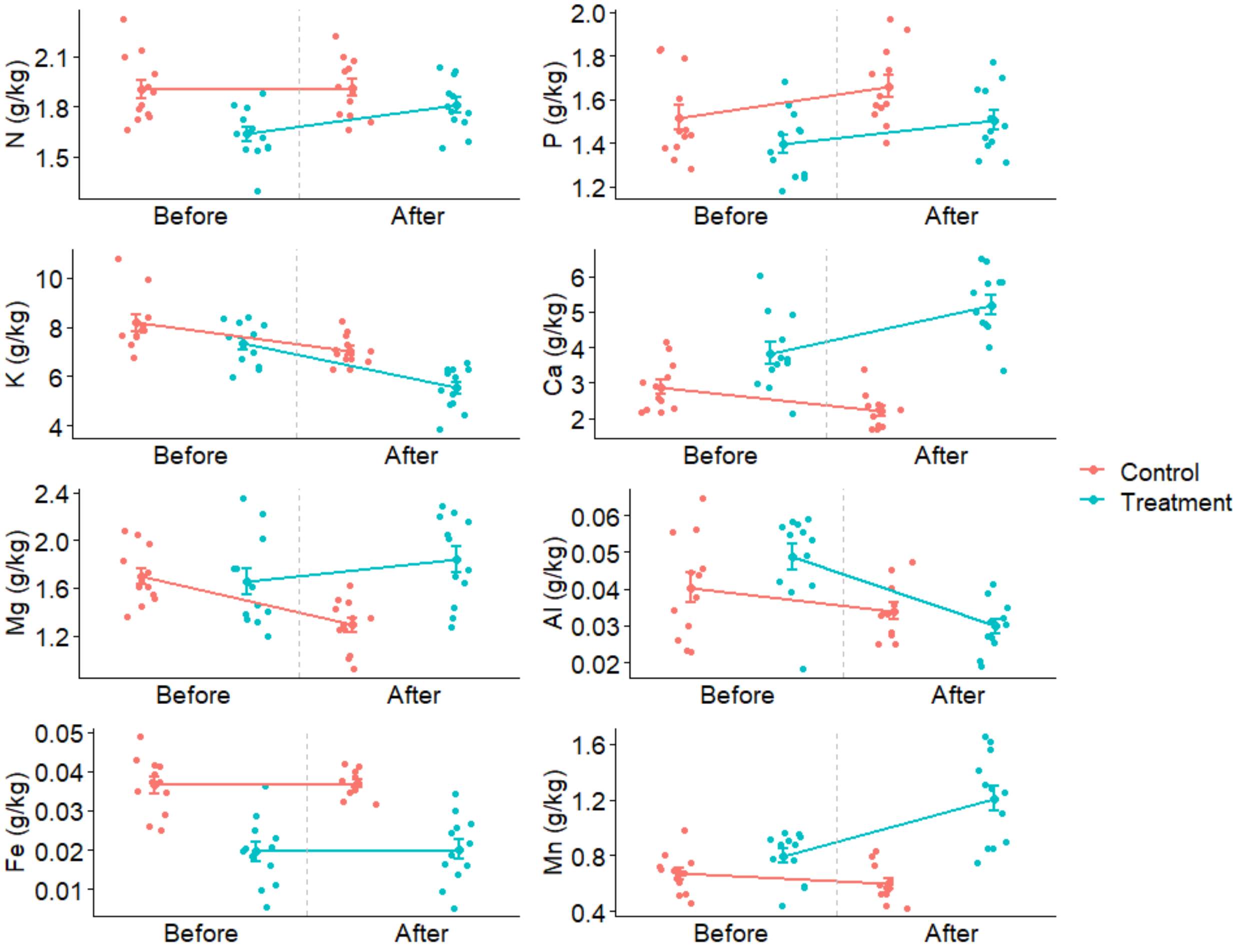


Figure 30. Sugar maple foliar total element concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), iron (Fe), and manganese (Mn) at the hardwood control (HWC) and treatment (HWT) sites before and after lime application. Error bars indicate mean ± 1 SE. The x-axis indicates the categorical timescale before and after lime application, and the grey line indicates the lime application.

Table 29. Mean change (SE) from year 1 to year 2 for sugar maple foliar chemical properties at the hardwood control (HWC) and hardwood treatment (HWT) sites, the P-values showing the mean change at each site from year 1 to year 2, and the differences between the change in means between the HWC and HWT sites.

Plant Tissue Properties	**HWC**	**P-Value (Year 1 to year 2 at HWC site)**	**HWT**	**P-Value (Year 1 to year 2 at HWT site)**	**P-Value (Change in means between sites)**
N	0.010 (0.052)	0.998	0.173 (0.060)	0.028	0.070
P	0.142 (0.039)	0.172	0.109 (0.082)	0.387	0.723
K	-1.14 (0.44)	0.024	-1.81 (0.38)	0.0001	0.282
Ca	-0.666 (0.14)	0.227	1.35 (0.59)	0.002	0.021
Mg	-0.411 (0.084)	0.012	0.187 (0.17)	0.453	0.015
Al	-0.007 (0.006)	0.328	-0.019 (0.005)	0.0002	0.156
Fe	0.000 (0.002)	0.864	0.001 (0.002)	0.864	0.866
Mn	-0.077 (0.025)	0.755	0.413 (0.15)	<0.0001	0.025

All DRIS nutrient indices except K were imbalanced (> 15 or < -15), and the foliar Ca index was the most imbalanced. Potassium became imbalanced at the HWT site after treatment, likely due to changes in the Ca/K ratio. This indicates that Ca is the most limiting nutrient in year 1 and year 2; however, with Ca additions, K also became deficient in year 2. The NBI showed no effect from lime but indicated that the HWC sites were more imbalanced than the treatment sites before and after treatment (Table 29).

Table 30. Diagnosis and Recommendation Integrated System (DRIS) indices for sugar maple based on foliar norms developed by Lozano and Hyunh (1989). Negative DRIS indices indicate a nutrient deficiency. Higher nutrient balance index (NBI) values indicate poorer health.

	DRIS				
	N	P	K	Ca	Mg	NBI
HWC, Before	44	15	7	-129	63	260
HWC, After	62	35	3	-153	53	312
HWT, Before	27	6	-2	-79	48	170
HWT, After	30	5	-30	-52	47	164

3.4.4 Lime-Plant-Soil Relationship

Calcium and magnesium concentrations increased significantly in the forest floor, wood fern, and in sugar maple foliage, but not in red maple foliage (Figure 36). Correlations between the lime loading rates and change in Ca and Mg from year 1 to year 2 at the plot level were further investigated here. There was a weak positive correlation between lime loading rates and change in Ca^{2+} concentration ($r = 0.49$) and a positive correlation between lime loading rates and change in Mg^{2+} concentration ($r = 0.79$) in the F horizon at the HWT site (Figure 31). There was a very weak positive correlation between lime loading rates and change in Ca concentration of wood fern ($r = 0.35$) and a weak negative correlation between lime loading rates and change in Mg concentration of wood fern ($r = -0.57$) (Figure 32). There was a very weak negative correlation between lime loading rates and sugar maple Ca concentration change ($r = -0.15$) and a very weak positive correlation between lime loading rates and sugar maple Mg concentration change ($r = 0.11$) at the plot level at the HWT site (Figure 33). Calcium change in the forest floor and wood fern showed a weak positive correlation ($r = 0.48$) (Figure 34), and Mg^{2+} change in the forest floor and Mg change in wood fern had a strong negative correlation ($r= -0.90$) (Figure 35). Despite little correlation to lime loading rates, there was a stronger correlation between the increase in Ca^{2+} in the forest floor horizon and the increase in Ca concentration in sugar maple foliage ($r = 0.74$) (Figure 34). Magnesium in the forest floor horizon and sugar maple had very little correlation ($r = 0.12$) (Figure 35).

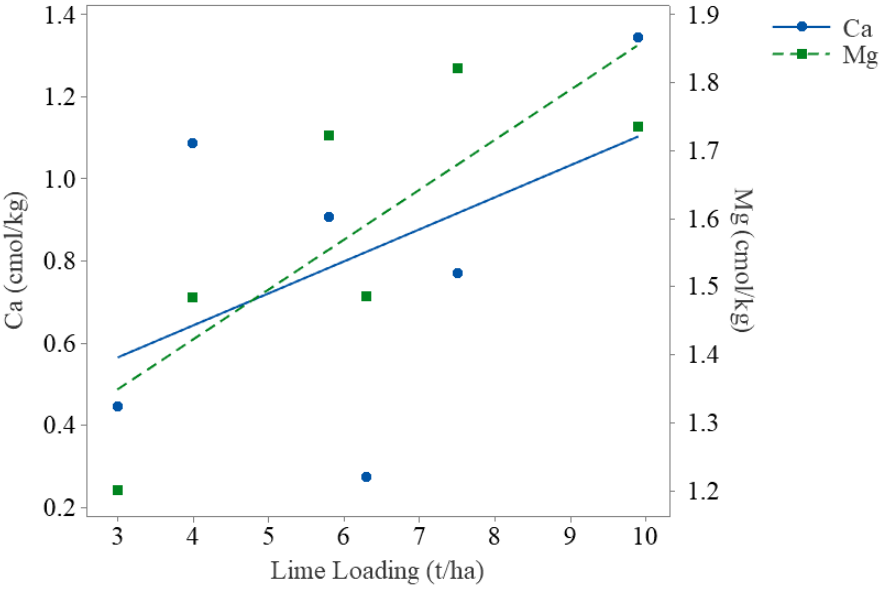


Figure 31. Correlation between lime loading rates and soil Ca^{2+} concentration (Ca) and lime loading rates and soil Mg^{2+} concentration (Mg) in the upper forest floor horizon after liming. Values represent the change in Ca and Mg concentrations from year 1 to year 2 at each plot at the hardwood treatment site.

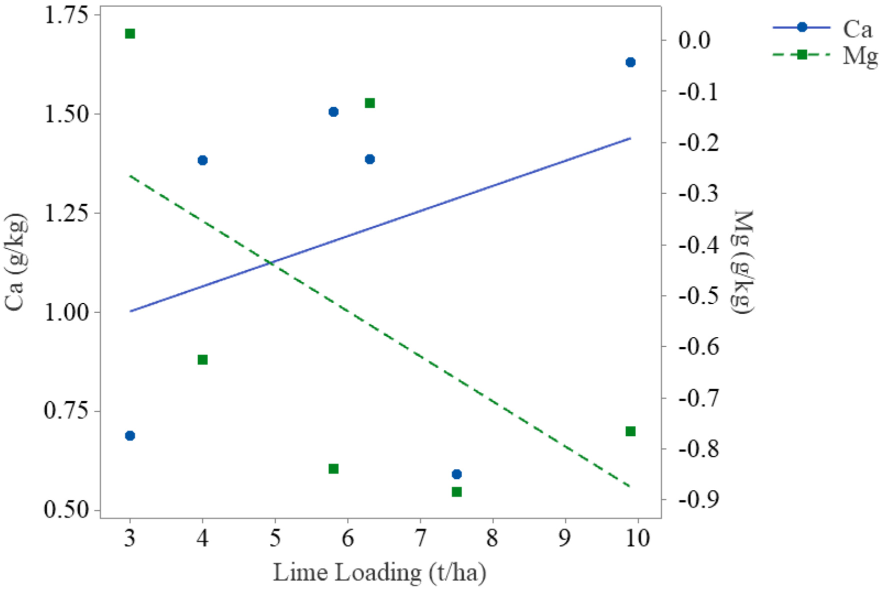


Figure 32. Correlation between lime loading rates and wood fern calcium (Ca) concentration and lime loading rates and wood fern magnesium (Mg) concentration. Values represent the change in Ca and Mg concentrations from year 1 to year 2 at each plot at the hardwood treatment site.

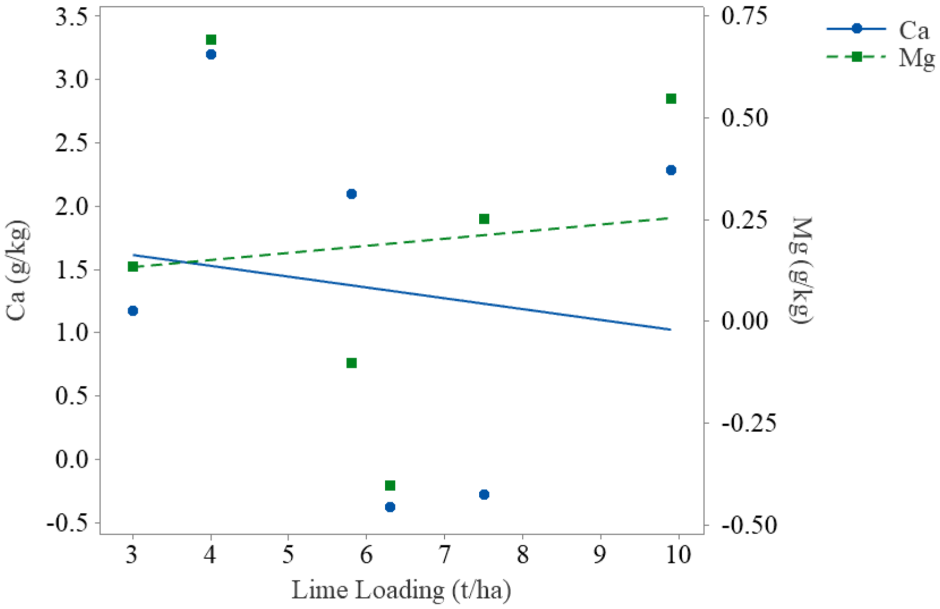


Figure 33. Correlation between lime loading rates and sugar maple calcium (Ca) concentration and lime loading rates and sugar maple magnesium (Mg) concentration. Values represent the change in Ca and Mg concentrations from year 1 to year 2 at each plot at the hardwood treatment site.

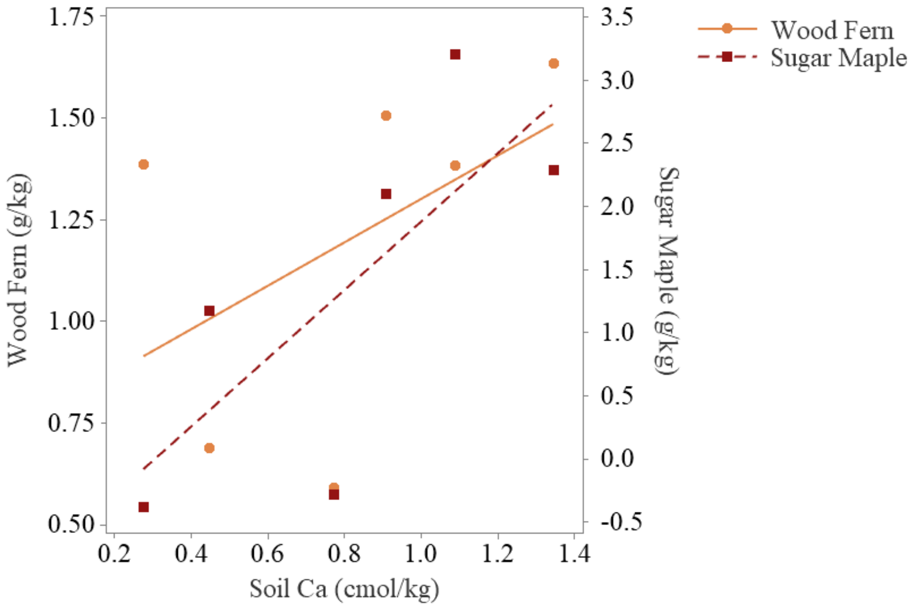


Figure 34. Correlation between Ca^{2+} concentration in the upper forest floor horizon and Ca concentration of wood fern and sugar maple foliage after liming. Values represent the change in calcium concentrations from year 1 to year 2 at the hardwood treatment site.

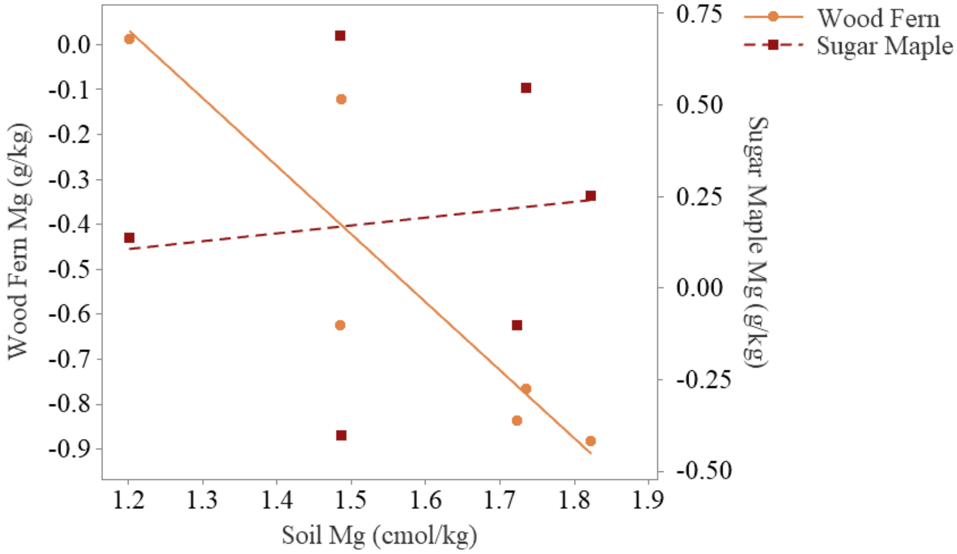
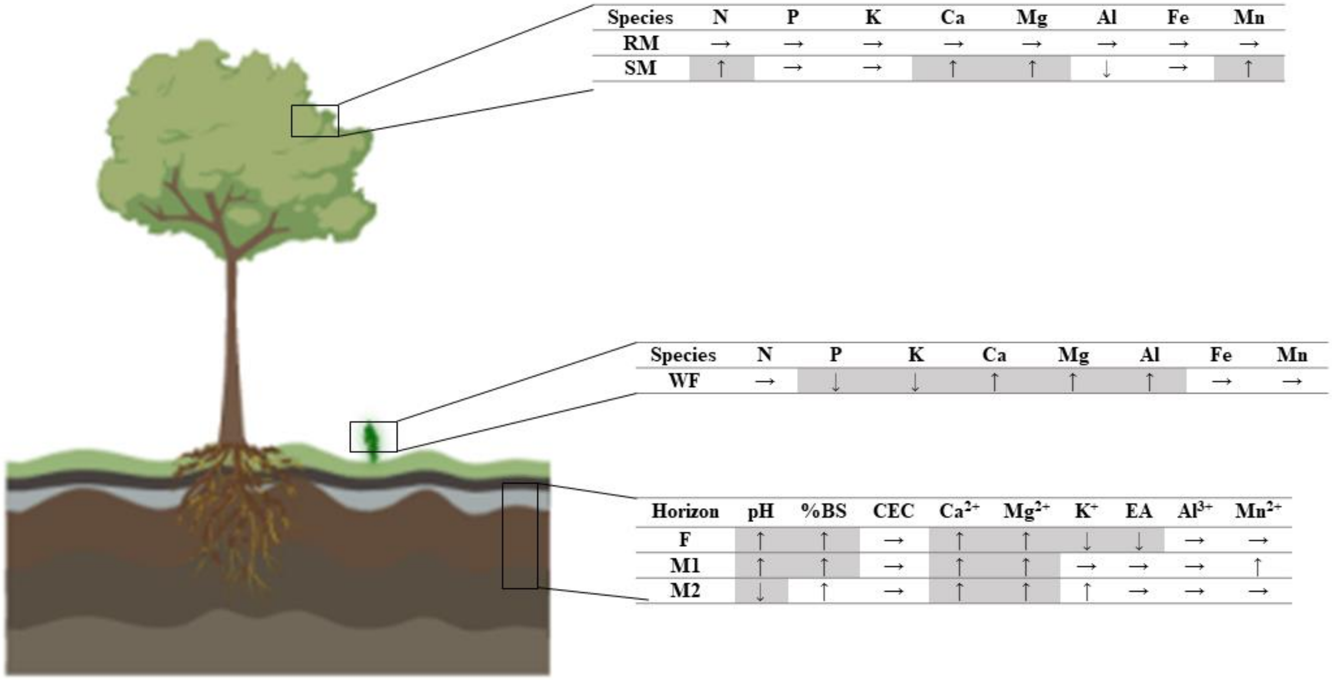


Figure 35. Correlation between Mg^{2+} concentration in the upper forest floor horizon and Mg concentration of wood fern and sugar maple foliage after liming. Values represent the change in calcium concentrations from year 1 to year 2 at the hardwood treatment site.



Species	N	P	K	Ca	Mg	Al	Fe	Mn
RM	→	→	→	→	→	→	→	→
SM	↑	→	→	↑	↑	↓	→	↑

Species	N	P	K	Ca	Mg	Al	Fe	Mn
WF	→	↓	↓	↑	↑	↑	→	→

Horizon	pH	%BS	CEC	Ca^{2+}	Mg^{2+}	K^+	EA	Al^{3+}	Mn^{2+}
F	↑	↑	→	↑	↑	↓	↓	→	→
M1	↑	↑	→	↑	↑	→	→	→	↑
M2	↓	↑	→	↑	↑	↑	→	→	→

Figure 36. Summary of chemical changes in all sampled soil horizons (F, M1, M2), evergreen wood fern (WF), red maple foliage (RM), and sugar maple foliage (SM) at the hardwood treatment (HWT) site after liming. The arrows indicate trends, and shaded arrows indicate a significant difference ($P < 0.05$). Trends may indicate an increase or decrease at the HWT site in direct response to lime or lack of increase or decrease at the HWT site compared with the hardwood control (HWC). If similar trends were shown at the HWT and HWC sites, they were not considered a response to liming.

3.5 Discussion

3.5.1 Sample Variability

Changes in soil chemical properties are often subject to spatial and temporal variability. Results from this study showed variability in soil Ca^{2+} and pH one year after liming. In general, pH and base cation data variability were lower in the control sites and before treatment in the treatment sites, indicating that liming contributed to the increased post-treatment variability. Variability was greater in the M2 horizons, particularly at the HWT site, likely due to the variability in clay content at these sampling depths. Clay content varied from 6.7 to 19.0% in the hardwood M2 horizons and from 5.5 to 12.3% in the softwood M2 horizons. Forested ecosystems often have high spatial variability; therefore, it is more difficult to distinguish changes over time (Yanai et al., 2003). For example, changes in exchangeable Ca^{2+} and Al^{3+} in northern hardwood stands in New Hampshire were not always detectable over 15 years despite having a high number of sampling blocks (Yanai et al., 2005). Additionally, soil nutrient variability can occur within a few centimetres in northern hardwood stands (Lawrence et al., 2013). Therefore, the spatial variability of soil properties within each site at the OPDF was expected.

Spatial variability can be reduced by re-sampling from the same soil type and horizon and increasing the sample size (Yanai et al., 2005). Multiple soil horizon identification techniques were used, sample collection occurred in a similar time frame each year, and samples were collected from similar horizon types and consistent sampling depths on similar microsites at the OPDF, which could help reduce some of the spatial variability (Hazlett et al., 2011). Furthermore, sample sizes in year 2 increased, which may help reduce the increased variability from liming.

3.5.2 Comparison of Softwood and Hardwood Sites

Similarities were observed between the hardwood and softwood sites in response to liming. Forest floor pH, %BS, Ca^{2+}, and Mg^{2+} increased significantly, and exchangeable acidity decreased significantly after liming at both sites. pH increased by similar amounts at both sites despite the softwood site having lower initial pH. Percent base saturation, Ca^{2+}, and Mg^{2+} increased by a larger margin at the softwood site than at the hardwood site. The larger increase at the softwood sites may have been because the initial %BS, Ca^{2+}, and Mg^{2+} were greater at the hardwood site before treatment; therefore, the softwood sites may have responded more to the initial spike in Ca^{2+} and Mg^{2+} from liming. Reid & Watmough (2014) showed that more highly acidic sites have a greater initial response to liming and base saturation is often correlated with forest type (hardwood vs. softwood). Additionally, soil Ca^{2+} and Mg^{2+} are often greater under sugar maple trees than in other species (Finzi et al., 1998), similar to the findings at the OPDF. However, these comparison studies did not use red spruce as one of the species; they simply compared hardwood and softwood stands or used eastern hemlock instead. In addition, Ca^{2+} may have been lost at the hardwood sites from leaching and plant uptake. The uptake of base cations is often greater at hardwood sites because sugar maple is a more nutrient-demanding species (Long et al., 2011). Plant uptake of Ca^{2+} was observed at the OPDF for wood fern and sugar maple. However, Ca concentrations also increased in vegetation at the softwood sites and therefore, plant uptake is likely not the main cause of smaller Ca^{2+} increases at the hardwood site.

Differences between the hardwood and softwood sites were also observed. Potassium decreased significantly in the HWT site F horizon after liming, while no changes in K^+ were observed at the softwood sites. The lack of decrease in K^+ at the SWT site is likely due to the capacity of the softwood site to retain nutrients in the forest floor because of a larger number of CES. The average total CES in the upper horizon of the forest floor at the SWT site was 1.06 cmol, while the average total CES in the forest floor horizon at the HWT site was 0.55 cmol, largely because of the difference in volumes. Also, Mn^{2+} only increased significantly at the SWT site and not the HWT site; the mechanism behind this is unclear (Section 3.5.4).

Calcium and Mg concentrations increased significantly in wood fern and Schreber’s moss after liming. Schreber’s moss Al, Fe, and Mn also increased significantly, and wood fern K decreased significantly after liming. Calcium concentrations increased in red spruce and sugar maple foliage, but the increase was only significant in sugar maple foliage. Magnesium concentrations increased significantly in both red spruce and sugar maple. Nitrogen and Mn also increased significantly in sugar maple foliage but not red spruce. No changes were observed in red maple foliage. The differences in nutrient uptake of the different plant species are likely a result of the plant requirements; for instance, sugar maple is a more Ca-demanding species than red maple and therefore took up more Ca.

3.5.3 Base Saturation

Percent base saturation increased significantly in all forest floor and upper mineral soil horizons and non-significantly in the lower mineral horizons after liming. Similar increases in %BS were found in other liming trials in northeastern North America (Moore et al., 2012; Ouimet et al., 2008) and Europe (Court et al., 2018; Kreutzer, 1995); however, these trials often recorded changes over longer periods. Short-term increases in %BS in the forest floor were indicated by Blette and Newton (1996) and Ouimet et al. (2008), in which %BS increased one year after lime application. However, both these trials used calcite, and sites had a much higher initial %BS than in this study. Although long-term trends cannot be discussed in this study, the initial spike in %BS may be the first sign of long-term improvements in soil acidity. Ouimet et al. (2008) showed long-term success in Quebec in which the addition of 0.8 t ha^{-1} of calcite increased the %BS by approximately 17% after one year and 35% after ten years, suggesting that initial increases in %BS have the potential to persist long-term. Increases in %BS were also observed in the mineral horizons; which was not expected after one year because the downward movement of lime through the soil profile is often slow and may take up to 10 years for changes to be apparent in mineral horizons (Moore et al., 2000; Moore et al., 2012).

3.5.4 Base Cations and Acidity

Calcium and Mg^{2+} increased significantly in all soil horizons at both sites, except Ca^{2+} increased non-significantly in the mineral horizons at the SWT site. Initial increases in pH and base cations in the top 0-5 cm of soil were found in a study in Pennsylvania one year after dolomite application; however, deeper soil horizons did not see changes until three years after application (Long et al., 1997). Calcium increased over 4-fold, and pH increased from below 4 to above 5 (Long et al., 1997). These increases are greater than those observed at this study site; however, they are comparable. The Pennsylvania site was re-sampled 21 years later and showed improvements in soil acidification status in upper soil horizons and at depths of up to 45 cm (Long et al., 2015). Similarly, Ca^{2+} concentrations increased significantly in the organic horizon one year after helicopter liming the MNF and pH increased by 1.3-1.7 units in the limed sites (Fowler et al., 2022). Increases in pH at the MNF were similar to the OPDF, in which the softwood F horizon pH increased by 1.38 units and the hardwood F horizon increased by 1.55 units. The initial improvement of soil chemical properties at these study sites and the long-lasting effects shown in other similar studies suggest a single liming dose may be effective for up to 10-20 years. Lime reacting with the mineral soil after only one year is unlikely, especially at the softwood site, which has a greater forest floor thickness. Fowler et al. (2022) observed no significant increases in upper B horizon Ca^{2+} or pH one year after liming; however, this study sampled an A horizon which was much thicker than that at the OPDF and observed significant increases in Ca^{2+} and pH in the A horizon. Increases in mineral soil Ca^{2+} and Mg^{2+} were observed at the softwood and hardwood treatment sites. Kreutzer (1995) showed that lime dissolution decreased exponentially, and it took approximately 6 years for 4 t ha^{-1} to dissolve completely. The dissolution of lime increases with increasing soil acidity (Jansone et al., 2020), and therefore, the dissolution rate may be high at the OPDF study sites.

Exchangeable acidity decreased significantly in the forest floor horizons after liming, but Al^{3+} did not. Exchangeable acidity greater than 20 $cmol_c$ kg^{-1} can be toxic to plants (Sparks, 2003).

All samples at the OPDF are well below the toxicity threshold except the F/H horizon at the SWC before liming; however, the acidity decreased at both the SWC and SWT sites the year after. Exchangeable acidity levels in the upper forest floor horizons at the hardwood sites were comparable to those at the MNF forest (6-9 cmol kg^{-1}) (Fowler et al., 2022).

Exchangeable Al^{3+} decreased non-significantly in the F horizon at the SWT site after liming, which suggests a decreasing trend in Al^{3+}. Still, no significant changes in Al^{3+} were observed in the F horizon of the HWT site. Changes in Al^{3+} in the forest floor were minimal, and therefore, decreases in exchangeable acidity can be mainly attributed to reductions in H^{+} concentration. The results of this study may be too short-term to observe changes in soil Al^{3+}; however, significant decreases in Al^{3+} in the organic horizon were observed at the MNF one year after liming (Fowler et al., 2022). The initial Al^{3+} concentration in the F horizon at the hardwood sites was much lower than that at the MNF, which may be the reason for the little impact on Al^{3+}. Long et al. (2015) observed significant decreases in Al^{3+} in the forest floor after lime application in Pennsylvania, but they were only evident approximately 8 years after liming. The longer response time of Al^{3+} is likely explained by the greater affinity of Al^{3+} to bind to organic matter exchange sites (Gruba & Mulder, 2015; Reuss & Johnson, 1983; Scheel et al., 2007). More elapsed time after liming is needed to determine the effect of lime on forest floor Al^{3+}, though the trends indicate that liming may be slowing the increase of Al^{3+}.

Manganese increased in the F and F/H horizons at the SWT site, contrary to what has been found in other studies. Manganese often behaves similarly to Al^{3+} in the forest floor and liming often promotes decreases in Mn^{2+} concentrations (Long et al., 1997; Long et al., 2015; Court et al., 2018). Houle et al. (2002) showed similar results in which Mn^{2+} increased in the forest floor and upper mineral soil five years after liming. They attributed the increase in Mn^{2+} to two possible mechanisms: (1) an increase in Mn^{2+} from an accompanying increase in CEC and (2) an increase in excretion of Mn^{2+} from vegetation. Cation exchange capacity did not increase, and Mn concentration in Schreber's moss increased after liming; therefore, neither of these explanations are likely. Exchangeable Mn^{2+} should decrease with increasing pH because it becomes less soluble at high pHs (Ross et al., 2008). However, correlation analysis showed that Mn^{2+} was strongly positively correlated with pH at the softwood sites (r = 0.89). Solubility of Mn^{2+} is increased at a pH <5.5 (Watmough et al., 2007), and the highest pH recorded at the SWT site in the forest floor was 5.04. Therefore, Mn^{2+} may still be soluble and continue to increase. In addition, Mn^{2+} could have increased initially from cation displacement on exchange sites. Keys (2018) also showed an initial increase in Mn^{2+} in the forest floor, followed by a decrease as pH increased after alkaline-treated biosolid application in spruce plantations. The increase in Mn^{2+} could also be explained by Mn^{2+} deposition within the lime. There was approximately 2805 mg kg^{-1} of Mn^{2+} in the lime deposited at the SWT site; however, similar amounts were deposited at the HWT site, with no significant increase in forest floor Mn^{2+} (A1 Table 2 & 3). Future sampling is required to better interpret the Mn^{2+} chemistry in the forest floor.

3.5.5 Cation Exchange Capacity

Cation exchange capacity results were not as expected and decreased significantly in both forest floor horizons at the SWT site. Significant differences in CEC were not found in the softwood mineral soil or any horizons at the hardwood sites. Studies have indicated that the addition of lime promotes the deprotonation of functional groups, which should increase the CEC (Blette and Newton, 1996; Kreutzer, 1995; Court et al., 2018; Houle et al., 2002). However, in response to liming, CEC has shown variable results (Lilly, 2006), and the relationship between pH and CEC is often not direct (Ross et al., 2008).

The decrease in CEC in the forest floor at the SWT site could result from several mechanisms. First, Lilly (2006) showed similar decreases in CEC and suggested that the decrease may be a result of changes in the solubility of the SOM. The increased solubility of SOM with increasing pH may lead to a reduction of SOM and, therefore, CEC. However, changes in SOM solubility are not likely in this study because the results span too short of a period to observe decreases in SOM. Second, despite significant decreases in H^+, new exchange sites may not have been created because of increased complexation of Al^{3+} from increased pH. As pH increases, the amount of organically complexed Al^{3+} increases, which can lead to a decrease in CEC while also reducing exchangeable acidity (Lilly, 2006; Ross et al., 2008). The increased complexation of Al^{3+} is also unlikely because there were no significant changes in Al^{3+} chemistry in the forest floor. Ouimet et al. (2008) also noted an initial decrease in CEC from a mean of 14.4 cmol kg $^{-1}$ to a mean of 12 cmol kg^{-1}; however, the following year showed a significant increase in CEC to 20 cmol kg^{-1}. Therefore, CEC is often highly variable within the first few years of sampling after liming, and the decrease in CEC may be an initial response but not long-term. Future analysis will provide more insight into the mechanisms which affect CEC over time.

3.5.6 Ground Vegetation

The moss layer of the forest floor is the first point of contact for the lime at the SWT site; therefore, the significant increase in Ca and Mg nutrient concentration in Schreber’s moss observed in this study was expected. However, there were also increases in Al, Fe, and Mn after liming, which was not expected. Schreber’s moss is considered an acidophilic species (Crum & Anderson, 1981) and soil Ca increases have caused declines in Schreber’s moss biomass; however, there is limited information on the nutrient chemistry of the moss itself (Brach and Raynal, 1992; Eriksson et al., 1983; Gunn et al., 2001; Traaen et al., 1997). Schreber’s moss has been recorded growing in soils with pH values up to 5.7 (Wyatt & Stoneburner, 1982). Therefore pH ranges at the softwood study sites provide suitable habitat for this species.

Observed increases in Al, Fe, and Mn were not expected in Schreber's moss after liming since pH increases should decrease the availability of these nutrients. However, pH is still low enough ($pH \leq 5.04$) in the forest floor horizons after liming to continue to promote solubility of these ions, and they are likely still plant available. It is possible that the flush of Ca and Mg from liming led to the exchange of Al, Fe, and Mn with Ca and Mg on the cation exchange complex, releasing Al, Fe, and Mn into soil solution. This mechanism would cause an initial pulse of Al, Fe, and Mn in soil solution, similar to the pulse of base cations in stream water after leaching from soils due to increased acidification (Lawrence et al., 2016). A similar phenomenon occurs when potassium sulphate is applied after liming, in which K^+ replaces Ca^{2+} and Mg^{2+} on the cation exchange complex, releasing Ca^{2+} and Mg^{2+} in soil solution (Moore et al., 2012). Correlation analysis of Schreber's moss nutrient concentration with soil chemical parameters revealed that Al, Fe, and Mn behaved similarly to Ca and Mg. These nutrients showed a strong positive correlation with soil pH, %BS, Ca^{2+}, Mg^{2+}, and Mn^{2+} and a strong negative correlation with CEC, exchangeable acidity, and Al^{3+}. This initial pulse was not observed in the ground vegetation at the hardwood site, and there is little evidence from other studies supporting this; however, short-term data on ground vegetation is limited.

Wood fern Ca concentrations at the HW study sites were similar to that of the HBEF (Likens, 1998). Potassium decreased in this study, likely because of an antagonistic relationship between Ca and K observed in the ground vegetation. An increase in Ca addition to soil can block K adsorption in plants (Bolan et al., 2003).

3.5.7 Foliage

Red spruce foliar Ca increased at both the SWT and SWC sites; therefore, it was difficult to say whether the increase at the SWT site was from liming. Foliar Mg concentrations increased at the SWT site from liming. Fewer studies examine lime's effects on red spruce compared to sugar maple. However, Keys (2018) showed similar results in which red spruce foliar Ca did not significantly increase in the short-term (approximately 400 days), but Mg did after an alkaline-treated biosolid application. The most important variable for determining the response of tree species to liming is the time since application (Reid & Watmough, 2014); therefore, a greater response is expected in future sampling.

Foliar Ca concentrations at all sites in years 1 and 2 were above sufficiency thresholds for healthy red spruce trees (Figure 37) (Borer et al., 2004). The health thresholds for foliar Ca concentrations in which cold tolerance decreases are not well defined. DeHayes et al. (1999) indicated that the sufficiency threshold for red spruce is above 1.2 g kg^{-1}, while decreases in winter hardiness were observed below that threshold. Hawley et al. (2006) showed an approximately 3-fold increase in loss to foliar injury when Ca concentrations were approximately 1.71 g kg^{-1} versus 2.23 g kg^{-1} at the HBEF. If foliar Ca levels remain above the sufficiency threshold in the following years, liming will likely help reduce winter injury in red spruce at the study sites.

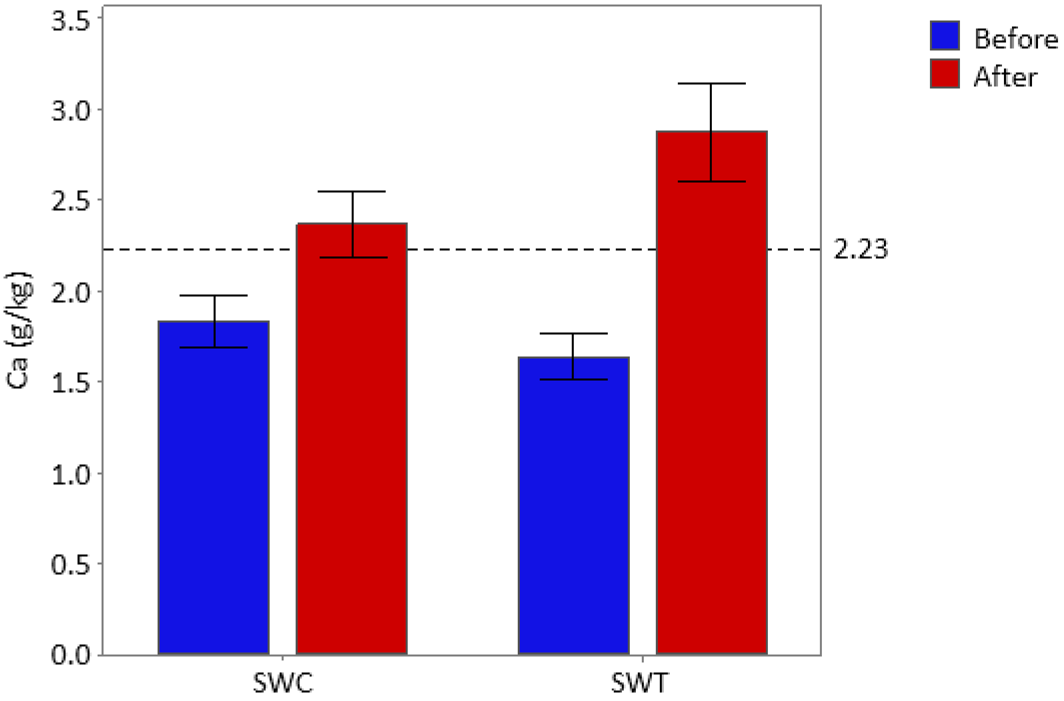


Figure 37. Foliar calcium concentrations of red spruce trees at the softwood control site (SWC) and the softwood treatment site (SWT) before and after liming. Error bars represent ±1 standard error, and the 2.23 threshold value represents the calcium concentration above which a 3-fold decrease in winter injury was observed at the Hubbard Brook Experimental Forest (Hawley et al., 2006).

Results showed that sugar maple had a greater response to liming than red maple. This was expected because sugar maple is a calcium-demanding tree species (Long et al., 1997; Moore et al., 2012). While there was no increase in foliar Mg at the HWT site in sugar maple, there was a significant decrease in Mg at the HWC site, which suggests that the addition of lime may have helped offset the loss of Mg from leaching. However, the decrease in Mg at the HWC site may be due to natural variation, and future sampling will help make these results more robust.

Critical Ca ranges for sugar maple are well defined and have been reported by Kolb & McCormick (1993) and Bal et al. (2014). The addition of lime at the HWT site increased mean Ca levels to above the minimum critical threshold for sugar maple health (Figure 38); however, not all trees sampled were above the minimum threshold. The acceptable range for foliar Ca in sugar maple is approximately 5 – 22 g kg^{-1} (Kolb & McCormick, 1993; Bal et al., 2014). Mean foliar Ca for sugar maple after liming at the HWT site was slightly above the minimum threshold, and further increases would benefit tree health.

Other trials in northeastern North America have shown Ca and Mg foliar increases persist upwards of 20 years in response to liming (Long et al., 2015; Moore & Ouimet, 2021); therefore, it is reasonable to expect similar increases at the treated sites over time. Studies have also identified relationships between Ca and Mg foliar concentration and tree growth and health. Long et al. (1997) showed significant increases in BAI seven years after the addition of dolomite at a rate of 22.4 t ha^{-1} in Pennsylvania, and even greater tree growth was evident 23 years after treatment (Long et al., 2011). Moore et al. (2015) also showed increases in BAI and decreases in crown dieback 15 years after liming in Quebec. Further research showed that sugar maple growth and vigour persisted 20 years after liming (Moore & Ouimet, 2021). Although not presented here, baseline tree health and growth assessments at the study sites have been conducted, allowing growth and health responses to be assessed in later years.

Despite the significant increase in Ca in sugar maple foliage, Ca remains the limiting nutrient. DRIS analysis indicated that Ca is becoming more balanced with the addition of lime, but K is becoming less balanced. Similar antagonistic relationships between Ca and K are evident in sugar maple foliage in other studies (Moore et al., 2000; Moore et al., 2006; Moore et al., 2012). Similar antagonisms were also noted in the soil and ground vegetation of the HWT site. If K and Ca continue this trend, liming may have to be supplemented with K amendments to compensate for the increased K deficiencies (Moore et al., 2012).

Most of the sample trees at the study sites did not exceed the Al toxicity threshold of 0.06 g kg^{-1} (Kolb & McCormick, 1993), in which Al can cause damage to trees (Bal et al., 2014). Similar to Al, Mn may cause damage in excess; however, Mn foliar concentration of sugar maple trees did not exceed the maximum threshold value of 1.6 g kg^{-1} (Kolb & McCormick, 1993) despite increases at the HWT site. Foliar Fe also did not exceed the toxicity threshold of 0.13 g kg$^{-1,}$ but it also did not reach the sufficiency threshold of 0.059 g kg^{-1}(Kolb & McCormick, 1993), which may indicate Fe deficiencies in sugar maple foliage.

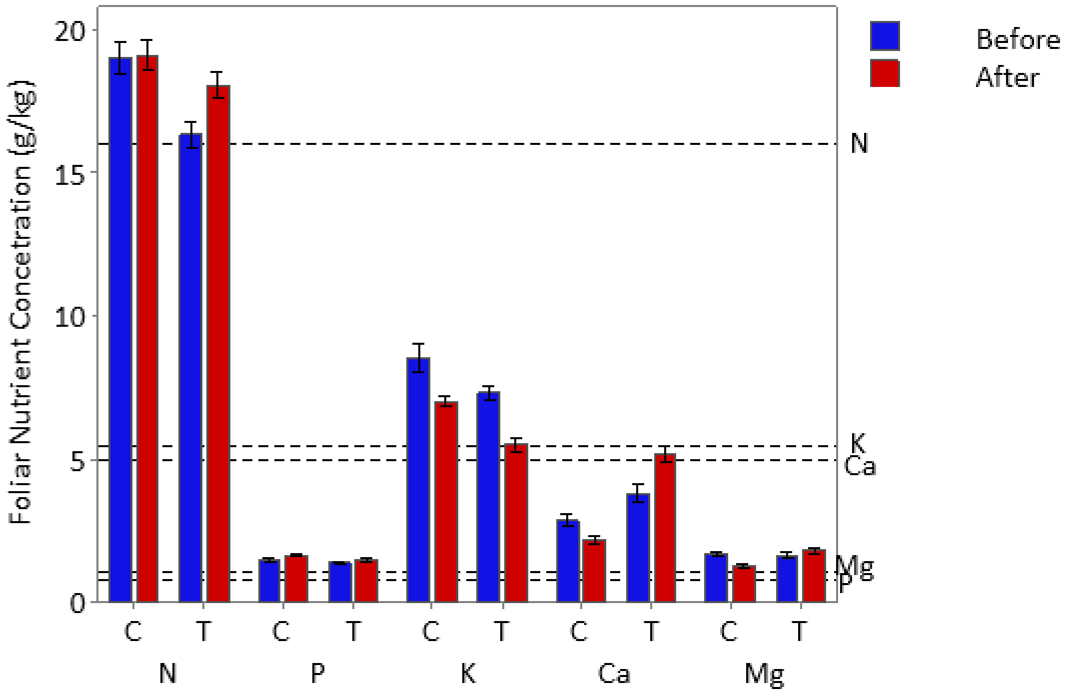


Figure 38. Mean foliar nutrient concentration of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) in sugar maple trees at the hardwood control (C) and the hardwood treatment (T) sites before and after liming. Threshold values represent the minimum threshold of each nutrient determined for healthy sugar maple trees developed by Kolb and McCormick (1993). Error bars indicate ±1 standard error.

Red maple is not often studied in liming trials because it is less sensitive to Ca deficiencies; therefore, comparisons between this liming trial and literature results are difficult. Red maple did not respond to liming at the study sites. Red maple seedling foliar nutrient concentration does not vary greatly across acidity gradients because they can adapt to nutrient limitations better than sugar maple and are not as susceptible to changes in soil pH (Bigelow and Canham, 2002; Collin et al., 2016). St. Clair et al. (2005) showed that red maple accumulated nutrients on acidic soils more efficiently than sugar maple. Therefore, the lack of response in red maple to lime was expected.

3.5.8 Lime-Plant-Soil Interactions

The relationships between lime loading rates and F horizon Ca^{2+} and Mg^{2+}, ground vegetation, and foliage provide insight into the interactions between soil nutrient concentration and plant availability. However, a larger sample size would make these relationships more robust. The positive correlation between lime loading rates and soil Ca^{2+} and Mg^{2+} at the SWT site was expected, as more Ca and Mg from higher lime loading rates should become more plant available. There was no relationship found between lime loading rates and red spruce foliage. The lack of relationship is likely because the comparison was between total foliar Ca in year 2 and not the change from year 1 to year 2. Sample trees were not associated with a plot but were randomly selected throughout the site; therefore, measuring the change from year 1 to year 2 was not possible.

There was a correlation between lime loading rates and soil Ca^{2+} and Mg^{2+} at the HWT site, and the correlation between lime loading and Mg^{2+} was stronger. The correlation between lime loading rates and Ca and Mg in wood fern and sugar maple were much weaker and/or had a negative correlation. The lack of relationship may result from less variability in the lime distribution. Although the lime loading rates had a large range, they were not significantly different from each other; therefore, a relationship with Ca and Mg was difficult to establish. Also, the hardwood site soil conditions are variable, and despite close attention to site selection, the variability of the site is difficult to capture with only six sampling points. There was a strong positive correlation between the changes in soil Ca^{2+} and wood fern Ca concentrations and soil Ca^{2+} and sugar maple foliage Ca concentrations. This was expected since Ca^{2+} in the soil is more available for plant uptake, and Ca concentrations increased in the soil, ground vegetation, and sugar maple foliage after treatment. However, soil Mg^{2+} was strongly negatively correlated with wood fern Mg and little correlation was observed between soil Mg^{2+} and sugar maple Mg. Despite lime's effect, Mg concentration in wood fern still declined one year after liming, but less so than at the HWC site. Wood ferns grow in patches; therefore, different patches may have had different proximity to lime rates, which might not have been captured at the plot level. More robust relationships could be formed with smaller, more localized data points.

These relationships provide insight into the response of different forest types to lime. Soil Ca^{2+} and Mg^{2+} at the SWT and HWT sites were positively correlated with lime loading rates. Ground vegetation Ca and Mg at the SWT site correlated more with lime loading rates, whereas ground vegetation at the HWT correlated more with soil nutrients. Schreber's moss had more coverage of the forest floor than wood fern and likely had more direct contact with lime. These relationships indicate that there may be more direct contact with lime and ground vegetation at the SWT site. In contrast, wood fern and sugar maple Ca depend more on the underlying soil Ca^{2+}.

3.6 Conclusion

Initial soil and plant chemical results showed evidence of a response to liming, which was expected in the upper soil horizons one year after liming. The most notable change in soil and plant tissue chemistry was the increased Ca^{2+} and Mg^{2+} concentrations in all soil horizons and Ca and Mg in all plant tissue samples except red maple at the hardwood and softwood sites. Additionally, observed increases in pH and %BS and decreases in exchangeable acidity in the forest floor horizons support liming as a method to promote recovery from soil acidification. Long-term (5 years and 10 years) changes in soil and plant tissue chemical properties will further increase the understanding of the effects of liming on the acidification status of forests in NS and provide insight into the effects on tree growth and health.

Chapter 4 - The value of helicopter liming in Nova Scotia red spruce and sugar maple dominated stands on acid-sensitive soils

4.1 Introduction

The impact of soil acidification and liming on economies is difficult to characterize because many variables come into play (Smith & MacDougall, 2017). Section 1.1.6.6 summarizes the research attempting to characterize the effect of soil acidification and liming on forest ecosystems. Within North America, many studies in the northeast have shown significant increases in forest productivity following liming, with benefits including:

- Increased tree growth, health, productivity, and regeneration (Lawrence et al., 2016),
- Increased biodiversity in both upland habitats (Moore et al., 2015) and drainage waters, such as rivers and lakes (Clair and Hindar, 2005),
- Increased resiliency of forest ecosystems to disturbances from climate change, pests, and diseases (Schaberg et al., 2011), and
- Increased soil health (Kreutzer, 1995).

The body of evidence presented in section 1.1.7 suggests that NS is emerging as a hotspot among regions facing delayed recovery from acidification, with elevated Al^{3+} levels above toxic thresholds and very low levels of base cations (Sterling et al., 2020; Rotteveel and Sterling, 2019). Delayed acidification recovery in NS suggests that liming may provide many benefits to NS forests and co-benefits to downstream aquatic habitats (Table 30). Liming upland forests, however, is logistically difficult and expensive due to accessibility and dispersion methods and has so far not been undertaken on a large scale in NS. The potential increase in value of red spruce and sugar/red maple stands in NS in response to liming has not been evaluated. Despite the many potential benefits of forest liming, it is not yet clear whether these benefits will outweigh the high costs.

Literature evaluating the economic impact of liming on red spruce stands on acidic soils is limited; however, the potential ecological benefits from liming may provide insight into the potential financial gains. Increased cold tolerance (Halman et al., 2008; Hawley et al., 2006) and increased growth and biomass (Melvin et al., 2013; Schaberg et al., 2011) in red spruce stands may indicate an increase in the economic value of red spruce stands after liming.

Sugar maple stands are valued for multiple industries, such as timber, maple syrup, and fall foliage tourism. The effect of liming on fall foliage has not been studied directly; however, the tourism data for Nova Scotia can give some indication of the value of the fall foliage tourism industry.

Table 31. Overview of the consequences and ability of lime to mitigate potential threats to industries in which sugar maple is a valuable tree species (timber, maple syrup, fall foliage tourism).

Threats	Consequence	References	Potential benefits of liming
Tree mortality	A lower number of taps.	Hallett et al., 2006; Moore et al., 2012	Increased tree survival.
Tree health	Decreases the photosynthetic capacity, decreasing the amount of carbon for sugar production.	Moore et al., 2020; van den Berg et al., 2016; Wilmot et al., 1995; Muhr et al., 2015	Improved tree health and canopy area increased sap sweetness and yield.
Tree Health (canopy)	Sugar maple and red maple provide two of the most vibrant colours in the fall. Without these species in the canopy, the impact of fall foliage would be limited because of the lower density of leaves in the canopy and potential discoloration.	Norris, 2000	Improved the canopy health, leading to more vibrant fall foliage colours.
Decreased tree growth	Decreases in tree ring width reduces xylem tissue which helps produce sap.	Long et al., 2015; Moore et al., 2015	Increased tree growth and xylem tissues.
Low regeneration	The inability of sugar maple to reproduce on poor soils impacts sugarbushes in the future.	Sullivan et al., 2013	Increased sugar maple regeneration.
Susceptibility of climate change	Migration of species northward and change in sap season.	Iverson & Prasad, 2002; Rapp et al., 2019; Houle et al., 2015; Duchesne et al., 2009; Lada and Nelson 2013	Increased the resilience of sugar maple trees to changes from climate change.
Pests and diseases	Decrease tree health and increases tree mortality.	Bal et al., 2014	Decreased susceptibility to pests and diseases.
Damages and boreholes	Ice storms and boreholes cause severe damage to sugar maple trees and impede sugar production—direct damage of acid deposition to root systems and foliage.	Noland et al., 2006; Robitaille et al., 1995	Trees with greater Ca concentrations recovered from damage more rapidly and reduced the amount of damage inflicted on root systems and foliage from acid deposition.
Low nutrient content in sap	Lower levels of Ca and Mg in sap make it less nutritious.	Wild & Yanai, 2015	Increased the level of Ca and Mg in sap.

In this chapter, I aim to answer RQ4: Do the potential increases in growth and health in red spruce and sugar maple trees from liming outweigh the operational costs of helicopter liming in NS? The first estimate of potential economic benefits from upland liming in NS are made, drawing upon a review of the literature, our helicopter liming trial research (Chapter 2 and 3), and the nutrient budget model of Nova Scotia (NBM-NS) to project some potential economic impacts of liming red spruce stands. This chapter examines (1) the cost of forest helicopter liming in a NS trial, (2) the projected increase in forest stand value from changes in harvest volume for red spruce stands, and (3) the projected economic benefits of liming on sugar maple dominated stands, specifically, timber, maple syrup, and tourism from fall foliage.

4.2 Methods

4.2.1 Cost Evaluation of a Forest Helicopter Liming Trial in Nova Scotia

The cost of liming was evaluated using data from liming trials conducted by the NS Salmon Association, in partnership with the NS Department of Natural Resources and Renewables and Dalhousie University. Costs for upland liming are based on 2017, 2018, and 2019 helicopter liming trials at the Keef Brook Catchment (44º59’59.95, 62º40’54.75”), the Otter Ponds Demonstration Forest (OPDF; 44º56’18.68, 62º446’15.16”), and Tent Brook Catchment (45º00’07.22”, 62º39’49.24”).

4.2.2 Forest Stand Value for Red Spruce Stands

The impact of liming on red spruce/eastern hemlock stands, as described by the forest ecosystem classification guide of Nova Scotia (Neily et al., 2011), was simulated because (1) calcium is usually the limiting nutrient in these stands when growing on acidic, slow weathering soils and (2) red spruce is a valuable tree species in NS. The increase in timber value was estimated using the NBM-NS (Keys et al., 2016) and different base cation scenarios (Table 31). The NBM-NS assesses different forest harvest scenarios and their sustainability, given different nutrient fluxes such as atmospheric deposition, soil weathering, and leaching, as well as nutrient concentrations found in the biomass components of different tree species.

Table 32. Potential scenarios and associated assumptions for input to the NBM-NS for liming red spruce stands in Nova Scotia.

Scenario	Assumption
1	Current conditions
2	Base cations were replenished to 30%.
3	Base cations were replenished to 20%.

4.2.3 Maple Syrup

The potential benefits of liming on maple syrup production in NS were estimated by developing likely maple syrup production scenarios based on previous literature (Table 34) (Barry et al., 2009; Moore et al., 2020; Perkins et al., 2004). These scenarios were derived from Ouimet et al. (2018) using the SaMARE model. The net present value (NPV) and the net profit of four scenarios were calculated (Table 32; Equation 15).

Table 33. Potential scenarios and associated assumptions for liming sugarbushes in Nova Scotia.

Scenario	Assumption
1	No liming occurred, and the amount of syrup produced remains consistent at 265,000 L year^{-1}.
2	No liming occurred, and maple syrup production decreased by 10% over ten years (1% per year).
3	Lime was applied, and a 10% increase in syrup production was observed after year two and remained consistent for the remainder of the 10 years.
4	Lime was applied, and a 20% increase in syrup production was observed after year two and remained consistent for the remainder of the 10 years.

$$\text{Net Profit} = \text{Scenario } (2,3,4) - \text{Scenario } 1 - \text{Cost of liming} \tag{15}$$

4.2.4 Fall Foliage

The proportion of tourists who visit NS to view fall foliage and associated costs were estimated using the Nova Scotia Exit Survey published in 2017 data (Tourism Nova Scotia, 2019) to determine the cost per trip for tourists visiting to view fall foliage—assuming that the cost per trip incurred in NS.

4.3 Results and Discussion

4.3.1 Cost of Liming

The cost of helicopter liming forest stands in NS between 2016-2018, not including capital costs, was \$2,660 ha^{-1} (Table 33).

Table 34. Liming equipment and their associated commercial costs. Costs are subject to change and vary depending on the distance from the lime source, the scale of the project, site conditions (soil type, initial stand health), and inflation.

Equipment	**Rate**
Cost of lime*	\$38 t^{-1}
Helicopter time and support	\$2100 hr^{-1}
Trucking	\$150 $load^{-1}$**
Front-end loader	\$4500 mo^{-1}
Personnel (5, including meals, miles, and overtime)	\$88 hr^{-1}**
Capital equipment (lime hopper, custom bucket for front-end loader)	\$21,600***
Miscellaneous (gas, repairs, on-site tools, site preparation)	\$12,000**

***Using pricing from Mosher Limestone Co. Ltd.**

****Average cumulative value,**

*****Not included in the cost per hectare.**

There are several limitations to consider while calculating the cost of helicopter liming. First, commercial helicopter prices may vary. Second, the costs shown here represent small-scale liming trials, i.e., not entire catchments. Economies of scale suggest that liming larger areas will likely decrease the per hectare cost of helicopter liming due to the amortization of equipment. Third, changes in the price of equipment and materials will likely alter the cost yearly. Additionally, helicopters may not be the most efficient method to apply lime in all cases; for example, sugarbushes could be limed using the hand application method or other off-road vehicles.

4.3.2 Red Spruce Timber Value

Under current conditions, whereby harvest rates need to be reduced to account for base cation depletion, the sustainable mean annual increment (SusMAI) for a representative red spruce/eastern hemlock stand underlain by coarse-textured granitic soil is estimated at 2.2 m^3 ha^{-1} yr^{-1} at 80 years. Suppose base cation stores were replenished through liming to 30% (scenario 1). In that case, model output suggests the SusMAI for this common red spruce vegetation type would be approximately 3.3 m^3 ha^{-1} yr^{-1} at 80 years (Table 34), an increase of 50% in sustainable harvest volume. If base cation stores were replenished through liming to 20% (scenario 2), the SusMAI would be approximately 2.9 m^3 ha^{-1} yr^{-1} at 80 years, an increase in sustainable harvest volume of 32%.

Table 35. Potential change in sustainable harvest volume and the associated dollar values for a typical red spruce/hemlock stand in Nova Scotia with and without liming applications used to raise Ca^{2+} and base saturation levels. Net profit is calculated by subtracting the cost of liming from the harvest value.

Base Saturation (BS%)	**SusMAI (m^3 ha^{-1} yr^{-1})**	**Sustainable Harvest Volume (m^3 ha^{-1})**	**Value (\$ ha^{-1})**	**Net Profit (Value ha^{-1} – Cost ha^{-1})**
Current BS%, without liming	2.2	176	$4,242	--
Minimum BS% threshold (20%)	2.9 (+0.7)	232 (+56)	$5,591 (+$1,349)	- $1,311
Target BS% threshold (30%)	3.3 (+1.1)	264 (+88)	$6,362 (+ $2,120)	-$540

Assumptions:

1. **The stand age is 80 years.**
2. **It is a ‘typical’ red spruce/hemlock stand described as vegetation type SH3 by Neily et al. (2013) with 40% red spruce, 30% eastern hemlock, 20% other hardwoods, and 10% other softwoods.**
3. **The product distribution is assumed to be 75% sawlogs and 25% pulp.**
4. **Estimated sawlog price is \$29.48 m^{-3}, and the estimated pulp price is \$7.96 m^{-3} (average of Grade 1 and 2 values) (Province of Nova Scotia, 2019).**
5. **SusMAI is based only on changes in %BS and not on changes to Al^{3+} or other agents of harm associated with acidification.**

The value of red spruce is mainly associated with timber; therefore, the value can often be more easily quantified. As shown above, increases in soil %BS from liming can increase sustainable harvest yields, increasing the stands' long-term economic value. In addition, restoring the %BS to 20% would improve ecosystem health and resilience against potential climate change impacts, as discussed by Campbell et al. (2009) and Huntington et al. (2009)

In theory, management based on the current conditions will allow gradual recovery of base saturation to a target of 30% while allowing for some harvest removal of nutrients. However, given that forest ecosystems tend to naturally acidify over time and that Ca^{2+} concentrations in base-poor soils in Nova Scotia were probably already decreasing before the accelerated losses from acid deposition (as suggested by Leys et al., 2016), it is unlikely that many forest soils in the province will return to "pre-acid rain" base cation levels without the use of liming amendments. In addition, natural recovery to a new steady-state condition will be very slow, as discussed by Lawrence et al. (2015) and supported by the soil study in Kejimkujik National Park (Keys, 2018).

4.3.3 Sugar Maple Timber Value

High-value hardwood timber represents a small portion of the market, but the amount of these products could potentially be increased through liming. Based on data compiled in 2007 and reviewed in 2010, hardwood trees represented approximately 30% of all merchantable trees in NS. Of these, only 28% were tolerant hardwoods, and 4% were of higher value, such as veneer logs (Keys et al., 2007; Townsend, 2004). Therefore, only approximately 0.3% of merchantable timber in NS was from veneer hardwood logs, despite having the highest value (Table 35). Targeted liming could help increase the volume of high-value sugar maple sawlogs and veneer logs by increasing tree vigour and diameter growth rate.

Table 36. The value of common wood products for sugar maple in Nova Scotia from 2017-to 2018 (Province of Nova Scotia, 2019).

Wood Product	**Value ($ m^{-3})**
Pulp	9.48
Sawlogs	26.26
Veneer Logs	71.68

The increase in economic benefits from sugar maple timber is associated with potential increases in high-value logs (related to increased vigour and diameter increment), not just overall volume increases. The value of sugar maple timber could not be measured directly because there have been no appropriate models developed for the region. However, studies in the Adirondack region of New York have attempted to quantify the value of wood products for sugar maple with different soil acidification conditions and harvest practices. Caputo et al. (2016) characterized the monetary value of sugar maple stands by simulating how the stands would behave with different soil acidity levels and silviculture treatments. They concluded that stands with %BS > 12% had greater BA and regeneration 100 years after harvest. They indicated that in stands with %BS < 12%, sugar maple trees were often outcompeted by red maple or American beech. Beier et al. (2017) evaluated the monetary value of wood products, including sawlogs, in the Adirondack region over a %BS gradient. This study indicated that wood products in acidified forests are worth approximately half that of non-acidified forests. In addition, they concluded that sugar maple trees in sites with low %BS were fewer and smaller than those at sites with greater %BS. Based on the literature, it is likely that the value of hardwood products will increase with increased %BS in acidified forests in Nova Scotia.

4.3.4 Sugar Maple Syrup Value

Maple syrup is an important industry in Nova Scotia but has not kept pace with the growth in other provinces. Nova Scotia represents approximately 1% of the Canadian maple syrup industry (Crops and Horticulture Division, 2020). Maple industry data are not always consistently compiled (Table 36) (Lada & Nelson, 2013), but the 2016 Maple Producers Association of Nova Scotia (MPANS) report indicated that Nova Scotia's maple syrup productivity has not kept pace with other producing provinces such as Quebec, New Brunswick, and Ontario (Crops and Horticulture Division, 2020).

Table 37. Nova Scotia sugarbush stand characteristics and the year values were reported.

Sugarbush Characteristic	Value	Reporting Year	Reference
Number of Maple Farms	187	2016	Crops and Horticulture Division, 2020
Number of Taps	446,300	2016	Crops and Horticulture Division, 2020
Average Sugarbush Age	50-80 years	2013	Lada & Nelson, 2013
Average DBH	17.25 cm	2013	Lada & Nelson, 2014
Litres Produced	265,000 L	2019	Crops and Horticulture Division, 2020
Value of Maple Products	$3,847,000	2019	Crops and Horticulture Division, 2021
Average Syrup Yield	0.33-0.87 L tap^{-1}*	2014	Crops and Horticulture Division, 2020; Lada et al., 2014
*** Highly variably, with multiple sources reporting different values**			

Using the value of litres produced currently in NS (Table 36) and the different liming scenarios (Table 32), liming would have to increase syrup production in NS by 20% for ten years for helicopter liming to be profitable at a 0% discount rate. If the effects from liming persisted for 20 years, production would only have to increase by 10% for it to be profitable (Table 37). However, higher discount rates reduce profitability.

Table 38. The total L produced, the net present value (NPV), and net profit over 10 years for 4 different liming scenarios in sugarbushes in Nova scotia at different discount rates. Values of in millions $ CAD.

Scenario	Discount Rate	Production (Total millions of L over 10 years)	NPV ($ Millions CAD)	Net Profit ($ NPV- $ Total Cost, in $ Millions CAD)
1	0	2.65	38.5	--
	2		34.6	
	4		31.2	
2	0	2.53	36.7 (-1.8)	-11.4
	2		33.1 (-1.5)	-3.9
	4		29.9 (-1.3)	-4.1
3	0	2.86	41.5 (+3.0)	-3
	2		37.2 (+2.6)	-3.4
	4		33.6 (+2.4)	-3.6
4	0	3.01	44.6 (+6.1)	0.1
	2		40 +(5.4)	-0.6
	4		36 (+4.8)	-1.2

Assumptions:

1. **Assume a consistent price for maple products throughout the 10 years.**
2. **Assume that 265,000 L of maple syrup production per year as the starting point for this analysis (Crops and Horticulture Division, 2020).**
3. **Assume liming over an area of 2,265 ha, in which liming costs approximately $ 6 million.**

There is a lot of uncertainty associated with yield values for the maple syrup industry in NS; therefore, these numbers may be subject to change depending on changes in the industry. The NPV for maple syrup in NS was similar to the results that Ouimet et al. (2018) reported, showing that liming was profitable with low discount values. Their findings showed that there would be a 10% decrease in sap yield at the control site (no lime), while there would be a 30% increase in sap yield at the limed sites. The increase in sap yield was correlated with a net profit of $837 to $1,813 ha^{-1} over 20 years. The increase in value is mostly due to an increase in healthy, tappable trees. The scenarios that provided these values were derived from Ouimet et al. (2018) and may not necessarily represent the response of NS sugarbushes to liming; however, no trials have been conducted in NS to date.

4.3.5 Sugar Maple Fall Foliage Tourism Value

The Nova Scotia Tourism Exit Surveys showed that although tourism for fall foliage represents a small portion of overall tourism in NS, it is still a valuable industry. The most recent completed exit surveys in NS (from 2017 and 2019) state that 8% of tourists visit during October when fall foliage is at its peak (Tourism Nova Scotia, 2017), that 58% of all visitors participated in outdoor activities, and 17% specifically visited for observing nature (Tourism Nova Scotia, 2019). There was no direct information on what tourists were looking to view in the fall; however, it can be assumed that tourists viewing nature in October were likely viewing fall foliage. This would result in approximately 0.79% of tourists coming to NS for fall foliage-related activities, equivalent to $20,540,000 in tourism revenue for 2019.

There were approximately 194,200 non-resident visitors to NS in October 2019 (Nova Scotia Tourism, 2019). Of these visitors, 22% stated their main reason for visiting was the scenery and natural landscape. It was assumed that all October 2019 scenery viewing visitors were viewing fall foliage, then approximately 42,724 people came to view fall foliage. The average trip party is 2.2 people; therefore, approximately 19,420 trips were made by visitors to view fall foliage in NS. This would be equivalent to approximately $1,057.67 trip^{-1}. The loss of an average of 2.3 trips per year approximately equals the value of liming 1 ha of forest.

Quantifying the value of fall foliage tourism is possible; however, it is more difficult to estimate the direct contribution of sugar maple. Caputo et al. (2016) suggested that sugar maple is twice as preferred for fall foliage as other tree species. Therefore, the potentially greater response of sugar maple to lime because of their sensitivity to acid conditions (Moore et al., 2015) may lead to additional economic benefits.

Quantifying the value of liming for tourism is difficult because it is not directly related to yield, such as wood products and syrup production. No direct link was found between Ca, Mg, or Al to red colour expression in red maple and some sugar maple; however, healthier trees can produce more starch, which may lead to increased red expression (Schaberg et al., 2003). In addition, decreased Ca levels from acid deposition can cause leaf necrosis and discoloration (Bal et al., 2014). This leads to decreases in the vibrance of fall foliage. Beier et al. (2017) estimated that the value of sugar maple is USD 53.22 trip^{-1}, which is much lower than our calculated value of CAD 1057.67 trip^{-1}; however, this value is similar to that seen for the overall average spent per trip for NS which is \$1,430 trip^{-1}. The value discrepancy is likely because Beier et al. (2017) accounted for total travel costs associated with local residents while the NS values do not. More information is needed about the value of fall foliage to tourists and their willingness to pay to maintain fall foliage in NS.

4.4 Conclusion and Recommendations

Liming can improve the value of important tree species in NS in several ways (Figure 39), such as increased growth for timber value and improved tree health for maple syrup and fall red expression. However, not all value from sugar maple can be recognized simultaneously, i.e., if you are using a sugar maple stand for maple syrup production, you will likely not receive the benefits from wood production. Studies from other acidified regions give insight into the potential benefits of liming in NS. In addition, the value of liming cannot only be considered through yield increases, but liming has the potential to slow down the decline in yield and tree health, i.e., maintain the current conditions and help prevent further decline. At this point, it is not conclusive whether the benefits from helicopter liming outweigh the costs; however, our first approximation shows the potential for helicopter liming to be an economically viable venture. In addition, this chapter does not capture other benefits, such as the value of carbon capture from improved growth and the trickle down-effects on streams and lakes which would or could significantly increase the benefits and value of liming.

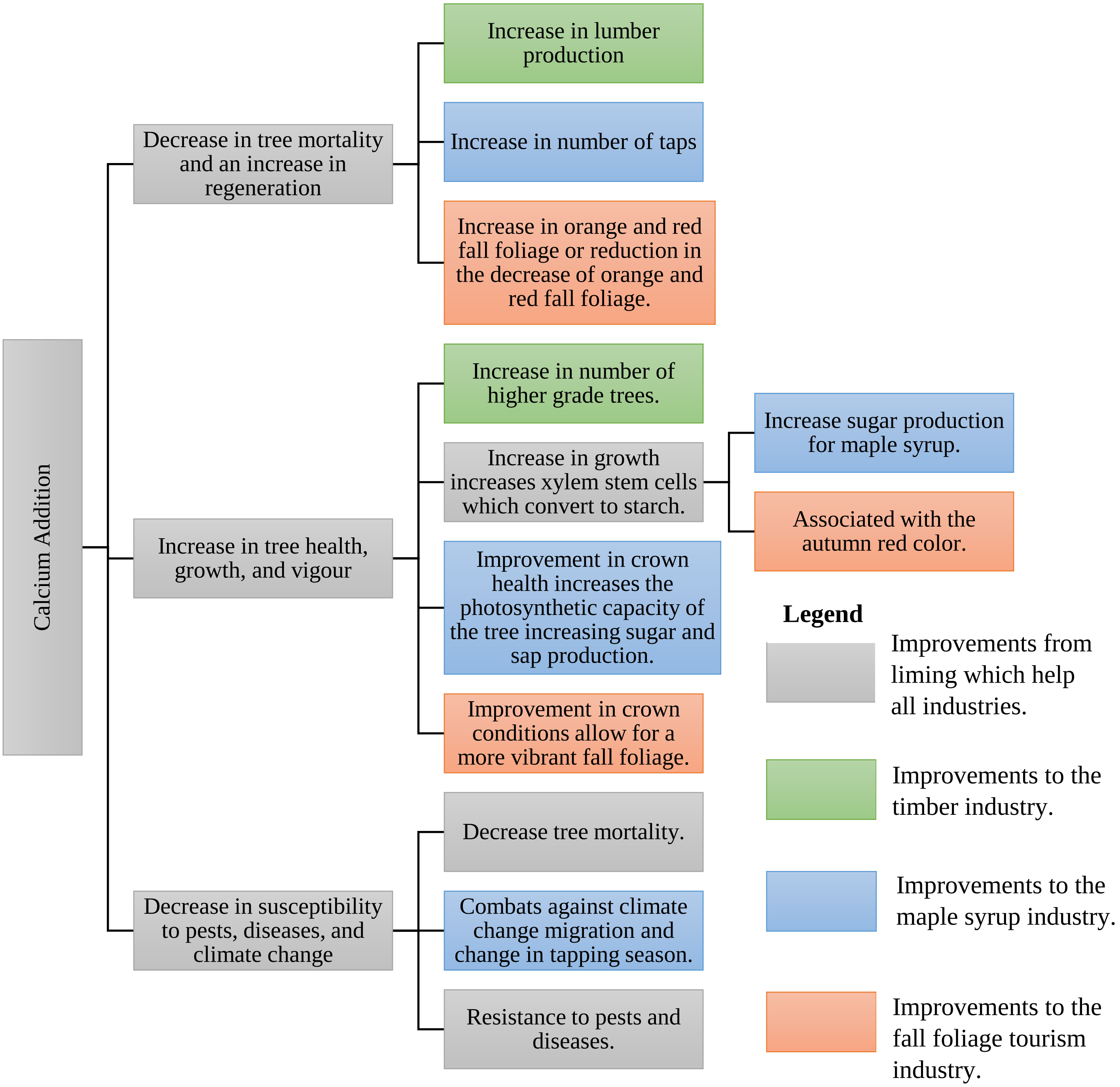


Figure 39. Overview of the potential benefits of catchment liming on wood products, maple syrup, and fall foliage tourism for red spruce and sugar maple-dominated stands in NS.

To appropriately define the benefits of helicopter liming in NS, additional research is required, such as:

- Determine the long-term relationship between lime addition and base cation chemistry in mature acidified red spruce and sugar maple-dominated forest stands in NS. An example of this research is currently underway at the Otter Ponds Demonstration Forest in Mooseland, NS.
- Evaluate the changes in basal area increment and volume production of sugar maple and red spruce stands in response to lime. Also, evaluate the changes in tree health and the increase in higher value products, such as veneer logs, in limed areas.
- Evaluate sugarbush response to lime for increases in sap production, quality, and recovery from injury and the subsequent value to the industry.
- Estimate the value of sugar maple in fall foliage compared with other hardwood species in NS and identify what proportion of tourism is directly related to the fall foliage industry.

Chapter 5 – Conclusion

Forest liming trials have been conducted in many acidified areas in northeastern North America and Europe; however, none have been conducted in Nova Scotia. Additionally, few studies have evaluated the effectiveness of helicopter liming as a feasible method for lime application in forests. The lingering impacts from acid deposition, in combination with poorly buffered Nova Scotia soils, provided a reasonable argument to implement forest helicopter liming in acidified forest stands in NS. There was evidence of slow recovery from soil acidification due to substantial base cation depletion, low pH, and high levels of mobile toxic Al^{3+} in the soils. These soil conditions can lead to poor forest productivity resulting in ecological and economic losses. Chapter 1 examined the justification for liming acidified forest stands in NS, identifying that poor base saturation and low pH were evident in many forest soils leading to poor growth and health of acid-sensitive tree species, particularly sugar maple and red spruce.

Previous literature provided evidence that forest liming could be used as a tool to help kick-start soil recovery from acidification (Lawrence et al., 2016). Forest liming is logistically difficult and expensive despite its many potential benefits, such as improved soil base saturation, pH, and improved forest productivity. Chapter 2 evaluated the helicopter application method, specifically, the uniformity of aerial deposition of lime and the potential response. Based on the analysis of lime distribution, the following conclusions can be made:

- The distribution of lime was not uniform throughout the sites, likely due to the helicopter flight path and deposition timing during the flight.
- The distribution of lime was more uniform in the hardwood forest compared to the softwood forest, contrary to what was expected.
- The chemical composition of the limestone had slightly less calcium than expected.

- Deposited lime and fresh lime differed slightly in their particle size distribution.
- Few studies have evaluated the method of helicopter liming, most notably, the Hubbard Brook research forest; however, there are limited results published on this topic.

Despite the non-uniform application, there was an initial response in soil chemistry throughout the hardwood and softwood sites. Chapter 3 assessed the response of soil and plant tissue chemical properties one year after liming compared to a control (unlimed) plot. Many previous liming studies have focused on the long-term response (10 + years) (Court et al., 2018; Long et al., 2015; Moore et al., 2008; 2012); however, the initial response can provide insight into the potential long-term responses. Based on the OPDF field trial of helicopter liming of dolomitic limestone over hardwood and softwood acidified forest stands in NS, the following conclusions can be made:

- Soil chemical properties which can indicate an initial recovery from soil acidification, such as pH, %BS, exchangeable Ca^{2+}, and exchangeable Mg^{2+}, increased significantly in response to liming treatment in the forest floor horizons at the hardwood and softwood sites. In addition, exchangeable acidity decreased significantly, and Al^{3+} decreased non-significantly, but only at the softwood upper forest floor horizon.
- The mineral soil horizons chemical properties had some initial response to liming, such as increases in %BS, Ca^{2+}, and Mg^{2+}; however, they were less dramatic than the forest floor, and a greater response is expected in the longer term.
- Ground vegetation responded to liming through increased Ca and Mg in wood fern and Schreber’s moss. However, Al also increased in wood fern and Schreber’s moss, and Fe and Mn increased in Schreber’s moss, contrary to what was expected.

- Sugar maple had the largest response of the three tree species studied because it is an acid-sensitive tree species, with significant increases in foliar Ca and Mg; however, red spruce also responded with significant increases in Mg and non-significant increases in Ca in the foliar tissue.
- There is a likely antagonistic relationship between increases in Ca and K concentrations at the hardwood site, as demonstrated by the decrease in K^+ in the forest floor horizon and K in wood fern plant tissue after liming. This antagonistic relationship was also apparent in the nutrient ratio changes in the DRIS analysis for sugar maple.
- Although initial signs of recovery from acid deposition were observed, many soil and plant tissue chemical properties remain below ideal conditions for forest health. For example, pH increased significantly in the forest floor horizons; however, the pH is still highly acidic. DRIS analysis showed improvements in Ca in sugar maple foliage; however, Ca remained the limiting nutrient.
- Lime loading rates were more correlated with changes in Schreber's moss Ca and Mg concentration than the forest floor. Still, they showed a weak positive correlation between lime loading rates and changes in forest floor Ca^{2+} and Mg^{2+} at the softwood sites. Lime loading rates had no correlation with red spruce foliar chemistry. Lime loading rates were more correlated with changes in forest floor Ca^{2+} and Mg^{2+} than wood fern at the hardwood site. Changes in forest floor Ca^{2+} were positively correlated with changes in sugar maple Ca, but similar correlations were not observed for Mg. The limited number of sample points limits the correlation analysis, but it provides insight into the difference in response between the softwood and hardwood sites.

Overall, the initial response one year after liming showed some initial signs of soil recovery from acid deposition; however, it is too early to determine whether these initial effects will increase and persist in the long term. Long-term data is required to further evaluate the impact of liming on acidified forests in NS.

The long-term results of this study will help determine whether liming in NS also improves forest health and productivity. If so, liming is a potential tool to improve forest productivity in acidified forests throughout the province. However, it is expensive and logistically difficult. Chapter 4 examined the costs of helicopter liming and the potential economic value of improved acidification status of red spruce and sugar maple stands in NS. Based on a review of the literature and likely scenarios for liming in NS, the following conclusions can be made:

- Improved %BS can lead to increase sustainable harvest yields in red spruce forests and increase the value of stands by up to 50% when %BS is 30%.
- Sugar maple timber value largely depends on tree health, compared to growth. Liming has the potential to greatly improve tree health and the number of high-value veneer hardwood logs produced in NS.
- Liming sugarbushes was profitable in Quebec with a low discount rate; similar results are likely in NS.
- The value of fall foliage tourism could be impacted by acid deposition due to reduced tree canopy health and foliar red expression. It is most likely that the value of liming in tourism would be from a reduced sugar maple decline in the tree canopy.
- Average %BS at the OPDF study sites was much lower than the maximized benefit threshold presented by Beier et al. (2017). In addition to a lack of an economic model for NS timber, the changes in %BS at the OPDF one year after liming were insufficient to

evaluate any significant increase in timber value. However, the OPDF research trial could be used to compare the economic value of these stands in the future to identify the value of liming forests in NS directly.

Overall, helicopter liming can promote recovery from soil acidification and increase the value of currently acidified forests in NS. More research is needed, particularly the extension of the trial at OPDF, to understand the long-term response of acidified forests to liming in NS.

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Appendix 1 – Supplementary Information for Chapter 2

A1 Table 1. Locations of the lime collection boxes in the hardwood treatment (HWT) and softwood treatment (SWT) sites in decimal degrees and their corresponding lime loading rates and canopy closure. Boxes with the letter A in the name were located within the corresponding plot and the other letters were located outside of the corresponding plot.

Box	X Coordinate	Y Coordinate	Lime Loading (t ha^{-1})	Canopy (%)
HWT 1A	44.933054	-62.754842	3.22	89
HWT 1B	44.932225	-62.754858	2.74	84
HWT 2A	44.932640	-62.754352	4.48	90
HWT 2B	44.932993	-62.754492	10.5	91
HWT 3A	44.932449	-62.754675	5.45	80
HWT 3B	44.932711	-62.754923	6.24	89
HWT 4A	44.932210	-62.754321	7.61	86
HWT 4B	44.932417	-62.754238	5.06	81
HWT 5A	44.932424	-62.753974	7.24	90
HWT 5B	44.932307	-62.753934	12.7	89
HWT 6A	44.932074	-62.753706	5.45	87
HWT 6B	44.931976	-62.754074	2.53	95
SWT 1A	44.936556	-62.762885	3.33	81
SWT 1B	44.936389	-62.762813	3.33	81
SWT 2A	44.936359	-62.762603	8.11	75
SWT 2B	44.936570	-62.762560	7.27	84
SWT 3A	44.935869	-62.761638	7.44	79
SWT 3B	44.935814	-62.761505	3.43	87
SWT 4A	44.935327	-62.761815	15.1	85
SWT 4B	44.935295	-62.761702	7.60	84
SWT 4C	44.935199	-62.761726	14.0	86
SWT 5A	44.935225	-62.761495	8.14	81
SWT 5B	44.935408	-62.761617	5.75	88
SWT 5C	44.935116	-62.761374	1.31	81

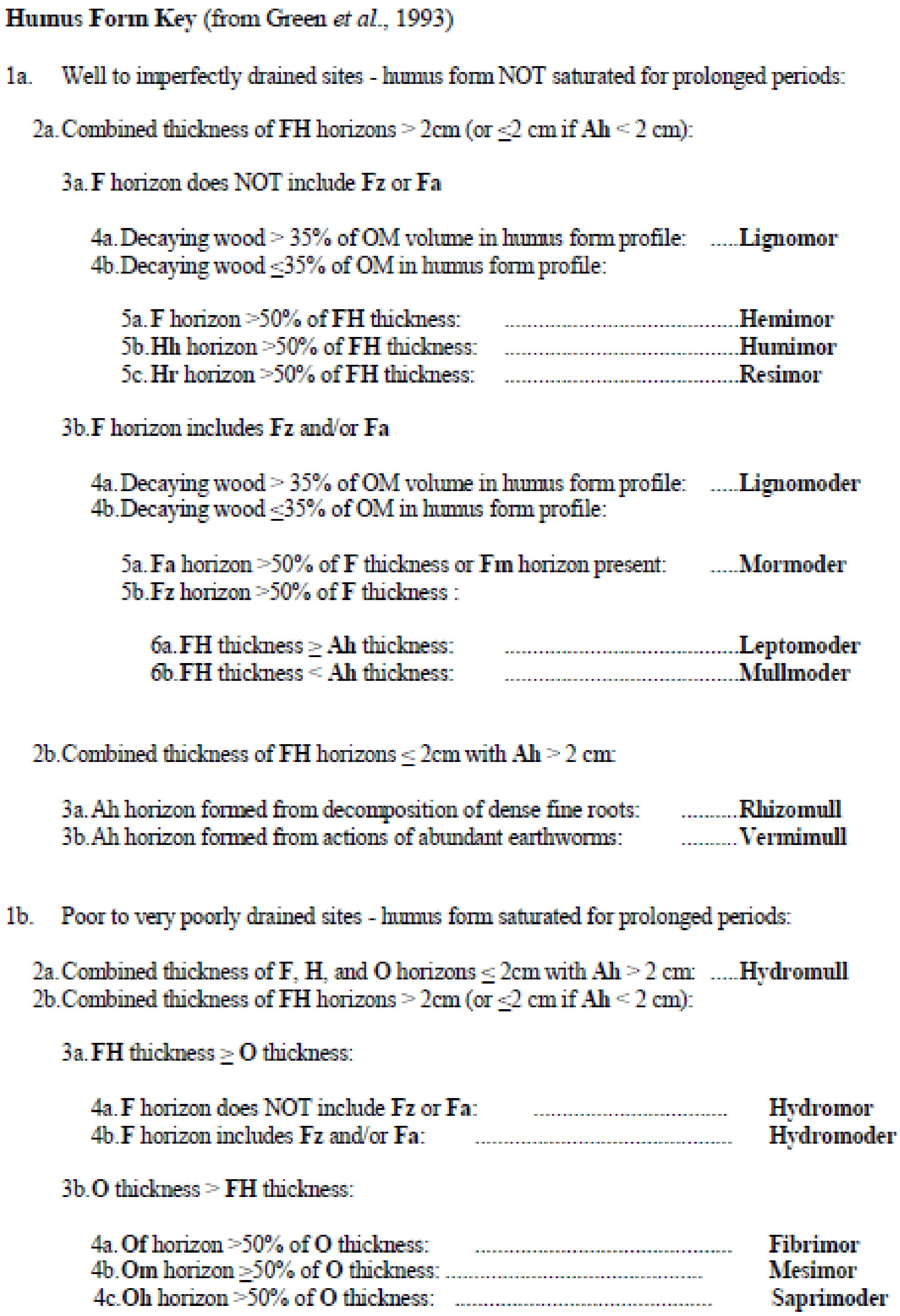
A1 Table 2. Base cation, metal, and carbon concentrations for lime samples collected at the softwood treatment (SWT) site. All samples were collected from the lime collection boxes after lime application, where RDL is the detection limit. Samples were analyzed at the AGAT Laboratory in Dartmouth, NS.

Element Concentration	Unit	RDL	SWT 1A	SWT 2A	SWT 3A	SWT 4A	SWT 5A	SWT 5C
Calcium	mg/kg	50	157,000	160,000	150,000	162,000	158,000	149,000
Magnesium	mg/kg	50	96,100	96,500	88,200	97,600	93,800	91,500
Sodium	mg/kg	50	651	518	471	434	372	374
Potassium	mg/kg	50	304	407	294	319	317	320
Aluminum	mg/kg	10	1,090	1,310	1,190	1,280	1,210	1,200
Antimony	mg/kg	1	<1	<1	<1	<1	<1	<1
Arsenic	mg/kg	1	12	13	12	13	12	13
Barium	mg/kg	5	1,150	1,560	1,380	1,870	2,250	1,090
Beryllium	mg/kg	2	<2	<2	<2	<2	<2	<2
Boron	mg/kg	2	41	38	40	37	34	39
Cadmium	mg/kg	0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Chromium	mg/kg	2	3	3	3	3	3	3
Cobalt	mg/kg	1	2	2	2	2	2	2
Copper	mg/kg	2	4	5	4	6	6	6
Iron	mg/kg	50	4,110	4,680	3,570	4,780	4,460	3,900
Lead	mg/kg	0.5	7.2	7.6	9.2	7.3	10.5	7.1
Lithium	mg/kg	5	12	11	12	12	11	12
Manganese	mg/kg	2	2,750	3,030	2,570	2,920	2,890	2,670
Molybdenum	mg/kg	2	<2	<2	<2	<2	<2	<2
Nickel	mg/kg	2	11	11	11	11	11	11
Selenium	mg/kg	1	<1	<1	<1	<1	<1	<1
Silver	mg/kg	0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Strontium	mg/kg	5	140	136	134	135	139	130
Thallium	mg/kg	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Tin	mg/kg	2	3	3	3	3	3	3
Uranium	mg/kg	0.1	0.9	0.9	0.9	1.0	0.9	1.0
Vanadium	mg/kg	2	5	5	5	5	5	5
Zinc	mg/kg	5	10	12	10	10	11	10
Inorganic Carbon - Total	%	0.02	10.5	10.4	10.5	10.5	10.5	10.5
Organic Carbon - Total	%	0.02	0.80	1.20	0.70	0.90	1.10	1.20

A1 Table 3. Base cation, metal, and carbon concentrations for lime samples collected at the hardwood treatment (HWT) site. All samples were collected from the lime collection boxes after lime application, where RDL is the detection limit. Samples were analyzed at

Element	Unit	RDL	HWT 1A	HWT 2A	HWT 3A	HWT 4A	HWT 5A	HWT 6A
Calcium	mg/kg	50	160,000	162,000	161,000	155,000	157,000	160,000
Magnesium	mg/kg	50	94,500	94,700	98,200	92,900	91,500	97,600
Sodium	mg/kg	50	1,680	1,400	1,220	1,090	931	772
Potassium	mg/kg	50	549	403	405	374	333	361
Aluminum	mg/kg	10	1,260	1,200	1,230	1,390	1,330	1,260
Antimony	mg/kg	1	<1	<1	<1	<1	<1	<1
Arsenic	mg/kg	1	13	12	12	14	13	12
Barium	mg/kg	5	2,200	3,020	1,620	1,760	2,980	2,810
Beryllium	mg/kg	2	<2	<2	<2	<2	<2	<2
Boron	mg/kg	2	49	43	42	46	42	42
Cadmium	mg/kg	0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Chromium	mg/kg	2	3	3	3	4	3	4
Cobalt	mg/kg	1	2	2	2	2	2	2
Copper	mg/kg	2	6	8	5	6	7	5
Iron	mg/kg	50	4,110	4,610	4,590	4,590	4,510	4,920
Lead	mg/kg	0.5	6.7	6.3	6.4	8.1	23.2	6.7
Lithium	mg/kg	5	13	12	12	14	13	12
Manganese	mg/kg	2	2,930	2,920	3,010	2,930	2,870	2,930
Molybdenum	mg/kg	2	<2	<2	<2	<2	<2	<2
Nickel	mg/kg	2	13	12	11	13	11	11
Selenium	mg/kg	1	1	<1	<1	1	<1	<1
Silver	mg/kg	0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Strontium	mg/kg	5	198	194	157	170	188	171
Thallium	mg/kg	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Tin	mg/kg	2	3	3	3	3	3	3
Uranium	mg/kg	0.1	0.9	0.9	0.9	1.0	0.9	0.9
Vanadium	mg/kg	2	6	5	5	6	5	5
Zinc	mg/kg	5	12	11	11	13	11	11
Inorganic Carbon - Total	%	0.02	10.5	10.5	10.5	10.5	10.6	10.5
Organic Carbon - Total	%	0.02	0.70	0.70	0.90	0.90	0.70	0.60

Appendix 2 – Supplementary Information for Chapter 3



Humus Form Key (from Green *et al.*, 1993)

1a. Well to imperfectly drained sites - humus form NOT saturated for prolonged periods:

  2a. Combined thickness of **FH** horizons > 2cm (or ≤2 cm if **Ah** < 2 cm):

    3a. **F** horizon does NOT include **Fz** or **Fa**

      4a. Decaying wood > 35% of OM volume in humus form profile: .....**Lignomor**
      4b. Decaying wood ≤35% of OM in humus form profile:

        5a. **F** horizon >50% of **FH** thickness: ....**Hemimor**
        5b. **Hh** horizon >50% of **FH** thickness: ....**Humimor**
        5c. **Hr** horizon >50% of **FH** thickness: ....**Resimor**

    3b. **F** horizon includes **Fz** and/or **Fa**

      4a. Decaying wood > 35% of OM volume in humus form profile: .....**Lignomoder**
      4b. Decaying wood ≤35% of OM in humus form profile:

        5a. **Fa** horizon >50% of **F** thickness or **Fm** horizon present: .....**Mormoder**
        5b. **Fz** horizon >50% of **F** thickness :

          6a. **FH** thickness ≥ **Ah** thickness: ....**Leptomoder**
          6b. **FH** thickness < **Ah** thickness: ....**Mullmoder**

  2b. Combined thickness of **FH** horizons ≤ 2cm with **Ah** > 2 cm:

    3a. Ah horizon formed from decomposition of dense fine roots: ....**Rhizomull**
    3b. Ah horizon formed from actions of abundant earthworms: ....**Vermimull**

1b. Poor to very poorly drained sites - humus form saturated for prolonged periods:

  2a. Combined thickness of **F**, **H**, and **O** horizons ≤ 2cm with **Ah** > 2 cm: .....**Hydromull**
  2b. Combined thickness of **FH** horizons > 2cm (or ≤2 cm if **Ah** < 2 cm):

    3a. **FH** thickness ≥ **O** thickness:

      4a. **F** horizon does NOT include **Fz** or **Fa**: .... **Hydromor**
      4b. **F** horizon includes **Fz** and/or **Fa**: .... **Hydromoder**

    3b. **O** thickness > **FH** thickness:

      4a. **Of** horizon >50% of **O** thickness: .... **Fibrimor**
      4b. **Om** horizon ≥50% of **O** thickness: .... **Mesimor**
      4c. **Oh** horizon >50% of **O** thickness: .... **Saprimoder**

A2 Figure 1. Soil humus form classification adapted from Green et al., 1993.

A2 Table 1. DRIS norms for sugar maple by crown position (upper, middle, and lower) for N, P, K, Ca, Mg, Fe, and Al adapted from Lozano and Hyunh (1989). No ratios containing Mn had a significant variance ratio and was not included. All other missing values did not have a significant variance ratio.

Ratio	**Upper**		**Middle**		**Lower**	
	Mean	CV	Mean	CV	Mean	CV
N/K	1.8145	19.83	1.8477	28.37	1.9	18.694
N/Fe			273.663	20.02	285.207	21.485
N/Al	390.7802	31.452	438.7914	26.714	467.105	28.045
P/K			0.1842	38.166	0.19	40.768
P/Ca	0.1871	37.879	0.1683	38.4	0.1646	38.889
P/Fe	24.6913	31.347	27.6343	37.003	28.112	36.946
P/Al	36.9443	29.131	43.3758	34.35	45.345	36.391
K/N	0.5774	24.648			0.5471	21.521
K/Al	226.1336	43.039				
Ca/N	0.6339	49.754	0.7207	50.995	0.7117	47.541
Ca/P	6.0925	37.725	7.0049	44.544	7.138	43.198
Ca/K	1.1104	48.476	1.2765	50.839		
Ca/Mg	7.5975	19.854	8.1205	24.241	7.574	22.942
Ca/Al					313.746	45.444
Mg/P			0.8383	25.037		
Mg/K	0.1404	35.79	0.1495	32.78	0.1672	33.359
Mg/Ca	0.1365	18.783			0.1388	22.527
Mg/Fe	19.4157	38.216	22.7842	36.24	24.995	33.462
Mg/Al	29.4834	41.395	36.0492	37.985	40.75	37.112
Fe/N	0.0043	29.432	0.0038	21.094		
Fe/P	0.0445	31.464			0.0399	31.764
Fe/K	0.0076	31.195	0.0069	27.438	0.0068	21.478
Fe/Ca			0.0069	57.452		
Fe/Mg	0.0601	41.728			0.0453	36.788
Al/N	0.0029	37.978	0.0024	27.755	0.0023	29.837
Al/P	0.0292	27.557				
Al/K			0.0044	31.8	0.0043	28.023
Al/Mg			0.0324	41.667		

A2 Table 2. Outliers removed in each soil horizon and plant tissue at the softwood sites and their reasoning where CEC is cation exchange capacity, EA is exchangeable acidity, and IQR is interquartile range. Removed outliers were deemed not ecologically relevant which meant did not represent an area that was different (e.g., wet area or no surrounding sample points), i.e., the trends could be captured by other sampling points.

Horizon	Parameter	Number of outliers detected	Number of outliers removed	Reasoning
F	K^+	1	1	One outlier was removed from the control site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	Al^{3+}	2	2	Two outliers were removed from the control site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	CEC	1	1	One outlier was removed from the control site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
F/H	pH	5	0	Five outliers were detected at the treatment site in year 2. No outliers were removed because outliers were clumped and may represent a relevant response to liming.
	%BS	5	0	Five outliers were detected at the treatment site in year 2. No outliers were removed because outliers were clumped and may represent a relevant response to liming.
	K^+	1	1	One outlier was removed from the control site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	Al^{3+}	3	3	One outlier was removed from the control site in year 1 and two outliers were removed from the control site in year 2. All outliers were greater than 1.5 IQR and were not ecologically relevant.
M1	%BS, Ca^{2+}, Mg^{2+}	2	2	Two outliers were removed from the treatment site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant. The removed outliers were the same points for %BS, Ca^{2+}, and Mg^{2+}.
	Mn^{2+}	2	2	Two outliers were removed from the treatment site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.

A2 Table 2 Con't.

Horizon	Parameter	Number of outliers detected	Number of outliers removed	Reasoning
M2	%BS	3	3	Three outliers were removed from the treatment site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant and was likely a results of sampling error.
	Ca^{2+}, Mg^{2+}	2	2	Two outliers were removed from the treatment site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant and was likely a result of sampling error.
Ground Vegetation	Ca, Mg	4	2	Four outliers were identified in the treatment site in year 2 but only two were removed because they were likely due to lime in the sample.
	N, P, K	1	1	One outlier had significantly greater N, P, K than all other samples in the control site in year 2.
Red Spruce Foliage	P	1	1	One outlier was removed from the control site in year 1 because it was greater than 1.5 the IQR and was not ecologically relevant.
	Ca	1	1	One outlier was removed from the treatment site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	Fe	1	1	One outlier was removed from the treatment site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	Mn	3	0	Three outliers were identified, but none were removed because all the outliers were within a clump which is likely representative of the variability within the sampling site.

A2 Table 3. Outliers removed in each soil horizon and plant tissue at the hardwood sites and their reasoning where CEC is cation exchange capacity, EA is exchangeable acidity, and IQR is the interquartile range. Removed outliers were deemed not ecologically relevant which meant did not represent an area that was different (e.g., wet area or no surrounding sample points), i.e., the trends could be captured by other sampling points.

Horizon	**Parameter**	**Number of outliers detected**	**Number of outliers removed**	**Reasoning**
F	CEC	7	3	Seven outliers were identified; however, not all were removed because 4 points were deemed ecologically significant. Three outliers were removed from the control site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	EA	2	2	Two outliers were removed from the control site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	Al^{3+}	3	1	Three outliers were identified, but 2 outliers were similar and were considered reasonable. One outlier was removed from the control site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	Mn^{2+}	1	1	One outlier was removed from the control site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
M1	pH	1	1	One outlier was removed from the treatment site in year 1 because it was less than 1.5 the IQR and was not ecologically relevant.
	%BS	2	2	Two outliers were removed from the treatment site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	Ca^{2+}, Mg^{2+}	1	1	One outlier was removed from the treatment site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	K^{+}	4	0	No outliers were removed because the outliers were all grouped together and were considered ecologically important.

A2 Table 3 Con't.

Horizon	Parameter	Number of outliers detected	Number of outliers removed	Reasoning
M2	pH	4	0	Four outliers were identified, but none were removed because they were considered ecologically relevant because of the variability of the results.
	%BS, Ca^{2+}	2	0	Two outliers were identified, but none were removed because they were considered ecologically relevant because of the variability of the results.
	Mg^{2+}	9	0	Nine outliers were identified, but none were removed because they were considered ecologically relevant because of the variability of the results.
	K^{+}	3	0	Three outliers were identified, but none were removed because all the outliers were within a clump which is likely representative of the variability within the sampling site.
	EA	1	1	One outlier was removed from the treatment site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	Mn^{2+}	7	1	Seven outliers were identified, but only one outlier was removed from the control and in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant. This outlier was significantly greater than all the other outliers and was likely a result of sampling error.
Ground Vegetation	N, K, Mg, Mn	1	1	One outlier was removed in the control site in year 2 because it had significantly lower N, K, Mg and significantly greater Al, Fe, and Mn than all other samples.
	Al	3	1	Three outliers were identified, but one was significantly greater than all other outliers and was likely due to sampling error. One outlier was removed from the control site in year 2.
	Fe	4	2	Four outliers were identified, but two were significantly greater than all other outliers and were likely due to sampling error. One outlier was removed from the control and treatment site in year 2.
Red Maple Foliage	P, K	1	1	One outlier was removed from the control site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	Ca	2	0	Two outliers were identified but were similar and deemed ecologically relevant to the study.

A2 Table 3 Con't

Horizon	Parameter	Number of outliers detected	Number of outliers removed	Reasoning
Sugar Maple Foliage	K	3	1	Three outliers were identified, but one was significantly greater than all other outliers and were likely due to sampling error. One outlier was removed from the site in year 1.
	Al	1	1	One outlier was removed from the control site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	Fe	1	1	One outlier was removed from the control site in year 2 because it was greater than 1.5 the IQR and was not ecologically relevant.
	Mn	3	0	Three outliers were identified, but none were removed because all the outliers were within a clump which is likely representative of the variability within the sampling site.

A2 Table 4. Soil acidity parameters at the SWC and SWT site before (2018) and after (2019) the application of dolomitic limestone for every soil horizon sampled. All units are cmol kg^{-1} except pH and %BS.

Site	Year	Plot	Horizon	pH	%BS	CEC	Ca^{2+}	Mg^{2+}	K^{+}	EA	Al^{3+}	Mn^{2+}
SWC	2018	1	F	2.44	13.3	7.49	0.17	0.52	0.18	6.50	0.25	0.02
SWC	2018	2	F	2.58	14.7	7.85	0.38	0.45	0.22	6.70	0.31	0.03
SWC	2018	3	F	2.56	15.0	7.65	0.26	0.52	0.24	6.50	0.25	0.03
SWC	2018	4	F	2.59	18.3	6.61	0.41	0.50	0.18	5.40	0.25	0.05
SWC	2018	5	F	2.63	13.9	7.44	0.30	0.41	0.22	6.40	0.43	0.04
SWT	2018	1	F	2.55	14.6	7.85	0.37	0.53	0.17	6.70	0.19	0.03
SWT	2018	2	F	2.50	14.1	7.68	0.27	0.58	0.16	6.60	0.44	0.02
SWT	2018	3	F	2.71	20.9	5.94	0.37	0.56	0.25	4.70	0.19	0.04
SWT	2018	4	F	2.52	12.6	8.58	0.22	0.52	0.21	7.50	0.16	0.04
SWT	2018	5	F	2.62	21.2	6.85	0.60	0.59	0.19	5.40	0.20	0.04
SWC	2019	1	F	2.30	8.2	11.33	0.20	0.46	0.15	10.40	0.95	0.01
SWC	2019	1	F	2.47	9.2	9.47	0.27	0.39	0.15	8.60	0.93	0.03
SWC	2019	1	F	2.47	14.0	8.96	0.57	0.48	0.15	7.70	0.44	0.02
SWC	2019	2	F	2.56	18.1	7.08	0.55	0.46	0.21	5.80	0.25	0.03
SWC	2019	2	F	2.42	7.7	8.88	0.12	0.42	0.13	8.20	0.33	0.01
SWC	2019	2	F	2.44	15.3	6.61	0.25	0.51	0.17	5.60	0.18	0.02
SWC	2019	3	F	2.74	21.3	6.48	0.43	0.57	0.27	5.10	0.21	0.04

A2 Table 4 Con't

Site	Year	Plot	Horizon	pH	%BS	CEC	Ca^{2+}	Mg^{2+}	K^{+}	EA	Al^{3+}	Mn^{2+}
SWC	2019	3	F	2.54	19.7	7.22	0.55	0.58	0.19	5.80	0.27	0.03
SWC	2019	3	F	2.41	12.5	7.77	0.31	0.35	0.20	6.80	0.23	0.02
SWC	2019	4	F	2.56	21.1	6.59	0.43	0.51	0.37	5.20	0.22	0.04
SWC	2019	4	F	2.46	16.3	7.05	0.17	0.64	0.21	5.90	0.22	0.02
SWC	2019	4	F	2.41	14.9	7.52	0.30	0.48	0.25	6.40	0.32	0.03
SWC	2019	5	F	2.46	13.6	7.53	0.17	0.55	0.22	6.50	0.37	0.03
SWC	2019	5	F	2.29	9.2	10.02	0.05	0.57	0.19	9.10	0.42	0.01
SWC	2019	5	F	2.45	13.0	8.16	0.21	0.51	0.22	7.10	0.22	0.03
SWT	2019	1	F	4.59	81.4	5.36	1.74	2.31	0.24	1.00	0.01	0.11
SWT	2019	1	F	4.26	79.6	5.39	1.88	2.14	0.20	1.10	0.21	0.08
SWT	2019	1	F	3.30	54.0	5.87	1.16	1.64	0.27	2.70	0.20	0.06
SWT	2019	2	F	2.96	29.0	7.19	0.71	1.15	0.14	5.10	0.32	0.03
SWT	2019	2	F	3.42	70.9	4.81	1.31	1.85	0.19	1.40	0.18	0.04
SWT	2019	2	F	3.55	70.1	5.02	1.46	1.79	0.20	1.50	0.14	0.06
SWT	2019	3	F	4.39	79.6	5.89	1.90	2.57	0.16	1.20	0.00	0.09
SWT	2019	3	F	4.15	72.8	5.89	1.77	2.24	0.21	1.60	0.12	0.09
SWT	2019	3	F	3.81	72.5	5.46	1.71	2.07	0.13	1.50	0.35	0.06
SWT	2019	4	F	4.07	80.8	5.72	1.80	2.59	0.15	1.10	0.30	0.06
SWT	2019	4	F	5.04	87.7	6.48	2.41	3.09	0.14	0.80	0.01	0.10
SWT	2019	4	F	4.59	85.1	6.03	2.16	2.78	0.15	0.90	0.02	0.10
SWT	2019	5	F	4.07	78.5	6.05	1.80	2.73	0.16	1.30	0.15	0.06
SWT	2019	5	F	3.74	68.9	5.78	1.59	2.16	0.17	1.80	0.20	0.06
SWT	2019	5	F	3.43	67.6	4.93	1.34	1.79	0.14	1.60	0.20	0.05
SWC	2018	1	H	2.37	6.2	14.82	0.04	0.58	0.15	13.90	1.47	0.01
SWC	2018	2	H	2.31	6.2	14.82	0.06	0.58	0.13	13.90	1.04	0.01
SWC	2018	3	H	2.40	5.9	14.25	0.04	0.52	0.15	13.40	1.64	0.01
SWC	2018	4	H	2.32	4.0	16.46	0.03	0.30	0.12	15.80	1.49	0.01
SWC	2018	5	H	2.53	2.8	20.89	0.03	0.32	0.15	20.30	2.64	0.01
SWT	2018	1	H	2.37	8.7	13.47	0.10	0.86	0.10	12.30	0.87	0.01
SWT	2018	2	H	2.37	4.1	16.17	0.04	0.43	0.10	15.50	1.73	0.01
SWT	2018	3	H	2.44	11.4	10.61	0.08	0.82	0.16	9.40	0.59	0.01
SWT	2018	4	H	2.36	6.6	14.13	0.03	0.57	0.13	13.20	1.10	0.01
SWT	2018	5	H	2.37	6.8	13.62	0.14	0.54	0.11	12.70	0.98	0.01
SWC	2019	1	H	2.29	3.7	17.13	0.06	0.38	0.09	16.50	1.97	0.00
SWC	2019	1	H	2.49	2.9	19.46	0.04	0.28	0.18	18.90	2.52	0.01
SWC	2019	1	H	2.36	10.2	10.91	0.35	0.57	0.13	9.80	0.75	0.01
SWC	2019	2	H	2.42	11.7	10.98	0.44	0.61	0.17	9.70	0.53	0.02
SWC	2019	2	H	2.40	9.6	10.07	0.11	0.58	0.18	9.10	0.42	0.01
SWC	2019	2	H	2.44	7.4	10.37	0.05	0.49	0.09	9.60	0.33	0.01

A2 Table 4 Con’t

Site	Year	Plot	Horizon	pH	%BS	CEC	Ca^{2+}	Mg^{2+}	K^{+}	EA	Al^{3+}	Mn^{2+}
SWC	2019	3	H	2.39	13.0	11.03	0.09	0.56	0.63	9.60	0.42	0.01
SWC	2019	3	H	2.31	10.3	12.59	0.10	0.85	0.24	11.30	0.66	0.01
SWC	2019	3	H	2.27	5.4	14.48	0.12	0.41	0.10	13.70	0.74	0.01
SWC	2019	4	H	2.33	8.6	11.38	0.13	0.61	0.14	10.40	0.79	0.02
SWC	2019	4	H	2.39	10.6	9.85	0.05	0.73	0.13	8.80	0.69	0.01
SWC	2019	4	H	2.31	8.6	10.50	0.11	0.54	0.14	9.60	0.54	0.01
SWC	2019	5	H	2.38	8.0	10.65	0.09	0.58	0.10	9.80	1.15	0.02
SWC	2019	5	H	2.29	7.3	11.86	0.03	0.62	0.10	11.00	0.63	0.00
SWC	2019	5	H	2.37	10.4	9.82	0.13	0.61	0.17	8.80	0.46	0.02
SWT	2019	1	H	2.43	13.3	8.76	0.27	0.69	0.10	7.60	0.41	0.01
SWT	2019	1	H	2.47	20.0	8.50	0.42	1.06	0.15	6.80	0.41	0.02
SWT	2019	1	H	2.49	19.0	9.02	0.31	1.18	0.14	7.30	0.68	0.01
SWT	2019	2	H	2.60	23.1	8.84	0.63	1.08	0.24	6.80	0.74	0.02
SWT	2019	2	H	2.64	30.0	7.29	0.59	1.30	0.22	5.10	0.62	0.02
SWT	2019	2	H	2.31	14.6	9.84	0.27	0.90	0.18	8.40	0.65	0.01
SWT	2019	3	H	3.09	63.5	5.21	1.10	2.06	0.11	1.90	0.38	0.04
SWT	2019	3	H	2.64	35.7	5.91	0.58	1.31	0.15	3.80	0.29	0.02
SWT	2019	3	H	3.16	62.1	5.28	1.37	1.76	0.11	2.00	0.49	0.04
SWT	2019	4	H	3.03	59.4	5.17	0.98	1.86	0.14	2.10	0.50	0.03
SWT	2019	4	H	3.48	73.7	4.94	1.34	2.14	0.12	1.30	0.44	0.05
SWT	2019	4	H	3.09	57.6	5.19	1.08	1.76	0.10	2.20	0.22	0.04
SWT	2019	5	H	2.38	17.0	9.88	0.25	1.27	0.09	8.20	0.47	0.01
SWT	2019	5	H	2.91	57.2	5.37	0.95	1.94	0.11	2.30	0.31	0.03
SWT	2019	5	H	2.51	27.1	7.41	0.57	1.27	0.10	5.40	0.59	0.02
SWC	2018	1	M1	3.36	1.7	4.17	0.00	0.01	0.02	4.10	3.12	0.00
SWC	2018	2	M1	3.36	1.0	5.35	0.01	0.01	0.01	5.30	3.96	0.00
SWC	2018	3	M1	3.65	1.1	3.34	0.00	0.01	0.02	3.30	4.11	0.00
SWC	2018	4	M1	3.39	0.6	4.43	0.00	0.01	0.01	4.40	2.66	0.00
SWC	2018	5	M1	3.36	0.7	4.23	0.00	0.01	0.02	4.20	2.46	0.00
SWT	2018	1	M1	3.51	0.7	3.73	0.00	0.01	0.00	3.70	2.54	0.00
SWT	2018	2	M1	3.64	0.7	3.83	0.00	0.01	0.00	3.80	3.23	0.00
SWT	2018	3	M1	3.45	0.7	4.23	0.00	0.01	0.00	4.20	3.04	0.00
SWT	2018	4	M1	3.48	0.7	4.53	0.00	0.01	0.00	4.50	3.58	0.01
SWT	2018	5	M1	3.45	0.5	4.72	0.00	0.01	0.00	4.70	3.52	0.00
SWC	2019	1	M1	3.40	1.0	6.87	0.01	0.02	0.02	6.80	2.62	0.00
SWC	2019	1	M1	3.57	1.2	4.56	0.01	0.01	0.01	4.50	2.37	0.00
SWC	2019	1	M1	3.42	0.5	7.14	0.01	0.01	0.01	7.10	2.45	0.00
SWC	2019	2	M1	3.57	0.8	5.44	0.01	0.01	0.02	5.40	3.63	0.00
SWC	2019	2	M1	3.59	0.7	5.14	0.01	0.01	0.01	5.10	3.40	0.00

A2 Table 4 Con't

Site	Year	Plot	Horizon	pH	%BS	CEC	Ca^{2+}	Mg^{2+}	K^{+}	EA	Al^{3+}	Mn^{2+}
SWC	2019	2	M1	3.44	1.0	5.96	0.01	0.02	0.02	5.90	2.50	0.00
SWC	2019	3	M1	3.73	2.1	3.17	0.03	0.01	0.01	3.10	2.70	0.00
SWC	2019	3	M1	3.61	0.4	5.32	0.01	0.01	0.01	5.30	3.79	0.00
SWC	2019	3	M1	3.84	1.0	2.93	0.01	0.01	0.01	2.90	4.25	0.00
SWC	2019	4	M1	3.84	0.9	4.24	0.01	0.01	0.01	4.20	2.74	0.00
SWC	2019	4	M1	3.55	0.7	4.94	0.00	0.01	0.01	4.90	2.39	0.00
SWC	2019	4	M1	3.59	0.8	4.74	0.01	0.01	0.01	4.70	2.63	0.00
SWC	2019	5	M1	3.70	0.8	3.83	0.00	0.01	0.01	3.80	2.64	0.00
SWC	2019	5	M1	3.42	0.6	5.84	0.00	0.01	0.01	5.80	2.58	0.00
SWC	2019	5	M1	3.68	1.2	4.05	0.00	0.01	0.01	4.00	3.28	0.00
SWT	2019	1	M1	3.59	3.5	3.83	0.04	0.05	0.01	3.70	3.17	0.00
SWT	2019	1	M1	3.69	1.4	4.76	0.01	0.02	0.01	4.70	4.06	0.00
SWT	2019	1	M1	3.46	1.8	5.90	0.02	0.03	0.01	5.80	3.12	0.00
SWT	2019	2	M1	3.78	3.3	3.31	0.03	0.03	0.01	3.20	4.62	0.00
SWT	2019	2	M1	3.53	1.8	5.50	0.03	0.04	0.01	5.40	3.23	0.00
SWT	2019	2	M1	3.55	4.5	3.87	0.07	0.07	0.01	3.70	3.06	0.01
SWT	2019	3	M1	3.97	22.8	3.50	0.40	0.39	0.01	2.70	3.35	0.01
SWT	2019	3	M1	3.47	0.6	5.33	0.01	0.02	0.01	5.30	3.34	0.00
SWT	2019	3	M1	3.65	0.5	3.32	0.00	0.01	0.00	3.30	3.00	0.00
SWT	2019	4	M1	3.47	1.5	3.96	0.02	0.03	0.00	3.90	2.18	0.00
SWT	2019	4	M1	3.47	1.4	4.87	0.02	0.03	0.01	4.80	3.40	0.00
SWT	2019	4	M1	3.36	0.5	5.73	0.01	0.02	0.01	5.70	2.61	0.00
SWT	2019	5	M1	3.56	1.7	5.19	0.04	0.04	0.00	5.10	3.15	0.00
SWT	2019	5	M1	3.18	0.8	6.75	0.01	0.02	0.01	6.70	2.50	0.00
SWT	2019	5	M1	3.74	2.8	2.98	0.03	0.04	0.00	2.90	4.18	0.00
SWC	2018	1	M2	3.72	0.6	2.52	0.00	0.01	0.00	2.50	3.89	0.00
SWC	2018	2	M2	3.79	0.7	2.92	0.00	0.00	0.01	2.90	4.29	0.00
SWC	2018	3	M2	4.00	1.4	1.52	0.00	0.00	0.00	1.50	4.35	0.00
SWC	2018	4	M2	3.71	0.8	2.72	0.00	0.01	0.01	2.70	3.35	0.00
SWC	2018	5	M2	3.72	1.0	2.93	0.00	0.01	0.01	2.90	2.63	0.00
SWT	2018	1	M2	4.00	0.4	1.41	0.00	0.00	0.00	1.40	4.00	0.00
SWT	2018	2	M2	4.08	1.2	1.32	0.00	0.00	0.00	1.30	3.87	0.00
SWT	2018	3	M2	3.96	0.7	1.81	0.00	0.00	0.00	1.80	4.33	0.00
SWT	2018	4	M2	3.85	0.6	2.01	0.00	0.00	0.00	2.00	4.07	0.00
SWT	2018	5	M2	3.65	0.6	1.71	0.00	0.00	0.00	1.70	4.32	0.00
SWC	2019	1	M2	3.65	1.1	4.15	0.01	0.01	0.01	4.10	2.65	0.00
SWC	2019	1	M2	3.75	1.3	3.55	0.01	0.01	0.01	3.50	2.76	0.00
SWC	2019	1	M2	3.80	0.7	3.32	0.01	0.01	0.01	3.30	3.35	0.00
SWC	2019	2	M2	3.79	0.7	4.13	0.01	0.01	0.01	4.10	4.30	0.00

A2 Table 4 Con't

Site	Year	Plot	Horizon	pH	%BS	CEC	Ca^{2+}	Mg^{2+}	K^{+}	EA	Al^{3+}	Mn^{2+}
SWC	2019	2	M2	3.94	1.1	2.02	0.01	0.01	0.01	2.00	3.41	0.00
SWC	2019	2	M2	3.87	0.5	3.02	0.00	0.01	0.00	3.00	3.93	0.00
SWC	2019	3	M2	3.80	1.9	3.16	0.03	0.01	0.01	3.10	3.43	0.00
SWC	2019	3	M2	3.89	0.5	3.52	0.01	0.00	0.00	3.50	4.51	0.00
SWC	2019	3	M2	3.89	0.8	2.52	0.00	0.01	0.00	2.50	3.57	0.01
SWC	2019	4	M2	3.78	0.9	3.63	0.00	0.01	0.01	3.60	2.58	0.00
SWC	2019	4	M2	3.67	0.8	3.63	0.00	0.01	0.01	3.60	2.42	0.00
SWC	2019	4	M2	3.66	0.8	3.33	0.01	0.01	0.01	3.30	3.11	0.00
SWC	2019	5	M2	3.66	0.7	3.73	0.00	0.01	0.01	3.70	2.44	0.00
SWC	2019	5	M2	3.74	0.8	3.12	0.00	0.01	0.00	3.10	3.14	0.00
SWC	2019	5	M2	3.97	2.1	1.84	0.00	0.01	0.00	1.80	2.64	0.00
SWT	2019	1	M2	4.14	8.8	1.54	0.05	0.05	0.00	1.40	3.71	0.01
SWT	2019	1	M2	3.92	6.1	2.45	0.06	0.06	0.01	2.30	4.25	0.01
SWT	2019	1	M2	3.97	4.2	2.09	0.03	0.03	0.00	2.00	3.61	0.00
SWT	2019	2	M2	3.98	3.3	1.55	0.01	0.01	0.01	1.50	3.49	0.01
SWT	2019	2	M2	4.12	14.3	1.98	0.13	0.13	0.00	1.70	3.88	0.01
SWT	2019	2	M2	3.99	6.0	2.02	0.05	0.06	0.00	1.90	4.09	0.01
SWT	2019	3	M2	4.16	13.2	1.96	0.13	0.13	0.00	1.70	3.93	0.01
SWT	2019	3	M2	3.36	0.9	4.44	0.01	0.02	0.01	4.40	2.50	0.01
SWT	2019	3	M2	3.86	0.7	2.52	0.00	0.01	0.00	2.50	3.30	0.01
SWT	2019	4	M2	3.85	0.7	2.22	0.00	0.01	0.00	2.20	4.01	0.00
SWT	2019	4	M2	3.94	0.8	1.61	0.00	0.01	0.00	1.60	4.20	0.00
SWT	2019	4	M2	3.68	0.7	3.42	0.01	0.01	0.00	3.40	3.52	0.00
SWT	2019	5	M2	3.63	0.3	4.62	0.00	0.01	0.00	4.60	2.99	0.00
SWT	2019	5	M2	3.71	1.1	3.44	0.01	0.01	0.01	3.40	4.25	0.00
SWT	2019	5	M2	3.77	4.3	2.61	0.05	0.05	0.00	2.50	4.08	0.00

A2 Table 4. Con't

Site	Year	Plot	Horizon	P (ppm)	Fe^{3+}	Na^{+}
SWC	2018	1	F	11.63	0.06	0.12
SWC	2018	2	F	10.82	0.08	0.10
SWC	2018	3	F	12.52	0.06	0.13
SWC	2018	4	F	10.53	0.06	0.12
SWC	2018	5	F	12.41	0.07	0.10
SWT	2018	1	F	7.95	0.20	0.08
SWT	2018	2	F	7.82	0.19	0.08
SWT	2018	3	F	10.60	0.23	0.07
SWT	2018	4	F	11.08	0.23	0.13
SWT	2018	5	F	11.34	0.25	0.07
SWC	2019	1	F	6.33	0.26	0.12
SWC	2019	1	F	9.65	0.24	0.05
SWC	2019	1	F	6.94	0.20	0.06
SWC	2019	2	F	9.00	0.25	0.06
SWC	2019	2	F	5.33	0.25	0.02
SWC	2019	2	F	8.10	0.12	0.09
SWC	2019	3	F	9.61	0.07	0.10
SWC	2019	3	F	8.65	0.06	0.11
SWC	2019	3	F	7.06	0.15	0.11
SWC	2019	4	F	10.61	0.20	0.09
SWC	2019	4	F	7.35	0.07	0.14
SWC	2019	4	F	6.78	0.09	0.09
SWC	2019	5	F	7.87	0.09	0.09
SWC	2019	5	F	4.16	0.05	0.11
SWC	2019	5	F	9.16	0.05	0.11
SWT	2019	1	F	9.08	0.18	0.07
SWT	2019	1	F	12.74	0.22	0.07
SWT	2019	1	F	13.00	0.22	0.11
SWT	2019	2	F	6.78	0.23	0.09
SWT	2019	2	F	10.00	0.23	0.05
SWT	2019	2	F	10.63	0.27	0.06
SWT	2019	3	F	7.90	0.27	0.06
SWT	2019	3	F	11.34	0.27	0.07
SWT	2019	3	F	7.68	0.22	0.04
SWT	2019	4	F	9.46	0.23	0.08
SWT	2019	4	F	7.13	0.04	0.04
SWT	2019	4	F	8.99	0.05	0.04
SWT	2019	5	F	11.02	0.06	0.05

A2 Table 4 Con't

Site	Year	Plot	Horizon	P (ppm)	Fe^{3+}	Na^{+}
SWT	2019	5	F	11.62	0.07	0.07
SWT	2019	5	F	10.32	0.03	0.07
SWC	2018	1	H	8.06	0.10	0.15
SWC	2018	2	H	5.79	0.08	0.15
SWC	2018	3	H	7.47	0.06	0.14
SWC	2018	4	H	7.70	0.06	0.22
SWC	2018	5	H	5.88	0.06	0.08
SWT	2018	1	H	8.41	0.04	0.11
SWT	2018	2	H	7.92	0.04	0.10
SWT	2018	3	H	8.52	0.05	0.15
SWT	2018	4	H	8.18	0.05	0.20
SWT	2018	5	H	8.25	0.04	0.14
SWC	2019	1	H	5.64	0.05	0.10
SWC	2019	1	H	6.87	0.05	0.07
SWC	2019	1	H	5.73	0.06	0.07
SWC	2019	2	H	7.54	0.07	0.06
SWC	2019	2	H	5.55	0.05	0.11
SWC	2019	2	H	3.90	0.20	0.14
SWC	2019	3	H	5.26	0.19	0.14
SWC	2019	3	H	5.23	0.10	0.12
SWC	2019	3	H	4.51	0.13	0.15
SWC	2019	4	H	5.95	0.08	0.10
SWC	2019	4	H	5.45	0.06	0.14
SWC	2019	4	H	5.87	0.06	0.12
SWC	2019	5	H	5.41	0.13	0.09
SWC	2019	5	H	3.76	0.16	0.12
SWC	2019	5	H	4.94	0.09	0.11
SWT	2019	1	H	4.36	0.11	0.11
SWT	2019	1	H	6.29	0.11	0.06
SWT	2019	1	H	7.27	0.15	0.09
SWT	2019	2	H	5.08	0.10	0.09
SWT	2019	2	H	7.51	0.09	0.08
SWT	2019	2	H	7.44	0.25	0.09
SWT	2019	3	H	8.17	0.29	0.04
SWT	2019	3	H	6.54	0.26	0.07
SWT	2019	3	H	8.04	0.23	0.04
SWT	2019	4	H	7.58	0.22	0.09
SWT	2019	4	H	6.92	0.25	0.04

A2 Table 4 Con't

Site	Year	Plot	Horizon	P (ppm)	Fe^{3+}	Na^{+}
SWT	2019	4	H	6.46	0.17	0.05
SWT	2019	5	H	5.83	0.16	0.06
SWT	2019	5	H	8.26	0.08	0.07
SWT	2019	5	H	7.50	0.19	0.07
SWC	2018	1	M1	0.21	0.23	0.03
SWC	2018	2	M1	0.26	0.20	0.02
SWC	2018	3	M1	0.28	0.23	0.00
SWC	2018	4	M1	0.27	0.24	0.00
SWC	2018	5	M1	0.22	0.25	0.00
SWT	2018	1	M1	0.06	0.17	0.01
SWT	2018	2	M1	0.18	0.27	0.01
SWT	2018	3	M1	0.07	0.15	0.02
SWT	2018	4	M1	0.17	0.09	0.02
SWT	2018	5	M1	0.20	0.15	0.01
SWC	2019	1	M1	0.36	0.08	0.02
SWC	2019	1	M1	0.28	0.05	0.02
SWC	2019	1	M1	0.14	0.08	0.01
SWC	2019	2	M1	0.49	0.09	0.01
SWC	2019	2	M1	0.38	0.19	0.01
SWC	2019	2	M1	0.19	0.24	0.01
SWC	2019	3	M1	0.25	0.14	0.02
SWC	2019	3	M1	0.32	0.21	0.00
SWC	2019	3	M1	0.45	0.17	0.00
SWC	2019	4	M1	0.41	0.11	0.01
SWC	2019	4	M1	0.22	0.13	0.01
SWC	2019	4	M1	0.29	0.16	0.01
SWC	2019	5	M1	0.33	0.10	0.01
SWC	2019	5	M1	0.25	0.12	0.01
SWC	2019	5	M1	0.31	0.10	0.02
SWT	2019	1	M1	0.14	0.08	0.04
SWT	2019	1	M1	0.40	0.12	0.03
SWT	2019	1	M1	0.33	0.10	0.03
SWT	2019	2	M1	0.49	0.17	0.04
SWT	2019	2	M1	0.21	0.19	0.01
SWT	2019	2	M1	0.22	0.16	0.02
SWT	2019	3	M1	0.29	0.14	0.00
SWT	2019	3	M1	0.29	0.15	0.00
SWT	2019	3	M1	0.38	0.15	0.00

A2 Table 4 Con't

Site	**Year**	**Plot**	**Horizon**	**P (ppm)**	**Fe^{3+}**	**Na^{+}**
SWT	2019	4	M1	0.05	0.12	0.01
SWT	2019	4	M1	0.28	0.13	0.02
SWT	2019	4	M1	0.17	0.13	0.00
SWT	2019	5	M1	0.26	0.20	0.01
SWT	2019	5	M1	0.24	0.21	0.01
SWT	2019	5	M1	0.35	0.18	0.01
SWC	2018	1	M2	0.26	0.17	0.01
SWC	2018	2	M2	0.26	0.15	0.00
SWC	2018	3	M2	0.27	0.12	0.01
SWC	2018	4	M2	0.32	0.20	0.00
SWC	2018	5	M2	0.22	0.21	0.01
SWT	2018	1	M2	0.32	0.19	0.00
SWT	2018	2	M2	0.29	0.12	0.01
SWT	2018	3	M2	0.19	0.19	0.01
SWT	2018	4	M2	0.28	0.15	0.00
SWT	2018	5	M2	0.30	0.20	0.00
SWC	2019	1	M2	0.42	0.23	0.02
SWC	2019	1	M2	0.42	0.22	0.02
SWC	2019	1	M2	0.35	0.28	0.00
SWC	2019	2	M2	0.39	0.12	0.00
SWC	2019	2	M2	0.41	0.27	0.01
SWC	2019	2	M2	0.35	0.24	0.00
SWC	2019	3	M2	0.33	0.24	0.02
SWC	2019	3	M2	0.27	0.25	0.00
SWC	2019	3	M2	0.35	0.26	0.00
SWC	2019	4	M2	0.36	0.28	0.01
SWC	2019	4	M2	0.26	0.25	0.01
SWC	2019	4	M2	0.34	0.25	0.01
SWC	2019	5	M2	0.28	0.20	0.01
SWC	2019	5	M2	0.36	0.36	0.01
SWC	2019	5	M2	0.43	0.13	0.02
SWT	2019	1	M2	0.62	0.08	0.03
SWT	2019	1	M2	0.48	0.12	0.03
SWT	2019	1	M2	0.51	0.09	0.03
SWT	2019	2	M2	0.66	0.10	0.03
SWT	2019	2	M2	0.40	0.09	0.02
SWT	2019	2	M2	0.46	0.06	0.01
SWT	2019	3	M2	0.49	0.07	0.00

A2 Table 4 Con't

Site	Year	Plot	Horizon	P (ppm)	Fe^{3+}	Na^{+}
SWT	2019	3	M2	0.27	0.25	0.00
SWT	2019	3	M2	0.26	0.11	0.00
SWT	2019	4	M2	0.47	0.05	0.01
SWT	2019	4	M2	0.42	0.04	0.00
SWT	2019	4	M2	0.37	0.10	0.00
SWT	2019	5	M2	0.30	0.22	0.00
SWT	2019	5	M2	0.42	0.12	0.01
SWT	2019	5	M2	0.42	0.08	0.01

A2 Table 5. Soil acidity parameters at the HWC and HWT site before (2018) and after (2019) the application of dolomitic limestone for every soil horizon sampled. All units are cmol kg^{-1} except pH and %BS.

Site	Year	Plot	Horizon	pH	%BS	CEC	Ca^{2+}	Mg^{2+}	K^{+}	EA	Al^{3+}	Mn^{2+}
HWC	2018	1	F	2.70	27.3	6.19	0.74	0.65	0.24	4.50	0.30	0.14
HWC	2018	2	F	2.83	32.7	7.28	1.27	0.75	0.27	4.90	0.18	0.27
HWC	2018	3	F	2.83	36.4	5.82	1.01	0.78	0.25	3.70	0.61	0.23
HWC	2018	4	F	2.59	29.4	6.38	0.86	0.80	0.15	4.50	0.20	0.11
HWC	2018	5	F	3.09	14.9	9.40	0.72	0.45	0.19	8.00	2.24	0.18
HWC	2018	6	F	3.19	40.2	5.85	1.28	0.79	0.24	3.50	0.46	0.58
HWT	2018	1	F	2.97	31.9	7.64	1.28	0.74	0.33	5.20	1.13	0.14
HWT	2018	2	F	2.79	30.5	7.33	1.13	0.72	0.28	5.10	0.33	0.25
HWT	2018	3	F	2.99	39.2	5.75	1.13	0.77	0.25	3.50	0.95	0.27
HWT	2018	4	F	2.93	38.0	6.61	1.41	0.69	0.33	4.10	0.31	0.24
HWT	2018	5	F	2.58	24.8	7.58	0.80	0.72	0.25	5.70	0.36	0.13
HWT	2018	6	F	2.79	30.7	6.64	0.74	0.86	0.32	4.60	0.76	0.14
HWC	2019	1	F	3.67	6.2	13.00	0.24	0.21	0.24	12.20	3.60	0.06
HWC	2019	1	F	3.30	12.4	10.70	0.41	0.45	0.34	9.40	2.27	0.10
HWC	2019	1	F	2.90	29.6	6.40	0.85	0.62	0.25	4.50	0.46	0.26
HWC	2019	2	F	2.73	25.1	6.81	0.76	0.55	0.28	5.10	0.28	0.12
HWC	2019	2	F	3.12	38.2	5.66	0.97	0.80	0.27	3.50	1.08	0.30
HWC	2019	2	F	2.92	35.1	5.70	0.95	0.65	0.26	3.70	0.48	0.22
HWC	2019	3	F	3.10	37.4	5.59	0.99	0.69	0.27	3.50	1.30	0.17
HWC	2019	3	F	2.88	19.1	9.27	0.85	0.60	0.22	7.50	1.87	0.09
HWC	2019	3	F	3.19	33.7	6.49	1.12	0.73	0.26	4.30	1.63	0.24
HWC	2019	4	F	2.80	41.1	5.26	1.01	0.81	0.24	3.10	0.33	0.13
HWC	2019	4	F	3.17	46.1	5.57	1.34	0.81	0.31	3.00	0.22	0.34
HWC	2019	4	F	3.01	7.3	14.80	0.41	0.39	0.18	13.70	2.62	0.04
HWC	2019	5	F	2.85	30.1	6.73	0.97	0.69	0.26	4.70	0.85	0.16
HWC	2019	5	F	2.95	25.1	7.34	0.86	0.60	0.26	5.50	1.64	0.22
HWC	2019	5	F	2.80	32.1	6.48	0.87	0.83	0.26	4.40	0.39	0.23
HWC	2019	6	F	2.72	16.5	8.98	0.51	0.62	0.25	7.50	1.82	0.13
HWC	2019	6	F	2.99	38.2	5.50	0.97	0.73	0.29	3.40	0.98	0.36
HWC	2019	6	F	2.96	40.5	5.54	1.04	0.78	0.30	3.30	0.53	0.22
HWT	2019	1	F	4.28	78.0	5.46	1.76	2.16	0.20	1.20	0.41	0.13
HWT	2019	1	F	3.53	69.9	5.31	1.62	1.68	0.29	1.60	0.37	0.16
HWT	2019	1	F	4.41	74.9	5.58	1.79	1.99	0.26	1.40	0.03	0.28
HWT	2019	2	F	4.61	75.8	6.19	1.74	2.55	0.25	1.50	0.00	0.16
HWT	2019	2	F	4.75	79.4	6.32	1.97	2.67	0.24	1.30	0.00	0.18
HWT	2019	2	F	4.76	74.0	6.54	1.99	2.42	0.29	1.70	0.04	0.24
HWT	2019	3	F	5.53	82.7	6.35	2.34	2.56	0.21	1.10	0.00	0.16

A2 Table 5 Con't

Site	Year	Plot	Horizon	pH	%BS	CEC	Ca^{2+}	Mg^{2+}	K^{+}	EA	Al^{3+}	Mn^{2+}
HWT	2019	3	F	4.85	81.4	5.90	2.05	2.40	0.23	1.10	0.07	0.13
HWT	2019	3	F	4.53	76.3	5.90	1.72	2.50	0.19	1.40	0.26	0.12
HWT	2019	4	F	4.00	80.0	5.51	1.70	2.43	0.16	1.10	0.76	0.09
HWT	2019	4	F	3.55	76.6	5.12	1.65	1.97	0.18	1.20	0.38	0.07
HWT	2019	4	F	3.79	72.2	5.76	1.71	2.12	0.20	1.60	0.15	0.11
HWT	2019	5	F	4.78	80.6	6.19	2.05	2.60	0.25	1.20	0.04	0.19
HWT	2019	5	F	4.77	84.1	5.67	2.12	2.38	0.17	0.90	0.02	0.13
HWT	2019	5	F	4.50	79.3	6.27	2.27	2.38	0.21	1.30	0.90	0.15
HWT	2019	6	F	4.37	77.2	6.14	1.88	2.56	0.19	1.40	0.35	0.10
HWT	2019	6	F	3.94	71.7	6.01	1.87	2.13	0.21	1.70	0.55	0.11
HWT	2019	6	F	4.07	70.0	6.33	1.74	2.34	0.24	1.90	0.09	0.14
HWC	2018	1	M1	3.62	6.7	5.36	0.01	0.01	0.01	5.00	2.32	0.02
HWC	2018	2	M1	3.69	7.7	4.44	0.00	0.01	0.01	4.10	2.36	0.01
HWC	2018	3	M1	3.51	8.4	4.15	0.01	0.12	0.01	3.80	2.11	0.03
HWC	2018	4	M1	3.58	9.3	3.64	0.00	0.01	0.01	3.30	2.20	0.03
HWC	2018	5	M1	3.52	9.7	3.43	0.00	0.01	0.01	3.10	2.26	0.02
HWC	2018	6	M1	3.37	9.3	3.64	0.00	0.01	0.01	3.30	2.24	0.02
HWT	2018	1	M1	3.07	8.3	4.04	0.00	0.00	0.00	3.70	3.06	0.02
HWT	2018	2	M1	3.40	7.7	4.44	0.00	0.01	0.00	4.10	2.18	0.01
HWT	2018	3	M1	3.65	11.2	3.04	0.00	0.01	0.00	2.70	2.49	0.02
HWT	2018	4	M1	3.47	10.5	3.47	0.00	0.01	0.00	3.10	1.96	0.02
HWT	2018	5	M1	3.52	10.2	3.45	0.00	0.01	0.01	3.10	2.23	0.02
HWT	2018	6	M1	3.36	8.0	4.46	0.00	0.01	0.01	4.10	1.86	0.02
HWC	2019	1	M1	3.95	13.0	3.45	0.00	0.01	0.00	3.00	2.51	0.01
HWC	2019	1	M1	3.89	14.5	3.27	0.01	0.02	0.01	2.80	2.49	0.02
HWC	2019	1	M1	3.69	10.1	4.89	0.00	0.01	0.01	4.40	2.45	0.01
HWC	2019	2	M1	3.78	14.9	3.17	0.01	0.01	0.03	2.70	2.39	0.01
HWC	2019	2	M1	3.72	13.8	3.36	0.00	0.01	0.02	2.90	2.39	0.02
HWC	2019	2	M1	3.66	15.1	3.18	0.00	0.01	0.02	2.70	2.47	0.01
HWC	2019	3	M1	3.52	9.1	5.39	0.00	0.01	0.01	4.90	2.64	0.01
HWC	2019	3	M1	3.70	16.3	2.87	0.01	0.00	0.02	2.40	3.13	0.01
HWC	2019	3	M1	3.81	15.7	2.97	0.00	0.01	0.01	2.50	2.61	0.01
HWC	2019	4	M1	3.81	12.7	3.78	0.00	0.00	0.00	3.30	3.36	0.01
HWC	2019	4	M1	3.76	12.6	3.78	0.00	0.01	0.00	3.30	2.99	0.02
HWC	2019	4	M1	3.81	12.8	3.78	0.00	0.01	0.00	3.30	2.63	0.00
HWC	2019	5	M1	3.80	11.0	4.49	0.04	0.01	0.04	4.00	2.64	0.03
HWC	2019	5	M1	3.68	10.9	4.38	0.04	0.01	0.04	3.90	3.24	0.02
HWC	2019	5	M1	3.75	11.0	4.16	0.05	0.02	0.05	3.70	2.57	0.02
HWC	2019	6	M1	3.56	9.9	4.77	0.05	0.01	0.04	4.30	2.24	0.01

A2 Table 5 Con't

Site	Year	Plot	Horizon	pH	%BS	CEC	Ca^{2+}	Mg^{2+}	K^{+}	EA	Al^{3+}	Mn^{2+}
HWC	2019	6	M1	3.61	10.9	4.26	0.04	0.01	0.05	3.80	2.55	0.03
HWC	2019	6	M1	3.74	13.4	3.46	0.05	0.01	0.05	3.00	2.18	0.03
HWT	2019	1	M1	3.55	8.3	5.56	0.05	0.02	0.05	5.10	2.45	0.02
HWT	2019	1	M1	3.61	10.2	4.57	0.05	0.01	0.05	4.10	1.98	0.02
HWT	2019	1	M1	3.55	9.4	5.08	0.04	0.01	0.05	4.60	3.02	0.01
HWT	2019	2	M1	3.53	7.8	5.21	0.05	0.01	0.05	4.80	2.48	0.02
HWT	2019	2	M1	3.85	11.0	3.37	0.05	0.01	0.05	3.00	2.26	0.04
HWT	2019	2	M1	3.76	10.1	4.45	0.05	0.01	0.05	4.00	2.47	0.02
HWT	2019	3	M1	4.12	19.8	2.37	0.05	0.02	0.05	1.90	2.34	0.04
HWT	2019	3	M1	3.80	9.7	4.76	0.05	0.02	0.05	4.30	2.23	0.01
HWT	2019	3	M1	3.88	9.3	3.86	0.04	0.01	0.04	3.50	2.41	0.02
HWT	2019	4	M1	3.88	11.5	3.61	0.05	0.01	0.05	3.20	2.18	0.01
HWT	2019	4	M1	3.74	10.9	3.59	0.05	0.01	0.04	3.20	2.13	0.03
HWT	2019	4	M1	3.43	11.6	5.99	0.05	0.01	0.04	5.30	2.21	0.04
HWT	2019	5	M1	3.68	11.0	3.82	0.00	0.01	0.00	3.40	2.63	0.02
HWT	2019	5	M1	3.70	12.1	3.30	0.00	0.01	0.00	2.90	1.93	0.01
HWT	2019	5	M1	3.88	11.7	3.17	0.00	0.00	0.00	2.80	2.35	0.01
HWT	2019	6	M1	3.80	11.3	3.27	0.00	0.01	0.00	2.90	1.80	0.01
HWT	2019	6	M1	3.67	8.1	5.76	0.00	0.01	0.01	5.30	1.85	0.02
HWT	2019	6	M1	3.63	8.2	4.90	0.00	0.01	0.00	4.50	1.63	0.01
HWC	2018	1	M2	3.63	16.8	1.92	0.00	0.01	0.01	1.60	2.35	0.02
HWC	2018	2	M2	3.52	13.5	2.43	0.00	0.01	0.00	2.10	1.62	0.02
HWC	2018	3	M2	3.50	14.2	2.33	0.00	0.01	0.01	2.00	3.62	0.02
HWC	2018	4	M2	3.45	13.4	2.54	0.00	0.01	0.01	2.20	2.78	0.02
HWC	2018	5	M2	3.44	12.6	2.75	0.00	0.01	0.00	2.40	3.04	0.04
HWC	2018	6	M2	3.34	11.1	3.15	0.00	0.00	0.00	2.80	3.14	0.03
HWT	2018	1	M2	3.79	18.1	1.83	0.01	0.01	0.01	1.50	3.09	0.07
HWT	2018	2	M2	3.93	16.8	2.04	0.00	0.01	0.00	1.70	2.59	0.03
HWT	2018	3	M2	3.86	13.7	2.55	0.00	0.01	0.00	2.20	3.15	0.04
HWT	2018	4	M2	3.97	14.9	2.23	0.00	0.00	0.00	1.90	3.26	0.01
HWT	2018	5	M2	3.89	15.0	2.24	0.00	0.01	0.00	1.90	2.86	0.04
HWT	2018	6	M2	3.80	11.8	2.83	0.00	0.01	0.00	2.50	3.36	0.04
HWC	2019	1	M2	4.02	18.6	2.46	0.04	0.02	0.04	2.00	2.12	0.01
HWC	2019	1	M2	3.93	16.7	2.76	0.05	0.02	0.04	2.30	2.43	0.03
HWC	2019	1	M2	4.06	20.5	2.26	0.05	0.02	0.04	1.80	2.16	0.01
HWC	2019	2	M2	3.94	21.8	2.05	0.02	0.02	0.03	1.60	2.28	0.01
HWC	2019	2	M2	3.84	18.4	2.57	0.02	0.02	0.01	2.10	3.39	0.03
HWC	2019	2	M2	3.80	23.5	1.96	0.06	0.06	0.01	1.50	2.30	0.01
HWC	2019	3	M2	3.75	14.0	3.37	0.06	0.06	0.02	2.90	3.18	0.03

A2 Table 5 Con't

Site	Year	Plot	Horizon	pH	%BS	CEC	Ca^{2+}	Mg^{2+}	K^{+}	EA	Al^{3+}	Mn^{2+}
HWC	2019	3	M2	3.81	21.7	2.17	0.06	0.07	0.02	1.70	2.61	0.03
HWC	2019	3	M2	3.99	19.9	2.37	0.02	0.02	0.02	1.90	2.63	0.02
HWC	2019	4	M2	3.88	17.9	2.68	0.05	0.05	0.01	2.20	2.53	0.02
HWC	2019	4	M2	3.99	18.7	2.46	0.05	0.02	0.01	2.00	2.71	0.02
HWC	2019	4	M2	4.03	23.7	1.97	0.18	0.20	0.02	1.50	2.08	0.01
HWC	2019	5	M2	3.79	13.5	3.59	0.04	0.05	0.02	3.10	2.36	0.04
HWC	2019	5	M2	3.73	13.1	3.57	0.04	0.04	0.02	3.10	2.16	0.04
HWC	2019	5	M2	3.87	14.5	3.16	0.02	0.03	0.01	2.70	3.14	0.02
HWC	2019	6	M2	3.93	17.7	2.55	0.02	0.03	0.02	2.10	2.41	0.02
HWC	2019	6	M2	3.87	15.3	2.95	0.05	0.07	0.03	2.50	2.33	0.02
HWC	2019	6	M2	4.01	18.3	2.45	0.03	0.04	0.01	2.00	2.39	0.02
HWT	2019	1	M2	3.68	11.8	3.86	0.04	0.01	0.03	3.40	2.17	0.01
HWT	2019	1	M2	3.85	15.0	3.06	0.05	0.01	0.04	2.60	2.66	0.01
HWT	2019	1	M2	3.88	16.1	2.86	0.05	0.01	0.04	2.40	2.61	0.01
HWT	2019	2	M2	3.87	12.0	2.95	0.01	0.01	0.01	2.60	2.48	0.00
HWT	2019	2	M2	4.19	16.4	2.15	0.01	0.01	0.01	1.80	3.86	0.02
HWT	2019	2	M2	3.87	10.7	3.58	0.02	0.03	0.01	3.20	2.67	0.01
HWT	2019	3	M2	4.05	17.2	2.54	0.05	0.04	0.02	2.10	2.59	0.03
HWT	2019	3	M2	4.07	13.0	2.64	0.01	0.01	0.01	2.30	3.56	0.01
HWT	2019	3	M2	4.02	15.7	2.61	0.05	0.05	0.01	2.20	2.70	0.02
HWT	2019	4	M2	3.88	11.8	3.51	0.04	0.05	0.01	3.10	2.51	0.02
HWT	2019	4	M2	3.87	16.1	2.62	0.06	0.05	0.01	2.20	2.62	0.02
HWT	2019	4	M2	3.81	13.2	2.88	0.03	0.03	0.01	2.50	2.69	0.02
HWT	2019	5	M2	4.21	15.9	2.26	0.02	0.02	0.01	1.90	2.73	0.02
HWT	2019	5	M2	4.04	19.3	1.86	0.02	0.02	0.01	1.50	3.03	0.02
HWT	2019	5	M2	3.91	15.5	2.37	0.02	0.03	0.01	2.00	2.64	0.03
HWT	2019	6	M2	3.90	13.7	2.55	0.01	0.01	0.01	2.20	2.76	0.01
HWT	2019	6	M2	3.73	8.4	4.70	0.02	0.04	0.02	4.30	2.36	0.02
HWT	2019	6	M2	4.05	14.1	2.45	0.01	0.01	0.01	2.10	2.69	0.01

A2 Table 5. Con't

Site	Year	Plot	Horizon	P (ppm)	Fe^{3+}	Na^{+}
HWC	2018	1	F	25.33	0.14	0.06
HWC	2018	2	F	31.20	0.08	0.09
HWC	2018	3	F	26.03	0.17	0.08
HWC	2018	4	F	19.85	0.09	0.07
HWC	2018	5	F	13.74	0.12	0.04
HWC	2018	6	F	24.83	0.10	0.05
HWT	2018	1	F	50.91	0.25	0.09
HWT	2018	2	F	26.64	0.22	0.11
HWT	2018	3	F	19.46	0.23	0.12
HWT	2018	4	F	25.93	0.19	0.08
HWT	2018	5	F	22.35	0.18	0.10
HWT	2018	6	F	25.35	0.19	0.11
HWC	2019	1	F	2.19	0.12	0.12
HWC	2019	1	F	9.43	0.19	0.12
HWC	2019	1	F	23.69	0.19	0.17
HWC	2019	2	F	21.55	0.24	0.12
HWC	2019	2	F	23.71	0.20	0.12
HWC	2019	2	F	21.78	0.19	0.14
HWC	2019	3	F	22.46	0.13	0.14
HWC	2019	3	F	11.53	0.11	0.10
HWC	2019	3	F	16.73	0.18	0.08
HWC	2019	4	F	19.20	0.12	0.10
HWC	2019	4	F	23.29	0.11	0.10
HWC	2019	4	F	5.71	0.19	0.09
HWC	2019	5	F	21.43	0.24	0.12
HWC	2019	5	F	18.31	0.20	0.11
HWC	2019	5	F	20.47	0.14	0.12
HWC	2019	6	F	21.84	0.18	0.10
HWC	2019	6	F	26.18	0.16	0.11
HWC	2019	6	F	17.86	0.20	0.12
HWT	2019	1	F	12.99	0.11	0.13
HWT	2019	1	F	16.83	0.07	0.12
HWT	2019	1	F	18.37	0.11	0.14
HWT	2019	2	F	12.55	0.08	0.17
HWT	2019	2	F	10.43	0.12	0.14
HWT	2019	2	F	16.58	0.17	0.14
HWT	2019	3	F	8.67	0.02	0.14
HWT	2019	3	F	10.81	0.11	0.11
HWT	2019	3	F	10.12	0.08	0.09
HWT	2019	4	F	11.39	0.07	0.12

A2 Table 5. Con't

Site	Year	Plot	Horizon	P (ppm)	Fe^{3+}	Na^{+}
HWT	2019	4	F	12.60	0.12	0.12
HWT	2019	4	F	14.86	0.08	0.13
HWT	2019	5	F	10.59	0.12	0.09
HWT	2019	5	F	9.42	0.09	0.09
HWT	2019	5	F	11.33	0.09	0.10
HWT	2019	6	F	10.24	0.08	0.10
HWT	2019	6	F	13.85	0.07	0.10
HWT	2019	6	F	13.97	0.06	0.11
HWC	2018	1	M1	0.22	0.15	0.00
HWC	2018	2	M1	0.14	0.14	0.00
HWC	2018	3	M1	0.13	0.08	0.00
HWC	2018	4	M1	0.13	0.13	0.00
HWC	2018	5	M1	0.18	0.19	0.00
HWC	2018	6	M1	0.26	0.11	0.00
HWT	2018	1	M1	0.43	0.09	0.00
HWT	2018	2	M1	0.23	0.08	0.00
HWT	2018	3	M1	0.25	0.26	0.00
HWT	2018	4	M1	0.25	0.18	0.00
HWT	2018	5	M1	0.29	0.10	0.00
HWT	2018	6	M1	0.25	0.15	0.00
HWC	2019	1	M1	0.48	0.15	0.00
HWC	2019	1	M1	0.45	0.20	0.00
HWC	2019	1	M1	0.54	0.07	0.01
HWC	2019	2	M1	0.24	0.09	0.00
HWC	2019	2	M1	0.42	0.14	0.00
HWC	2019	2	M1	0.47	0.12	0.01
HWC	2019	3	M1	0.45	0.11	0.00
HWC	2019	3	M1	0.29	0.24	0.00
HWC	2019	3	M1	0.50	0.16	0.01
HWC	2019	4	M1	0.44	0.24	0.01
HWC	2019	4	M1	0.33	0.20	0.01
HWC	2019	4	M1	0.48	0.20	0.01
HWC	2019	5	M1	0.63	0.08	0.06
HWC	2019	5	M1	0.38	0.16	0.08
HWC	2019	5	M1	0.29	0.15	0.08
HWC	2019	6	M1	0.36	0.20	0.08
HWC	2019	6	M1	0.26	0.16	0.07
HWC	2019	6	M1	0.26	0.16	0.07
HWT	2019	1	M1	0.22	0.09	0.07
HWT	2019	1	M1	0.26	0.21	0.07
HWT	2019	1	M1	0.27	0.11	0.07

A2 Table 5. Con't

Site	Year	Plot	Horizon	P (ppm)	Fe^{3+}	Na^{+}
HWT	2019	2	M1	0.28	0.19	0.07
HWT	2019	2	M1	0.57	0.18	0.07
HWT	2019	2	M1	0.22	0.14	0.08
HWT	2019	3	M1	0.52	0.18	0.07
HWT	2019	3	M1	0.34	0.23	0.07
HWT	2019	3	M1	0.34	0.19	0.07
HWT	2019	4	M1	0.27	0.18	0.07
HWT	2019	4	M1	0.34	0.21	0.06
HWT	2019	4	M1	0.25	0.13	0.06
HWT	2019	5	M1	0.26	0.13	0.00
HWT	2019	5	M1	0.26	0.13	0.00
HWT	2019	5	M1	0.45	0.12	0.00
HWT	2019	6	M1	0.35	0.12	0.00
HWT	2019	6	M1	0.37	0.13	0.00
HWT	2019	6	M1	0.35	0.08	0.01
HWC	2018	1	M2	0.47	0.14	0.01
HWC	2018	2	M2	0.20	0.14	0.01
HWC	2018	3	M2	0.23	0.15	0.01
HWC	2018	4	M2	0.05	0.15	0.02
HWC	2018	5	M2	0.18	0.16	0.02
HWC	2018	6	M2	0.23	0.11	0.01
HWT	2018	1	M2	0.62	0.11	0.01
HWT	2018	2	M2	0.36	0.17	0.01
HWT	2018	3	M2	0.19	0.14	0.01
HWT	2018	4	M2	0.41	0.19	0.01
HWT	2018	5	M2	0.32	0.15	0.01
HWT	2018	6	M2	0.26	0.13	0.01
HWC	2019	1	M2	0.50	0.25	0.07
HWC	2019	1	M2	0.38	0.22	0.07
HWC	2019	1	M2	0.30	0.25	0.07
HWC	2019	2	M2	0.34	0.25	0.04
HWC	2019	2	M2	0.45	0.12	0.02
HWC	2019	2	M2	0.35	0.26	0.02
HWC	2019	3	M2	0.57	0.18	0.03
HWC	2019	3	M2	0.28	0.20	0.01
HWC	2019	3	M2	0.59	0.18	0.01
HWC	2019	4	M2	0.48	0.17	0.01
HWC	2019	4	M2	0.39	0.20	0.01
HWC	2019	4	M2	0.67	0.26	0.01
HWC	2019	5	M2	0.58	0.23	0.01
HWC	2019	5	M2	0.41	0.23	0.01

A2 Table 5. Con't

Site	Year	Plot	Horizon	P (ppm)	Fe^{3+}	Na^{+}
HWC	2019	5	M2	0.38	0.15	0.01
HWC	2019	6	M2	0.30	0.21	0.02
HWC	2019	6	M2	0.25	0.20	0.02
HWC	2019	6	M2	0.29	0.23	0.02
HWT	2019	1	M2	0.23	0.23	0.07
HWT	2019	1	M2	0.33	0.12	0.07
HWT	2019	1	M2	0.56	0.11	0.07
HWT	2019	2	M2	0.35	0.19	0.03
HWT	2019	2	M2	0.56	0.07	0.02
HWT	2019	2	M2	0.57	0.21	0.03
HWT	2019	3	M2	0.29	0.19	0.03
HWT	2019	3	M2	0.34	0.10	0.02
HWT	2019	3	M2	0.39	0.12	0.01
HWT	2019	4	M2	0.24	0.16	0.01
HWT	2019	4	M2	0.45	0.18	0.01
HWT	2019	4	M2	0.50	0.16	0.01
HWT	2019	5	M2	0.37	0.15	0.01
HWT	2019	5	M2	0.57	0.13	0.01
HWT	2019	5	M2	0.42	0.11	0.01
HWT	2019	6	M2	0.41	0.14	0.02
HWT	2019	6	M2	0.41	0.19	0.02
HWT	2019	6	M2	0.28	0.17	0.02

A2 Table 6. Soil carbon (C), nitrogen (N), and sulphur (S) parameters at the SWC and SWT site before (2018) and after (2019) the application of dolomitic limestone for every soil horizon sampled. All units are cmol kg^{-1} except where indicated.

Site	Year	Plot	Horizon	LOI (%)	Total C (%)	Total N (%)	NH_4^+ (mg/L)	NO_3^- (mg/L)	Total S (%)	SO_4^- (ppm)
SWC	2018	1	F	98.41	53.09	0.99	1.24	0.13	0.17	23.81
SWC	2018	2	F	97.92	52.73	0.97	1.90	0.16	0.15	33.81
SWC	2018	3	F	98.22	53.26	0.97	1.40	0.13	0.18	31.57
SWC	2018	4	F	98.43	52.94	0.96	1.40	0.14	0.20	27.04
SWC	2018	5	F	89.44	53.05	0.90	1.57	0.15	0.19	24.14
SWT	2018	1	F	98.00	52.68	1.18	1.01	0.05	0.20	16.60
SWT	2018	2	F	98.19	51.52	1.14	2.55	0.08	0.21	14.44
SWT	2018	3	F	97.90	51.83	1.01	1.25	0.07	0.16	20.28
SWT	2018	4	F	98.41	52.50	1.13	3.33	0.06	0.17	24.34
SWT	2018	5	F	98.31	52.38	1.17	2.32	0.06	0.17	16.97
SWC	2019	1	F	98.53	52.22	1.28	0.91	0.02	0.16	23.36
SWC	2019	1	F	97.94	52.50	1.00	2.14	0.01	0.15	14.11
SWC	2019	1	F	98.32	52.07	1.33	1.23	0.02	0.21	13.70
SWC	2019	2	F	98.35	52.43	1.09	1.13	0.02	0.17	15.47
SWC	2019	2	F	98.68	53.28	1.02	0.50	0.03	0.20	12.47
SWC	2019	2	F	98.88	53.04	0.89	0.47	0.02	0.16	12.51
SWC	2019	3	F	98.44	52.24	0.92	0.74	0.02	0.14	18.62
SWC	2019	3	F	98.68	52.27	1.13	0.93	0.02	0.19	14.92
SWC	2019	3	F	98.46	52.69	1.03	0.75	0.01	0.16	14.45
SWC	2019	4	F	98.56	52.88	1.00	0.97	0.01	0.13	13.68
SWC	2019	4	F	98.87	53.14	0.92	0.69	0.02	0.15	16.52
SWC	2019	4	F	98.56	52.43	1.22	0.66	0.02	0.17	14.17
SWC	2019	5	F	98.47	52.73	0.90	0.65	0.01	0.12	9.79
SWC	2019	5	F	98.77	52.31	1.12	0.36	0.02	0.18	8.87
SWC	2019	5	F	98.46	53.19	0.90	0.62	0.02	0.14	18.87
SWT	2019	1	F	91.64	46.91	0.97	1.98	0.01	0.08	18.39
SWT	2019	1	F	93.09	49.68	1.10	2.81	0.01	0.10	15.71
SWT	2019	1	F	96.49	51.71	1.17	1.26	0.01	0.14	21.63
SWT	2019	2	F	97.84	52.09	1.10	0.75	0.01	0.14	15.19
SWT	2019	2	F	96.57	51.80	1.14	1.02	0.01	0.18	16.94
SWT	2019	2	F	96.31	50.93	1.01	0.70	0.01	0.11	18.50
SWT	2019	3	F	95.33	49.61	1.02	1.30	0.01	0.13	16.90
SWT	2019	3	F	95.88	50.43	1.17	2.01	0.01	0.17	19.30
SWT	2019	3	F	93.96	50.14	1.35	1.13	0.01	0.16	14.60
SWT	2019	4	F	94.43	50.32	1.21	1.22	0.01	0.14	22.37

A2 Table 6 Con't

Site	Year	Plot	Horizon	LOI (%)	Total C (%)	Total N (%)	NH_4^+ (mg/L)	NO_3^- (mg/L)	Total S (%)	SO_4^- (ppm)
SWT	2019	4	F	92.17	49.48	0.91	1.08	0.01	0.11	15.34
SWT	2019	4	F	91.80	50.06	1.15	1.17	0.01	0.16	16.43
SWT	2019	5	F	94.60	50.98	1.31	1.26	0.01	0.15	19.33
SWT	2019	5	F	95.01	49.69	1.10	1.02	0.00	0.16	23.44
SWT	2019	5	F	96.21	51.28	1.09	0.49	0.01	0.18	19.17
SWC	2018	1	H	95.60	51.22	1.18	1.21	0.16	0.19	28.09
SWC	2018	2	H	96.35	51.82	1.13	0.84	0.17	0.20	26.57
SWC	2018	3	H	90.77	49.41	1.18	0.75	0.17	0.22	27.83
SWC	2018	4	H	92.19	49.81	1.27	0.93	0.16	0.23	29.33
SWC	2018	5	H	93.82	50.59	1.25	1.51	0.16	0.20	34.34
SWT	2018	1	H	96.33	51.21	1.48	1.33	0.06	0.26	32.35
SWT	2018	2	H	92.30	49.02	1.45	1.74	0.06	0.24	18.26
SWT	2018	3	H	95.38	50.30	1.40	2.01	0.05	0.26	23.37
SWT	2018	4	H	92.90	50.08	1.62	1.92	0.03	0.27	27.77
SWT	2018	5	H	90.90	48.89	1.50	1.74	0.04	0.27	20.59
SWC	2019	1	H	97.40	51.47	1.51	0.61	0.02	0.31	15.74
SWC	2019	1	H	94.62	49.86	1.29	1.00	0.03	0.21	21.06
SWC	2019	1	H	98.31	52.02	1.43	0.66	0.03	0.25	10.96
SWC	2019	2	H	97.47	52.27	1.10	0.82	0.03	0.18	13.58
SWC	2019	2	H	98.24	53.00	1.05	0.45	0.03	0.16	11.75
SWC	2019	2	H	98.88	53.40	0.96	0.30	0.03	0.16	8.59
SWC	2019	3	H	98.66	52.15	1.03	0.62	0.03	0.19	14.13
SWC	2019	3	H	98.27	51.99	1.38	0.63	0.03	0.26	13.83
SWC	2019	3	H	97.42	52.15	1.23	0.55	0.03	0.21	12.31
SWC	2019	4	H	98.46	52.72	1.10	0.82	0.02	0.21	11.60
SWC	2019	4	H	97.85	52.36	1.05	0.45	0.02	0.19	15.43
SWC	2019	4	H	97.73	52.10	1.32	0.62	0.00	0.21	13.27
SWC	2019	5	H	97.61	52.19	1.06	0.49	0.02	0.20	10.55
SWC	2019	5	H	98.26	52.51	1.27	0.39	0.02	0.22	9.02
SWC	2019	5	H	98.23	53.26	0.98	0.46	0.02	0.16	13.09
SWT	2019	1	H	96.37	51.86	1.26	0.74	0.01	0.21	14.63
SWT	2019	1	H	97.28	52.32	1.42	0.72	0.02	0.24	13.02
SWT	2019	1	H	94.73	51.43	1.35	0.89	0.01	0.21	14.90
SWT	2019	2	H	94.14	49.66	1.31	0.56	0.02	0.21	15.90
SWT	2019	2	H	93.22	50.55	1.19	0.64	0.02	0.16	19.87
SWT	2019	2	H	95.07	52.04	1.35	0.54	0.01	0.22	20.06
SWT	2019	3	H	95.18	50.21	1.38	0.54	0.02	0.19	15.94

A2 Table 6 Con't

Site	Year	Plot	Horizon	LOI (%)	Total C (%)	Total N (%)	NH_4^+ (mg/L)	NO_3^- (mg/L)	Total S (%)	SO_4^- (ppm)
SWT	2019	3	H	96.75	51.80	1.20	0.60	0.01	0.19	15.66
SWT	2019	3	H	93.81	49.35	1.60	1.03	0.02	0.19	16.10
SWT	2019	4	H	95.47	50.03	1.29	0.74	0.01	0.19	21.42
SWT	2019	4	H	95.09	51.11	1.13	0.43	0.02	0.16	16.03
SWT	2019	4	H	96.46	51.26	1.20	0.50	0.01	0.18	12.80
SWT	2019	5	H	96.51	51.65	1.59	0.50	0.01	0.26	16.73
SWT	2019	5	H	96.34	51.41	1.30	0.57	0.00	0.20	19.67
SWT	2019	5	H	94.40	51.24	1.29	0.52	0.01	0.20	16.70
SWC	2018	1	M1	14.37	4.56	0.20	0.98	0.06	0.04	19.70
SWC	2018	2	M1	20.77	7.84	0.32	1.38	0.07	0.04	14.20
SWC	2018	3	M1	21.05	6.76	0.26	0.96	0.07	0.05	25.44
SWC	2018	4	M1	13.76	4.32	0.21	1.02	0.25	0.03	13.91
SWC	2018	5	M1	9.07	3.31	0.17	1.15	0.07	0.01	14.00
SWT	2018	1	M1	10.92	3.54	0.15	0.51	0.12	0.02	12.81
SWT	2018	2	M1	9.83	2.72	0.09	0.38	0.13	0.02	17.61
SWT	2018	3	M1	10.08	3.17	0.11	0.36	0.13	0.03	15.78
SWT	2018	4	M1	13.87	4.48	0.18	0.56	0.12	0.03	9.50
SWT	2018	5	M1	16.39	6.27	0.25	0.67	0.11	0.03	8.71
SWC	2019	1	M1	16.20	6.64	0.32	0.28	0.03	0.05	11.75
SWC	2019	1	M1	8.71	3.30	0.14	0.43	0.01	0.03	10.08
SWC	2019	1	M1	12.12	4.08	0.19	0.39	0.02	0.04	9.47
SWC	2019	2	M1	18.52	6.74	0.38	0.45	0.00	0.06	12.97
SWC	2019	2	M1	11.96	4.94	0.31	0.31	0.01	0.05	11.98
SWC	2019	2	M1	15.68	6.13	0.90	0.56	0.08	0.04	14.83
SWC	2019	3	M1	18.98	6.92	0.39	0.44	0.07	0.07	19.70
SWC	2019	3	M1	21.78	8.32	0.60	0.42	0.02	0.05	10.30
SWC	2019	3	M1	17.26	6.52	0.31	0.30	0.04	0.05	14.25
SWC	2019	4	M1	11.59	4.63	0.25	0.51	0.02	0.04	12.95
SWC	2019	4	M1	11.18	4.47	0.22	0.40	0.04	0.03	10.10
SWC	2019	4	M1	12.72	4.82	0.25	0.74	0.00	0.05	12.45
SWC	2019	5	M1	9.48	3.50	0.18	0.36	0.02	0.05	14.88
SWC	2019	5	M1	12.21	4.63	0.31	0.70	0.00	0.04	13.80
SWC	2019	5	M1	11.44	4.23	0.20	0.58	0.01	0.00	14.94
SWT	2019	1	M1	12.58	4.39	0.17	0.48	0.02	0.04	20.89
SWT	2019	1	M1	12.95	4.77	0.19	0.39	0.02	0.03	15.35
SWT	2019	1	M1	14.10	5.68	0.29	0.76	0.02	0.03	13.04
SWT	2019	2	M1	14.01	4.30	0.16	0.30	0.02	0.02	15.74

A2 Table 6 Con't

Site	Year	Plot	Horizon	LOI (%)	Total C (%)	Total N (%)	NH_4^+ (mg/L)	NO_3^- (mg/L)	Total S (%)	SO_4^- (ppm)
SWT	2019	2	M1	12.22	4.14	0.16	0.28	0.02	0.04	18.68
SWT	2019	2	M1	10.69	4.03	0.16	0.36	0.00	0.03	20.78
SWT	2019	3	M1	12.11	4.50	0.19	0.28	0.01	0.03	21.19
SWT	2019	3	M1	11.64	4.37	0.18	0.35	0.00	0.04	14.84
SWT	2019	3	M1	7.19	2.53	0.11	0.32	0.01	0.03	14.38
SWT	2019	4	M1	6.80	2.22	0.08	0.35	0.00	0.03	18.99
SWT	2019	4	M1	12.63	5.08	0.22	0.45	0.00	0.05	16.24
SWT	2019	4	M1	12.82	5.05	0.21	0.35	0.03	0.02	9.92
SWT	2019	5	M1	10.22	3.35	0.11	0.32	0.00	0.01	12.89
SWT	2019	5	M1	9.49	3.46	0.16	0.24	0.01	0.03	11.92
SWT	2019	5	M1	12.76	5.23	0.20	0.19	0.03	0.03	16.12
SWC	2018	1	M2	12.15	3.91	0.17	0.65	0.10	0.02	10.78
SWC	2018	2	M2	15.16	4.75	0.20	0.74	0.12	0.03	13.14
SWC	2018	3	M2	12.57	4.23	0.18	0.62	0.17	0.03	16.27
SWC	2018	4	M2	9.58	3.49	0.15	0.80	0.13	0.02	14.92
SWC	2018	5	M2	7.30	2.28	0.10	0.65	0.11	0.01	16.60
SWT	2018	1	M2	7.98	2.53	0.10	0.21	0.10	0.03	9.01
SWT	2018	2	M2	8.35	2.17	0.08	0.23	0.10	0.00	11.12
SWT	2018	3	M2	13.24	3.98	0.17	0.28	0.09	0.04	12.75
SWT	2018	4	M2	10.54	3.25	0.12	0.28	0.09	0.03	8.27
SWT	2018	5	M2	11.58	3.82	0.16	0.30	0.08	0.01	6.88
SWC	2019	1	M2	8.13	3.00	0.13	0.70	0.02	0.03	10.38
SWC	2019	1	M2	8.18	3.30	0.20	0.37	0.02	0.03	11.73
SWC	2019	1	M2	9.62	3.32	0.57	0.25	0.01	0.03	11.69
SWC	2019	2	M2	16.53	6.34	0.31	0.35	0.01	0.05	10.61
SWC	2019	2	M2	6.48	2.27	0.86	0.22	0.02	0.01	12.52
SWC	2019	2	M2	14.05	5.27	0.34	0.24	0.03	0.04	11.06
SWC	2019	3	M2	15.92	6.15	0.38	0.32	0.06	0.04	9.91
SWC	2019	3	M2	16.11	6.12	0.26	0.25	0.03	0.04	9.92
SWC	2019	3	M2	13.63	4.30	0.25	0.28	0.02	0.04	13.25
SWC	2019	4	M2	8.46	2.75	0.13	0.52	0.02	0.04	11.18
SWC	2019	4	M2	7.51	2.72	0.09	0.33	0.03	0.01	10.24
SWC	2019	4	M2	11.00	4.06	0.20	0.43	0.02	0.01	11.87
SWC	2019	5	M2	8.15	2.72	0.12	0.23	0.03	0.02	12.64
SWC	2019	5	M2	8.65	3.02	0.15	0.30	0.01	0.03	15.04
SWC	2019	5	M2	5.28	1.81	0.08	0.21	0.02	0.03	12.04
SWT	2019	1	M2	5.73	1.72	0.07	0.17	0.02	0.02	12.99

A2 Table 6 Con't

Site	Year	Plot	Horizon	LOI (%)	Total C (%)	Total N (%)	NH_4^+ (mg/L)	NO_3^- (mg/L)	Total S (%)	SO_4^- (ppm)
SWT	2019	1	M2	10.92	3.95	0.16	0.36	0.02	0.03	14.70
SWT	2019	1	M2	7.81	2.54	0.11	0.28	0.01	0.02	11.21
SWT	2019	2	M2	5.09	1.48	0.05	0.14	0.01	0.01	10.27
SWT	2019	2	M2	8.81	3.06	0.11	0.18	0.01	0.01	14.51
SWT	2019	2	M2	8.28	2.93	0.12	0.20	0.00	0.02	13.25
SWT	2019	3	M2	7.82	2.73	0.11	0.23	0.02	0.02	12.68
SWT	2019	3	M2	7.77	3.10	0.11	0.24	0.00	0.04	11.47
SWT	2019	3	M2	6.54	2.36	0.09	0.22	0.01	0.01	10.66
SWT	2019	4	M2	7.99	2.86	0.11	0.21	0.01	0.02	11.83
SWT	2019	4	M2	8.95	2.79	0.13	0.14	0.02	0.02	9.65
SWT	2019	4	M2	11.12	4.15	0.18	0.25	0.06	0.04	11.89
SWT	2019	5	M2	6.94	2.32	0.08	0.20	0.01	0.01	10.93
SWT	2019	5	M2	10.71	4.24	0.16	0.20	0.02	0.03	15.69
SWT	2019	5	M2	9.57	3.57	0.14	0.16	0.05	0.02	14.36

A2 Table 7. Soil carbon (C), nitrogen (N), and sulphur (S) parameters at the HWC and HWT site before (2018) and after (2019) the application of dolomitic limestone for every soil horizon sampled. All units are cmol kg^{-1} except where indicated.

Site	Year	Plot	Horizon	LOI (%)	Total C (%)	Total N (%)	NH_4^+ (mg/L)	NO_3^- (mg/L)	Total S (%)	SO_4^- (ppm)
HWC	2018	1	F	93.72	49.28	2.46	10.33	0.52	0.38	26.68
HWC	2018	2	F	95.79	51.04	2.18	7.04	0.13	0.26	29.65
HWC	2018	3	F	89.81	47.67	2.27	7.96	0.13	0.31	30.40
HWC	2018	4	F	94.92	50.51	2.30	8.85	0.26	0.30	23.09
HWC	2018	5	F	87.84	42.91	2.40	6.18	0.17	0.31	31.77
HWC	2018	6	F	91.14	47.52	2.27	6.96	0.16	0.30	28.38
HWT	2018	1	F	92.72	49.88	2.25	7.83	0.03	0.34	45.18
HWT	2018	2	F	93.91	50.13	2.41	8.53	0.04	0.34	44.55
HWT	2018	3	F	86.06	47.47	2.15	6.24	0.03	0.31	33.00
HWT	2018	4	F	92.19	50.06	1.98	8.93	0.03	0.29	46.39
HWT	2018	5	F	95.99	51.24	2.19	7.05	0.09	0.32	34.10
HWT	2018	6	F	90.53	50.28	2.25	8.09	0.05	0.33	39.66
HWC	2019	1	F	94.00	47.88	2.31	2.25	0.00	0.31	28.06
HWC	2019	1	F	94.27	48.45	2.48	6.43	0.00	0.35	27.35
HWC	2019	1	F	95.52	51.02	2.39	4.79	0.00	0.33	26.96
HWC	2019	2	F	95.21	50.47	2.32	4.18	0.01	0.32	22.07
HWC	2019	2	F	94.25	49.60	2.31	4.73	0.00	0.27	22.18
HWC	2019	2	F	95.55	50.94	2.25	3.49	0.00	0.27	20.89
HWC	2019	3	F	91.63	48.38	2.30	7.45	1.46	0.29	30.48
HWC	2019	3	F	94.61	49.08	2.16	3.10	0.33	0.31	25.00
HWC	2019	3	F	93.57	49.21	2.40	4.31	0.03	0.29	25.70
HWC	2019	4	F	94.27	50.09	2.16	3.42	0.00	0.30	14.53
HWC	2019	4	F	94.35	49.76	2.24	4.88	0.02	0.26	19.79
HWC	2019	4	F	93.88	48.66	2.27	1.50	0.00	0.31	21.17
HWC	2019	5	F	94.65	49.75	2.37	6.57	0.17	0.30	31.11
HWC	2019	5	F	94.24	48.31	2.44	4.74	0.33	0.26	24.86
HWC	2019	5	F	94.04	50.20	2.17	4.22	0.23	0.29	27.36
HWC	2019	6	F	90.01	48.13	2.30	3.15	0.17	0.33	22.54
HWC	2019	6	F	89.84	47.51	2.29	3.82	0.16	0.31	25.21
HWC	2019	6	F	93.46	48.54	2.31	5.74	0.26	0.31	31.81
HWT	2019	1	F	90.24	46.49	1.97	2.15	0.01	0.21	25.87
HWT	2019	1	F	92.38	48.52	2.07	1.99	0.02	0.22	28.56
HWT	2019	1	F	88.52	47.08	2.06	2.36	0.04	0.19	27.08
HWT	2019	2	F	91.50	48.64	2.02	1.83	0.04	0.21	27.45
HWT	2019	2	F	88.19	45.77	1.91	3.05	0.04	0.22	30.59
HWT	2019	2	F	88.50	47.89	1.96	3.48	0.04	0.21	33.75
HWT	2019	3	F	73.76	44.99	1.73	2.94	0.04	0.14	19.85

A2 Table 7 Con't

Site	Year	Plot	Horizon	LOI (%)	Total C (%)	Total N (%)	NH_4^+ (mg/L)	NO_3^- (mg/L)	Total S (%)	SO_4^- (ppm)
HWT	2019	3	F	83.76	45.57	1.99	2.60	0.00	0.21	22.33
HWT	2019	3	F	83.07	44.46	1.93	1.79	0.03	0.21	24.76
HWT	2019	4	F	89.37	47.25	2.22	1.45	0.15	0.26	25.40
HWT	2019	4	F	89.70	47.97	2.27	1.52	0.12	0.26	26.02
HWT	2019	4	F	93.78	49.15	2.13	2.00	0.02	0.24	30.10
HWT	2019	5	F	88.01	46.59	1.95	3.91	0.04	0.20	28.47
HWT	2019	5	F	83.32	42.80	1.75	3.64	0.06	0.20	23.27
HWT	2019	5	F	83.40	44.12	1.78	2.39	0.04	0.19	31.84
HWT	2019	6	F	83.33	43.97	2.01	2.99	0.01	0.22	28.78
HWT	2019	6	F	89.47	47.47	2.11	3.31	0.03	0.23	30.09
HWT	2019	6	F	89.47	47.92	2.17	3.83	0.09	0.26	29.27
HWC	2018	1	M1	11.47	4.14	0.26	1.03	0.38	0.04	7.43
HWC	2018	2	M1	8.84	3.43	0.21	0.97	0.34	0.03	7.50
HWC	2018	3	M1	7.18	2.54	0.18	1.06	0.34	0.02	7.27
HWC	2018	4	M1	7.34	2.55	0.18	1.05	0.30	0.01	10.95
HWC	2018	5	M1	7.58	2.67	0.19	0.95	0.29	0.01	11.28
HWC	2018	6	M1	8.60	3.24	0.19	1.05	0.31	0.02	8.64
HWT	2018	1	M1	9.85	3.34	0.18	0.91	0.29	0.02	8.22
HWT	2018	2	M1	11.55	4.16	0.25	0.77	0.29	0.03	6.95
HWT	2018	3	M1	9.08	3.36	0.17	0.60	0.00	0.02	10.02
HWT	2018	4	M1	9.03	3.05	0.17	0.83	0.01	0.03	13.70
HWT	2018	5	M1	10.38	3.67	0.18	0.79	0.01	0.03	14.11
HWT	2018	6	M1	10.10	4.07	0.23	0.77	0.01	0.03	12.31
HWC	2019	1	M1	9.63	3.59	0.26	1.39	0.50	0.05	13.55
HWC	2019	1	M1	10.28	3.69	0.24	1.04	0.46	0.05	15.50
HWC	2019	1	M1	9.31	4.10	0.25	1.02	0.50	0.05	13.81
HWC	2019	2	M1	6.18	2.08	0.13	0.69	0.37	0.03	15.53
HWC	2019	2	M1	9.23	3.76	0.26	1.05	0.48	0.04	16.32
HWC	2019	2	M1	6.99	2.68	0.18	1.25	0.54	0.02	12.38
HWC	2019	3	M1	12.10	5.25	0.32	0.73	0.44	0.05	10.70
HWC	2019	3	M1	5.74	2.64	0.15	0.48	0.39	0.02	14.01
HWC	2019	3	M1	10.68	3.95	0.25	0.64	0.48	0.05	14.32
HWC	2019	4	M1	11.43	4.49	0.28	0.60	0.36	0.05	12.26
HWC	2019	4	M1	9.23	3.60	0.24	0.66	0.41	0.05	13.22
HWC	2019	4	M1	10.03	3.71	0.24	0.63	0.47	0.04	12.07
HWC	2019	5	M1	12.56	5.52	0.37	0.78	0.49	0.04	13.35
HWC	2019	5	M1	8.67	3.44	0.23	0.62	0.46	0.04	11.93
HWC	2019	5	M1	8.76	4.08	0.25	1.29	0.46	0.03	15.10
HWC	2019	6	M1	7.44	3.10	0.20	1.29	0.43	0.04	10.33
HWC	2019	6	M1	7.98	3.30	0.22	1.44	0.42	0.03	11.09

A2 Table 7 Con't

Site	Year	Plot	Horizon	LOI (%)	Total C (%)	Total N (%)	NH_4^+ (mg/L)	NO_3^- (mg/L)	Total S (%)	SO_4^- (ppm)
HWC	2019	6	M1	8.09	2.83	0.20	1.47	0.47	0.02	12.45
HWT	2019	1	M1	7.47	2.81	0.15	1.06	0.34	0.00	8.79
HWT	2019	1	M1	10.28	4.03	0.22	1.63	0.46	0.03	8.40
HWT	2019	1	M1	8.67	3.31	0.18	1.03	0.01	0.02	8.01
HWT	2019	2	M1	6.67	2.65	0.14	0.55	0.05	0.01	8.28
HWT	2019	2	M1	8.45	3.21	0.17	0.50	0.03	0.03	14.58
HWT	2019	2	M1	9.40	3.61	0.19	0.77	0.04	0.03	10.67
HWT	2019	3	M1	7.66	3.00	0.19	0.71	0.02	0.03	15.20
HWT	2019	3	M1	13.26	5.36	0.33	1.61	0.01	0.05	11.92
HWT	2019	3	M1	9.59	3.68	0.19	0.85	0.01	0.03	13.34
HWT	2019	4	M1	9.45	3.61	0.20	0.44	0.02	0.03	14.16
HWT	2019	4	M1	10.18	3.86	0.21	0.36	0.04	0.04	12.29
HWT	2019	4	M1	11.03	5.11	0.29	0.48	0.03	0.03	9.49
HWT	2019	5	M1	10.00	2.99	0.15	0.43	0.00	0.02	15.09
HWT	2019	5	M1	7.17	2.92	0.17	0.36	0.00	0.04	11.00
HWT	2019	5	M1	8.91	3.85	0.24	0.29	0.00	0.05	12.76
HWT	2019	6	M1	9.06	3.30	0.21	0.33	0.06	0.03	12.62
HWT	2019	6	M1	14.20	5.71	0.39	0.79	0.08	0.03	12.41
HWT	2019	6	M1	8.70	3.10	0.18	0.51	0.11	0.03	9.97
HWC	2018	1	M2	5.81	1.50	0.09	0.50	0.28	0.03	10.15
HWC	2018	2	M2	6.33	1.94	0.12	0.55	0.29	0.01	12.82
HWC	2018	3	M2	6.11	1.89	0.11	0.38	0.06	0.01	11.41
HWC	2018	4	M2	5.25	1.48	0.09	0.26	0.08	0.02	12.27
HWC	2018	5	M2	6.54	2.00	0.13	0.54	0.09	0.00	11.66
HWC	2018	6	M2	7.73	2.85	0.18	0.72	0.10	0.02	9.26
HWT	2018	1	M2	5.03	1.36	0.06	0.42	0.03	0.01	9.32
HWT	2018	2	M2	6.66	2.16	0.11	0.44	0.02	0.02	12.23
HWT	2018	3	M2	8.30	2.89	0.12	0.44	0.03	0.01	16.88
HWT	2018	4	M2	7.90	2.52	0.13	0.46	0.03	0.01	8.85
HWT	2018	5	M2	7.25	2.12	0.11	0.49	0.04	0.01	11.46
HWT	2018	6	M2	7.32	2.17	0.10	0.41	0.04	0.03	10.37
HWC	2019	1	M2	6.49	2.16	0.15	0.76	0.42	0.04	14.01
HWC	2019	1	M2	7.61	2.34	0.15	0.75	0.41	0.05	15.58
HWC	2019	1	M2	7.73	2.39	0.14	0.54	0.38	0.05	24.77
HWC	2019	2	M2	4.17	1.02	0.05	0.52	0.35	0.01	14.65
HWC	2019	2	M2	6.26	2.35	0.16	0.76	0.41	0.03	15.93
HWC	2019	2	M2	3.59	0.90	0.05	0.57	0.37	0.02	10.07
HWC	2019	3	M2	25.42	3.91	0.28	0.62	0.47	0.05	12.89
HWC	2019	3	M2	4.23	1.33	0.07	0.49	0.39	0.02	14.18
HWC	2019	3	M2	8.02	2.76	0.16	0.52	0.38	0.03	15.51

A2 Table 7 Con't

Site	Year	Plot	Horizon	LOI (%)	Total C (%)	Total N (%)	NH_4^+ (mg/L)	NO_3^- (mg/L)	Total S (%)	SO_4^- (ppm)
HWC	2019	4	M2	6.68	2.28	0.13	0.76	0.36	0.02	13.59
HWC	2019	4	M2	6.67	2.40	0.15	0.63	0.36	0.03	15.90
HWC	2019	4	M2	4.72	1.36	0.07	0.49	0.36	0.03	11.70
HWC	2019	5	M2	7.52	2.94	0.20	0.72	0.38	0.03	12.62
HWC	2019	5	M2	6.39	2.33	0.15	0.58	0.41	0.04	11.49
HWC	2019	5	M2	6.35	2.62	0.16	0.83	0.35	0.04	17.05
HWC	2019	6	M2	5.92	2.04	0.11	0.59	0.32	0.04	19.08
HWC	2019	6	M2	5.82	1.96	0.11	0.54	0.39	0.03	14.41
HWC	2019	6	M2	6.44	2.41	0.16	0.73	0.39	0.04	16.92
HWT	2019	1	M2	5.98	2.23	0.11	0.76	0.34	0.03	9.44
HWT	2019	1	M2	7.75	3.02	0.14	0.79	0.38	0.02	10.86
HWT	2019	1	M2	5.90	2.00	0.10	0.45	0.04	0.00	10.08
HWT	2019	2	M2	5.28	1.67	0.08	0.30	0.04	0.03	11.91
HWT	2019	2	M2	8.62	2.84	0.15	0.42	0.04	0.03	13.21
HWT	2019	2	M2	8.03	3.13	0.17	0.68	0.02	0.05	12.26
HWT	2019	3	M2	6.56	2.31	0.14	0.54	0.04	0.04	18.47
HWT	2019	3	M2	8.90	3.52	0.20	0.72	0.01	0.03	16.52
HWT	2019	3	M2	7.86	2.74	0.15	0.53	0.01	0.02	14.54
HWT	2019	4	M2	9.15	3.60	0.20	0.69	0.01	0.05	14.64
HWT	2019	4	M2	7.12	2.50	0.12	0.33	0.03	0.03	11.84
HWT	2019	4	M2	7.78	2.86	0.16	0.41	0.03	0.03	13.58
HWT	2019	5	M2	5.18	1.66	0.08	0.20	0.01	0.01	13.59
HWT	2019	5	M2	5.66	2.04	0.11	0.20	0.02	0.01	12.61
HWT	2019	5	M2	7.33	2.76	0.16	0.28	0.03	0.04	13.44
HWT	2019	6	M2	6.85	2.11	0.12	0.20	0.05	0.02	12.26
HWT	2019	6	M2	11.49	4.88	0.32	0.41	0.19	0.05	13.61
HWT	2019	6	M2	5.82	1.79	0.08	0.48	0.11	0.02	14.66

A2 Table 8. Plant tissue chemistry for Schreber's moss (SchM) and red spruce foliage (RS) at the softwood control (SWC) and softwood treatment (SWT). Plot locations for red spruce samples were no available because they sampled throughout the site and not at the plot level.

Site	Year	Plot	Species	C	N	S	P	K	Ca	Mg	Al	Fe	Mn
				%			g/kg						
SWC	2018	1	SchM	47.08	0.67	0.09	1.63	6.70	1.98	1.34	0.12	0.10	0.34
SWC	2018	1	SchM	46.97	0.71	0.10	1.79	7.02	2.32	1.31	0.13	0.11	0.38
SWC	2018	2	SchM	46.95	0.65	0.12	1.54	6.44	2.11	1.23	0.12	0.12	0.37
SWC	2018	2	SchM	46.96	0.64	0.10	1.51	5.92	2.01	1.23	0.12	0.13	0.35
SWC	2018	3	SchM	46.91	0.64	0.08	1.46	5.73	2.10	1.24	0.14	0.12	0.31
SWC	2018	3	SchM	46.72	0.62	0.08	1.43	6.29	1.98	1.28	0.12	0.13	0.32
SWC	2018	4	SchM	46.65	0.64	0.09	1.59	6.87	2.19	1.19	0.11	0.10	0.51
SWC	2018	4	SchM	46.67	0.66	0.11	1.66	7.02	2.25	1.20	0.11	0.10	0.51
SWC	2018	5	SchM	46.74	0.63	0.12	1.48	6.55	1.65	1.24	0.16	0.11	0.41
SWC	2018	5	SchM	47.38	0.59	0.09	1.48	6.35	1.63	1.25	0.14	0.12	0.44
SWT	2018	1	SchM	46.61	0.68	0.11	1.29	6.57	1.75	1.33	0.11	0.09	0.37
SWT	2018	1	SchM	46.25	0.69	0.09	1.21	6.72	1.84	1.21	0.35	0.09	0.38
SWT	2018	2	SchM	46.48	0.84	0.12	1.59	7.42	1.73	1.25	0.12	0.12	0.38
SWT	2018	2	SchM	45.86	0.74	0.11	1.53	7.75	1.54	1.27	0.09	0.11	0.39
SWT	2018	3	SchM	46.42	0.71	0.12	1.42	7.26	1.85	1.08	0.10	0.11	0.44
SWT	2018	3	SchM	46.47	0.84	0.14	1.57	7.85	2.09	1.34	0.12	0.13	0.45
SWT	2018	4	SchM	46.62	0.64	0.14	1.27	6.73	1.79	1.18	0.09	0.11	0.36
SWT	2018	4	SchM	46.30	0.67	0.13	1.40	7.63	1.93	1.31	0.10	0.10	0.38
SWT	2018	5	SchM	46.17	0.72	0.14	1.46	7.01	2.18	1.34	0.13	0.12	0.45
SWT	2018	5	SchM	46.36	0.79	0.13	1.66	7.65	2.06	1.40	0.12	0.12	0.42
SWC	2019	1	SchM	46.91	0.67	0.10	1.58	5.89	2.22	1.05	0.24	0.26	0.33
SWC	2019	1	SchM	46.57	0.66	0.08	1.51	5.66	1.81	1.08	0.19	0.22	0.29
SWC	2019	2	SchM	46.73	0.63	0.07	1.58	6.16	2.30	1.09	0.22	0.25	0.39
SWC	2019	2	SchM	46.82	0.58	0.06	1.41	5.14	2.04	1.04	0.21	0.23	0.32
SWC	2019	3	SchM	47.57	0.59	0.09	1.36	5.43	2.02	0.93	0.39	0.31	0.32
SWC	2019	3	SchM	47.06	0.62	0.11	1.29	5.45	2.13	1.02	0.22	0.25	0.29
SWC	2019	4	SchM	47.60	0.65	0.09	1.40	5.49	2.11	0.85	0.26	0.22	0.39
SWC	2019	4	SchM	47.54	0.64	0.10	1.39	5.44	2.13	0.85	0.22	0.19	0.36
SWC	2019	5	SchM	46.77	2.22	0.19	0.19	2.52	3.44	3.87	0.10	0.00	0.57
SWC	2019	5	SchM	47.26	0.68	0.09	1.49	5.94	1.94	1.01	0.20	0.23	0.41
SWT	2019	1	SchM	44.01	0.72	0.08	1.51	6.07	15.67	6.09	0.44	0.90	0.54
SWT	2019	1	SchM	43.89	0.63	0.05	1.27	5.70	15.34	5.98	0.42	0.84	0.59
SWT	2019	2	SchM	41.77	0.63	0.06	1.42	6.89	24.85	9.04	0.60	1.20	0.68
SWT	2019	2	SchM	42.79	0.79	0.07	1.64	5.82	18.72	7.17	0.54	1.07	0.54
SWT	2019	3	SchM	44.58	0.77	0.06	1.59	5.79	12.30	4.69	0.42	0.83	0.49
SWT	2019	3	SchM	43.07	0.78	0.05	1.62	6.90	16.60	6.39	0.48	1.05	0.55

A2 Table 8 Con't

Site	Year	Plot	Species	C	N	S	P	K	Ca	Mg	Al	Fe	Mn
					%					g/kg			
SWT	2019	4	SchM	42.47	0.67	0.04	1.43	6.00	18.89	7.20	0.45	0.99	0.55
SWT	2019	4	SchM	38.41	0.70	0.02	1.35	6.46	37.63	13.18	0.66	1.48	0.64
SWT	2019	5	SchM	43.61	0.78	0.06	1.49	6.78	14.05	5.68	0.42	0.87	0.45
SWT	2019	5	SchM	43.78	0.76	0.07	1.49	6.11	13.52	5.31	0.36	0.78	0.41
SWC	2018	N/A	RS	51.46	0.93	0.08	1.45	6.78	2.33	1.34	0.08	0.02	0.79
SWC	2018	N/A	RS	51.94	0.93	0.13	1.26	5.84	2.06	1.45	0.06	0.02	0.72
SWC	2018	N/A	RS	51.55	0.88	0.10	1.33	6.48	1.78	1.42	0.08	0.02	0.68
SWC	2018	N/A	RS	51.61	0.94	0.08	1.40	6.29	2.39	1.39	0.09	0.01	0.64
SWC	2018	N/A	RS	52.21	0.94	0.11	1.45	6.65	1.08	1.47	0.11	0.02	0.57
SWC	2018	N/A	RS	51.43	0.99	0.11	2.00	7.51	1.38	1.60	0.11	0.02	0.86
SWC	2018	N/A	RS	52.15	0.78	0.07	1.19	6.26	1.82	1.34	0.10	0.02	0.72
SWC	2018	N/A	RS	51.68	0.99	0.11	1.69	7.94	1.59	1.29	0.09	0.02	0.67
SWC	2018	N/A	RS	52.24	0.89	0.08	1.20	6.05	2.39	1.36	0.09	0.01	0.68
SWC	2018	N/A	RS	51.75	0.85	0.11	1.25	4.84	1.46	1.39	0.08	0.02	0.78
SWT	2018	N/A	RS	51.60	1.02	0.17	1.68	8.65	1.27	1.19	0.06	0.02	0.47
SWT	2018	N/A	RS	51.68	0.90	0.13	1.25	6.36	2.16	1.64	0.06	0.01	0.93
SWT	2018	N/A	RS	51.94	0.89	0.09	1.33	7.12	2.19	1.40	0.12	0.02	0.79
SWT	2018	N/A	RS	51.77	1.08	0.12	1.30	6.76	1.49	1.23	0.10	0.03	0.42
SWT	2018	N/A	RS	51.38	0.95	0.10	1.30	8.10	2.04	1.22	0.06	0.03	0.58
SWT	2018	N/A	RS	50.87	0.89	0.10	1.28	6.44	1.64	1.39	0.06	0.02	0.52
SWT	2018	N/A	RS	51.61	0.97	0.12	1.31	6.41	1.30	1.10	0.06	0.02	0.59
SWT	2018	N/A	RS	52.17	0.96	0.14	1.42	6.28	1.37	1.20	0.04	0.02	0.62
SWT	2018	N/A	RS	52.23	0.93	0.13	1.08	5.72	1.13	1.11	0.07	0.01	0.55
SWT	2018	N/A	RS	51.31	1.06	0.10	1.45	6.97	1.79	1.27	0.10	0.02	0.62
SWC	2019	N/A	RS	51.33	0.94	0.09	1.44	9.14	2.55	1.42	0.08	0.01	0.51
SWC	2019	N/A	RS	51.00	0.75	0.10	1.50	7.69	2.71	1.14	0.09	0.00	0.50
SWC	2019	N/A	RS	51.81	0.87	0.06	1.57	6.36	2.94	1.22	0.05	0.01	0.48
SWC	2019	N/A	RS	51.11	0.84	0.09	1.31	6.19	3.33	1.21	0.07	0.01	0.52
SWC	2019	N/A	RS	51.40	0.84	0.09	1.31	6.51	2.22	0.90	0.07	0.01	0.33
SWC	2019	N/A	RS	51.70	0.88	0.11	1.17	6.02	1.97	1.11	0.07	0.02	0.42
SWC	2019	N/A	RS	51.98	0.69	0.05	1.25	6.37	1.23	1.05	0.07	0.02	0.33
SWC	2019	N/A	RS	51.79	0.90	0.08	1.56	5.82	2.43	1.13	0.06	0.01	0.51
SWC	2019	N/A	RS	50.84	0.97	0.14	1.64	8.86	2.18	1.42	0.09	0.01	0.49
SWC	2019	N/A	RS	51.22	0.83	0.07	1.38	8.01	2.07	0.92	0.07	0.00	0.34
SWT	2019	N/A	RS	51.73	0.92	0.10	1.31	6.32	2.21	1.32	0.05	0.00	0.55
SWT	2019	N/A	RS	51.34	1.09	0.07	1.45	6.83	2.63	1.26	0.10	0.02	0.58
SWT	2019	N/A	RS	51.38	0.77	0.05	1.17	5.69	3.49	1.16	0.05	0.00	0.45
SWT	2019	N/A	RS	51.18	0.97	0.08	1.43	7.53	2.35	1.36	0.08	0.01	0.45

A2 Table 8 Con't

Site	Year	Plot	Species	C	N	S	P	K	Ca	Mg	Al	Fe	Mn
					%					g/kg			
SWT	2019	N/A	RS	51.23	0.91	0.08	1.36	8.79	4.92	1.57	0.06	0.00	0.45
SWT	2019	N/A	RS	50.76	1.00	0.08	1.41	7.75	2.31	1.23	0.06	0.01	0.50
SWT	2019	N/A	RS	51.35	0.86	0.13	1.27	5.93	2.49	1.30	0.05	0.01	0.53
SWT	2019	N/A	RS	51.92	0.79	0.06	1.07	5.71	3.13	1.54	0.07	0.00	0.52
SWT	2019	N/A	RS	51.05	0.98	0.10	1.30	5.78	2.09	1.58	0.10	0.09	0.56
SWT	2019	N/A	RS	51.69	0.99	0.08	1.38	7.73	3.10	1.42	0.07	0.01	0.61

A2 Table 9. Plant tissue chemistry for Wood fern (WF), sugar maple foliage (SM), and red maple foliage (RM) at the hardwood control (HWC) and hardwood treatment (HWT). Locations of sampled trees were not always associated with a plot when no suitable sample trees were available, EX represent extra trees that were sampled within the site but outside the plot range.

Site	Year	Plot	Species	C	N	S	P	K	Ca	Mg	Al	Fe	Mn
				%			g/kg						
HWC	2018	1	WF	47.06	2.38	0.18	2.03	13.91	3.63	5.85	0.19	0.02	0.89
HWC	2018	1	WF	47.06	2.01	0.17	1.85	14.73	3.04	5.86	0.14	0.02	0.69
HWC	2018	2	WF	47.11	1.86	0.15	1.54	13.97	2.57	5.48	0.07	0.02	0.80
HWC	2018	2	WF	47.01	2.19	0.18	1.99	16.40	2.73	5.64	0.13	0.02	0.73
HWC	2018	3	WF	46.47	2.26	0.18	1.84	15.79	3.96	5.74	0.14	0.02	0.82
HWC	2018	3	WF	46.89	2.26	0.16	2.01	15.29	3.93	6.07	0.16	0.02	0.91
HWC	2018	4	WF	46.90	2.24	0.17	2.04	17.19	3.05	5.47	0.13	0.03	0.96
HWC	2018	4	WF	46.83	2.41	0.17	2.02	15.94	3.05	6.27	0.09	0.03	1.20
HWC	2018	5	WF	46.95	2.40	0.16	2.21	16.96	3.82	5.82	0.18	0.01	0.82
HWC	2018	5	WF	46.85	2.45	0.18	2.37	17.22	3.64	5.56	0.15	0.02	1.08
HWC	2018	6	WF	47.08	2.71	0.18	3.30	20.07	3.23	5.01	0.08	0.02	1.08
HWC	2018	6	WF	46.94	2.57	0.19	2.94	17.89	3.10	5.59	0.12	0.03	0.88
HWT	2018	1	WF	46.81	1.89	0.15	3.19	16.06	3.35	5.52	0.05	0.01	0.90
HWT	2018	1	WF	46.37	2.01	0.15	2.79	16.92	3.84	5.31	0.11	0.01	0.91
HWT	2018	2	WF	46.92	1.89	0.14	2.25	17.48	3.65	5.63	0.08	0.01	1.09
HWT	2018	2	WF	46.65	2.04	0.14	2.30	18.03	3.58	5.44	0.07	0.01	0.63
HWT	2018	3	WF	46.46	2.00	0.16	1.86	15.76	3.38	5.50	0.06	0.02	1.05
HWT	2018	3	WF	46.68	2.23	0.14	2.10	15.79	3.54	6.34	0.09	0.01	0.94
HWT	2018	4	WF	46.91	2.08	0.15	1.66	15.92	3.34	5.23	0.05	0.01	1.06
HWT	2018	4	WF	47.03	2.08	0.17	1.62	16.83	3.42	5.48	0.05	0.01	0.97
HWT	2018	5	WF	46.88	1.87	0.14	2.05	15.63	3.00	5.98	0.06	0.01	0.80
HWT	2018	5	WF	46.51	1.91	0.16	2.32	16.39	3.21	5.55	0.07	0.01	0.92
HWT	2018	6	WF	46.84	1.94	0.13	2.85	20.65	3.14	5.31	0.02	0.02	1.17
HWT	2018	6	WF	46.44	1.95	0.18	2.64	18.21	3.39	5.84	0.06	0.02	1.46
HWC	2019	1	WF	47.40	2.32	0.18	2.36	19.17	2.91	3.87	0.09	0.02	0.85
HWC	2019	1	WF	46.52	2.09	0.15	2.60	19.60	2.97	4.83	0.09	0.02	1.09
HWC	2019	2	WF	46.88	2.16	0.16	2.38	22.09	3.20	3.97	0.08	0.03	0.68
HWC	2019	2	WF	47.33	2.24	0.13	2.74	20.31	2.39	3.79	0.08	0.04	0.92
HWC	2019	3	WF	47.64	0.63	0.07	1.39	5.55	1.67	1.67	0.85	0.27	0.33
HWC	2019	3	WF	47.15	1.99	0.16	2.19	20.65	2.91	3.71	0.08	0.02	0.48
HWC	2019	4	WF	47.06	2.12	0.16	2.77	21.01	3.06	3.71	0.10	0.04	1.19
HWC	2019	4	WF	47.18	2.23	0.14	2.08	17.47	3.18	4.01	0.07	0.02	0.98
HWC	2019	5	WF	47.19	2.02	0.16	2.74	20.48	3.57	3.37	0.07	0.03	1.26
HWC	2019	5	WF	46.91	2.27	0.14	3.35	19.20	3.43	4.35	0.15	0.03	0.90
HWC	2019	6	WF	46.57	1.93	0.13	2.55	20.58	4.02	3.86	0.07	0.03	1.40
HWC	2019	6	WF	47.10	2.01	0.13	2.61	20.40	3.52	3.75	0.07	0.04	1.29

A2 Table 9 Con't

Site	Year	Plot	Species	C	N	S	P	K	Ca	Mg	Al	Fe	Mn
					%					g/kg			
HWT	2019	1	WF	46.74	1.81	0.10	2.42	13.35	4.17	5.45	0.06	0.03	1.02
HWT	2019	2	WF	46.80	1.89	0.18	2.08	16.42	4.16	4.58	0.05	0.02	0.93
HWT	2019	2	WF	46.79	1.74	0.12	2.07	14.53	4.25	4.72	0.05	0.02	0.87
HWT	2019	3	WF	46.90	1.79	0.11	1.63	12.51	4.97	5.27	0.04	0.03	0.77
HWT	2019	3	WF	46.89	1.86	0.13	1.65	12.67	4.96	4.90	0.06	0.03	0.64
HWT	2019	4	WF	46.65	2.11	0.18	1.61	13.01	4.96	5.40	0.06	0.02	0.63
HWT	2019	4	WF	46.68	1.86	0.15	1.44	13.30	4.57	5.06	0.06	0.06	0.81
HWT	2019	5	WF	46.81	1.94	0.16	1.89	13.18	4.70	4.97	0.05	0.03	0.76
HWT	2019	5	WF	46.66	1.87	0.14	1.97	14.69	4.77	5.03	0.04	0.02	0.81
HWT	2019	6	WF	46.37	1.71	0.15	2.00	13.84	4.74	5.01	0.05	0.03	1.05
HWT	2019	6	WF	46.87	1.49	0.08	1.71	13.17	4.55	4.89	0.06	0.02	0.60
HWC	2018	1	SM	51.07	1.79	0.19	1.38	6.74	2.59	1.61	0.03	0.04	0.63
HWC	2018	1	SM	51.07	1.81	0.20	1.46	7.60	2.49	1.45	0.02	0.04	0.51
HWC	2018	2	SM	50.41	1.99	0.22	1.44	9.93	2.28	1.51	0.05	0.03	0.46
HWC	2018	2	SM	50.20	1.66	0.20	1.38	7.68	2.23	1.36	0.03	0.05	0.80
HWC	2018	3	SM	50.17	1.74	0.20	1.46	7.89	3.96	1.97	0.04	0.03	0.52
HWC	2018	3	SM	51.07	2.13	0.26	1.61	7.69	2.15	1.67	0.04	0.04	0.60
HWC	2018	4	SM	50.34	1.73	0.19	1.32	7.28	2.91	2.05	0.02	0.03	0.69
HWC	2018	4	SM	49.52	1.92	0.26	1.79	7.88	4.15	1.73	0.04	0.04	0.98
HWC	2018	5	SM	50.94	1.75	0.15	1.43	8.02	3.15	1.61	0.06	0.04	0.67
HWC	2018	5	SM	49.08	2.10	0.24	1.83	10.81	3.01	2.08	0.03	0.03	0.70
HWC	2018	6	SM	50.50	1.89	0.17	1.28	8.41	3.48	1.55	0.06	0.03	0.75
HWC	2018	6	SM	49.63	2.32	0.26	1.83	12.47	2.17	1.83	0.06	0.04	0.72
HWT	2018	1	SM	49.35	1.61	0.17	1.46	8.37	3.67	2.01	0.05	0.02	0.96
HWT	2018	1	SM	50.17	1.67	0.16	1.57	6.28	3.54	1.61	0.06	0.01	0.90
HWT	2018	2	SM	49.02	1.55	0.16	1.26	8.43	4.91	1.40	0.05	0.01	0.58
HWT	2018	2	SM	49.49	1.64	0.15	1.32	8.11	6.04	1.76	0.06	0.02	0.77
HWT	2018	3	SM	51.00	1.88	0.21	1.46	5.95	3.57	2.23	0.06	0.02	0.93
HWT	2018	3	SM	50.71	1.79	0.16	1.68	6.41	3.37	1.33	0.06	0.03	0.97
HWT	2018	4	SM	50.24	1.73	0.22	1.44	7.22	5.04	2.36	0.05	0.02	0.88
HWT	2018	4	SM	49.86	1.54	0.17	1.53	8.21	3.71	1.46	0.06	0.04	0.77
HWT	2018	5	SM	50.32	1.55	0.21	1.18	6.97	2.88	1.38	0.04	0.03	0.44
HWT	2018	5	SM	49.75	1.30	0.10	1.25	6.73	4.21	1.32	0.02	0.01	0.88
HWT	2018	6	SM	50.21	1.81	0.22	1.36	7.72	2.98	1.76	0.04	0.02	0.91
HWT	2018	6	SM	51.38	1.56	0.20	1.24	7.63	2.11	1.20	0.04	0.02	0.57
HWC	2019	1	SM	51.11	1.66	0.21	1.48	7.01	1.68	1.01	0.08	0.04	0.53
HWC	2019	1	SM	50.86	1.71	0.22	1.92	6.71	2.24	1.35	0.03	0.03	0.42
HWC	2019	3	SM	50.79	1.83	0.17	1.58	6.61	2.39	1.62	0.05	0.04	0.56
HWC	2019	3	SM	50.88	1.75	0.21	1.40	7.28	1.79	1.03	0.05	0.04	0.44
HWC	2019	3	SM	50.46	2.01	0.18	1.56	7.81	2.05	1.25	0.04	0.03	0.52

A2 Table 9 Con't

Site	Year	Plot	Species	C	N	S	P	K	Ca	Mg	Al	Fe	Mn
					%					g/kg			
HWC	2019	4	SM	50.78	2.03	0.19	1.82	8.25	2.23	1.48	0.03	0.04	0.52
HWC	2019	4	SM	51.29	1.89	0.16	1.74	7.67	2.35	1.35	0.03	0.04	0.56
HWC	2019	5	SM	51.09	1.76	0.15	1.58	6.29	2.35	1.25	0.04	0.04	0.83
HWC	2019	5	SM	51.78	2.07	0.20	1.97	6.92	1.77	0.92	0.03	0.04	0.62
HWC	2019	6	SM	50.88	2.23	0.19	1.72	6.72	3.38	1.42	0.02	0.04	0.79
HWC	2019	6	SM	51.46	1.92	0.18	1.54	6.26	2.65	1.50	0.03	0.03	0.73
HWC	2019	6	SM	51.01	2.09	0.25	1.62	7.07	1.69	1.30	0.03	0.07	0.59
HWT	2019	1	SM	49.47	2.01	0.20	1.77	6.31	4.02	1.69	0.03	0.02	0.85
HWT	2019	2	SM	49.60	2.04	0.18	1.65	5.98	5.54	2.20	0.03	0.01	0.75
HWT	2019	2	SM	49.29	1.72	0.18	1.41	3.83	5.82	2.23	0.02	0.01	1.28
HWT	2019	3	SM	49.76	1.99	0.26	1.51	6.31	4.58	1.44	0.03	0.03	1.56
HWT	2019	3	SM	49.78	1.86	0.23	1.46	4.93	6.43	1.35	0.04	0.03	1.62
HWT	2019	3	SM	49.57	1.88	0.24	1.43	5.26	4.70	2.01	0.03	0.03	1.31
HWT	2019	4	SM	49.54	1.76	0.23	1.31	6.12	3.34	1.75	0.04	0.02	0.90
HWT	2019	4	SM	49.55	1.77	0.16	1.39	6.31	4.66	1.27	0.03	0.03	0.85
HWT	2019	5	SM	49.12	1.59	0.16	1.48	4.86	5.82	2.16	0.03	0.01	1.25
HWT	2019	5	SM	50.26	1.71	0.19	1.70	6.53	5.84	1.64	0.03	0.02	1.10
HWT	2019	6	SM	49.76	1.55	0.13	1.32	4.45	4.99	2.29	0.03	0.02	1.41
HWT	2019	6	SM	49.33	1.80	0.16	1.64	5.43	6.51	2.05	0.02	0.02	1.65
HWC	2018	1	RM	51.04	1.83	0.15	1.63	7.42	4.46	1.45	0.03	0.03	0.87
HWC	2018	1	RM	51.05	1.73	0.15	1.59	7.01	3.59	1.05	0.01	0.03	0.75
HWC	2018	2	RM	51.65	1.68	0.15	1.51	6.38	2.45	1.06	0.04	0.04	0.51
HWC	2018	2	RM	51.36	1.51	0.14	1.39	4.27	4.11	1.27	0.03	0.02	0.65
HWC	2018	3	RM	50.65	1.78	0.14	1.68	4.70	4.00	1.40	0.01	0.03	0.67
HWC	2018	3	RM	50.47	1.53	0.15	1.42	9.22	4.14	1.02	0.03	0.03	0.62
HWC	2018	4	RM	50.74	1.44	0.12	1.42	6.53	3.75	1.00	0.02	0.03	0.68
HWC	2018	4	RM	50.95	1.67	0.15	1.44	6.23	3.18	0.99	0.03	0.03	0.62
HWC	2018	5	RM	50.61	1.84	0.14	1.66	6.74	4.42	1.23	0.06	0.03	0.60
HWC	2018	5	RM	50.90	2.03	0.14	1.84	6.38	4.19	1.37	0.04	0.02	0.66
HWC	2018	6	RM	50.41	1.98	0.18	1.90	7.75	4.75	1.40	0.05	0.02	0.65
HWC	2018	6	RM	50.60	2.13	0.15	1.68	7.38	5.01	1.47	0.05	0.03	0.54
HWT	2018	1	RM	50.20	1.59	0.14	1.50	7.37	5.04	1.98	0.05	0.02	0.65
HWT	2018	1	RM	50.94	1.59	0.12	1.57	6.02	4.98	1.55	0.03	0.02	0.61
HWT	2018	2	RM	50.55	1.47	0.11	1.40	7.16	4.88	1.34	0.04	0.02	0.56
HWT	2018	2	RM	50.41	1.70	0.12	1.54	6.64	4.75	1.47	0.03	0.02	0.53
HWT	2018	3	RM	50.70	1.59	0.12	1.37	7.31	6.03	1.31	0.09	0.04	0.91
HWT	2018	4	RM	50.38	1.34	0.11	1.28	4.36	5.86	1.41	0.02	0.01	0.52
HWT	2018	5	RM	50.64	1.86	0.13	1.66	6.37	5.18	1.55	0.05	0.05	0.84

A2 Table 9 Con’t

Site	**Year**	**Plot**	**Species**	**C**	**N**	**S**	**P**	**K**	**Ca**	**Mg**	**Al**	**Fe**	**Mn**
					%					g/kg			
HWT	2018	5	RM	50.47	1.69	0.14	1.62	5.97	5.85	1.55	0.03	0.02	1.22
HWT	2018	5	RM	50.85	1.53	0.13	1.48	5.54	3.69	1.36	0.01	0.02	0.85
HWT	2018	5	RM	49.45	1.37	0.12	1.19	7.21	5.26	1.48	0.02	0.02	0.71
HWT	2018	6	RM	51.22	1.77	0.14	1.58	6.61	4.60	1.62	0.03	0.03	0.75
HWT	2018	6	RM	50.82	1.60	0.11	1.34	6.46	5.70	1.45	0.04	0.02	0.70
HWC	2019	1	RM	50.92	1.87	0.17	1.63	6.06	4.28	1.05	0.05	0.02	0.45
HWC	2019	1	RM	51.67	1.51	0.09	1.35	5.63	2.68	1.13	0.05	0.02	0.43
HWC	2019	1	RM	51.22	1.50	0.10	1.44	7.08	3.31	1.07	0.04	0.02	0.57
HWC	2019	2	RM	51.14	1.46	0.11	1.46	7.89	4.09	1.10	0.04	0.02	0.38
HWC	2019	2	RM	50.78	1.80	0.13	1.62	6.00	5.08	1.66	0.04	0.03	0.70
HWC	2019	2	RM	50.49	1.82	0.13	1.82	8.74	3.69	1.01	0.04	0.04	0.68
HWC	2019	3	RM	50.55	2.05	0.16	2.25	10.13	4.53	0.98	0.02	0.03	0.43
HWC	2019	4	RM	51.12	1.60	0.13	1.39	6.10	4.96	1.13	0.02	0.02	0.68
HWC	2019	4	RM	50.97	2.17	0.14	1.80	8.20	5.23	1.30	0.03	0.03	0.49
HWC	2019	6	RM	51.38	2.17	0.15	1.98	7.61	3.65	1.17	0.02	0.04	0.86
HWC	2019	6	RM	50.63	2.14	0.15	1.86	7.22	5.88	1.42	0.01	0.04	0.88
HWC	2019	6	RM	50.97	1.96	0.14	1.93	6.91	3.47	1.16	0.03	0.04	0.99
HWT	2019	1	RM	50.51	1.91	0.17	1.98	6.11	6.38	2.25	0.03	0.03	0.81
HWT	2019	1	RM	50.37	1.79	0.14	1.63	8.23	4.36	1.36	0.04	0.02	0.52
HWT	2019	5	RM	49.89	1.60	0.11	1.46	6.64	5.91	1.90	0.03	0.01	0.66
HWT	2019	5	RM	49.49	1.53	0.11	1.42	6.73	6.52	1.95	0.02	0.00	0.57
HWT	2019	EX	RM	49.83	1.64	0.13	1.52	6.65	8.78	2.14	0.04	0.03	0.84
HWT	2019	EX	RM	51.73	1.40	0.12	1.24	3.98	4.43	1.31	0.02	0.01	0.53
HWT	2019	EX	RM	50.77	1.54	0.09	1.64	6.04	5.00	1.45	0.02	0.01	0.66
HWT	2019	EX	RM	50.20	1.81	0.14	1.78	8.21	6.59	1.56	0.04	0.02	0.77
HWT	2019	EX	RM	50.43	1.77	0.09	1.36	6.10	7.90	1.64	0.02	0.02	1.13
HWT	2019	EX	RM	50.99	1.61	0.11	1.50	6.58	3.38	0.94	0.03	0.02	0.58
HWT	2019	EX	RM	50.60	1.67	0.13	1.49	6.02	4.47	1.39	0.03	0.01	0.72
HWT	2019	EX	RM	50.29	1.52	0.11	1.36	6.63	5.54	1.39	0.04	0.01	0.50

A2 Table 10. Diagnostic and Recommendation Integrated System (DRIS) analysis values for all sampled sugar maple trees before and after lime application at the OPDF.

Site	Year	Plot	N	P	K	Ca	Mg	NBI
HWC	2018	1	47	15	-3	-125	67	257
HWC	2018	1	46	19	6	-128	57	257
HWC	2018	2	53	18	23	-158	64	316
HWC	2018	2	46	21	12	-137	59	275
HWC	2018	3	25	2	-3	-81	57	167
HWC	2018	3	69	28	3	-180	81	361
HWC	2018	4	37	3	-3	-122	85	251
HWC	2018	4	28	14	-5	-76	40	163
HWC	2018	5	33	10	5	-99	51	197
HWC	2018	5	40	17	15	-143	71	287
HWC	2018	6	32	3	6	-85	44	170
HWC	2018	6	66	30	33	-212	83	424
HWT	2018	1	22	3	3	-90	62	180
HWT	2018	1	31	14	-12	-81	47	186
HWT	2018	2	12	-2	7	-41	24	86
HWT	2018	2	11	-6	-2	-34	31	84
HWT	2018	3	40	4	-25	-101	82	253
HWT	2018	3	37	22	-10	-83	34	185
HWT	2018	4	20	-6	-14	-63	63	166
HWT	2018	4	20	11	7	-71	34	143
HWT	2018	5	32	7	4	-91	48	182
HWT	2018	5	13	3	1	-45	28	90
HWT	2018	6	38	7	2	-111	65	223
HWT	2018	6	44	18	17	-131	52	262
HWC	2019	1	65	41	15	-172	50	343
HWC	2019	1	51	43	-1	-147	54	296
HWC	2019	3	53	25	-5	-144	71	299
HWC	2019	3	64	34	15	-162	48	324
HWC	2019	3	66	32	11	-163	54	326
HWC	2019	4	60	36	9	-167	62	333
HWC	2019	4	53	32	6	-143	51	285
HWC	2019	5	52	30	-4	-126	48	260
HWC	2019	5	84	64	5	-185	32	371
HWC	2019	6	51	21	-14	-95	37	218
HWC	2019	6	53	22	-11	-122	58	266
HWC	2019	6	89	43	6	-212	74	424
HWT	2019	1	38	17	-21	-78	43	197
HWT	2019	2	31	3	-32	-55	53	175
HWT	2019	2	36	1	-64	-43	70	215

A2 Table 10 Con't

Site	Year	Plot	N	P	K	Ca	Mg	NBI
HWT	2019	3	34	9	-17	-54	28	142
HWT	2019	3	29	7	-32	-23	19	111
HWT	2019	3	35	2	-34	-62	59	192
HWT	2019	4	37	5	-14	-90	62	209
HWT	2019	4	26	7	-11	-44	21	109
HWT	2019	5	23	0	-39	-42	57	162
HWT	2019	5	18	8	-16	-37	27	105
HWT	2019	6	28	-4	-45	-55	76	208
HWT	2019	6	24	3	-35	-36	44	142

Appendix 3 – Supplementary Information for Chapter 4

A3 Table 1. Overview of the number of taps and maple syrup production in 2016 for the four main maple syrup producing provinces. Maple production per tap was calculated using these values, each individual tap may produce more or less than the value presented.

Province	Number of Maple Taps Per Province	Maple Syrup Production Per Province (Thousands of liters)	Liters of maple syrup product per tap per province
Nova Scotia	372,452	218	0.59
New Brunswick	1,896,773	2,400	1.27
Quebec	40,632,512	50,848	1.25
Ontario	1,508,651	1,768	1.17

A3 Table 2. Summary of findings of Ca2+ amendment trials and sap sweetness and production in sugar maple trees (Adapted from Moore et al., 2020).

Study	Location	Findings
Wilmot et al., 1995	Vermont	No effect on sap sweetness; however, did indicate a relationship between sap yield and crown health.
Perkins et al., 2004	Northern Vermont	Sap production increased by 15% 2 and 3 years after lime application. They predict effects from fertilization will last approximately 7 years after treatment.
Noland et al., 2006		Liming did not increase sap volume production, sap sugar content, syrup production, or taphole closure; however, not enough time may have passed to see significant results.
Barry et al., 2009	Northern New Brunswick	Sap yield, sap sweetness and syrup yield increased only 2 years after application with an increase in sugar production of 29.9%.
Wild and Yanai, 2015	Vermont	The addition of Ca had no effect on sap sweetness; however, few trees in the sample site were considered unhealthy.
Moore et al., 2020	Quebec	Lime increased tree ring-width which increased syrup production by 0.34 ± 0.17 kg $tree^{-1}$ with a lime dose of 2 Mg ha^{-1}. Increased sap sweetness by up to 20%.

Appendix 4 – Stand characteristics at the Otter Ponds Demonstration Forest and baseline tree health, growth, regeneration, and forest floor properties

A4.1 Introduction

The response of forest stand properties may not be measurable in the short-term. While one-year changes in foliar chemistry were evident at the OPDF (Chapter 3), changes in tree growth and health will likely only be measurable after several years. Long-term liming trials have been established in several areas across northeastern North America to assess the impacts on growth, health, and changes in vegetation over time (Long et al., 2015; Moore et al., 2012). Improvements in sugar maple tree growth and health were shown (Long et al., 2015; Moore et al., 2012) and decreases in susceptibility to freezing damage in red spruce (Schaberg et al., 2010). However, all of these changes occurred more than one year after treatment.

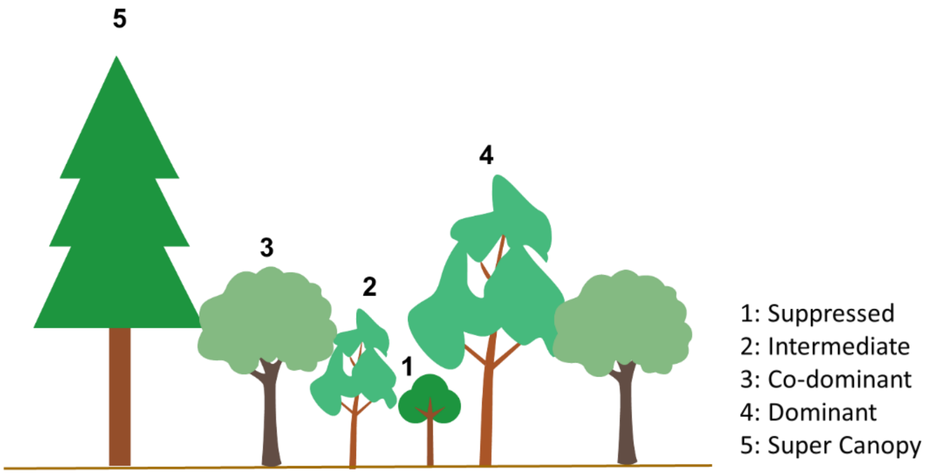
Evaluation of chemical changes in the upper soil layers can often be significant after a few years (Blette & Newton, 1996). However, there are many soil properties that will likely take several years to show changes (Lawrence et al., 2013). Morphological changes in the forest floor and humus quality have a response time of up to 10-100 years to change (Lawrence et al., 2013).

Here, we establish a baseline of tree growth, tree health, regeneration, ground vegetation, and bark and wood chemistry for the softwood and hardwood sites at the OPDF. We aim to provide the baseline measurements for a long-term assessment of terrestrial liming in acidified forests in Nova Scotia. In addition, we established a baseline for forest floor classification, morphology, depth, and organic matter content. Future forest floor research at the OPDF will be compared with these results to determine mid (5-year) and long (10-year) responses to terrestrial liming.

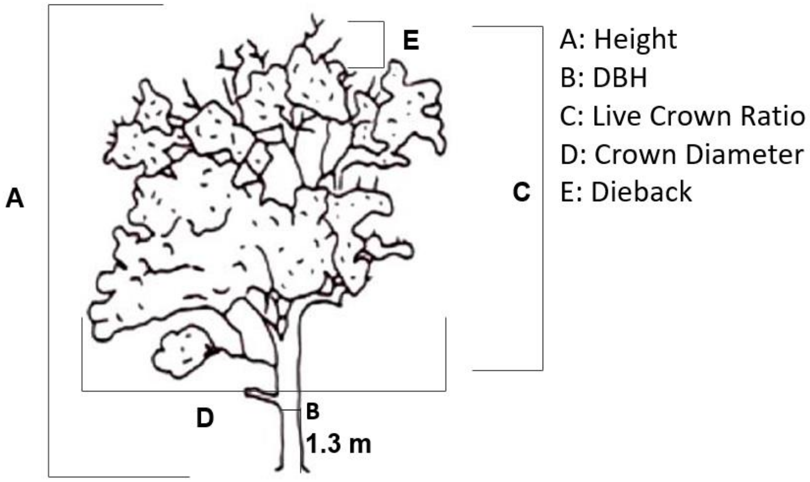
A4.2 Methods

A 4.2.1 Growth Plot Measurements

Establishment of growth plots is described in section 1.3. The species, tree height, diameter at breast height (DBH), canopy class, and tree health of each tree within the growth plots was assessed. Tree height was measured using a laser height finder and DBH was measured using a DBH tape. Canopy class was estimated visually using a five-class system (A4 Figure 1; Neily et al., 2011). The tree health assessment consisted of a bole and canopy assessment. Tree bole health was ranked on a scale from 1 to 3 in which 3 indicated least healthy and 1 indicated most healthy. Any visible damages were noted using the damage codes provided in the Nova Scotia Forest Inventory PSP management guide (NSDNR, 2006). The canopy health assessment consisted of live crown ratio (LCR), crown diameter, crown density, and dieback measurements (A4 Figure 2). The live crown ratio was measured using a laser height finder. Average crown diameter was measured using a 30 m tape and measuring the widest and narrowest parts of the crown. Crown density and dieback percentage were visually estimated using 5% interval classes (Zarnoch et al, 2004; Cooke et al., 2001).



A4 Figure 1. Forest canopy classes ranked in which 1 is suppressed which indicates a tree below the intermediate canopy with little light exposure, intermediate indicates tree in the lower crown canopy section which receive little light from above and none from the sides, co-dominant indicates trees with the upper main canopy level which receive light from above and some light from the sides, dominant indicates trees which extend above the co-dominant canopy and receive light from above and some light from the sides, and super canopy indicates trees remaining from previous harvests which extend well above the main canopy and receive light on all sides (Neily et al., 2011).

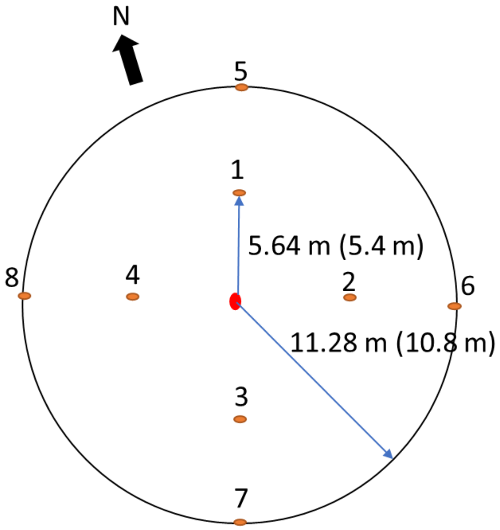


A4 Figure 2. Tree health parameters measure for each within each growth plot. The measurements include height, diameter at breast height (DBH), live crown ratio which is the proportion of live crown to total height, average crown diameter estimated by measuring the largest and smallest crown widths and averaging them, and dieback which was visually estimated in 5% interval classes.

A4.2.2 Regeneration Plots

Ground vegetation and regeneration were characterized using small circular subplots within each growth plot. The first subplot was located at a random bearing halfway between the growth plot edge and growth plot center (5.40 m and 5.64 m from center for softwood and hardwood sites, respectively). Further subplots were located every 90° from the initial subplot and numbered in a clockwise direction (A4 Figure 3). Hardwood sites included four additional plots at the same bearing but at the plot edge to account for greater site variability. Subplots were moved if they were located in an area that was not representative of the site. Subplots were moved 1 m to the right, then left, then forward, then backwards until a suitable location was found. Subplots were marked with a metal stake and an orange flag, and they had a radius of 1.36 m as per the Nova Scotia Forest Timber Management Group research PSP protocol (A4 Figure 4; Timber Management Group, 2009).

Within each subplot every vegetative species was identified, the percent cover estimated, and average height measured. Every tree with a DBH < 8.1 cm within the subplots was identified, counted, sorted into height classes (A4 Table 1), and was determined whether they were derived from seed or sprout.



A4 Figure 3. Plot design of regeneration subplots. The outer circle represents one growth plot, and the orange circles are numbered regeneration subplots. Subplots 5, 6, 7, and 8 were only established at the HW sites.

A4 Table 1. Tree regeneration height classes for tree with a DBH < 8.1 cm. Height classes continue in 100 cm intervals.

Height Range	**Height Class**
0 -10 cm	5
11-30 cm	20
31-60 cm	45
60-100 cm	80
101-200 cm	150
201-300 cm	250
301-400 cm	350
401-500 cm	450
501-600 cm	550

A4 Figure 4. Typical regeneration/ground vegetation subplots at the softwood (left) and hardwood (right) sites. The orange flag represents subplot center, and the wooden stick represents the plot radius.

A4.2.3 Bark and Wood

Sample trees for bark and wood were the same sample trees selected for foliage sampling and the methods are described in Section 3.2.3. Bark samples were collected using a spoke shave and wood was sampled using an increment corer. Samples were analyzed using the same methods described for foliage results in Section 3.2.4.

A4.2.4 Forest Floor

An in-depth analysis of the forest floor was performed to better understand the potential biological and chemical changes that may occur from liming. The forest floor analysis consisted of classification of the forest floor horizons, depth measurements, bulk density measurements, and humus form classification. Four transects at the hardwood and softwood sites were established. The transects were 40 m long at hardwood sites and 32 m long at softwood sites. The beginning of the transects were established from randomly selected points and the direction using random bearings. Forest floor sampling occurred along each transect at 8 m intervals beginning at 0 m. If locations were unsuitable for sampling, plots were moved 1 m to the right, then 1 m to the left until a suitable location was found. Locations may have been moved if the plot fell too close to a tree or a large root system, within a regeneration plot, near coarse woody debris, or was impacted by other disturbances.

At each sampling location, forest floor thickness was measured, and the humus form was classified for each site using the classification system outlined by Green et al. (1993) (A2 Table 3). Bulk density of the forest floor was sampled using a 20 cm X 20 cm metal square (A4 Figure 5; Maynard & Curran, 2008). All organic matter within the square was removed using clippers and a trowel and placed in a plastic bag. Sampling was halted once mineral soil was reached, and each side of the square was measured for an average depth. Softwood sites were divided into F upper and F lower samples in which the F lower also included the H horizon. Since forest floor horizons were thin at the hardwood site, A-horizon mineral soil bulk densities were also measured using a soil corer with a cylinder of known volume. Mineral soil bulk density samples were corrected for coarse fragment content.

Bulk density samples forest floor and mineral soil samples were dried and weighed. Forest Floor (ff) bulk density was calculated using questions A4 1 and A4 2 and mineral soil bulk density was calculated using equations A4 3 and A4 4.

$$D_{b(ff)} = Wt_{ff}/V_{ff} \tag{A4 1}$$

Where $D_{b(ff)}$ is the bulk density of the forest floor, Wt_{ff} is the oven-dried weight of the forest floor and V_{ff} is the volume of the forest floor.

$$V_{ff} = 400\ cm^2 * Depth_{ff}(cm) \tag{A4 2}$$

Where 400 cm^2 is the area of the sampling square and $Depth_{ff}$ is the average depth of the forest floor in cm.

$$D_{b(min)} = Wt_{min}/V_{min} \tag{A4 3}$$

Where $D_{b(min)}$ is the bulk density of the mineral soil, Wt_{min} is the total oven-dried weight of the soil (equation 4) and V_{min} is the volume of the cylinder.

$$Wt_{min} = Wt_f + Wt_c \tag{A4 4}$$

Where Wt_f is the total over-dried weight of fine fines, and Wt_c is the total oven-dried weight of coarse fragments.

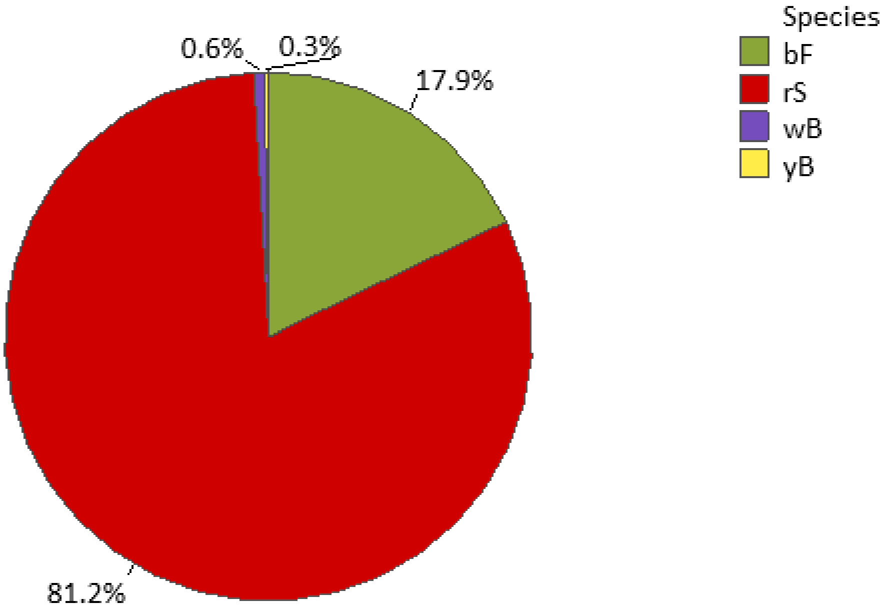
A4 Figure 5. Forest floor bulk density sampling at the Otter Ponds Demonstration Forest softwood (left) and hardwood (right) sites using a 20 cm X 20 cm metal square in which all forest floor within the square up to the mineral soil was sampled.

A4.3 Results

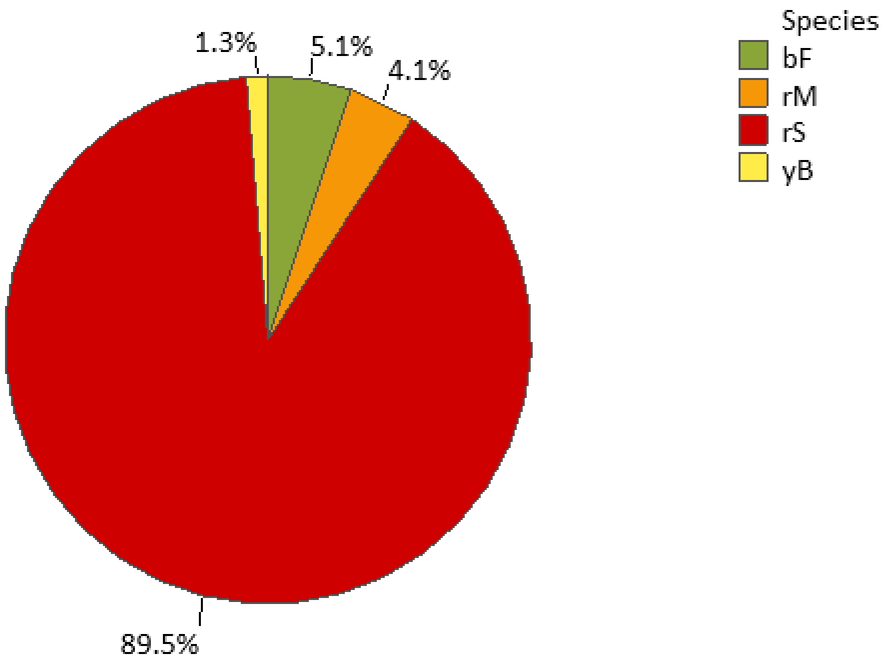
A4.3.1 Stand Characteristics

A4.3.1.1 Softwood Sites

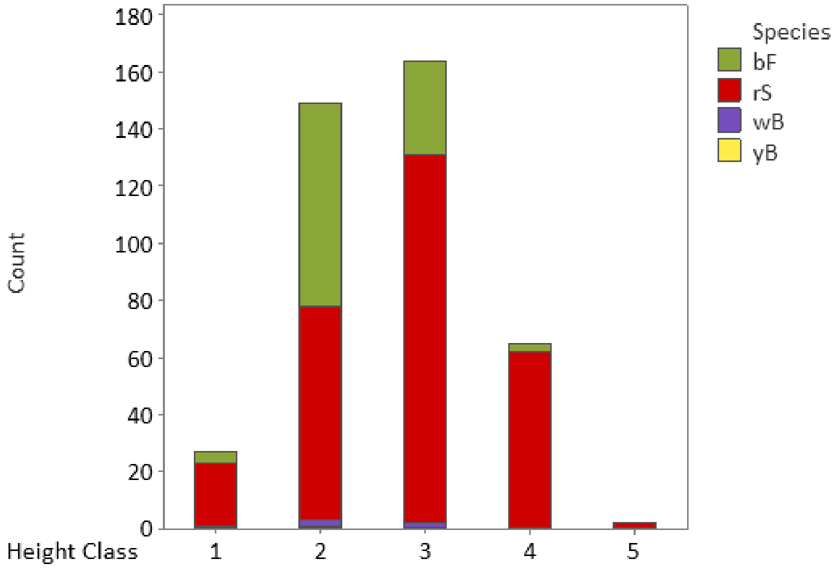
The softwood treatment and control sites are dominated by red spruce and balsam fir (A4 Figure 6 and A4 Figure 7). The SWC site had a total basal area of 42.0 m^2 ha^{-1} and the SWT site had a basal area of 38.6 m^2 ha^{-1}. The treatment and control site were similar in species composition with the treatment site having slightly more hardwood species, such as red maple. Red spruce had a relatively uniform distribution in the co-dominant canopy at both sites (A4 Figure 8 and A4 Figure 9). Average height of co-dominant red spruce trees is 13.8 m and 13.9 m at the treatment and control site, respectively (A4 Figure 10 and A4 Figure 11).



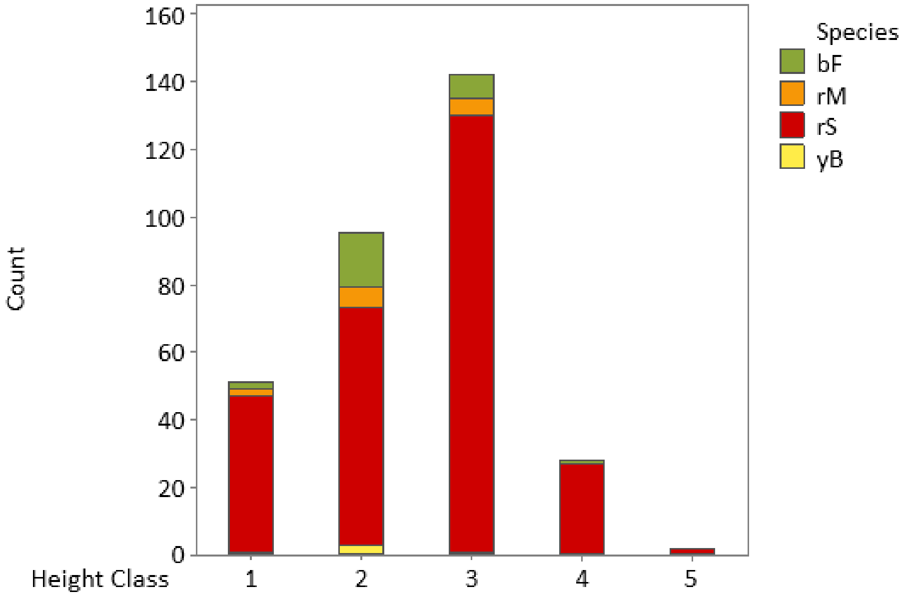
A4 Figure 6. Basal area species composition of the softwood control site at the Otter Ponds Demonstration Forest in which rS is red spruce, bF is balsam fir, wB is white birch, and yB is yellow birch.



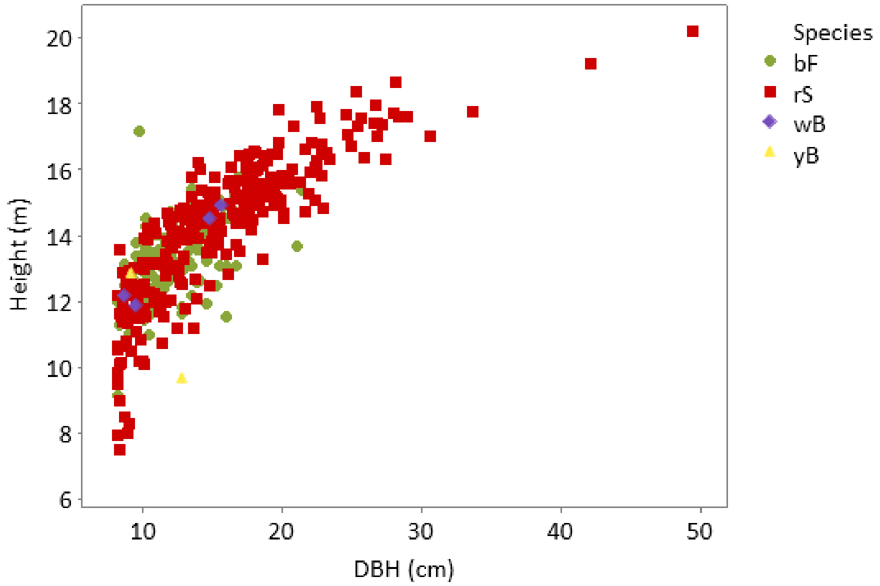
A4 Figure 7. Basal area species composition of the softwood treatment site at the Otter Ponds Demonstration Forest in which rS is red spruce, bF is balsam fir, wB is white birch, and yB is yellow birch.



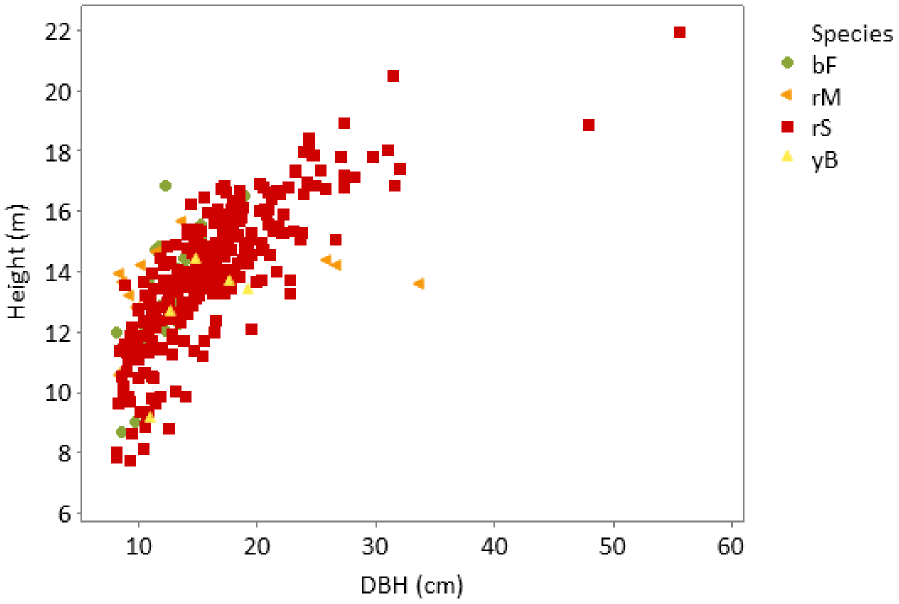
A4 Figure 8. Tree count of species for each height class at the softwood control site at the Otter Ponds Demonstration Forest in which bF is balsam fir, rS is red spruce, wB is white birch, and yB is yellow birch.



A4 Figure 9. Tree count of species for each height class at the softwood treatment site at the Otter Ponds Demonstration Forest in which bF is balsam fir, rS is red spruce, wB is white birch, and yB is yellow birch.



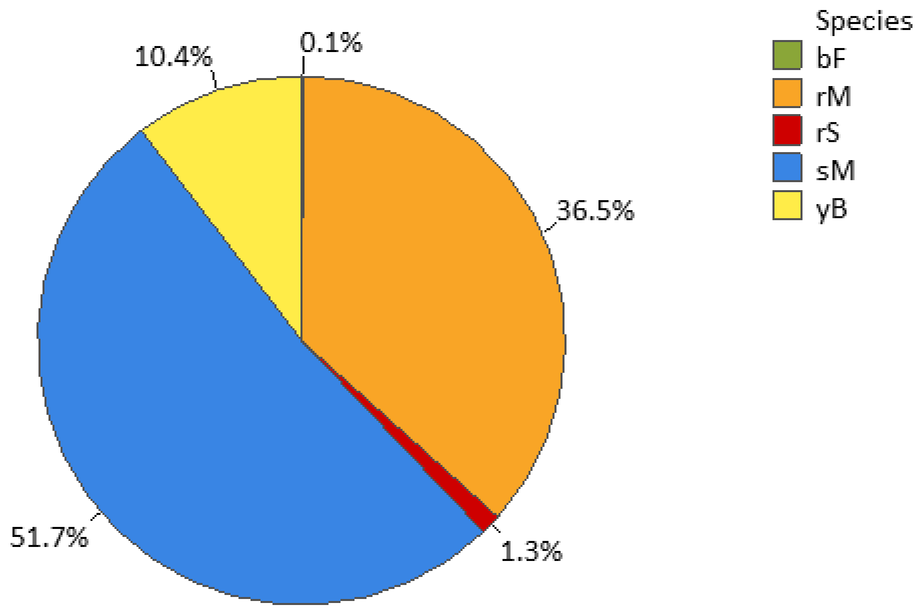
A4 Figure 10. Height to DBH ratio of all trees at the softwood control site by species.



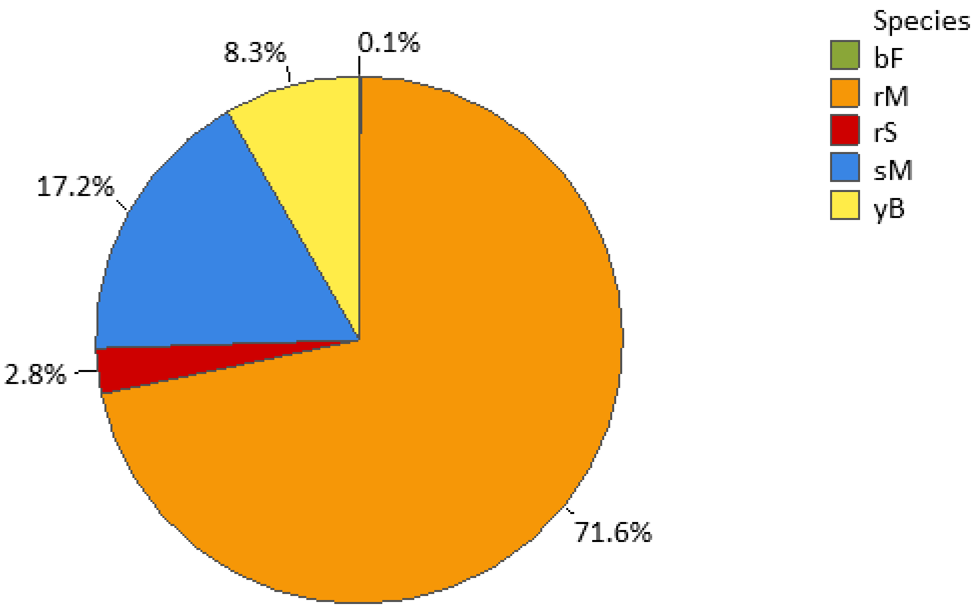
A4 Figure 11. Height to DBH ratio of all trees at the softwood treatment site by species.

A4.1.3.1.2 Hardwood Sites

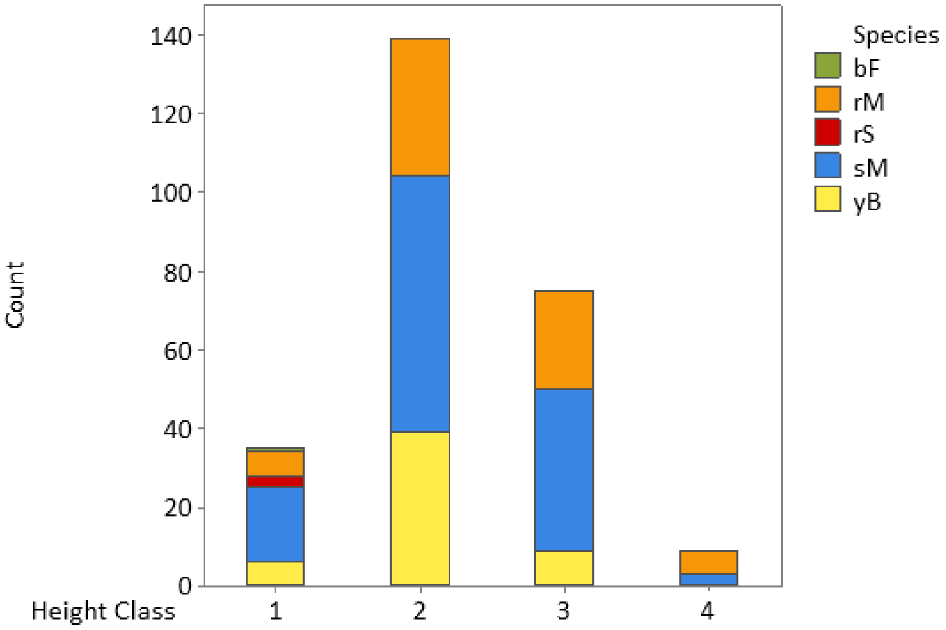
The treatment and control sites are dominated by red maple and sugar maple in both the co-dominant and intermediate canopies. However, the species composition differs slightly at each site where sugar maple is the most dominant tree species at the control site and red maple is the most dominant tree species at the treatment site (A4 Figure 12 and A4 Figure 13). The HWC site had a mean basal area of 27.8 m^2 ha^{-1} and the HWT site had a basal area of 35.8 m^2 ha^{-1}. There are multiple canopy layers with intermediate and co-dominant being the most dominant (A4 Figure 14 and A4 Figure 15). Sugar maple dominated the intermediate canopy and red maple dominated the co-dominant canopy class in the HWT site, while there was a more uniform distribution at the HWC site (A4 Figure 16 and A4 Figure 17).



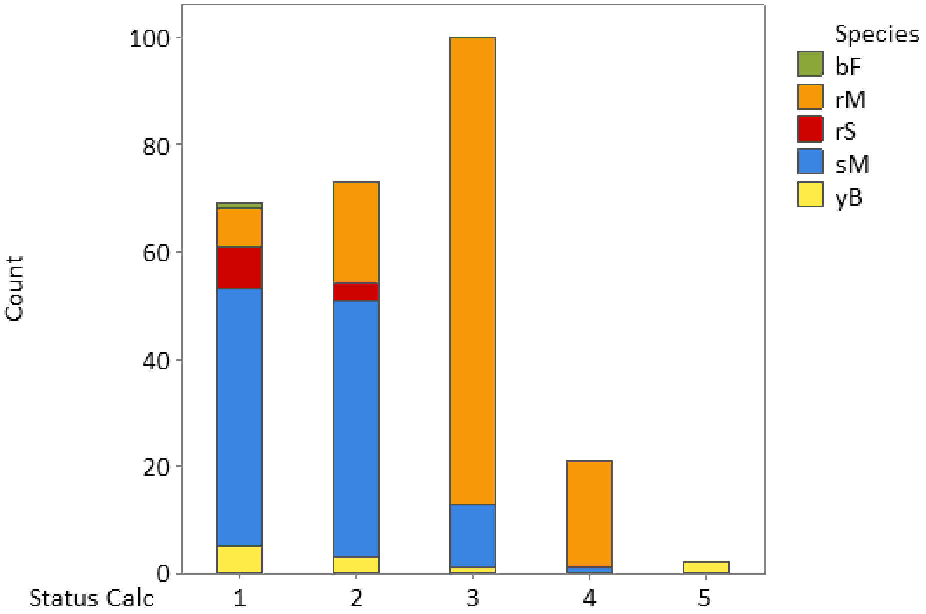
A4 Figure 12. Basal area species composition of the hardwood control site at the Otter Ponds Demonstration Forest in which bF is balsam fir, rM is red maple, rS is red spruce, sM is sugar maple, and yB is yellow birch.



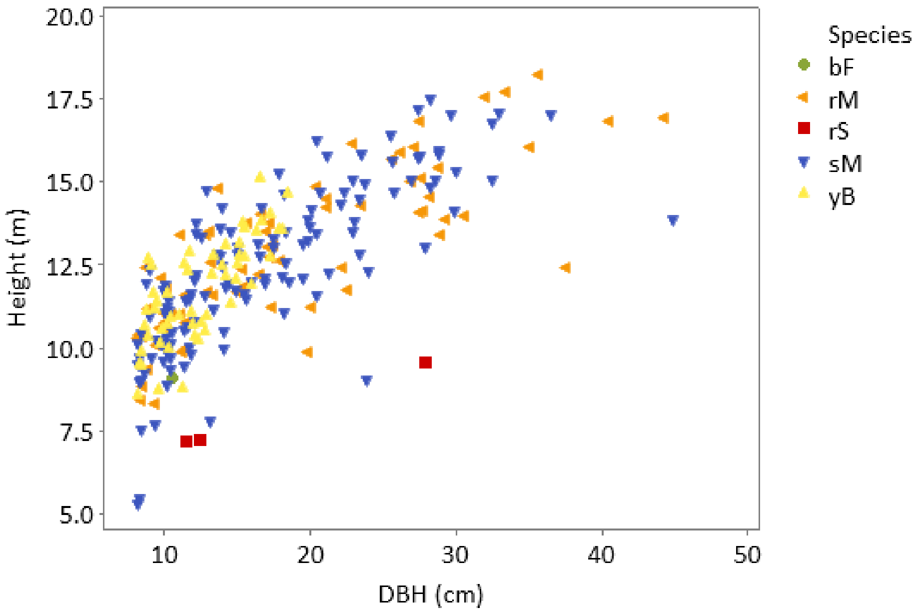
A4 Figure 13. Basal area species composition of the hardwood treatment site at the Otter Ponds Demonstration Forest in which bF is balsam fir, rM is red maple, rS is red spruce, sM is sugar maple, and yB is yellow birch.



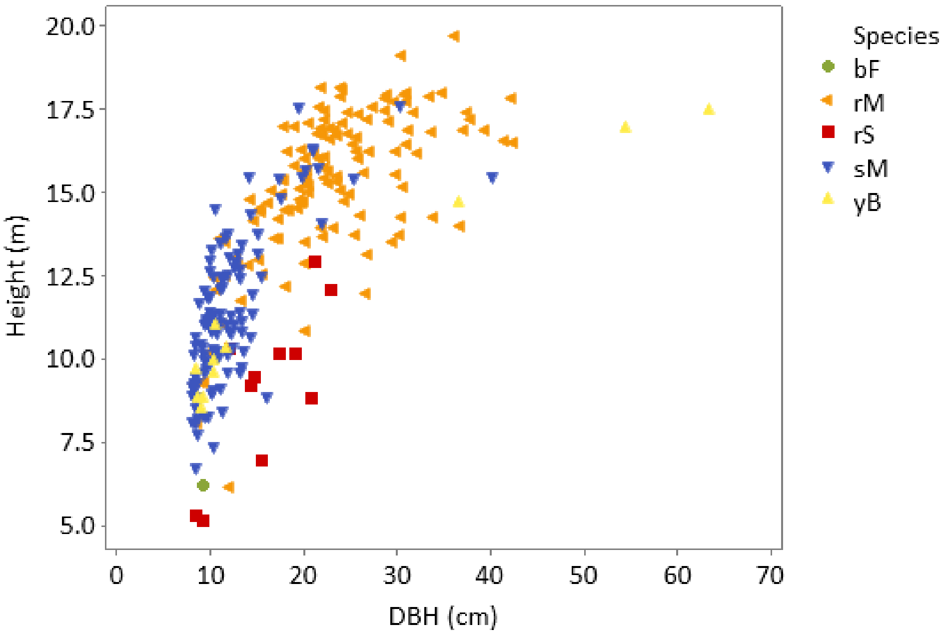
A4 Figure 14. Tree count of species for each height class at the hardwood control site at the Otter Ponds Demonstration Forest in which bF is balsam fir, rM is red maple, rS is red spruce, sM is sugar maple, and yB is yellow birch.



A4 Figure 15. Tree count of species for each height class at the hardwood treatment site at the Otter Ponds Demonstration Forest in which bF is balsam fir, rM is red maple, rS is red spruce, sM is sugar maple, and yB is yellow birch.



A4 Figure 16. Height to DBH ratio of all trees at the hardwood control site by species.

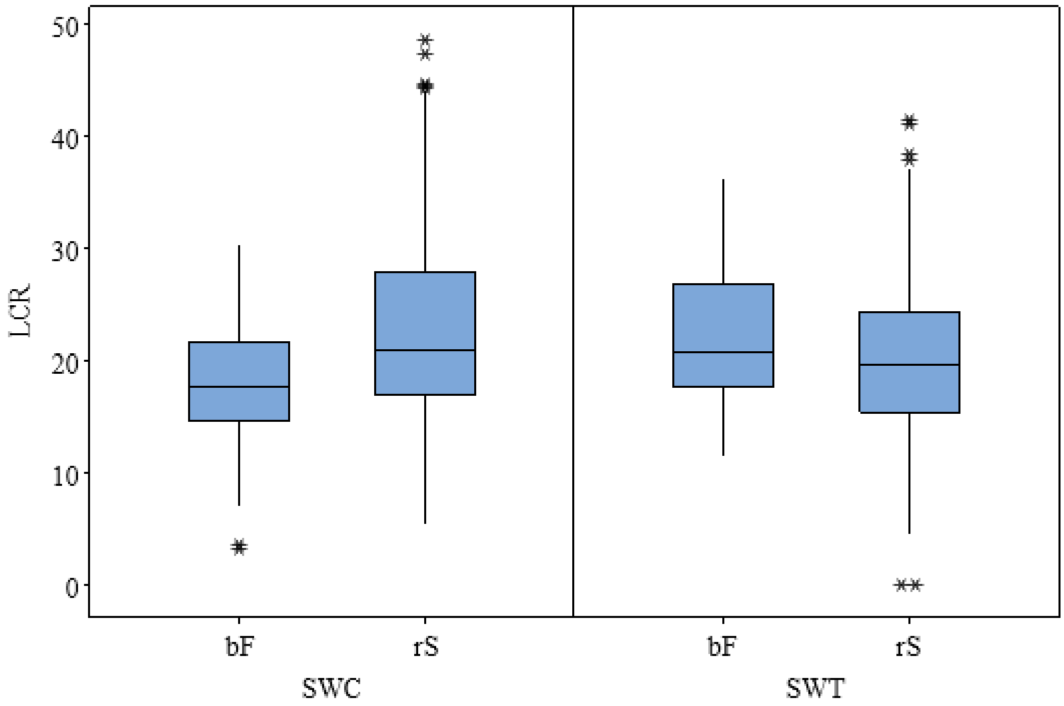


A4 Figure 17. Height to DBH ratio of all trees at the hardwood treatment site by species.

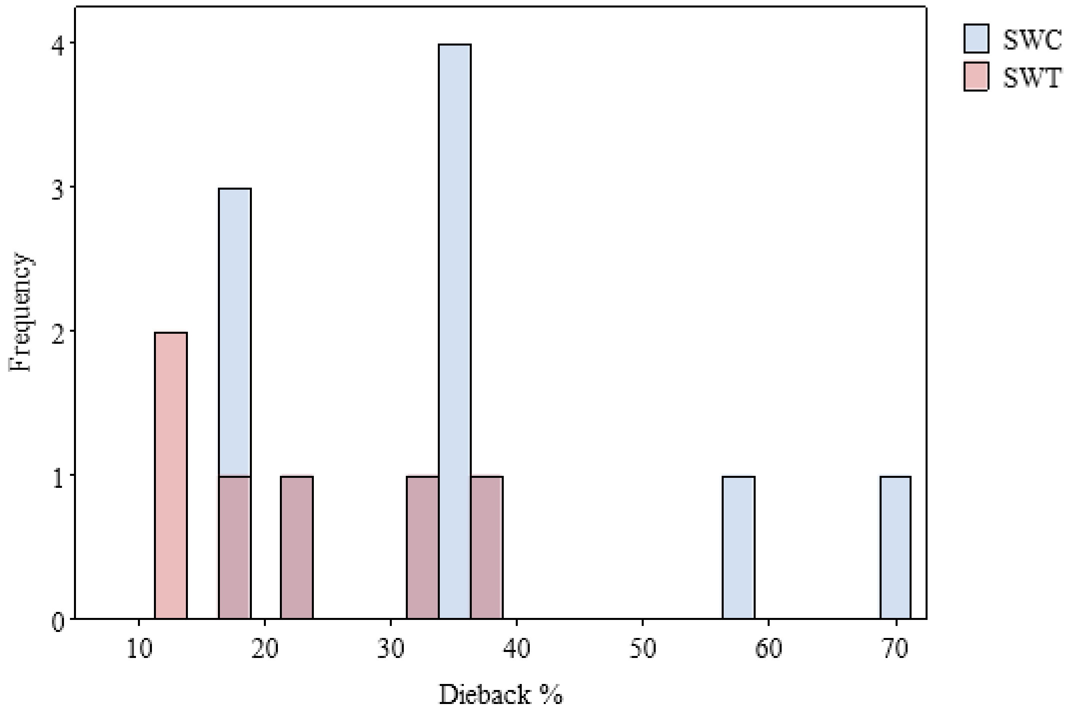
A4.3.2 Tree Health

A4.3.2.1 Crown Health

The mean live crown ratio of balsam fir at the SWC site is 17.9 ± 0.5 (mean ± SE) and 21.9 ± 1.3 at the SWT site. The mean live crown ratio for red spruce at the SWC site is 22.6 ± 0.5 and 20.0 ± 0.4 at the SWT site (A4 Figure 18). Most trees at the SWC and SWT site did not have any crown dieback and few had greater than 40% dieback (A4 Figure 19).

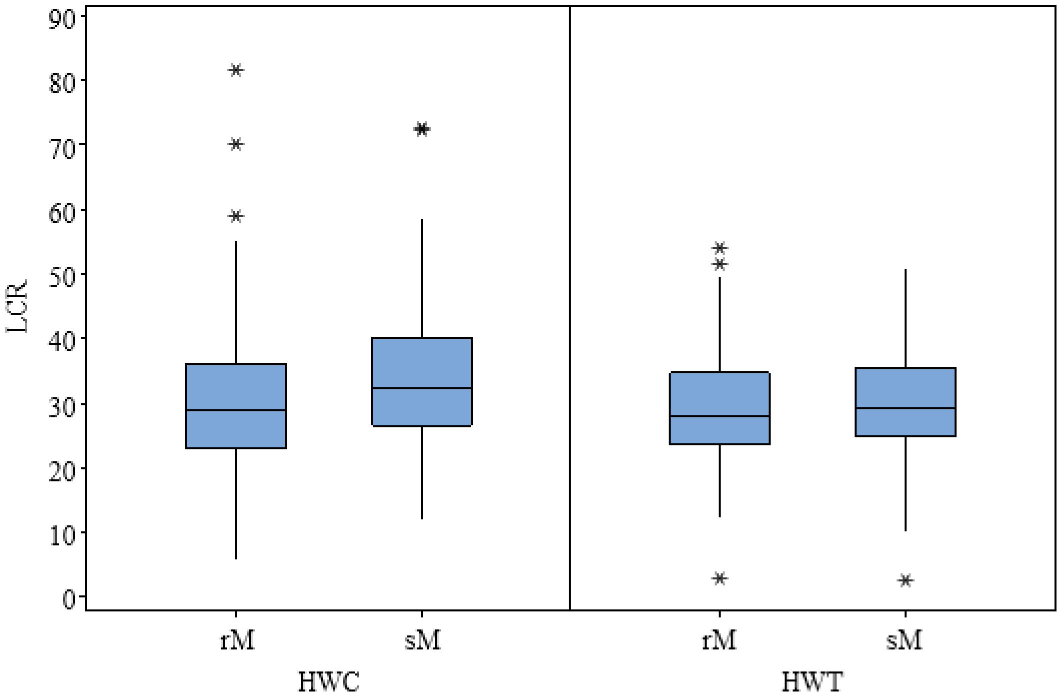


A4 Figure 18. Live crown ratio for balsam fir (bF) and red spruce (rS) plot trees at the SWC and SWT sites.

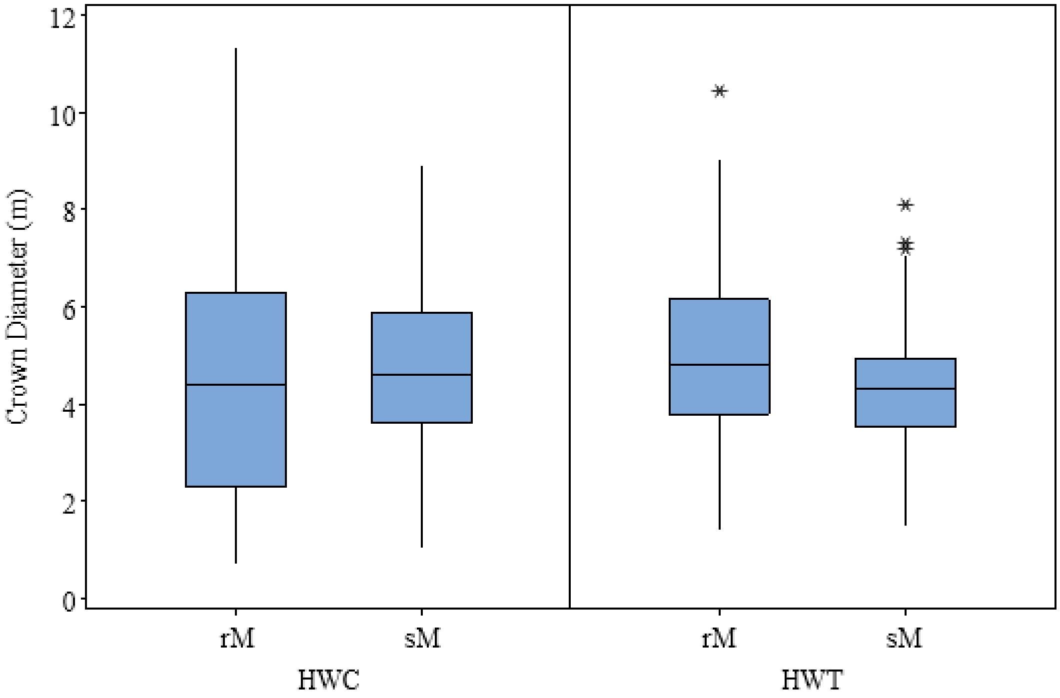


A4 Figure 19. Number of trees with visible dieback at the SWC and SWT sites.

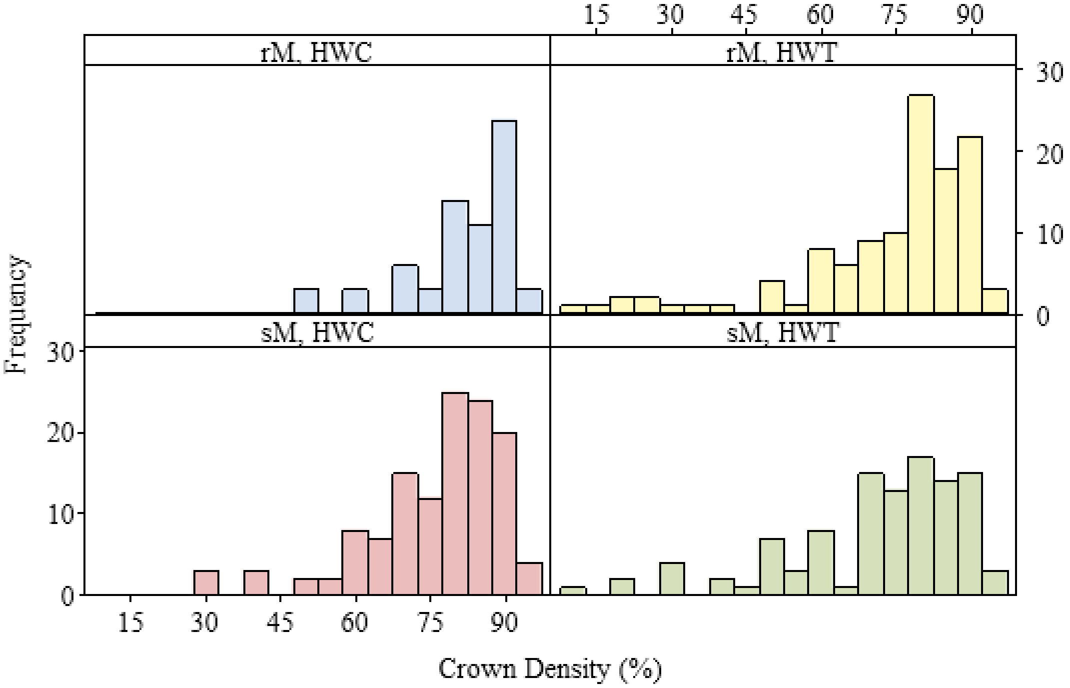
The mean LCR of red maple at the HWC site is 30.5 ± 1.5 (mean ± SE) and 29.5 ± 0.8 at the HWT site. The mean live crown ratio for sugar maple at the HWC site is 33.8 ± 1.0 and 29.7 ± 0.9 at the HWT site (A4 Figure 20). Mean crown diameter of red maple at the HWC site is 4.5 ± 0.3 m and 5.0 ± 0.1 m at the HWT site. Mean crown diameter of sugar maple at the HWC site is 4.8 ± 0.1 m and 4.4 ± 0.1 at the HWT site (A4 Figure 21). Crown density for red maple and sugar maple at both sites ranged, but most trees fell within 60-90% (A4 Figure 22). Many trees had dieback; however, few had greater than 50% dieback (A4 Figure 23).



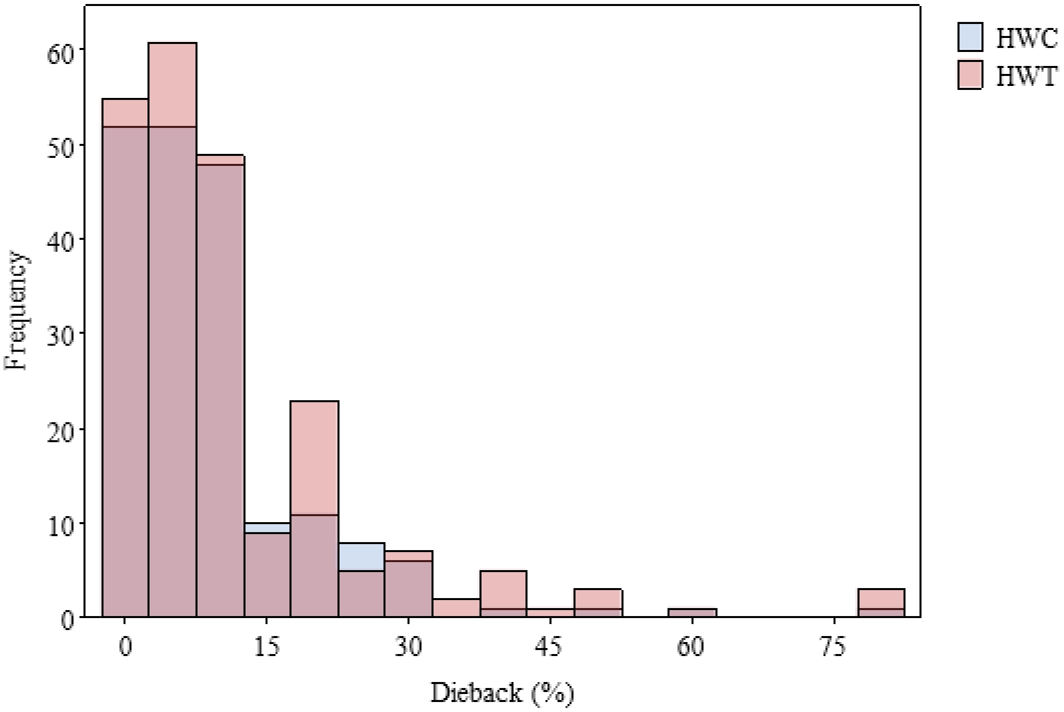
A4 Figure 20. Live crown ratio for red maple (rM) and sugar maple (sM) plot trees at the HWC and HWT sites.



A4 Figure 21. Crown diameter for red maple (rM) and sugar maple (sM) plot trees at the HWC and HWT sites



A4 22. Number of red maple (rM) and sugar maple (sM) plot trees at the HWC and HWT sites that fall within different crown density classes.

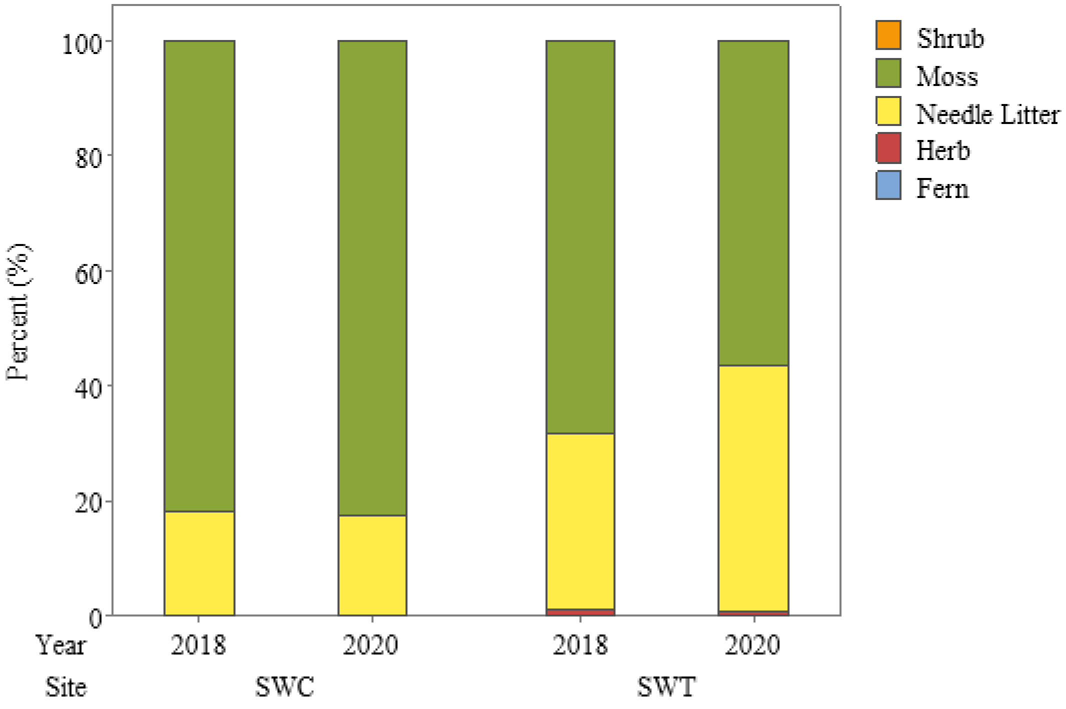


A4 Figure 23. Number of trees with visible dieback at the HWC and HWT sites.

A4.3.3 Regeneration and Ground Vegetation

Vegetation covered approximately 82% of the SWC site in 2018 and 2020, while the remaining was needle litter (A4 Figure 24). Ground vegetation at the SWC site was dominated by Hylo moss (36%), Schreber's moss (12%), and Bazzania (30%) in both 2018 and 2020.

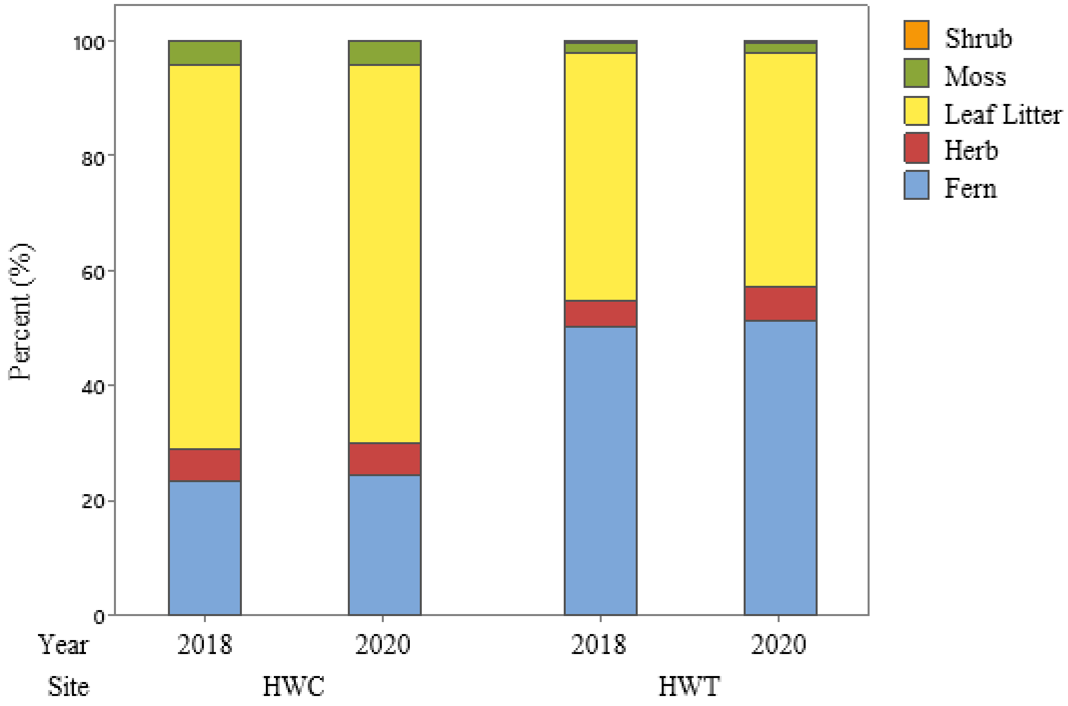
The SWT site had slightly less ground vegetation total cover than the SWC site in 2018, with approximately 69% in 2018, dominated by Hylo moss (37%), Schreber's moss (5%), and Bazzania (23%). Total cover decreased two years after liming to 57% with the most dramatic change in Bazzania to 13% (A4 Figure 24). The decrease in Bazzania may be similar to decreases in other moss species such as sphagnum species, as this moss may be a more acid-tolerant species. Visible declines in Bazzania after liming were also noted.



A4 Figure 24. Mean distribution of shrub, bryophyte, herb, and fern species and needle litter for the SWC and SWT sites in 2018 and 2020.

Vegetation covered approximately 33% of the HWC site in 2018 and 34 % in 2020, while the remaining was leaf litter (A4 Figure 25). Ground vegetation at the SWC site was dominated by wood fern (3%), New York fern (4%), and hay-scented fern (15% in 2018 and 16% in 2020).

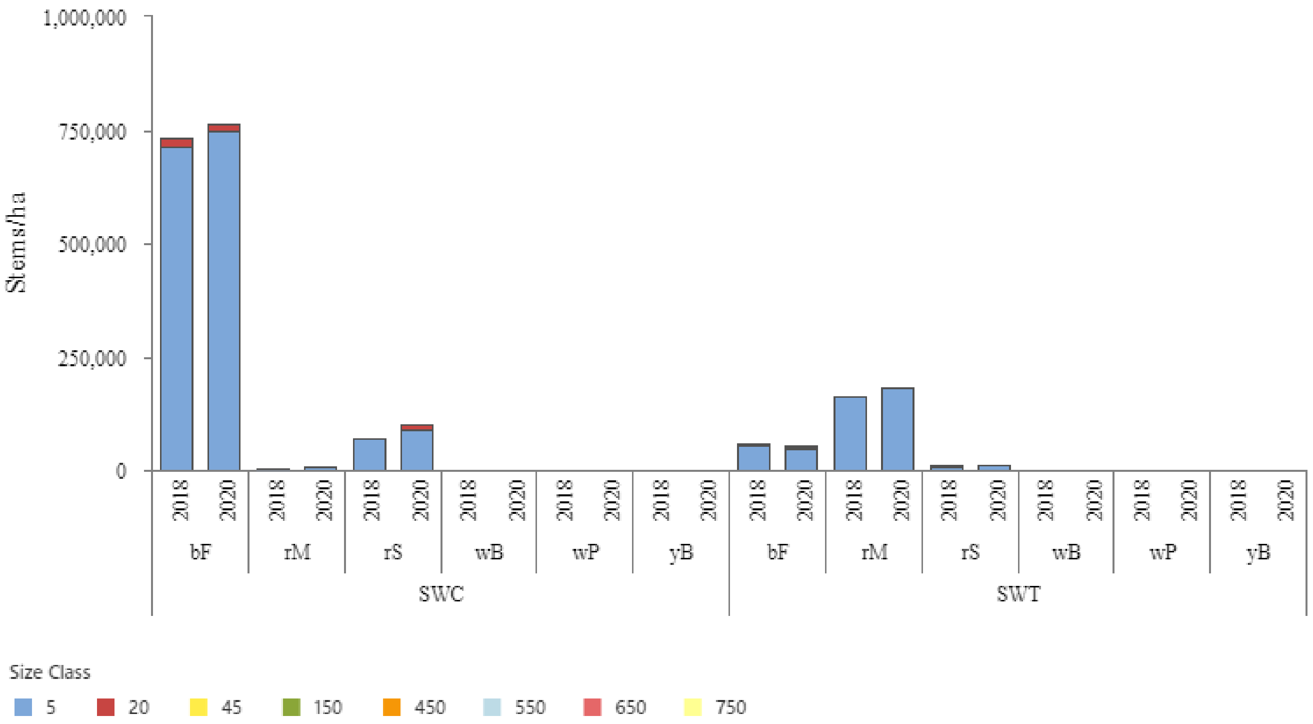
The HWT site had more ground vegetation total cover than the HWC site in 2018, with approximately 57% in 2018, dominated by wood fern (18%), New York fern (15%), and hay-scented fern (16%). Total cover was similar two years after liming at 60% with slightly less hay-scented fern (12%) and slightly more New York fern (21%) (A4 Figure 25).



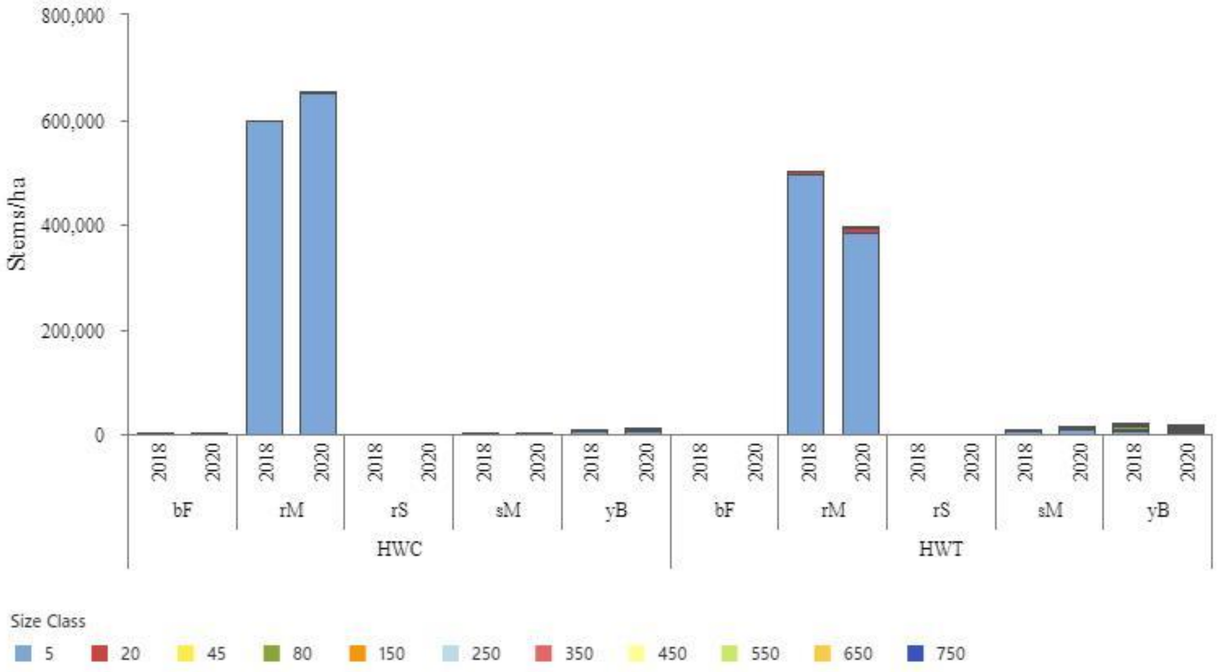
A4 Figure 25. Mean distribution of shrub, bryophyte, herb, and fern species and leaf litter for the HWC and HWT sites in 2018 and 2020.

The SWC site regeneration was dominated by small balsam fir followed by red spruce at the SWC site. The SWT site had much lower overall regeneration which was dominated by red maple as more hardwood species were present at the SWT site (A4 Figure 26).

The HWC site regeneration was dominated by red maple with few sugar maple. The HWT regeneration was also dominated by red maple but had more sugar maple regeneration than the HWC site (A4 Figure 27). Most regeneration were in the 5 cm size class.



A4 Figure 26. Stocking density in stems per hectare of all regeneration at the SWC and SWT sites in 2018 and 2020 by size class and species, where bF is balsam fir, rM is red maple, rS is red spruce, wB is white birch, wP is white pine, and yB is yellow birch. Species with non-visible bars indicate a presence.



A4 Figure 27. Stocking density in stems per hectare of all regeneration at the HWC and HWT sites in 2018 and 2020 by size class and species, where bF is balsam fir, rM is red maple, rS is red spruce, sM is sugar maple, and yB is yellow birch. Species with non-visible bars indicate a presence.

A4.3.4 Tree Tissue Chemistry

A4 Table 2. Mean and standard error (SE) bark and wood chemistry for red spruce trees at the SWC and SWT sites in 2018.

Site	**Type**	**C**	**N**	**S**	**P**	**K**	**Ca**	**Mg**	**Al**	**Mn**	**Fe**
			%					g/kg			
SWC	**Bark**	51.7 (0.3)	0.19 (0.01)	0.03 (0.00)	0.29 (0.01)	1.32 (0.10)	7.24 (0.47)	0.76 (0.04)	0.06 (0.01)	0.62 (0.05)	0.00 (0.00)
	Wood	48.6 (0.4)	0.03 (0.00)	0.014 (0.00)	0.08 (0.01)	0.49 (0.05)	0.42 (0.02)	0.12 (0.01)	0.02 (0.00)	0.10 (0.01)	0.01 (0.01)
SWT	**Bark**	50.8 (0.2)	0.25 (0.01)	0.04 (0.01)	0.40 (0.02)	1.53 (0.14)	8.33 (0.29)	1.00 (0.04)	0.04 (0.00)	0.66 (0.12)	0.00 (0.00)
	Wood	48.6 (0.4)	0.04 (0.00)	0.02 (0.00)	0.09 (0.01)	0.40 (0.05)	0.43 (0.02)	0.12 (0.01)	0.02 (0.00)	0.11 (0.02)	0.00 (0.00)

A4 Table 3. Mean and standard error (SE) for bark, wood and co-dominant foliage chemistry for sugar maple (SM) and red maple (RM) trees in 2018. Sugar maple samples are from intermediate trees and red maple are from Co-dominant trees. co-dominant foliage samples were collected in 2019.

Site	**Species**		**C**	**N**	**S**	**P**	**K**	**Ca**	**Mg**	**Al**	**Mn**	**Fe**
				%					g/kg			
HWC	**Int. SM**	**Bark**	52.2 (0.2)	0.54 (0.02)	0.05 (0.00)	0.37 (0.02)	1.62 (0.21)	8.14 (0.54)	1.22 (0.07)	0.02 (0.00)	0.54 (0.03)	0.01 (0.00)
		Wood	49.6 (0.1)	0.11 (0.01)	0.02 (0.00)	0.20 (0.01)	0.58 (0.10)	0.50 (0.02)	0.22 (0.01)	0.03 (0.00)	0.11 (0.01)	0.01 (0.00)
		Co-dom Foliage	51.0 (0.1)	1.83 (0.03)	0.18 (0.01)	1.59 (0.06)	6.30 (0.21)	2.53 (0.18)	1.26 (0.08)	0.04 (0.01)	0.62 (0.05)	0.03 (0.00)
	Co-dom RM	**Bark**	51.6 (0.5)	0.52 (0.03)	0.05 (0.00)	0.41 (0.02)	1.03 (0.11)	7.44 (0.71)	0.48 (0.04)	0.03 (0.00)	0.50 (0.03)	0.01 (0.00)
		Wood	49.3 (0.3)	0.13 (0.02)	0.02 (0.00)	0.24 (0.03)	0.82 (0.10)	0.66 (0.05)	0.15 (0.01)	0.03 (0.00)	0.11 (0.01)	0.01 (0.00)
		Co-dom Foliage	51.3 (0.1)	1.82 (0.06)	0.14 (0.01)	1.65 (0.07)	6.00 (0.32)	4.75 (0.25)	1.26 (0.05)	0.03 (0.00)	0.66 (0.08)	0.03 (0.00)
HWT	**Int. SM**	**Bark**	52.0 (0.1)	0.50 (0.02)	0.04 (0.00)	0.34 (0.02)	2.11 (0.23)	9.72 (0.92)	0.99 (0.05)	0.04 (0.01)	0.62 (0.03)	0.00 (0.00)
		Wood	49.3 (0.2)	0.09 (0.01)	0.02 (0.01)	0.17 (0.01)	0.52 (0.08)	0.46 (0.03)	0.20 (0.02)	0.03 (0.00)	0.13 (0.01)	0.00 (0.00)
		Co-dom Foliage	49.4 (0.1)	1.78 (0.03)	0.20 (0.01)	1.57 (0.05)	6.05 (0.24)	5.11 (0.36)	1.91 (0.10)	0.03 (0.00)	1.32 (0.10)	0.02 (0.00)
	Co-dom RM	**Bark**	52.0 (0.4)	0.48 (0.01)	0.04 (0.00)	0.37 (0.02)	0.91 (0.10)	7.49 (0.45)	0.47 (0.03)	0.03 (0.01)	0.49 (0.02)	0.002 (0.00)
		Wood	49.1 (0.1)	0.06 (0.01)	0.02 (0.00)	0.11 (0.01)	0.42 (0.03)	0.57 (0.02)	0.12 (0.00)	0.03 (0.00)	0.09 (0.00)	0.01 (0.00)
		Co-dom Foliage	50.1 (0.2)	1.64 (0.06)	0.12 (0.01)	1.55 (0.05)	6.91 (0.59)	6.24 (0.52)	1.62 (0.09)	0.03 (0.00)	0.74 (0.05)	0.02 (0.00)

4.3.5 Forest Floor Characteristics

Humus form at the softwood sites was hemimor for all plots which indicates a well to imperfectly drained site in which F and H horizons are > 2 cm thick, fungal mycelia is dominant, there is low amounts of decaying wood, and the F horizon consists of > 50% of the forest floor (Green et al., 1993; Neily et al., 2011). The forest floor consisted of a moss layer, Fm horizon, and an Hh horizon. The Hh horizon was not present at all plots. The SWC Fm horizon ranged from 6 – 22.5 cm thick and the Hh horizon ranged from 0 – 1 cm thick. The SWT Fm horizon ranged from 6.5 – 18.5 thick cm and the Hh horizon ranged from 0 – 3 cm thick. The forest floor bulk density in the upper forest floor horizon was greater than the lower forest floor horizon at both sites (A4 Table 4).

A4 Table 4. Mean and standard error (SE) of the depths of the Fm and Hh horizons, sampling bulk density (Db) depth and Db of the upper forest floor (FU) and lower forest floor (FL) at the softwood control (SWC) and softwood treatment (SWT) forest floor plots at the Otter Ponds Demonstration Forest in Mooseland, NS.

Horizon		SWC	SWT
Fm Depth (cm)		10.7 (1.00)	10.9 (0.75)
Hh Depth (cm)		0.68 (0.08)	0.80 (0.16)
FU	**Depth (cm)**	5.92 (0.14)	6.03 (013)
	Db (g cm^{-3})	0.083 (0.003)	0.077 (0.003)
FL	**Depth (cm)**	9.69 (0.73)	9.30 (0.42)
	Db (g cm^{-3})	0.040 (0.003)	0.040 (0.003)

Humus form at the hardwood sites was mormodor for all plots which indicates a well to imperfectly drained site in which F and H horizons are > 2 cm thick, both fungal mycelia and faunal droppings are present, there is low amounts of decaying wood, and the F horizon consists of > 50% of the forest floor (Green et al., 1993; Neily et al., 2011). The forest floor consisted of a leaf litter (L) horizon, and Fa horizon, and an Hh. The L and Hh horizon were not present at all plots. The HWC L horizon ranged from 0 – 3.5 cm thick, the Fa horizon ranged from 1.5 – 5 cm thick, and the Hh horizon ranged from 0 – 4 cm thick which trace amounts were common. The HWT L horizon ranged from 1 – 3 cm thick, the Fa horizon ranged from 2.5 – 7.5 cm thick, and the Hh horizon ranged from 0 – 2 cm thick with trace amounts were common. Bulk density was slightly greater in the Hh horizon than the Fa horizon; however, sample sizes were low. Bulk densities in the forest floor horizons were slightly greater at the HWT site than the HWC site;

however, sampling sizes for the Hh horizons were only 1 and 3 for the HWC and HWT site, respectively. Bulk density in the upper mineral horizon ranged from 0.55 – 1.24 g cm^{-3} at the HWC site and 0.53 – 1.30 g cm^{-3} at the HWT site (A4 Table 5).

A4 Table 5. *Mean and standard error (SE) of the depths of the L, Fa and Hh horizons, sampling bulk density (Db) depth and Db of the Fa, Hh, and upper mineral soil horizons at the hardwood control (HWC) and hardwood treatment (HWT) forest floor plots at the Otter Ponds Demonstration Forest in Mooseland, NS.*

Horizon		**HWC**	**HWT**
L Depth (cm)		2.10 (0.16)	2.13 (0.15)
Fa Depth (cm)		3.01 (0.16)	4.56 (0.33)
Hh Depth (cm)		0.73 (0.25)	0.23 (0.10)
Fa	**Depth (cm)**	2.53 (0.17)	3.51 (0.21)
	Db (g cm^{-3})	0.048 (0.005)	0.064 (0.004)
Hh	**Depth (cm)**	5.23 (0.60)	6.88
	Db (g cm^{-3})	0.055 (0.003)	0.081
Min	**Db (g cm^{-3})**	0.800 (0.038)	0.798 (0.043)

A4.4 Conclusion

The results presented in this Appendix gives an idea of the stand characteristics, tree health, baseline chemical measurements for bark, wood, and foliar tissue which was not resampled after liming, regeneration, ground vegetation, and forest floor properties. This information can be used for a reassessment at five years when these parameters will be resampled.

Appendix 5 – List of Species Latin Names

Common Name	Latin Name
American beech	*Fagus grandifolia*
Balsam fir	*Abies balsamea*
Bazzania	*Bazzania trilobata*
Black cherry	*Prunus serotina*
Clubmoss	*Lycopodium lucidulum*
Evergreen wood fern	*Dryopteris intermedia*
Hair-cap moss	*Polytrichum spp.*
Hay-scented fern	*Dennstaedtia punctilobula*
Hylo moss	*Hylocomium splendens*
Lichen	*Rhizocarpon geographicuna*
New York fern	*Amauropelta noveboracensis*
Red maple	*Acer rubrum*
Red spruce	*Picea rubens*
Schreber's moss	*Pleurozium schreberi*
Scots pine	*Pinus sylvestris*
Sphagnum moss	*Sphagnum spp.*
Sugar maple	*Acer saccharum*
White birch	*Betula papyrifera*
White pine	*Pinus strobus*
Wood sorrel	*Oxalis acetosella*
Yellow birch	*Betula alleghaniensis*