

NUTRITIONAL AND ENVIRONMENTAL FACTORS AFFECTING SAP FLOW
AND YIELD IN NOVA SCOTIAN MAPLE TREES

by

Rachel Rand West

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DEDICATION PAGE

To the most incredible partner for providing me with all the patience and support a person could ever ask for. Without you “holding down the fort”, this project would have never ended. One more step toward our kickass future together.

And to my wonderful children; Kolstyn, Lockryn, Jadeyn, Camdyn, for understanding that “momma was trying to improve herself and our future.”

I love you all beyond words can express.

TABLE OF CONTENTS

LIST OF TABLES vii

LIST OF FIGURES ix

ABSTRACT xi

LIST OF ABBREVIATIONS AND SYMBOLS USED xii

ACKNOWLEDGEMENTS xiv

CHAPTER 1 – INTRODUCTION 1

CHAPTER 2 – LITERATURE REVIEW 2

 2.1 PREFACE 2

 2.2 MAPLE SAP 2

 2.2.1 Sap Physiology 2

 2.2.2 Sap and Syrup Yield 3

 2.3 MAPLE MANAGEMENT PRACTICES 4

 2.3.1 General Management 4

 2.3.2 Soil Management 6

 2.3.3 Fertilization of Maple Stands 7

 2.3.4 Liming Maple Stands 8

 2.4 NUTRIENT MOVEMENT IN MAPLE WOODS 10

 2.4.1 Nutrient Cycling 10

 2.4.2 Decomposition of Leaf Litter 11

2.4.3 Tree Root Interactions with Soil.....	14
2.4.4 Nitrate Leaching in Maple Stands	16
2.5 MAPLE DECLINE AND SOIL NUTRITION	17
2.6 SUMMARY	20
2.7 OBJECTIVES AND HYPOTHESES.....	22
2.7.1 Research Question	22
2.7.2 Objectives.....	22
2.7.3 Hypotheses	22
CHAPTER 3 – GENERAL METHODOLOGY.....	24
3.1 EXPERIMENTAL SITE DESCRIPTION	24
3.2 SOIL.....	25
3.2.1. Soil Moisture Content (%).....	25
3.2.2. Soil Moisture Potential (kPa)	25
3.2.3. Soil Nutrition.....	26
3.3 TREE CHARACTERISTICS	26
3.3.1. Trunk Circumference (cm)	26
3.3.2. Core Nutrition.....	26
3.4 LEAF CHARACTERISTICS	27
3.4.1. Leaf Area Index (LAI).....	27
3.4.2. Leaf Nutrition	27

3.5 ENVIRONMENTAL FACTORS	27
3.5.1. Site Weather	27
3.5.2. Latitude, Longitude, Elevation & Slope.....	28
3.5.3. Tree Competition/Density	28
3.5.4. Associated Vegetation.....	28
3.6 SAP CHARACTERISTICS	29
3.6.1. Sap Flow and Yield	29
3.6.2. Sap Nutrition	29
3.7 STATISTICAL ANALYSIS.....	30
CHAPTER 4 – SOIL FACTORS INFLUENCING SAP YIELD & FLOW	31
4.1 SOIL MOISTURE	31
4.2 SOIL NUTRIENTS.....	33
CHAPTER 5 – THE RELATIONSHIP BETWEEN VARIOUS TREE PHYSIOLOGICAL FACTORS & SAP FLOW & YIELD.....	36
5.1 TRUNK CIRCUMFERENCE.....	36
5.2 CORE NUTRIENTS	37
5.3 LEAF AREA INDEX.....	38
5.4 LEAF NUTRITION	41
CHAPTER 6 – ROLE OF ENVIRONMENTAL FACTORS ON MAPLE FLOW	43
6.1 SITE WEATHER.....	43
6.2 SITE CHARACTERISTICS.....	49

CHAPTER 7 – SAP CHARACTERISTICS RELATED TO SAP FLOW AND YIELD	52
7.1 SAP NUTRIENTS	52
7.2 SAP FLOW & YIELD	52
7.3 SAP NUTRITION	56
CHAPTER 8 – INFLUENCE OF ASSOCIATED VEGETATION ON MAPLE FLOW & YIELD.....	58
8.1 SAP FLOW.....	58
8.2 SAP YIELD	59
CHAPTER 9 – GENERAL DISCUSSION AND CONCLUSIONS	61
9.1 DISCUSSION	61
9.2 CONCLUSIONS	66
9.3 SIGNIFICANCE TO INDUSTRY.....	66
REFERENCES	68

LIST OF TABLES

Table 1. Site-specific information and producer size based on number of taps. 25

Table 2. Weather stations where data was gathered for each research location. 28

Table 3. Pearson correlations between monthly % soil moisture, sap flow, and yield..... 31

Table 4. Correlation coefficients between water potential, sap flow, and yield. 33

Table 5. Correlation coefficients of monthly soil nutrients, average sap flow, and yield. 35

Table 6. Correlation coefficients between trunk size, average sap flow and yield..... 37

Table 7. Correlation coefficients between core nutrients and average sap flow and yield.
..... 38

Table 8. Correlation coefficients between leaf area index, average sap flow, and yield.. 40

Table 9. Correlation coefficients between leaf area index in year 1 related to sap flow and
yield in year 2..... 41

Table 10. Correlation coefficients between leaf nutrients, average sap flow, and yield. . 42

Table 11. Correlation coefficients between average maximum monthly temperature and
average sap flow and yield..... 44

Table 12. Correlation coefficients between average minimum temperature and average sap
flow and yield. 44

Table 13. Correlation coefficients between monthly mean temperature and average sap
flow and yield. 45

Table 14. Correlation coefficients between heating degree days, average sap flow and yield.
..... 46

Table 15. Correlation coefficients between cooling degree days, average sap flow and
yield..... 46

Table 16. Correlation coefficients between monthly total precipitation, average sap flow
and yield..... 48

Table 17. Correlation coefficients between monthly snow ground thickness, average sap flow and yield.	49
Table 18. Correlation coefficients between various site characteristics, average sap flow and yield.....	51
Table 19. Correlation coefficients between average sap flow and yield in Year 1 and Year 2.....	55
Table 20. Correlation coefficients between sap nutrients, average sap flow and yield. ...	57
Table 21. Summary of factors with the strongest correlations ($r > 0.33$) to sap yield consistently in year 1 and 2.....	62

LIST OF FIGURES

Figure 1. Map of Nova Scotia displaying locations of research sites.	24
Figure 2. Comparison of mean monthly soil moisture for 2015 and 2016.	32
Figure 3. Comparison of soil water potential between June to December of 2015	33
Figure 4. Tree trunk circumference at each site in 2015 and 2016.	36
Figure 5. Leaf area index at study sites in 2015 and 2016.	39
Figure 6. Comparison of leaf area index between summer and fall of 2015 (2015-16 tapping year) and 2016 (2016-17 tapping year).	40
Figure 7. Average site elevation for all 10 research locations.	50
Figure 8. Installed graduated sap collection unit.	52
Figure 9. Average flow across research sites.	53
Figure 10. Difference in average flow at research locations between study years (year 2 minus year 1).	53
Figure 11. The number of sap flow days at each location from the time the sap collection unit was installed to when it was removed, for each year of study.	54
Figure 12. Difference in sap flow days between 2016 and 2017 tapping seasons.	55
Figure 13. Comparison of total sap yield (L) collected from the research trees, at each site, from the two study years.	56
Figure 14. Difference in sap yield (L) between the 2016 and 2017 tapping seasons.	56
Figure 15. Correlation coefficients for several species growing in the sugar bush versus sap flow.	58
Figure 16. Relationship between tree seedling density and average sap flow in maple trees.	59
Figure 17. Correlation coefficients for a variety of species growing in the sugar bush versus yield.	60

Figure 18. Graphical representation of most significant factors affecting sap yield displayed over the 12-month period..... 65

ABSTRACT

Maple is an important industry to the Canadian economy accounting for \$615 million in exports in 2023. The sugar maple (*Acer saccharum* L.) is a native tree species, especially in Eastern Canada and United States, and is the preferred tree species for tapping due to the higher sugar content of its sap. Of the maple producing regions, Nova Scotia has some of the lowest recorded tap yields. The purpose of this study was to determine factors that were most likely to affect sap flow and yield in Nova Scotian sugarbushes. One hundred trees over ten sites located in primary maple producing regions of mainland Nova Scotia were observed over a two-year period. Data was collected on weather, soil characteristics, tree physiology, nutrient content, associated vegetation, and site characteristics, and compared to sap flow and yield. Although, numerous factors showed correlations with sap yield, the strongest relationships consistent over the two years, were between the zinc content of soil, leaf, and core tissues, soil moisture, amount of snow on the ground, associated vegetation, longitude of the site, and sap pH of the first run. Associated vegetation provided a positive correlation with yield, where concentrations of zinc and iron had a negative relationship. The further west the site was in NS and having snow on the ground from December to March was indicative of higher yields. High soil moisture in August and September had a negative relationship with yields, as did the pH of the sap in the first run of the season. Although the relationships were statistically significant in this study, they were weak. Additional years of study, with a focus on the factors that showed the strongest correlations would be needed to further understand the true reason for the lower sap yield and to determine if a management practice could be developed to combat this issue.

LIST OF ABBREVIATIONS AND SYMBOLS USED

Al	Aluminum
Anti	Antigonish County site
Approx	Approximate
Avg	Average
B	Boron
Ca	Calcium
CaMg (CO ₃) ₂	Dolomite Mineral (lime)
CDD	Cooling Degree Days
CEC	Cation Exchange Capacity
Colc1	Colchester County site 1
Colc2	Colchester County site 2
Cu	Copper
Cumb1	Cumberland County site 1
Cumb2	Cumberland County site 2
Cumb2	Cumberland County site 2
Cumb3	Cumberland County site 3
Fe	Iron
Hali	Halifax County site
HDD	Heating Degree Days
K	Potassium
King	Kings County site
K ₂ O	Potassium oxide
L	Liter
LAI	Leaf Area Index
Lune	Lunenburg County site
Mg	Magnesium

Mn	Manganese
N	Nitrogen
Na	Sodium
OM	Organic Matter
P	Phosphorus
P ₂ O ₅	Phosphorus pentoxide
S	Sulfur
Y1	Year one of study (May 2015 to April 2016)
Y2	Year two of study (May 2016 to April 2017)
Zn	Zinc

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CHAPTER 1 – INTRODUCTION

Acer saccharum L., commonly known as the Sugar Maple, is one of Canada's native tree species growing especially well in the Eastern provinces. These trees, through the production of maple syrup and other maple products, contributed \$615 million from exports alone, to the economy in 2023 (Agriculture and Agri-Food Canada, 2023) making it a profitable bioresource. Canada is the world's leading supplier of maple syrup and maple products, having produced a record high 65.87 million liters of sap in 2022 (Statistics Canada, 2021). Canada is responsible for between 70-80% of the world's pure maple syrup. Quebec, Ontario, New Brunswick, and Nova Scotia are Canada's main maple producing provinces with Quebec being responsible for roughly 89.9% of the country's production (Agriculture and Agri-Food Canada, 2023). In contrast, USA produced 19.04 million liters in 2022 (United States Department of Agriculture, 2022) with Vermont, New York, Maine, Michigan, and New Hampshire being USA's main contributors (Agriculture and Agri-Food Canada, 2021). Nova Scotia produced around 211,983L of syrup in 2020 (Agriculture and Agri-Food Canada, 2022) accounting for less than 1% of the national maple production (Statistics Canada, 2021). Maple syrup production has increased from around 30,283 liters in the 1950s to the current 211,983L in 2020 (Agriculture and Agri-Food Canada, 2022), which is down from a high of 215,768L in 2017 (Statistics Canada, 2017). There are approximately 39 Maple farms in Nova Scotia producing sap from around 420,383 taps (Agriculture and Agri-Food Canada, 2021).

There are many factors, known or suspected, that affect the sap flow through the maple tree and, thus, the resulting syrup. These factors include soil nutrients, the climate of the region, the weather in a particular year, tree species, the physiology of the individual tree itself, the surrounding ecosystem, the landscape, the slope, and the location. This research aims to uncover the possible relationships between some of the known factors involved in maple sap flow and maple sap yield in relation to Eastern Canada, specifically Nova Scotia.

CHAPTER 2 – LITERATURE REVIEW

2.1 PREFACE

The introduction and literature review were first submitted (in part) as a review paper for the American Journal of Plant Sciences. The full reference is included below:

West RR, MacDonald MT, Lada RR. 2023. Nutrition and Related Factors Affecting Maple Tree Health and Sap Yield. American Journal of Plant Science. 14, 125-149.

2.2 MAPLE SAP

2.2.1 Sap Physiology

Maple sap contains carbohydrates and trace levels of oligosaccharides, organic acids, minerals, amino acids, phenolic compounds, aromatic compounds, and vitamins. Sucrose is the main sugar found in the sap, with glucose and fructose being present in smaller amounts (Stuckel and Low, 1996). Malic acid, potassium, magnesium, and calcium are other notable components (Stuckel and Low, 1996).

Maple sap is collected from trees during the freeze-thaw cycle that occurs between February and April in Nova Scotia, where temperatures fluctuate approximately between -10°C and +10°C. Sap flowing from the tree, also known as sap exudation, is a process that is still not well understood. Sap exudation appears to be driven by an increase in root pressure or an increase in stem pressure, though it could also be due to a combination of both stem and root pressures (Kozłowski and Pallardy, 1996). There is a “back and forth” between positive pressures, which develop during the day when temperatures are above freezing, and negative pressures, which develop at night when the temperature is below freezing. Ultimately, positive xylem pressure is created (Cortes and Sinclair, 1985), which will push the sap through the tree and out small wounds. The negative pressure creates a type of a suction, which pulls water up from the roots refilling what was lost during the day with the positive pressure (Cornell University, 2017). Pressure within the tree(s) can reach up to 276 kPa (Perkins and van den Berg, 2009).

It has also been found that sucrose concentration might play a role in the magnitude of pressure generated with the various maple species (Johnson et al., 1987) and is positively linked to the pressure and volume of the sapwood cells following the freeze-thaw cycle (Mervin et al., 1967; Johnson et al., 1987). Johnson's (1987) experiments showed that absorption amounts increased, and exudation occurred only when sucrose was present in the winter months where concentrations are typically around 2.0-5.0%. In summer, sucrose is found in negligible amounts and exudation does not occur with maple species. However, the exact role of sucrose in the exudation process is still under debate.

2.2.2 Sap and Syrup Yield

Sap flow and syrup yield are directly linked. It takes approximately forty liters of sap to create 1 liter of syrup. This 40:1 ratio is dependent upon the sugar concentration contained within the harvested sap. The sugar (brix) concentration varies between species, individual trees of the same species (genetics), seasons, tree health, time of day, day of collection, and weather conditions (Hiligman, 2006). The natural variability of sugar levels in sap from a random selection of sugar maples has been well documented (Jones et al 1903; Taylor, 1956; Blum and Gibbs, 1968). Factors affecting this variability, however, are poorly understood. Sugar maples and black maples (*Acer nigrum*, L.) generally average between 2.0 and 2.5 percent sap sugar content (Hiligman, 2006), but with high variability. Red maples (*Acer rubrum*, L.), silver maples (*Acer saccharium*, L.) and the boxelder (*Acer negundo*, L.) have a much lower average sap sugar content. While surveying producers, Lada and Nelson (2013) found that the average brix level of Nova Scotia maple sap was around 2.0%.

The duration of sap flow is another important factor in the yield relationship. Tapping season lengths vary by the age of the tree, year and location. In general, a longer tapping season results in greater yields. However, there have been cases where a short season has resulted in high yields due to the weather and other factors. Lada and Nelson (2013) found drastic differences in syrup yield per tap among various maple production regions within Nova Scotia. Syrup yields ranged from an average of 0.243 L tap⁻¹ in Cape Breton to 0.72L

tap⁻¹ in Kings County (Lada and Nelson, 2013). Lada and Nelson (2013) also documented that the highest average syrup yield per tap was found in Vermont (1.5L tap⁻¹), followed by Maine (1.3L tap⁻¹), New York (1.2L tap⁻¹), and Quebec (1L tap⁻¹), with Nova Scotia accounting for the lowest average at 0.325L tap⁻¹.

There is a lack of information in the literature regarding the influence of stand density (trees hectare⁻¹), age of the trees, tree growth, canopy density, and competing vegetation on sap and syrup yield. While the exact reasons for the lower and the declining sap/tap yield in NS are unknown, there are speculations on what may contribute to a decline. There was no significant relationship between tree age, diameter, and the technology used by producers and the syrup yield (Lada and Nelson, 2013). Anatomical variations between trees relating to starch storage capacity accounts for only a minor amount of the variability in sap sugar concentration (Morselli et al., 1978; Wallner and Gregory, 1980). The size of the crown and the interception of light have long been suspected to be linked to the phenotypic variation in sap sugar concentration (Moore et al., 1951; Morrow, 1955; Blum, 1971), but this has not been proven. The sugar concentration of the sap is directly influenced by the photosynthesis taking place in the canopy. This is regulated by the nutritional health of the foliage where photosynthesis occurs, as well as the soil fertility and soil moisture status that dictate the canopy nutritional and moisture status (Lada, 2014). Although there are direct links between the sap and the foliage, the timing of defoliation has little influence on the sweetness of sap between trees (Gregory and Wargo, 1986; Kolb et al., 1992).

2.3 MAPLE MANAGEMENT PRACTICES

2.3.1 *General Management*

General forest management practices include harvesting, land drainage, tillage, fertilization, and vegetation control using fire and herbicides, all of which can have positive or negative effects on the soil quality (Burger and Kelting, 1999). Negative effects include soil displacement, waterlogging, compaction, organic matter and nutrient depletion, shift in soil microcosm and acidification. Positive effects include enhanced soil fertility, tilth, water and air availability and organic matter placement (Burger and Kelting, 1999). The

maple industry typically uses a less invasive type of managed forest system, which includes thinning or silviculture practices, which removes or minimizes many of the non-maple tree species and keeps the underbrush/growth cut to a minimum. Sugarbushes are entered at regular intervals to manage undergrowth, remove or thin out the maple trees, check sap lines, to prepare for tapping season, as well as to monitor the system when the sap begins to flow and to untap the trees when the season is over. Houston et al. (1990) states that human activities in the maple woods surpass those of any other managed forest. Burger and Kelting (1999) state that at minimum, forest operations potentially affect soil quality when trees are harvested, during site preparation for the next rotation, during stand closure (fertilization), and during intermediate management (e.g., thinning, prescribed burning, etc.). There are several hypotheses in relation to changes in growth and nutrition of forest trees including acidic deposition, excessive nitrogen input, and severe climatic events. These stress factors could have direct or soil-mediated impacts on the trees (Ouimet and Camire, 1995).

Most sugarbushes in Canada come from natural mixed forest stands containing a naturally large population of maple trees. Sugar maples and black maples are the favored trees to tap for maple production as sap sugar concentrations are higher than other maple trees, averaging 2.0-2.5%, with some trees well surpassing the 3% level (Heiligmann et al., 2006). Even though sugar maples are the best option for tapping, red maples (*Acer rubrum*, L.) are also tapped in Nova Scotia (McIsaac, 2012). Silver maple (*Acer saccharinum*, L.) and boxelder (*Acer negundo*, L.) are two other trees that can be tapped for syrup production but seldom are tapped due to the lower sap sugar content (Heiligmann et al., 2006). Sugar, red and silver maples are native to the Nova Scotian region, whereas the Black maple are native more centrally through southern Ontario, Quebec, and the Northern USA. Boxelders are similar to that of Black Maple, but their native region is much larger and extends further into the western provinces and states (University of Vermont, 2022; NS Department of Natural Resources, 2012; Heiligmann et al., 2006).

A process called “thinning” is used to help keep the sugarbush healthy, less competitive, and productive. Thinning is the process where trees which are sick, dying, crowding or of the wrong species are removed (Heiligmann, 2006; MPANS, 2016). Thinning promotes increased tree growth rate, crown development, and improves the overall health of the stand (MPANS 2016). It is only recommended to remove up to 10% of the maples in the sugarbush and up to 30% of the non-maple species (MPANS, 2016) to maintain stand diversity. Historically, little outside of thinning was done to manage the sugarbush. Thinning was a way to gain fuel for fires to boil the sap (Heiligman, 2006) as well as to clean up the stand to facilitate site access and the maintenance of taps and lines. More recently, producers have become more aware of the impacts of maple production on the stand and soil health. Soil compaction from equipment and damage from grazing animals, both domesticated (i.e. Cows, sheep, horse, etc.) and wild (i.e. Deer, moose, etc.) are concerns because sugar maple roots are quite shallow, with fine roots predominately staying in the top 60cm of the soil profile (McIsaac, 2012). Inputs to the sugarbush are often low to non-existent, but some producers and researchers have experimented with the addition of lime and fertilizers to the soil to aid in stands where the soil quality is poor or to help combat maple tree dieback. For the most part, Sugarbushes rely on the decomposed leaf litter and nutrient cycling in the soil to provide the nutrients needed for growth and development.

Sap is collected from trees using the traditional spile and bucket method or the more modern method of tubing with or without the use of a vacuum system. Most producers choose tubing because the traditional method is more labour intensive, requiring one bucket per tap that may be collected multiple times per day. Tubing lines connect multiple trees together and can be either gravity fed or placed under vacuum, with sap collection points at the bottom of slopes (Heiligmann, 2006; MPANS, 2016).

2.3.2 Soil Management

Though much focus regarding soil quality relates to traditional agriculture, the emphasis of this section is on soil quality of forests and tree stands. Unlike other agricultural soils,

forest soils are relatively untouched. To support plant growth a soil must: (1) promote root growth, (2) accept, hold and supply water, (3) hold, supply and cycle mineral nutrients, (4) promote optimum gas exchange, (5) promote biological activity, and (6) accept, hold and release carbon (Burger and Kelting, 1999).

Forest soils produce various products from wild mushrooms and fiddleheads to medicinal plants, decorative materials, maple and other tree saps, timber, firewood, and Christmas trees. The C:N ratio of the surface soil can be used as defining the essential differences between forest soils and soils used for agricultural cropping. The C:N ratio lies between 15-30:1 for forest soils, the result of continuous input of large amounts of woody litter, and closer to 10 for cultivated soils (Attiwill and Adams, 1993). Just like any production area, for the longevity of usefulness and health, these areas should be monitored and managed to ensure the health and site are not negatively affected by the human interaction.

Sugar maples can have a life expectancy of more than 300 years (Duchesne et al., 2002) and grow successfully in a wide range of soils, exhibiting a large pH tolerance by growing in soils with pH of 3.7-7.3 (Coughlan et al., 2000). Depending on the region, there is often minimal interaction with the soil by producers. Maple stands and other forests often do not obtain much in the way of inputs and must rely on the naturally occurring organic matter, leaf litter, and the seasonal dieback of the undergrowth. According to Attiwill and Adams (1993), up to ten tonnes of litter of low nutritional quality is deposited annually on the forest floor in highly productive forests. Some producers, region and site dependent, do add liming agents and fertilizer to their stands, but many are left as a mostly “closed system” with no use of inputs. Still, the effect of fertilizers and liming must be examined more in-depth in the Nova Scotian region.

2.3.3 Fertilization of Maple Stands

It is believed that there is a link between soil fertility and sap yield, but most of the literature focuses on the links between soil fertility and tree health. For a tree to provide sap it must

be alive and functional, and one can conclude more sap will come from a healthy tree than if that same tree had compromised growth. Dieback, for instance, has been shown to be negatively linked to sap volume (Wilmot et al., 1995).

A study conducted by Ouimet et al. (1996) on Quebec maple stands confirmed that growth and nutrition of sugar maples are negatively affected by imbalances in exchangeable basic cations in soils. The use of fertilizers in the sugarbush can be risky and have negative effects such as worsening nutrient imbalances if applied incorrectly or the wrong fertilizer is used (Houston et al., 1990). Definite leaf patterns typical of deficiencies do not develop until the element has been in short supply for longer periods of time thus, trees could respond to low levels of K by reduced growth and yield for several years before the symptoms become apparent (Bernier and Brazeau, 1988a), making fertilizer recommendation and applications more complex. Bernier and Brazeau (1988b), state that trees supplied with K can also exhibit poor root development and are less resistant to frost, pathogens, and pests. As well, several authors have noted that base cation fertilization may have low efficacy, in part due to the low solubility of fertilizer substances and the high leachability of cations in acidic soils (Wilmot et al., 1996). Sampling of the soil and the plant tissue should be completed before nutrients are added to the system. With nutrients presenting themselves differently and in different concentrations in the various tissues of the tree during different times within seasons (Houston et al. 1990), accurate results from tissue samples can be difficult to obtain, thus making it hard to accurately suggest an appropriate fertilizer plan. Bailey et al. (2004) also suggest that there is evidence that coarse soil fragments may contain important nutrient pools in some forest soils and that standard laboratory procedures for testing soils would not detect these as the tests are performed on soil that passes through a 2mm screen.

2.3.4 Liming Maple Stands

Although, sugar maples occur on soils with a wide range of pH and base cation levels, Lovett and Mitchell (2004) explain that maples often grow poorly in soils with low calcium (Ca) and magnesium (Mg), high aluminum (Al), and low pH. The loss of base cations,

especially, Ca^{2+} and Mg^{2+} is of special concern to sugar maples because of how poorly the trees perform on base-poor sites where they will display a reduction of vigor in adult trees and reduced growth and survival of saplings (Lovett and Mitchell, 2004). Thus, there is a potential benefit to liming maple stands.

Ouimet et al. (1996) confirmed that the growth and nutrition of sugar maples are negatively influenced by imbalances of exchangeable basic cations in the soil. It has been found that the addition of lime to acidic sugarbush soils can have positive effects on tree health (Wilmot et al., 1996) and lower levels of tree dieback have been observed in experimental stands when compared to plots that were not limed (Moore and Ouimet, 2006). Although the exact cause of maple dieback is unknown, soil acidification and low Ca levels (Ouimet and Camire, 1995) are thought to be important factors affecting this process.

The practice of liming forest soils has had positive effects in many areas but should be treated with caution according to Wilmot et al. (1996). An increase in pH can initiate certain undesirable changes, such as increased mineralization of organic matter, potential loss of nutrient holding capacity, and a shift in fine root growth to the upper soil horizons making them more susceptible to wind, drought, and frost damage. Low rates of net nitrification are observed in many acidic forest soils and increases in the pH can increase that rate (Finzi et al., 1998). The economic feasibility of liming forest stands also must be taken into consideration.

Liming may also have a positive effect on the population of mycorrhizal fungi present in the soils. Sugar maples are one of the few tree species of northern hardwood forest known to have symbiotic relationship with arbuscular mycorrhizal fungi (Ouimet et al., 1996; Coughlan et al., 2000). Beech, oak, hemlock and birch have ectomycorrhizae, which differ in nutrient-cycling properties than that of arbuscular mycorrhizae (Lovett and Mitchell, 2004). In low P soils, maple seedling nutrient status was improved by the colonization of the fine roots by arbuscular mycorrhizae fungi (Ouimet et al., 1996). Coughlan et al. (2000)

found that the quantity of mycorrhizal colonization generally increased with pH for sites studied and that the declining site with more acidic soil had initially larger fungal spore populations, but lower taxonomic diversity than that of the healthy maple site. The addition of lime can increase the survival, vigor, diameter growth and seed production of sugar maples in base-poor sites (Lovett and Mitchell, 2004). Lime application may also reduce the Al-mediated inhibition of Ca uptake by roots (Wilmot et al., 1996). However, application of too much lime can decrease the availability of certain nutrients, such as having high Ca:K ratios can lead to foliar K deficiency in K poor soils (Wilmot et al., 1996) and can inhibit mycorrhizae (Houston et al. 1990). Coughlan et al. (2000) also mention that although possible effects of liming on arbuscular mycorrhizal fungi associated with forest vegetation has not been studied in-depth, results from agriculture studies indicate that considerable changes could occur. Large-scale liming and/or fertilization treatments of spruce forest in Europe has resulted in improved base saturation of soils but has not necessarily increased the growth of the stand (Wilmot et al., 1996).

2.4 NUTRIENT MOVEMENT IN MAPLE WOODS

2.4.1 *Nutrient Cycling*

Nutrient cycling is the process in which chemical elements, both organic and inorganic, move from specific locations in the environment (i.e. soil or water) into a living organism (i.e. plant) and then back out into the environment again. Ecologists refer to the use, transformation, movement, and reuse of nutrients in ecosystems as nutrient cycling (Rahman et al. 2013). Nutrient cycling can be broken down into specific elemental cycling such as with the phosphorus and nitrogen cycles or it can be generalized and looked at on a broad level with the understanding that there are numerous elements at work. The nitrogen, carbon and phosphorus cycles play especially prominent roles in most ecosystems (Rahman et al., 2013).

The general model of nutrient cycling in forests as described by Attiwill and Adams (1993), has three components: (1) The input of nutrients into the ecosystem in rain and dust by

biological fixation and the output of these nutrients in stream water and in gaseous forms; (2) The transfer of nutrients between plant and soil including uptake and return to the soil by leaching, litter and root turnover, and by death of individuals; and (3) The internal redistribution of mobile nutrients such as nitrogen. Forest nutrient cycling is largely controlled by climate, large annual and seasonal fluctuations of soil fertility, and root production, and could be strongly affected by climatic events such as drought and soil frost (Cote et al., 1998). Rates of mineralization, in particular nitrification, generally increase after major, single disturbances, such as after forest dieback, after logging, after the addition of fertilizer or herbicide treatments, after fires and especially, after a combination of these events (Attiwill and Adams, 1993), all of which could also strongly affect the whole nutrient cycle.

Litter decomposition is a major pathway through which organic and inorganic compounds for the nutrient cycling processes are provided and returned to the natural ecosystem (Chen et al., 2015). Ground vegetation in sparse open stands can make a substantial contribution to total litter fall in the stand, but litter from the trees is generally the largest natural source for the inflow of organic material and nutrients to the forest floor (Rahman et al., 2013). Soil microorganisms decay the litter in order to gain nutrients and energy for their growth and reproduction and during this decomposition processes convert the C structures of fresh residues into transformed C products in the soil (Rahman et al., 2013) for use by plants.

Soil pH is a “master” variable (Kogelmann and Sharpe, 2006) when determining the availability of nutrients to plants. Different elements are available at different pH levels. Not only do nutrients move through the environment and organisms, but also nutrients themselves move to locations within the soils and can be replaced such as the case with Manganese (Mn) by other elements. Mn exchanges readily with Ca, Mg and monovalent cations (Kogelmann and Sharpe, 2006), or they can be leached out of the soil into the atmosphere in gaseous form or into the watersheds.

2.4.2 Decomposition of Leaf Litter

In many ecosystems, especially in arctic and alpine ecosystems, plant productivity largely depends on the nutrients returned from litter to soil (Chen et al., 2015). The rate of decomposition is influenced by at least three general factors: the composition and activity of the decomposer community, the quantitative traits of the litter, and the physicochemical environment (Rahman et al., 2013). Attiwill and Adams (1993) state the two most important factors affecting the rate of decomposition are climate and the quality of litter in terms of its susceptibility to attack by decomposers. The environment, what materials are included in the litter, if the litter is single or multi-species litter, the chemical compositions of the litter, and the thickness of the litter layer are also important factors. However, Rahman et al. (2013) explain chemical composition is one of the main factors controlling decomposition rate and quality of litter and becomes a better determinant of decomposition rates than that of climate (Rahman et al., 2013). Litter quantitative traits are often linked to physical and chemical characteristics such as leaf toughness, leaf mass per unit area, lignin content, tannin, and total phenolics (Rahman et al., 2013). Chen et al. (2015) suggest that even if the chemical composition of the litter is known, the decomposition of multi-species litter is more complex than single species litter because of complex interactions. Plant material with chemical compounds that stimulate decomposition may interact with litter with chemical compounds that reduce decomposition.

Leaves with low leaf mass per unit area and with high nutrient content decompose most rapidly, leading to increased carbon and nutrient cycling (Rahman et al., 2013). Cellulose plays a major role in N immobilization where it breaks down very rapidly and has a high C:N ratio, where plant litter of low C:N ratios were more susceptible to decomposition and mineralization (Rahman et al., 2013). Lignin concentration in leaves has been used as an index of organic-matter quality, with negative correlations being reported between lignin concentration and decomposition rates (Rahman et al., 2013). Rahman et al. (2013) state lignin is one of the most slowly decomposing components of dead vegetation, contributing a major fraction of the material that becomes humus as it decomposes. Lignin and N control carbon dioxide production and N mineralization in soils (Rahman et al., 2013). Litter with high lignin and low N concentration has slower decomposition rate and immobilizes more N than litter with low lignin and high N content (Rahman et al., 2013; Finzi et al., 1998).

Litter with high C:N ratio also decomposes more slowly than litter of low C:N or low lignin: N ratios (Finzi et al., 1998).

C and N turnover in forests is dependent upon the species composition of the forests because species differ widely in their effect on N availability (Finzi et al., 1998). Virtually all the N in tree leaves is in organic form, and studies of the release of nutrients from decomposing forest litter demonstrate that N is immobilized during the first stages of the decomposition process (Attiwill and Adams, 1993). The effects of tree species on surface soil C and N dynamics can occur over short time scales. However, subtle differences in the rate of litter decomposition spanning temporal scales of decades to centuries can lead to large differences in organic matter accumulation and the C and N content of the soils (Finzi et al., 1998). C:N and lignin: N ratios of leaf litter are typically lower in sugar maple, white ash (*Fraxinus americana*, L.) and red maple, than that of beech (*Fagus*, L.), red oak (*Quercus rubra*, L.) and hemlock (*Tsuga* L.) (Finzi et al., 1998). According to a study conducted by Finzi et al. (1998) on six tree species, the C and N pools on the forest floor were lowest beneath the sugar maple and the highest under the hemlock. C:N ratios were lower under the sugar maple, red maple and white ash than that of the beech, red oak and hemlock with the opposite being true of midsummer rate of net N mineralization, which was also positively correlated with the rate of net nitrification and nearly twofold greater (Finzi et al., 1998). Finzi et al. (1998) found there was no difference in forest floor mass between the two study sites, but significant differences were observed under the various tree species, with sugar maple having the lowest and hemlock with the highest. There were no differences in soil bulk density.

Phenolic compounds may influence rates of decomposition as they bind to the N components in the leaves forming compounds that resist decomposition (Rahman et al., 2013). It has been suggested that because the bulk of phenolic compounds remain present during leaf senescence and after death, these compounds may negatively affect microbial decomposers, which would delay microbial decomposition of the plant litter (Rahman et al., 2013). However, phenolic substances can comprise a substantial pool of C substrates

in the soil, which could potentially increase microbial activity and result in short-term immobilization of N. Phenolic compounds can reduce soil nutrient availability either indirectly by stimulating microbial N immobilization or directly by enhancing physical protection within the soil. Thus, phenolic-rich plants could negatively affect the growth of nearby plants by restricting N supply (Rahman et al., 2013). Attiwill and Adams (1993), discuss studies showing allelochemicals including tannins, phenols and volatile terpenoids that are capable of inhibiting N mineralization, particularly nitrification, in a wide variety of forest soils. These allelochemicals may come from the decomposing litter or be exuded from the roots growing in the soil.

Rahman et al. (2013) mention that litter tannins specifically may play an important role in decomposition and nutrient cycling as leaves high in initial condensed tannins seem to decompose slowly in both terrestrial and aquatic ecosystems. They suggest the tannin content may deter invertebrate shredders in the aquatic ecosystems, especially where condensed tannins deter herbivore feeding by acting as toxins. Condensed tannin released from litter may react with N compounds in the soil to form recalcitrant complexes capable of retarding N mineralization (Chen et al., 2015). Tannins may limit litter decomposition in five main ways according to Kraus et al. (2003): by themselves being resistant to decomposition, by sequestering proteins in protein-tannin complexes that are resistant to decomposition, by coating other compounds (e.g. cellulose) and protecting them from microbial attack, by direct toxicity to microbes, and by complexing or deactivating microbial exoenzymes. Tannins may also reduce insect predation because they increase the toughness of the leaves (Rahman et al., 2013). Hemlock litter, for example, is known for high tannic acid content, which reduces its rate of decomposition (Finzi et al., 1998).

2.4.3 Tree Root Interactions with Soil

Trees typically have between four and eleven major woody roots originating from the “root collar” and grow horizontally through the soil (Perry, 1982). Fine roots are concentrated in the litter layers and the surface soils (Attiwill and Adams, 1993). Fine root production is associated with two groups of variables: soil fertility (mineralized N and extractable P) and

physical soil environment (moisture and temperature) (Cote et al., 1998). Cote et al. (1998) state that root growth has been widely referenced as responding positively to soil P fertility and negatively to soil N fertility. Attiwill and Adams (1993) state there is an abundance of evidence that roots of many herbaceous and woody species exude compounds, which have the capacity to solubilize compounds containing nutrients. In particular, P would otherwise be of low availability to plants (Attiwill and Adams, 1993). Where root growth responds poorly to soil N fertility, high levels of N mineralization may cause less small root growth, whereas high levels of extractable P could be associated with increased small root growth after canopy development (Cote et al., 1998). The “feeder roots” are part of the fine root system (Perry, 1982) that collect the nutrients and water from the soil and deliver it to the rest of the tree. The non-woody root systems of different trees often intermingle with one another so that the roots of 4 to 7 trees can occupy the same square meter of soil surface (Perry, 1982) competing for water and nutrients. Surface layers of soils often dry out and are subjected to extremes of temperature, frost heaving (Perry, 1982) as well as other weather. The delicate, non-woody root systems are killed frequently by the fluctuations in the soil environment, but new roots grow back rapidly after injuries (Perry, 1982) making the root system ever changing. Broadleaved forests show a decrease in the rate of root turnover with increasing litter-fall and return of N from plant to soil in litter fall (Attiwill and Adams, 1993).

Frost action and the alternate swelling and shrinking of soils between wet and dry conditions can heave and break up the soil’s surface layers. This effect of the climate and the tunneling done by animals’ “fluff” the surface layers of undisturbed forest soil so that more than 50% of its volume can be pore space (Perry, 1982). This “fluffing” of the soil can positively influence the growth of roots by making the soil less compact and allowing the roots to grow out for greater distances and into deeper soil horizons. The breaking up of the soil and tunneling by organisms, is also a way for nutrients and water to move throughout the soil layers without mechanical incorporation. Duchesne et al. (2002) found in a study using 14 different sites that the mineral B horizons nutrient concentrations were on average 7 and 17 times lower than the humus nutrient concentrations for total N and exchangeable basic cations, respectively. These deeper nutrients, although in low

concentrations, would still be available to the trees which had roots deep enough to collect them.

2.4.4 Nitrate Leaching in Maple Stands

According to Lovett and Mitchell (2004), studies show that among the trees of the northern hardwood forests, sugar maples have unique characteristics that exert strong influences on nitrogen cycling and retention in forest watersheds. According to Lovett and Mitchell (2004), sugar maples do not readily take up nitrate. This adds evidence to why maple stands seem to leach nitrate so readily. The transition from conifer to hardwood-dominated forests lead to increases in net primary production and N availability due to the hardwood species having high intrinsic growth rates, high tissue N concentrations, and rapid rates of litter decomposition (Finzi et al., 1998). Research has shown that the sugar maple is more often associated with soils of high nitrification rates and nitrate productions than other dominant species in northern hardwood forests (Lovett and Mitchell, 2004). When compared to other deciduous tree species, sugar maples do not have unusually high nitrogen concentrations in the wood or foliage, but its litter is low in lignin and has a low lignin: N ratio, leading to high rates of decomposition (Lovett and Mitchell, 2004). This often leads to a low C:N ratio in the soil organic matter under maple stands and, consequently, to high rates of net nitrification (Lovett and Mitchell, 2004).

Forest stands high in sugar maple populations and pure sugar maple stands tend to have lower C:N ratio in the organic horizons of the soil, which is associated with elevated concentrations of nitrate in drainage waters. Lovett and Mitchell (2004) also found in their New York state experimental sites, there was a positive relationship between concentrations of nitrate in soil solution below the rooting zone and the abundance of maple trees. Nitrate below the root zone is generally considered an indicator of N loss from the forest ecosystem. The decomposing leaf litter under trees in the forests is known to bind positively charged cations and functions to trap plant nutrients and prevent their leaching into the deeper layers of the soil (Perry, 1982) and potentially out into the environment. Finzi et al. (1998) finding of lesser amounts of litter under maple trees supports the leaching

of nutrients from maple stands. Soils under sugar maples, studied in New York State, had the highest rates of net nitrification in laboratory incubations and highest levels of extractable soil nitrate when compared to soils associated with Beech, Hemlock, Red oak and Yellow birch (Lovett and Mitchell, 2004). Where sugar maples are considered “hydraulic lifters” that move water from deeper soil and release it into the surface soils at night, thus keeping the surface soils at a higher moisture level during dry periods, it may enhance soil microbial N cycling including nitrification (Lovett and Mitchell, 2004). Nitrate is the most mobile form of inorganic N in soils and is more readily lost from ecosystems by leaching into ground and surface waters (Lovett and Mitchell, 2004). If atmospherically deposited N is not retained by forest ecosystems but instead is leached through the forest to the surface waters, it can acidify soils, streams and lakes and pollute estuaries and coastal waters (Lovett and Mitchell, 2004).

2.5 MAPLE DECLINE AND SOIL NUTRITION

Decline refers to an irreversible, gradual deterioration of tree health resulting from a complex of biotic and abiotic casual factors that are conceptualized as predisposing, inciting, and contributing (Kogelmann and Sharpe, 2006). Understanding decline is difficult due to the complex array of stresses of which trees are exposed. Predisposing factors may have weakened the trees but may not ultimately be responsible for the dieback and mortality of trees (Kogelmann and Sharpe, 2006). Symptoms of crown thinning, decreased growth, and nutrient deficiencies have all been associated with the maple decline phenomenon (Bernier and Brazeau, 1988a,b, Ouimet and Fortin, 1992). Forest dieback and decline are considered two-phase processes in which environmental stresses first trigger crown dieback, which includes bud, twig, and branch mortality, and then trees decline and succumb to lethal attacks by a secondary action, normally held in check by vigorous trees (Bernier and Brazeau, 1988a, b). A combination of climatic factors, forest management, secondary insects and fungi, stand dynamics, poor soil quality due to low nutrients availability and aluminum toxicity (Duchesne et al. 2002) are all included in the many hypotheses and factors. Gradual loss of vigor, reduced growth rate, bud and branch death and increased susceptibility to secondary biotic and abiotic stresses are all part of maple

decline, but there is still considerable disagreement on the actual nature and causes of this decline (Duchesne et al. 2002).

Maple decline has been linked to both soil acidification and reduced tissue concentrations of base cations (Coughlan et al., 2000; Ouimet and Camire, 1995). Stress events such as defoliations, droughts, and extreme weather events have also been common themes around declines (Bailey et al., 2004). Nutrient deficiencies have also been linked to the decline of sugar maple stands in southeastern Quebec, to declines in spruce in southern Appalachians in the US, and to forest decline in Germany and other European countries (Ouimet and Camire, 1995). K plays a key role in the uptake and loss of water by trees and there is evidence that water relations are disturbed in declining sugar maples (Bernier and Brazeau, 1988a, b). Bernier and Brazeau (1988a, b) found that the most widespread visual symptoms of declining deciduous forest observed in the Quebec Appalachians were nutrient deficiencies of P or K or a combination of both. Ouimet and Camire (1995) state the most common deficiencies observed in declining maple stands in Quebec are K, P, Ca and Mg, with N deficiency being diagnosed very rarely. Studies have also shown that poor levels of base cation elements, including Ca, Mg and K, are predisposing factors for decline (Bailey et al. 2004). It was found that low soil Ca levels and Ca/Al ratio in the soil solution are responsible for maple decline and the reduction in root growth in Central Ontario (Ouimet and Camire, 1995). Kogelmann and Sharpe (2006) suggest excessive Mn may also play a role in observed decline and mortality of sugar maples as seen in northern Pennsylvania. Mn is a common soil element and an essential micronutrient for plants but is highly sensitive to changes in soil acidity and reducing conditions (Kogelmann and Sharpe, 2006). Mn can be toxic to plants through induced nutrient deficiencies, decreased photosynthesis and reduced yield and could be considered the second most important growth-limiting factor, after Al, in acid soils (Kogelmann and Sharpe, 2006). Excessive Mn in foliage has been associated with decreased net photosynthesis (St. Clair and Lynch, 2005), inhibited chlorophyll synthesis and chlorotic and necrotic spotting (Kogelmann and Sharpe, 2006). Attiwill and Adams (1993), claim foliar and soil nutrient imbalances, particularly those of N/Ca and N/Mg, are considered the primary cause of maple tree decline. Bernier and Brazeau (1988a, b) found that K deficiency (sometimes accompanied by an acute P

deficiency) influences the integrity of forest ecosystems and may play a significant role in the decline of deciduous forest in the Quebec Appalachians. One of the first signs of K deficiency in sugar maples observed was abnormal dark green colour of foliage and the tendency for the leaf to curl upward at the margin (Bernier and Brazeau, 1988a, b). Maple stands with foliar K levels less than 0.55% in July exhibited high levels of decline, while most stands with K in excess of 0.55% showed low levels of decline, suggesting that K deficiency influences the integrity of the forest ecosystem and play a significant role in the decline of the deciduous forests of the Quebec Appalachians (Bernier and Brazeau, 1988a, b). Bernier and Brazeau (1988a, b) also found that P deficiency remains an important feature of many declining stands in the deciduous forest of the Quebec St. Lawrence region. Ouimet and Camire (1995) conclude that relatively high soil Mg saturation, potential soil Al toxicity related to low Ca saturation, and unfavorable soil humus properties were strongly linked to the level of nutrient stress of sugar maples stands in the Quebec region.

Even with maples being tolerant to acidic soils, maple decline has been regularly correlated with low soil pH (Coughlan et al., 2000). In a study conducted by Wilmot et al. (1996) in the third years' growing season, trees in limed plots had significantly less crown dieback than that of the controls and fertilizer alone treatments. Fertilization with cations alone did not induce any significant change in pH or soil extractable P, K, Ca, Mg and Al concentrations when compared to the control plots. However, plots having the cation fertilizer with lime induced large changes in pH and extractable Ca after one growing season and soil extractable K also increased significantly, but at a slower rate than Ca over the four-year study. From years zero to three, dieback decreased significantly in plots treated with cations plus lime when compared to the control (there was no difference between controls and plot treated with cations alone). No K deficiency symptoms were noticed in the plots where lime was applied despite having a high Ca:K ratio.

The presence of mature sugar maples on declining sites indicates that at some point conditions were amenable to colonization, stand establishment and development (Kogelmann and Sharpe, 2006). It was suggested that the individual genotypes of the trees

might affect the tolerance limit to different nutrient deficiencies and stresses (Duchesne et al. 2002). However, there is the counter argument that the sites where decline is occurring are naturally unsuitable for sugar maples and the maturation of the forest may be causing the increased susceptibility to defoliation and other stresses (Kogelmann and Sharpe, 2006).

2.6 SUMMARY

Soil nutrition is an important, but sometimes overlooked, factor in maple stands and forest health and should be included in every management plan. The ability of sugar maple trees to tolerate a wide range of soil pH and nutrients results in many producers leaving the maple stands as a closed system. As a closed system, the forest relies on nutrient inputs from predominantly leaf litter decomposition and biological fixation. Though trees may survive in such a system, there is increasing evidence that soil nutrition management could be of benefit.

Deficiencies in nutrients such as potassium, phosphorus, and calcium are all linked to maple stand decline and may be addressed through fertilization programs. Such deficiencies seem to be exacerbated by increased soil acidity in forests and maple stands, which suggests liming may be of great benefit. However, fertilization and liming would have to be carefully controlled because the oversaturation of soils with nutrients, such as magnesium and manganese, can cause various problems such as nutrient inhibition and even the promotion of tree decline and dieback. As well, where sugar maple stands are already known to leach nitrates into the environment, adding even more nutrients may increase this issue.

Nutrient cycling is of great importance to the forest ecosystems not only in a natural setting, but also when used as production sites. When cycling of nutrients is impeded, altered or interrupted there can be devastating effects as seen by the issue of maple decline/dieback.

Although, still in debate over what the true cause is of this major problem for the maple and forest industries, nutrients seem to be at the forefront.

Sap flow and syrup yield are directly linked to each other with sap flow being related to tree health and the freeze-thaw cycle of the season. However, there is a great lack of information in relation to exactly how all environmental factors, physiological factors, climatic factors and producer activities could positively influence the overall sap yield.

2.7 OBJECTIVES AND HYPOTHESES

2.7.1 Research Question

The aim of this research is to discover if soil, plant and climatic factors affect Nova Scotia's maple sap and syrup yield. This research will also investigate factors which may determine why Nova Scotia maple trees seem to have the lowest average yield per tap of the other maple producing regions.

2.7.2 Objectives

The specific objectives of this study are to:

- 1) Identify temporal and spatial differences in soil and tissue nutrition in sugar maples in the maple producing regions of Nova Scotia (Antigonish, Colchester, Cumberland, Halifax, Kings, Lunenburg, and Pictou counties).
- 2) Uncover the relationships between various soil and tissue nutrients with maple sap yield and flow across the experimental sites.
- 3) Establish any effect of associated vegetation on maple sap flow and yields in Nova Scotian sugar bushes.
- 4) Determine which environmental and climatic factors affect maple sap flow and yields in Nova Scotia.

2.7.3 Hypotheses

It is hypothesized that:

- 1) There is great variability in soil and tree nutrient status between the maple producing regions of Nova Scotia. Tree nutrient status will reflect soil nutrient characteristics.

- 2) Soil and tree mineral nutrient status, as well as moisture content, will be similar between the 2 Cumberland sites, between Colchester and Halifax, between Lunenburg and Kings, and between Antigonish and Pictou, but they will be vastly different between these 4 groupings.

- 3) There is a positive relationship between soil moisture and sap yield, but a negative relationship between soil moisture and sugar content. The soil and tree nutrient status will play a positive role in sap yield, but the heavy metal concentrations will negatively impact sap yield.

- 4) Associated vegetation will have a negative relationship with yield and sap sugar content.

- 5) Certain climate factors will have mixed effects on sap sugar and yield; specifically factors that encourage growth will promote yields while those imposing stress will decrease yields.

- 6) Site related factors such as longitude, latitude, slope, etc., play no role in affecting the yield or sugar content.

CHAPTER 3 – GENERAL METHODOLOGY

3.1 EXPERIMENTAL SITE DESCRIPTION

Ten experimental sites (Fig 1) around mainland Nova Scotia were set up based on intensity of maple production in the region and producer cooperation. Specific details related to each site are shown in Table 1. Each of the ten research locations were divided into two blocks, an “A” and “B”, based on site characteristics. Five trees in each block were randomly selected (i.e. 10 trees per site), to account for a total of one hundred trees being included in this study. Trees were chosen at random with consideration being giving to the below factors:

- Trunk size: trees needed to be no less than 50cm in circumference at breast height.
- Trunk health: no splits or rot in the sampling zone(s) or close to the sampling zone(s).
- Branch height: leaves need to be within reach of a researcher with pole pruners.
- Tapping potential: trees need to be those that would be tapped by the producer in future seasons (i.e. correct size, health, and species).

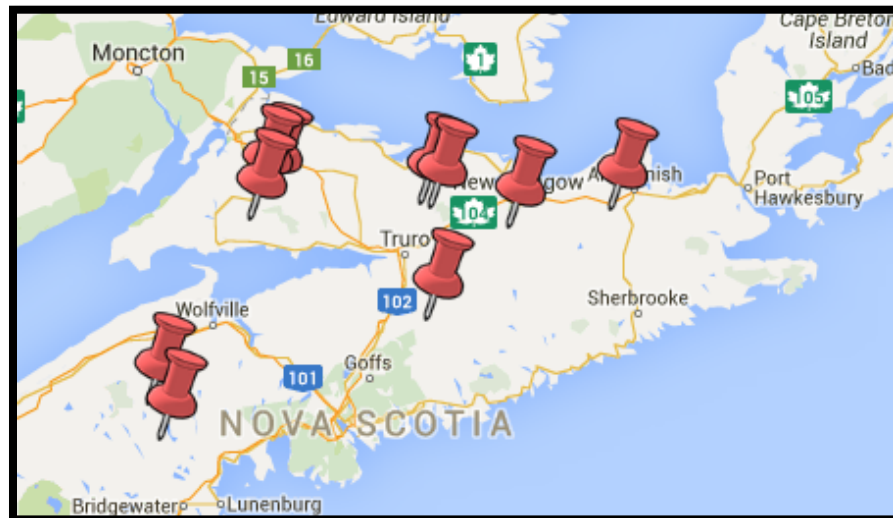


Figure 1. Map of Nova Scotia displaying locations of research sites.

Table 1. Site-specific information and producer size based on number of taps.

Site	Approx. Age of trees (years)	Approx. Years in Production	Number of Taps 2016	Number of Taps 2017	Soil type	Latitude	Longitude	Average Slope
Anti	50+	18a, 8b	11500	11000	Thom	45°32.2'N	-62°6.7'W	Slight
Colc1	50+	7	1200	1600	Wyvern	45°33.2'N	-63°10.5'W	Slight
Colc2	70+	25	8350	8500	Wyvern	45°32.7'N	-63°7.2'W	Medium
Cumb1	120+	32+	31500	33000	Rodney	45°35.6'N	-64°3.4'W	Flat
Cumb2	90+	9	31500	33000	Rodney	45°34.8'N	-64°5.2'W	Slight
Cumb3	50+	7	12000	17000	Cobequid	45°29.7'N	-64°7.9'W	Flat
Hali	50+	16	2210	2225	Queens	45°5.9'N	-64°8.9'W	Flat
King	90+	5a, 4b	60000	60000	Bridgewater	44°46.2'N	-64°42.8'W	Medium
Lune	90+	7a, 17b	3500	3000	Wolfville	44°37.4'N	-64°38.4'W	Flat
Pict	n/a	n/a	n/a	n/a	Woodbourne	45°27.7'N	-62°40.4'W	Steep

*Research site soil types were determined using Perennia's CanSIS Soils of Nova Scotia Database: Nova Scotia Soils Series Map. Accessed March 23, 2025. [Nova Scotia Soils Series Map - Interactive Web Map](#)

3.2 SOIL

3.2.1. Soil Moisture Content (%)

A FieldScout TDR 300 (Spectrum Technologies, Inc., Aurora, IL) moisture probe meter was used to measure the soil moisture content. Five readings were taken under each tree, between the trunk and dripline. The five readings were averaged to account for variability in soil under the trees. Measurements were taken once a month unless the experimental blocks became inaccessible (i.e. snow or frost). Readings were taken roughly between the hours of 9am and 3pm, at a depth of roughly 15cm.

3.2.2. Soil Moisture Potential (kPa)

Watermark soil sensors (The Irrrometer Company, Inc., Riverside, CA) were placed one per tree, under the canopy dripline, roughly 10cm deep, to measure soil moisture potential. The sensors were read once a month, after the initial installation and stabilization of the sensor in the environment. Readings were taken roughly between the hours of 9am and 3pm.

3.2.3. Soil Nutrition

Soil samples were taken monthly from each block (A and B) at each location, until the soil became frozen or buried under snow. Two soil cores from under each tree were gathered and mixed thoroughly and sent for analysis to the Harlow Analytical Laboratory, Bible Hill, Nova Scotia. Cores were removed from the ground between the trunk and the dripline, at approximately 15cm in depth. Analysis for P₂O₅, K₂O, Ca, Mg, Na, S, Al, B, Cu, Fe, Mn, Zn, and CEC was completed using the Mehlich III analysis (Mehlich, 1984). Organic matter was determined with loss on ignition (Donald and Harnish, 1993).

3.3 TREE CHARACTERISTICS

3.3.1. Trunk Circumference (cm)

A flexible field tape was used to measure the trunk girth, at approximately 1.5 meters above the ground. Measurements were taken once a month.

3.3.2. Core Nutrition

A 16” tree borer was used to core roughly to the middle of each tree, at approximately 1.5 meters above the ground. Cores from each of the 100 trees to be included in the study were removed in June of each of the two experimental years. A single core, from a randomly selected tree, from both the “A” and “B” blocks of each location was also taken every other month (August, October, December, February and April). Samples were dried at 80°C for 72 hours, cut into ~1cm sections and ground using a bead mill. Ground samples were sent to the Harlow Analytical Laboratory on Dalhousie Agricultural Campus for analysis. Analysis for N, Ca, K, Mg, P, Na, B, Cu, Fe, Mn, and Zn was completed as described by AOAC 990.03 Protein (Crude) in Animal Feed, Combustion Method 2002 (Total Nitrogen) (TruSpec CN Carbon Nitrogen Determinator Instruction manual. Version 2.5x, May 2011. LECO Corporation).

3.4 LEAF CHARACTERISTICS

3.4.1. *Leaf Area Index (LAI)*

The LAI-2000 Plant Canopy Analyzer (LI-COR Environmental, Nebraska, USA) was used to take readings of the tree canopy densities. Readings were taken at four locations under the drip line of the canopy around each tree being measured. The one quarter opening cover was used to reduce the field of view and reduce the possible inclusion of canopies from other trees. Readings were taken monthly starting in June and ending when all leaves had fallen from the selected trees.

3.4.2. *Leaf Nutrition*

Leaf samples were taken from trees 1, 2 and 3 from blocks A and B. Samples consisted of a cluster of 3-4 leaves on a single branch collected from 3 to 4 different locations in the canopy using pole pruners. Samples contained both leaves and petioles, which were dried at 80°C and sent to Harlow Analytical Laboratory on the Dalhousie Agriculture campus. Samples were taken bi-monthly starting in June and ending when leaves became unobtainable from the trees in October or November. Analysis on samples was completed for N, Ca, K, Mg, P, Na, B, Cu, Fe, Mn, and Zn as described by AOAC 990.03 Protein (Crude) in Animal Feed, Combustion Method 2002 (Total Nitrogen) (TruSpec CN Carbon Nitrogen Determinator Instruction manual. Version 2.5x, May 2011. LECO Corporation).

3.5 ENVIRONMENTAL FACTORS

3.5.1. *Site Weather*

Data was collected from the government stations located nearest the research sites (Table 2). Data on maximum temperature (°C), minimum temperature (°C), mean temperature (°C), heating degree days (the number of days which the average temperature of a day is below 18°C), cooling degree days (the number of days which the average temperature of a day is above 18°C), total precipitation (mm), and depth of snow on ground (cm) on last day of the month, were gathered. The data was downloaded from the Government of

Canada historical climate database. (http://climate.weather.gc.ca/historical_data/search_historic_data_e.html).

Table 2. Weather stations where data was gathered for each research location.

Research Location	Weather Station Name	Latitude	Longitude
Antigonish	Tracadie	45.61	-61.68
Colchester 1 & 2	Tatamagouche	45.68	-63.23
Cumberland 1, 2 & 3	Nappan Auto	45.76	-64.24
Halifax	Upper Stewiacke RCS	45.23	-63.06
Kings & Lunenburg	Greenwood A	44.98	-64.92
Pictou	Lyons Brook	45.66	-62.80

3.5.2. Latitude, Longitude, Elevation & Slope

A handheld Garmin eTrex20 GPS (Garmin, Lenexa, KS) unit was used to mark the location of each of the 100 trees in the study. The unit was held at about 1.25 meters above the ground with the top of the unit touching the tree to gather the data.

3.5.3. Tree Competition/Density

A 10m x 10m quadrat was set up to estimate site density of maple trees and other competing species. The quadrat included at least one of the study trees. One quadrat was taken in each experimental site block (A and B). Any tree or shrub measuring greater than 1 meter was counted and identified using various keys and photos of trees of Nova Scotia. Tree competition/density counts were completed in the month of April 2016.

3.5.4. Associated Vegetation

Five 1m x 1m quadrats were taken in each block (A and B) to identify the vegetative competition in each location. The quadrat was randomly placed by walking a rough “W-shaped” path between the experimental trees of the specific block. Paths created by producers/workers were avoided. Species in the undergrowth were identified using various identification keys and photos of wild plants found in Nova Scotia forests. The species were broken down into 11 categories based on prevalence among the sites: Grass clumps (all types of grass), ferns (all types of ferns), total other (all small, non-woody plants, often

called “weeds”), total tree seedlings (all types of tree seedlings less than 1.5 meters in height), total stems (inclusive of all individual plant stems), scrub brush (unidentified woody plants, bushes, shrubs, smashed trees that were not of upright growth), evergreens (all evergreen trees), other hardwoods (trees greater than 2 meters, not inclusive of maples), small maples (maples under 1.5 meters in height), large maples (maples greater than 1.5 meters), and total trees (all trees excluding seedlings).

For larger plants (>5cm) each individual stem was counted by hand. For smaller plants (<5cm) the quadrat was divided into quarters, stems were counted and then multiplied by 4 to estimate the total population of the quadrat. Associated Vegetation measurements were completed only once in August of 2016, due to the shortened timeline of the project.

3.6 SAP CHARACTERISTICS

3.6.1. *Sap Flow and Yield*

A graduated sample collection unit was created using 20L food grade pails with covers, 1-liter graduations, ratchet straps, sap tubing, and tubing joints. Sap was gathered using gravity fed mechanisms, not vacuum. Producers were responsible for monitoring the sap flow every 2 to 5 days, depending on flow. The producers recorded the amount of sap to the nearest quarter of a liter. The date and time of observations were recorded, and the unit was emptied, “resetting” the measurement to zero. Producers installed the units for the first sap run and uninstalled the units on the last sap run. Sap flow was calculated as liters per hour, based on hour of day when the measurement was taken and the amount of sap in the bucket for each individual tree.

3.6.2. *Sap Nutrition*

Sap samples were collected from 3 trees per site (6 at each research location) after the initial “sap run” immediately following the installation of the collection unit (early sap collection) and at the end of the season with the hopes of getting the “last run” or close to the “last run” of the season. Two samples were taken from each tree, with one sample being sent to Harlow Analytical Laboratory, Bible Hill, NS, for Greenhouse II water analysis.

Analysis was completed for pH (SMEWW (22nd Edition) 4500 H⁺B), CEC (SMEWW (22nd Edition) 2510B), Ca, K, Mg, P, B, Cu, Fe, Mn, and Zn (Mineral Analysis by ICP-OES*). The second sample was used for brix analyses completed using an ATAGO digital pocket refractometer, model PAL-S (ATAGO USA Inc., Bellevue, WA).

3.7 STATISTICAL ANALYSIS

Correlation and regression analysis was completed between all factors measured in relation to sap flow and yield. Repeated measures analysis was then used to measure changes in response variables with respect to time in months. Tukey's means separation test was used for mean separation. Minitab version 17 was used to run the analysis, with significance being assessed at a level of 5%. Marginal significance was included from $0.05 \leq P \leq 0.10$, to reduce the risk of missing significant factors due to only having two field seasons.

CHAPTER 4 – SOIL FACTORS INFLUENCING SAP YIELD & FLOW

4.1 SOIL MOISTURE

Using the previously mentioned techniques (Chapter 3), soil moisture was found to significantly affect average sap flow and sap yield (Table 3). The soil moisture in both August and September for both years of the study exerted a significant negative influence on average yield with the highest r-value consistently showing in August (Table 3). This showed that a higher soil moisture content in these months would predict a lower yield in the coming sap season. Where the moisture was measured in the soil, it may be that the tree wasn't able to uptake the moisture for various reasons thus limiting the trees internal stores as it heads into the preparation for dormancy.

Table 3. Pearson correlations between monthly % soil moisture, sap flow, and yield. All values are significant at $P \leq 0.05$. The dashes (--) represent non-significance. There were no correlations of marginal significance ($0.05 \leq P \leq 0.10$).

Factor	Year 1 (2015-16)		Year 2 (2016-17)	
	Avg Flow	Yield	Avg Flow	Yield
Soil Moisture (Jun)	--	--	0.255	--
Soil Moisture (Aug)	--	-0.459	--	-0.354
Soil Moisture (Sept)	--	-0.401	--	-0.342
Soil Moisture (Oct)	--	--	0.287	--
Soil Moisture (Mar)	--	-0.506	--	--

The highest overall correlation was found to be between soil moisture in March and yield for the first year. Soil moisture data was not collected in March of the second year due to snow on the ground and ice, making it so a second-year relationship could not be analyzed. March data for the first year was also incomplete for the same reason and only Anti, Colc2, Hali and Pict sites had data, which could explain the higher r-values. As shown in figure 2, 2016 was a drier year than that of 2015 which would also explain the higher values.

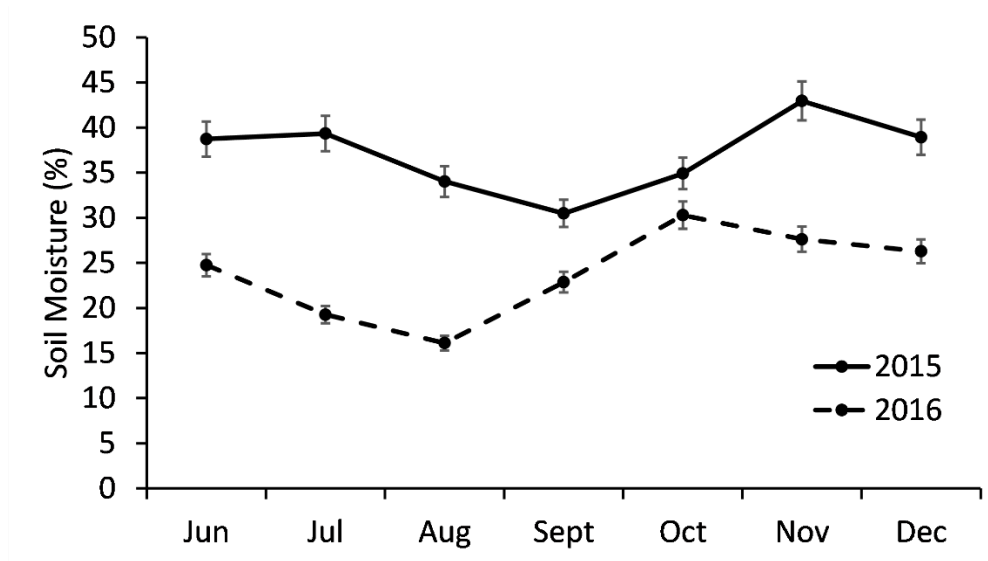


Figure 2. Comparison of mean monthly soil moisture for 2015 and 2016. Each data point represents the average of all sites included in study.

Figure 3 displays higher soil water potential in year one than in year two, with September being a slight exception with lower soil water potential. Soil water potential in August showed a significant relationship with yield in the following year and a marginal significant relationship with yield in September of year one, however there was no significance in year two (Table 4). Soil water potential declined from July in year one, whereas the decline initiated in October in year two. June water potential of year one cannot be accurately judged as this was when the sensors were installed, and the sensors had not equalized to the soil moisture after being prepared for installation. The trees experienced the highest (less negative) soil water potential in October of both years. The decline in soil moisture in August had a significant influence on sap yield in the first year.

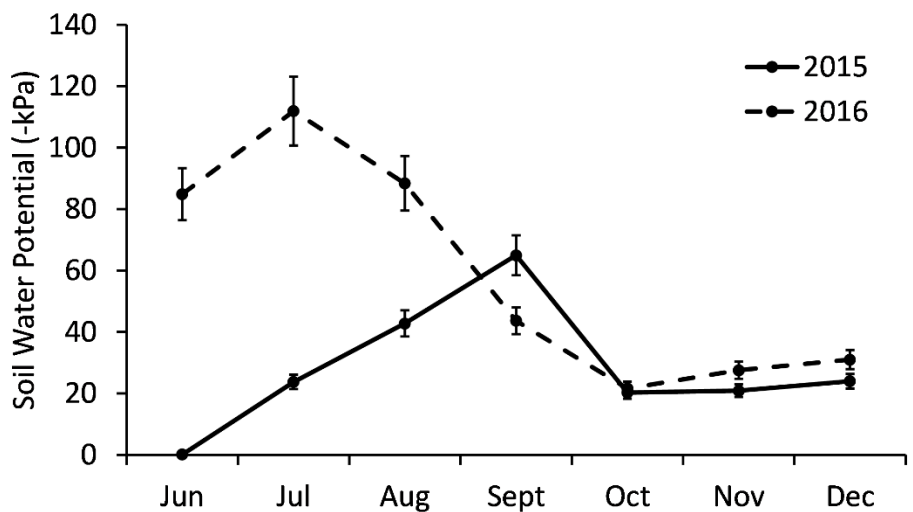


Figure 3. Comparison of soil water potential between June to December of 2015 (2015-2016 tapping season) and 2016 (2016-2017 tapping season).

Table 4. Correlation coefficients between water potential, sap flow, and yield. Significant values ($P \leq 0.05$ are highlighted in grey), marginally significant values ($0.05 \leq P \leq 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash.

Factor	Year 1 (2015-16)		Year 2 (2016-17)	
	Avg Flow	Yield	Avg Flow	Yield
Watermark (Aug)	--	0.267	--	--
Watermark (Sept)	--	0.245	--	--

4.2 SOIL NUTRIENTS

Analysis on the collected soils showed significant differences between soil organic matter, pH, Ca, Mg, Na, Al, Fe, Mn, Zn, Cu, S, K₂O and CEC and the site at which they were collected (all at $p < 0.001$). There were also significant differences between the month of collection and soil K₂O ($p < 0.001$), Na ($p < 0.006$), Al ($p < 0.041$), Fe ($p < 0.021$), Mn ($p < 0.020$), CEC ($p < 0.005$) and P₂O₅ ($p < 0.001$). While the individual differences between sites were noteworthy, the goal of this project was to look at the relationship between soil nutrition and influence on sap flow.

Various significant correlations between soil nutrients, within months, with regards to yield and average sap flow (Table 5) were found. There were significant variations in the level and the strength of relationship among the nutrient elements and sap yield (Table 5). Zinc

displayed significance in relation to yield over both years in September, August and October, and significant/marginal significance in July. Iron showed significance in relation to yield in both years during July, September and October, and significance/marginal significance in August. The highest level of significant correlation existed between soil Zn levels in May and June, and the average sap flow and yield. In general, soil Zn had the highest influence (negative) on average sap flow and yield in year one. While in year two, soil Fe in June and July held the highest significant relationship, also negative, which affected both average sap flow and yield (Table 5) with the soil Fe in July being the strongest relationship amongst all. Both soil Zn and Fe are significant regarding yield, in various other months in year one. All soil nutrients, except K, S, Cu, Mg, Al, were negatively correlated to sap yield. Nova Scotia is known to have acidic soils, and these maple sites were no exception. Fe and Zn become more available in lower pH soils (Boguta et al. 2019; Reddy et al. 1995). This relationship between pH and availability may cause toxic levels of these nutrients and degrade the tree health. Healthy trees allow for a faster sap recruitment rate (Moore et al. 2020) while poor tree health could result in poor sap flow (Wilmot et al. 1995). Soil OM and CEC had weak but significantly negative relationships. Soil S content in July and September displayed a marginally significant correlation over both years to sap yield (actual significance shows up in September of year one) (Table 5). Soil organic matter for August displayed high level of significance in year one, which negatively correlated to sap yield. However, in year two OM was positively correlated to yield, suggesting more years of data are needed for making any conclusions on the role of OM on sap yield. Soil nutrients played significant roles in sap flow in various months, but not in the same months over the two-year period.

Table 5. Correlation coefficients of monthly soil nutrients, average sap flow, and yield. Significant values ($P < 0.05$ are highlighted in grey), marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash.

Soil Nutrient	Year 1 (15-16)		Year 2 (16-17)		Soil Nutrient	Year 1 (15-16)		Year 2 (16-17)	
	Flow	Yield	Flow	Yield		Flow	Yield	Flow	Yield
P (Jun)	--	--	-0.278	--	Al (Sept)	--	0.437	--	--
K (Jun)	--	--	--	0.278	Fe (Sept)	-0.257	-0.260	--	-0.511
S (Jun)	--	--	--	0.269	Zn (Sept)	-0.305	-0.557	--	-0.302
Cu (Jun)	--	--	--	0.274	OM (Oct)	--	--	-0.281	--
Fe (Jun)	--	-0.244	--	-0.614	P (Oct)	--	0.252	-0.356	--
Zn (Jun)	-0.296	-0.575	--	--	Mg (Oct)	-0.262	-0.253	--	--
CEC (Jun)	--	-0.288	--	--	S (Oct)	--	0.381	--	--
P (Jul)	--	--	-0.354	--	Al (Oct)	--	0.322	--	--
K (Jul)	--	--	0.245	--	Fe (Oct)	--	-0.296	--	-0.520
S (Jul)	--	0.250	--	0.241	Zn (Oct)	-0.291	-0.577	--	-0.404
Cu (Jul)	--	--	0.343	0.349	Mg (Nov)	-0.273	-0.251	--	--
Fe (Jul)	-0.245	-0.399	--	-0.687	Al (Nov)	--	0.301	--	--
Zn (Jul)	-0.259	-0.543	--	-0.242	Fe (Nov)	-0.238	-0.470	--	--
CEC (Jul)	--	--	--	-0.371	Zn (Nov)	-0.270	-0.450	--	--
OM (Aug)	-0.270	-0.296	--	0.306	OM (Dec)	--	-0.306	--	--
OM (Sept)	-0.270	-0.249	--	--	K (Dec)	--	-0.269	--	--
P (Sept)	--	--	-0.329	--	Ca (Dec)	--	-0.249	--	--
Mg (Sept)	--	--	0.298	--	Mg (Dec)	--	-0.324	--	--
K (Sept)	--	--	-0.360	--	S (Dec)	--	0.296	--	--
S (Sept)	--	--	-0.378	--	Fe (Dec)	--	-0.285	--	--
OM (Sept)	--	--	0.351	--	Zn (Dec)	-0.245	-0.477	--	--
Fe (Aug)	--	-0.248	--	-0.600	CEC (Dec)	-0.244	-0.351	--	--
Zn (Aug)	-0.249	-0.458	--	-0.327	S (Apr)	--	0.351	--	--
CEC (Aug)	-0.307	--	--	--	Al (Apr)	--	0.371	--	--
OM (Sept)	--	--	-0.261	--	Fe (Apr)	-0.268	-0.314	--	--
P (Sept)	--	--	-0.259	-0.248	Zn (Apr)	--	-0.459	--	--
Mg (Sept)	-0.253	-0.269	--	--	Al (May)	--	0.250	--	--
K (Sept)	--	--	0.328	--	Zn (May)	-0.296	-0.589	--	--
S (Sept)	--	0.324	--	0.244					

CHAPTER 5 – THE RELATIONSHIP BETWEEN VARIOUS TREE
PHYSIOLOGICAL FACTORS & SAP FLOW & YIELD

5.1 TRUNK CIRCUMFERENCE

Over the two year the study, there was no significant change in the trunk circumference at any location. Lunenburg and Cumberland 1 sites had the largest average trunk size, with Lunenburg having a much larger average than the rest (Fig 4). Kings and Pictou County sites had the smallest average trunk size of trees included in the study (Fig 4).

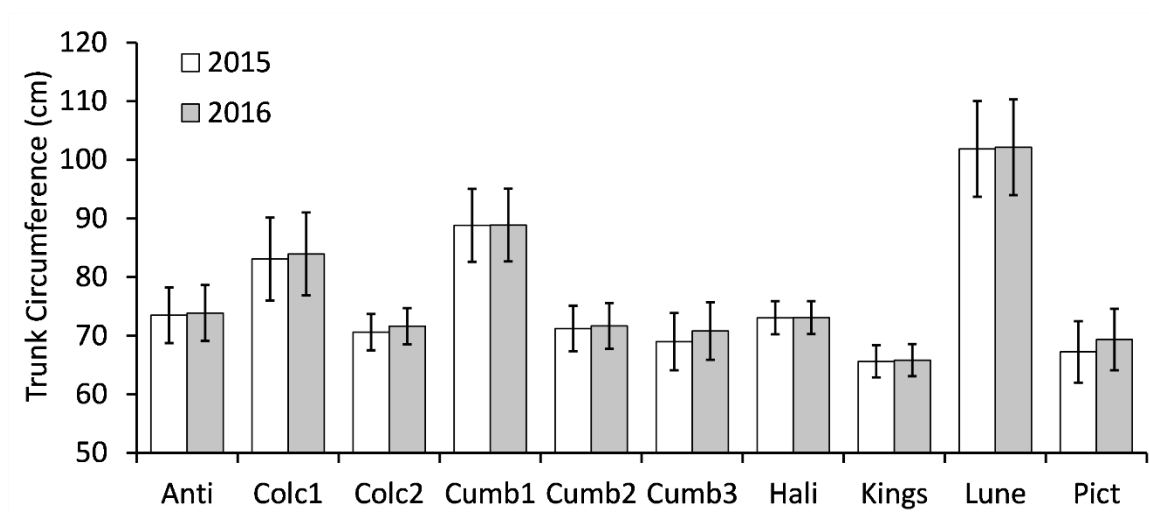


Figure 4. Tree trunk circumference at each site in 2015 and 2016. Error bars represent standard error.

Surprisingly, the trunk size was not significantly correlated to yield but was significantly correlated with average sap flow for both years (Table 6). It appears that the larger the tree trunk, the greater the average sap flow. This trend can be seen across both year one and year two. It can also be noted that there appears to be a trend between slope and tree girth. Where larger trees seem to grow on flatter lands and greater slopes lead to trees of smaller girth (Table 6). This could be due to the idea that flatter lands hold moisture and nutrients more easily as they would run down the slope and gather on the flatter land (Zhang et al 2016).

Table 6. Correlation coefficients between trunk size, average sap flow and yield. All values are significant at $P < 0.05$. The dashes (--) represent non-significance. There were no correlations of marginal significance ($0.05 < P < 0.10$).

Factor	Year 1 (2015-16)		Year 2 (2016-17)	
	Flow	Yield	Flow	Yield
Avg Trunk	0.381	--	0.286	--
Slope	--	-0.218	--	-0.218

5.2 CORE NUTRIENTS

Nutrients found in the core tissue were analyzed with significant differences found between month and core N, Ca, K, P, Fe, Mn and Zn content (all at $p < 0.001$). There were also significant interaction effects between sample year and site for all the previously listed nutrients (also all at $p < 0.001$). This informs us that the nutrients at each site behaved differently depending on the year which was most likely due to the microclimate at the individual site and tree location/environments. Weather data were collected from weather stations located within the region of the site, but not at the exact site or at each individual tree. Tissue nutrients are gathered from the nutrients that move through the tree mostly coming from the roots, which is affected by the solubility of nutrients, available moisture, temperature, and many other factors (Baligar et al. 2001).

Core nutrients had various levels of influence on both sap flow and yield between the two study years. Amongst all, core Zn in Dec, August and February had the highest, significant negative influence on sap yield while core K in October had the highest significant positive relationship amongst all for sap yield. All other nutrients had either low or marginally low influence on average flow and yield (Table 7). August N, Zn and to a marginal extent K all had significant correlations in both years one and two on yield, as did December Zn and Februarys K, Mg and Fe concentrations. The two strongest correlations were with core Zn in August and December, where their average r-values were -0.461 and -0.411, respectively (Table 7). August N and February Mg both had significant positive relationships in year one with yield but switch to significant negative correlations in year two. The reverse can be stated for February K and Fe, where year one displays a negative correlation and year two had positive (Table 7). This suggests that there may be an interactive effect between

these four core nutrients and some other unknown factor. Ca content of the core tissue in October proved to have a significant positive correlation with sap flow over years one and two of the study.

Table 7. Correlation coefficients between core nutrients and average sap flow and yield. Significant values ($P < 0.05$ are highlighted in grey), marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash.

Core Nutrients	Year 1 (15-16)		Year 2 (16-17)		Core Nutrients	Year 1 (15-16)		Year 2 (16-17)	
	Flow	Yield	Flow	Yield		Flow	Yield	Flow	Yield
N (Jun)	--	--	--	-0.437	Mn (Dec)	--	0.376	--	--
Fe (Jun)	--	--	--	0.249	N (Dec)	--	--	0.471	0.368
P (Jun)	-0.344	--	--	--	P (Dec)	--	--	--	0.291
Mn (Jun)	--	0.246	--	--	Zn (Dec)	--	-0.302	--	-0.519
N (Aug)	--	0.414	--	-0.414	Ca (Feb)	0.466	--	--	--
K (Aug)	0.342	0.246	--	0.246	K (Feb)	-0.246	-0.308	--	0.322
Fe (Aug)	--	-0.286	--	--	Mg (Feb)	--	0.308	-0.463	-0.572
Mg (Aug)	--	--	--	-0.501	Fe (Feb)	--	-0.268	0.331	0.502
P (Aug)	--	--	--	-0.246	P (Apr)	--	-0.294	--	--
Zn (Aug)	-0.241	-0.365	--	-0.556	Zn (Feb)	--	--	--	-0.557
N (Oct)	0.272	--	--	--	N (Apr)	--	--	-0.379	-0.428
Ca (Oct)	0.317	--	0.272	--	Ca (Apr)	--	--	0.481	--
K (Oct)	0.294	--	--	0.572	K (Apr)	--	--	--	-0.308
Mg (Oct)	--	--	-0.249	0.261	Mg (Apr)	--	--	--	-0.252
Mn (Oct)	--	0.353	--	--	Fe (Apr)	--	-0.396	--	0.237
Ca (Dec)	--	0.255	--	--	Zn (Apr)	--	--	0.253	--
Mg (Dec)	--	--	-0.258	--					

5.3 LEAF AREA INDEX

As shown in figure 5, there were variations in canopy density between sites for both years of study. These variations showed not only between sites, but also between the summer/fall of the two years as well (Fig. 6). In summer/fall of 2015, Halifax, Kings and Lunenburg sites had the highest LAI, with Pictou and Cumberland 3 the lowest. In the second year Cumberland 3 and Pictou still had the lowest LAI, but Colchester 1 and 2 had the highest (Fig 5). It can also be noted that the canopies appear to be less variable in density in the second season (Figs 5 & 6).

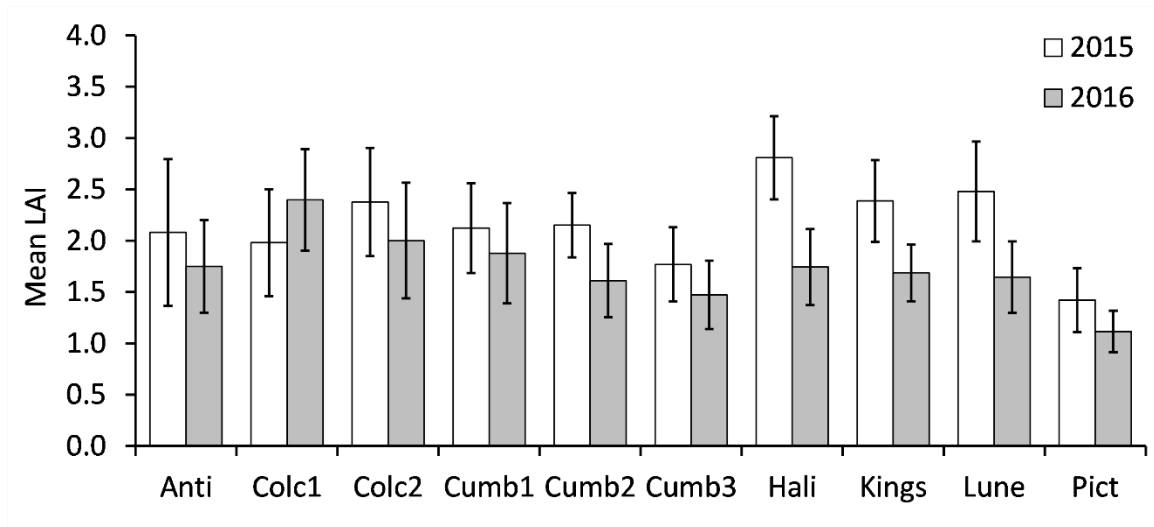


Figure 5. Leaf area index at study sites in 2015 and 2016.

The canopy was denser in the first year of the study and held more of its leaves later into fall (Fig 6). This could have been due to the greater amount of soil moisture present in the 2015 summer/fall season. It could also be as simple as the fall of 2016 having higher winds than that of 2015. There were significant interaction effects between month and research location, experimental year and research location and experimental year and month (all at $p < 0.001$) on LAI.

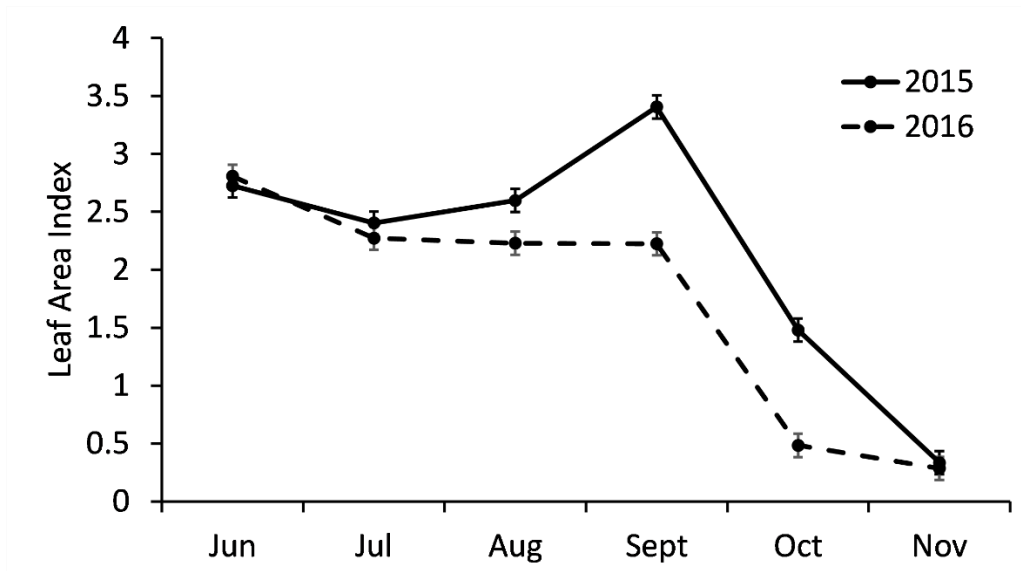


Figure 6. Comparison of leaf area index between summer and fall of 2015 (2015-16 tapping year) and 2016 (2016-17 tapping year).

Although there were no significant correlations that existed consistently over the two years of the study between LAI and yield or LAI and average sap flow, there were significant relationships with yield that appeared in four (Table 8) of the six months where trees had their foliage. This suggests a potential trend might exist if additional years of LAI and sap yield would have been observed. The data suggests that July LAI is negatively but significantly correlated with yield. Significant negative correlations were noted between August and September in year one and the average sap flow and yield in year two (Table 9). This suggest that the foliage from the summer two years prior to a tapping season may affect the average flow and yield.

Table 8. Correlation coefficients between leaf area index, average sap flow, and yield. Significant values ($P < 0.05$ are highlighted in grey), marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash.

Month of LAI	Year 1 (2015-16)		Year 2 (2016-17)	
	Flow	Yield	Flow	Yield
LAI (Jun)	--	--	--	-0.359
LAI (Jul)	-0.246	-0.400	--	--
LAI (Sept)	--	--	--	-0.395
LAI (Nov)	--	--	--	0.341
No. Months LAI > 0	-0.244	--	--	--

Table 9. Correlation coefficients between leaf area index in year 1 related to sap flow and yield in year 2. Significant values ($P < 0.05$ are highlighted in grey), marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash.

Month of LAI	Avg Flow	Yield
LAI (Jun)	--	0.253
LAI (Aug)	-0.259	-0.287
LAI (Sept)	-0.272	-0.312

5.4 LEAF NUTRITION

Significant differences in nutrients were found in the leaf tissue between year and leaf N ($p < 0.001$), Ca ($p < 0.009$), Na ($p < 0.006$), and Mn ($p < 0.052$). Significant differences were also found between month and leaf N, Ca, Mg, B, Cu, and Mn (all at $p < 0.001$). Research site proved to be significant for leaf N, Ca, Mg, B, Mn ($p < 0.001$), and Cu ($p < 0.003$). There were also significant interaction effects between sample year and month on leaf P ($p < 0.022$), K ($p < 0.027$), Fe ($p < 0.003$) and Zn ($p < 0.001$), sample month and site on leaf P ($p < 0.024$), Fe ($p < 0.001$) and Zn ($p < 0.038$) and sample year and site on leaf Fe ($p < 0.033$) and Zn ($p < 0.042$).

Amongst all, both leaf Zn (Jun, Aug) and Fe (Jun) showed the highest level of significance for both years for sap yield. The strength of relationships between other leaf nutrients and sap yield was weak. The content of Zn in leaf tissue in June showed a significant negative correlation with yield, with a similar trend noted with the June Fe content leaf Fe content, as well. The relationship was weaker as it was only significant in year two, with marginal significance in year one. The marginal significance could be due to the greater moisture in year one, which may have caused some leaching or another interaction of some type. Regardless, the relationship was still present and negative. The sap flow also had a significant negative trend, which was affected by the content of Mg in June leaf tissue (Table 10).

Table 10. Correlation coefficients between leaf nutrients, average sap flow, and yield. Significant values ($P < 0.05$ are highlighted in grey), marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash.

Leaf Nutrient	Year 1 (2015-16)		Year 2 (2016-17)	
	Flow	Yield	Flow	Yield
Leaf Mg (Jun)	-0.358	--	-0.267	-0.261
Leaf P (Jun)	--	--	--	-0.271
Leaf B (Jun)	0.285	--	--	--
Leaf Cu (Jun)	--	--	--	-0.256
Leaf Fe (Jun)	--	-0.240	--	-0.493
Leaf Mn (Jun)	--	0.253	--	--
Leaf Zn (Jun)	--	-0.397	--	-0.403
Leaf N (Aug)	-0.275	-0.270	--	--
Leaf Ca (Aug)	0.255	--	--	--
Leaf Fe (Aug)	-0.092	-0.249	--	--
Leaf Cu (Aug)	--	--	0.445	--
Leaf Mn (Aug)	--	--	--	0.293
Leaf Zn (Aug)	--	-0.467	--	--
Leaf Ca (Oct)	0.290	--	--	--
Leaf B (Oct)	0.267	--	--	--

CHAPTER 6 – ROLE OF ENVIRONMENTAL FACTORS ON MAPLE FLOW

6.1 SITE WEATHER

Weather is an extremely unpredictable factor, which provides a wide range of variability to a study. Great variability was expected with research sites located in various regions of Nova Scotia, some more than 300km apart. Despite that, significant correlations were found between sap flow and yield for the following seven weather parameters: average monthly maximum temperature, average monthly minimum temperature, average monthly mean temperature, total heat degree days, total cool degree days, total precipitation, and total snow on the ground.

The monthly average maximum temperature in February 2016 had a positive correlation with sap flow for both years of the study, with the same being observed between April 2016 average maximum temperature and sap yield (Table 11). The March 2016 average minimum temperature also played a significantly positive role in maple sap yield (Table 12) over the course of the two years.

The average monthly mean temperature in October 2015 displayed a significant negative correlation with the sap yield (Table 13). Where the average mean temperature in February 2016 had a significant positive relationship in year one with sap flow but exhibited only a marginally significant relationship in year two (Table 13). This may have been caused by the variation in the weather between years and site-specific weather.

Table 11. Correlation coefficients between average maximum monthly temperature and average sap flow and yield. Significant values ($P < 0.05$) are highlighted in grey), marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash. Months with no significance in flow or yield are no shown.

Month	Year 1 (2015-16)		Year 2 (2016-17)	
	Flow	Yield	Flow	Yield
June 2015	--	--	--	0.419
July 2015	--	--	--	0.417
Sept 2015	0.255	--	--	--
Nov 2015	--	-0.252	--	--
Jan 2016	--	-0.273	--	--
Feb 2016	0.338	--	0.291	--
Apr 2016	--	0.271	--	0.496
May 2016	n/a	n/a	0.240	--
Aug 2016	n/a	n/a	--	0.334
Oct 2016	n/a	n/a	0.336	--
Nov 2016	n/a	n/a	0.285	--
Feb 2017	n/a	n/a	0.259	--
Mar 2017	n/a	n/a	--	0.414
Apr 2017	n/a	n/a	--	0.440

Table 12. Correlation coefficients between average minimum temperature and average sap flow and yield. Significant values ($P < 0.05$) are highlighted in grey), marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash. Months with no significance in flow or yield are no shown.

Month	Year 1 (2015-16)		Year 2 (2016-17)	
	Flow	Yield	Flow	Yield
Oct 2015	--	--	--	-0.300
Feb 2016	--	--	--	0.366
Mar 2016	--	0.277	--	0.433
Sept 2016	n/a	n/a	--	-0.314

Table 13. Correlation coefficients between monthly mean temperature and average sap flow and yield. Significant values ($P < 0.05$ are highlighted in grey), marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash.

Month	Year 1 (2015-16)		Year 2 (2016-17)	
	Flow	Yield	Flow	Yield
June 2015	--	--	--	0.357
July 2015	--	--	--	0.337
Oct 2015	--	-0.287	--	-0.316
Feb 2016	0.290	--	0.242	0.278
Mar 2016	--	--	--	0.353
Apr 2016	--	--	--	0.357
Mar 2017	n/a	n/a	--	0.330
Apr 2017	n/a	n/a	--	0.349

Correlations were run for the months of June 2015 to April of 2016 on sap yield and average flow for year one (sap data was collected February, March, and April of 2016). Correlations were also run for months of June 2015 to April 2017 on sap yield and average flow for year 2 (sap data collected February to April of 2017). Total HDD had significant trends with both average sap flow and sap yield. Average sap flow had significant negative correlations in November 2015, December 2015 and February 2016 and significant/marginal significant relationships with June 2015, October 2015 and January 2016 (Table 14). HDD days appear to lower the yield and average sap flow as the relationship between them were all negative (Table 14). HDD calculated up to April 2016 showed a significant relationship consistently for two years for yield, of which it was much stronger in year two than year one. Total HDD for March also gave a significant negative trend for yield for both sap seasons (Table 14). This would suggest that a low HDD would promote greater flow or movement of sap through the tree by being warmer during the day (Tyree 1983). Overall, April HDD had the strongest relationship regarding yield with average r-value, between the two years, being -0.362, which would indicate warmer day time temperature influencing the temperature flux which would directly affect the root pump which controls sap flow (Tyree 1983). The greatest correlation, consistent over the two years of the study, with average flow was displayed by the HDD present as of November 2015. However, December 2015 and February 2016 also displayed consistent negative relationships with the stronger relationships with sap flow of year one (sap ran from late February to early April 2016) (Table 14).

CDD did not have the same level of influence on either average sap flow or yield. Total CDD of October 2015 was the only month where there was a relationship for both years, with a significant negative correlation in year two to sap yield and only a marginal significant correlation in year one (Table 15).

Table 14. Correlation coefficients between heating degree days, average sap flow and yield. Significant values ($P < 0.05$ are highlighted in grey), marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash.

Month	Year 1 (2015-16)		Year 2 (2016-17)	
	Flow	Yield	Flow	Yield
June 2015	-0.249	--	-0.367	--
July 2015	--	--	--	-0.496
Oct 2015	-0.289	--	-0.251	--
Nov 2015	-0.392	--	-0.311	--
Dec 2015	-0.380	--	-0.311	--
Jan 2016	-0.336	--	-0.252	-0.255
Feb 2016	-0.375	--	-0.300	--
Mar 2016	--	-0.274	--	-0.445
Apr 2016	-0.284	-0.291	--	-0.432
May 2016	n/a	n/a	-0.255	--
Aug 2016	n/a	n/a	--	-0.468
Nov 2016	n/a	n/a	-0.279	--
Mar 2017	n/a	n/a	-0.311	--
Apr 2017	n/a	n/a	--	-0.259

Table 15. Correlation coefficients between cooling degree days, average sap flow and yield. Significant values ($P < 0.05$ are highlighted in grey), marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash.

Month	Year 1 (2015-16)		Year 2 (2016-17)	
	Flow	Yield	Flow	Yield
Aug 2015	-0.274	-0.252	--	--
Oct 2015	--	-0.245	--	-0.351

Monthly total precipitation displayed significance for yield over the two years in July 2015, December 2015 and January 2016, with the greatest relationship being in January 2016 (Table 16). Both July 2015 and January 2016 had negative correlations, with December 2015 displaying a positive correlation (Table 16) to sap yield. March 2016 also had a

positive correlation with yield showing marginal significance in year one and significance in year two suggesting that higher total precipitation in the July and January preceding the sap seasons may factor into lower sap yields for the current season as well as the next season. While Stern et al. (2023) found that moisture was positive to growth during the growing season, it was also noted moisture outside the seasonal norm could be detrimental. This might not be linked only to excess moisture which could cause water logging, run off, and other negatives to aerobic factors but due to the lack of sunlight during rainy periods as sunlight is widely known to be essential to growth and over all environmental health. Excess moisture can also lead to adverse health effect such as rot and mold which may influence tissue and soil health. However, the data suggests if December (with potential for March) has a higher total precipitation sap yield may be higher in the two following seasons. This positive correlation could be due to the precipitation falling in winter typically being in the form of snow/ice, which is discussed in detail later in the results. Average sap flow was significantly, negatively correlated with the total precipitation in November 2015 over both years (Table 16). Average sap flow also showed a trend in relation to February 2016 total precipitation, with a negative but significant relationship in year one and marginal significance in year two (Table 16). This suggests that higher total precipitation in November and potentially February, leading up to tapping, may contribute to low sap flow. All relationships existing over both years, displayed greater strength toward the year two sap season (late February 2017 to early April 2017) than that of year one sap season (late February 2016 to early April 2016) (Table 16).

Table 16. Correlation coefficients between monthly total precipitation, average sap flow and yield. Significant values ($P < 0.05$ are highlighted in grey), marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash.

Month	Year 1 (2015-16)		Year 2 (2016-17)	
	Flow	Yield	Flow	Yield
June 2015	-0.276	0.259	--	--
July 2015	--	-0.328	--	-0.384
Aug 2015	--	0.241	--	--
Nov 2015	-0.371	--	-0.280	-0.296
Dec 2015	--	0.325	--	0.375
Jan 2016	--	-0.432	--	-0.439
Feb 2016	-0.311	--	-0.246	--
Mar 2016	--	0.246	0.252	0.538
Apr 2016	--	--	--	0.316
May 2016	n/a	n/a	0.268	--
Jun 2016	n/a	n/a	--	-0.442
Jul 2016	n/a	n/a	--	-0.258
Aug 2016	n/a	n/a	-0.295	-0.371
Oct 2016	n/a	n/a	0.255	-0.333
Nov 2016	n/a	n/a	--	-0.383
Feb 2017	n/a	n/a	0.259	--

Total snow present on the ground was broken out from total precipitation as it can be looked at as a separate factor. Snow can accumulate in one individual month or accumulate over many, and it may melt in the same fashion (i.e. melt at various rates either in the same month as it accumulated or over numerous months) thus, affecting soil and plants in varying ways over time. Snow can also act as an insulator for the soil and anything below the snow line, as well as a light reflector for everything above the top of the snow. Stern et al. (2022) discuss how snowpack positively influences tree growth and health, as well as protect the roots from damage. Snow present on the ground in December 2015 and January through April 2016 was significantly, positively correlated to yield over both years (Table 17). There was also a positive significant relationship between yield and snow on the ground in November 2015 for year one, and a marginally significant relationship for year two (Table 17). The strongest correlation was found between the amount of snow on the ground in January 2016 and yield, with an average r-value of 0.499. This could be due to many reasons of which the highest probability would be colder temperatures and the act of

snow being an insulator. Although we have not measured the depth of snow on the experimental sites, if there was snow on the ground the ground is frozen and not experiencing the great temperature fluctuations that occur from different day time temperature especially those influenced by sun exposure on bare soil (Comerford et al. 2013; Kurokawa et al. 2025). This insulating effect would allow the roots to stay in dormancy and not get “confused” with the normal seasonal flux. The insulation also protects root from the harsh conditions of winter (Comerford et al. 2013). Sap flow was also positively, significant correlated with the amount of snow present on the ground in October 2015 (Table 17).

Table 17. Correlation coefficients between monthly snow ground thickness, average sap flow and yield. Significant values ($P < 0.05$) are highlighted in grey, marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash.

Month	Year 1 (2015-16)		Year 2 (2016-17)	
	Flow	Yield	Flow	Yield
Oct 2015	0.359	--	0.283	--
Nov 2015	--	0.359	--	0.238
Dec 2015	--	0.435	--	0.371
Jan 2016	--	0.423	--	0.574
Feb 2016	--	0.455	--	0.412
Mar 2016	--	0.452	--	0.365
Apr 2016	--	0.397	--	0.346
Oct 2016	n/a	n/a	-0.301	-0.350
Dec 2016	n/a	n/a	--	0.331
Jan 2017	n/a	n/a	--	0.324
Feb 2017	n/a	n/a	--	0.333
Mar 2017	n/a	n/a	--	0.334
Apr 2017	n/a	n/a	0.374	--

6.2 SITE CHARACTERISTICS

There were many of differences between the ten research locations such as: region, tree size, canopy density, elevation, slope, latitude and longitude. As seen in figure 7, there is a wide range of elevations with Colchester 1 having the highest average elevation and Pictou having the lowest. There was no significant relationship spanning the two years between site elevation, sap flow and yield. Slope also did not display a consistent significant trend between the two years (Table 18).

There was a positive significant correlation between yield and site longitude, where the yield increased the further west, the site was located in Nova Scotia. This may be related to the site's proximity to the ocean, where the more westerly sites were further inland, and the ocean is a known temperature modulator. For example, eastern sites such as Antigonish and Pictou were less than 20km from the ocean. In comparison, more western sites such as Halifax, Lunenburg, and Kings were greater than 35km from the ocean. Thus, the more inland a site was the greater the temperature fluctuations may have been between freezing and thawing/warming allowing for greater yields. The temperature fluctuation would also influence the other periods of the yearly tree's cycle, such as the growing season. Another possible explanation might be the regionally specific weather, where the more westerly sites often see much different weather than those more easterly due to the typical storm and pressure system paths (i.e. site receiving snow versus rain, the overall amount of precipitation received, or getting a weather event vs. not getting the event). Year two had a stronger correlation (r-value of 0.468) to longitude than that of year one (r-value of 0.260) (Table 18).

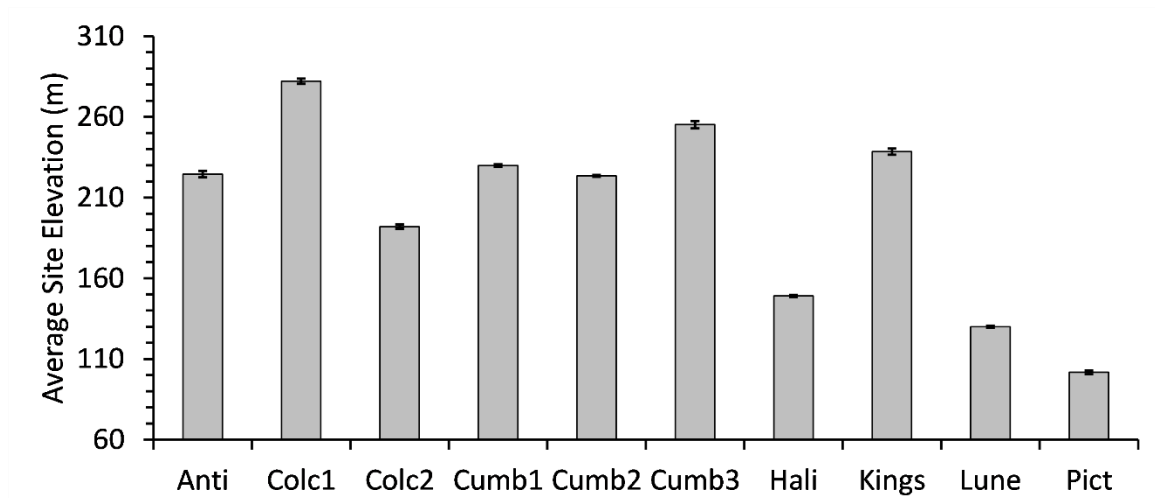


Figure 7. Average site elevation for all 10 research locations.

Table 18. Correlation coefficients between various site characteristics, average sap flow and yield. Significant values ($P < 0.05$ are highlighted in grey), marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash.

Site Characteristic	Year 1 (2015-16)		Year 2 (2016-17)	
	Flow	Yield	Flow	Yield
Elevation	-0.285	--	--	--
Slope	--	-0.370	--	--
Longitude	--	0.260	--	0.468
Latitude	--	--	--	-0.357

CHAPTER 7 – SAP CHARACTERISTICS RELATED TO SAP FLOW AND YIELD

7.1 SAP NUTRIENTS

Data were collected over two tapping seasons during the spring of 2016 (year one) and spring of 2017 (year two). Figure 8 depicts the collection units graduated to one-liter increments.



Figure 8. Installed graduated sap collection unit.

Significant differences in sap nutrients and other factors were found in relation to study year, research site and sap run. Sap run was broken down into an early run (initial sample) or late run (last sample gathered from collection unit). There were significant 3-way interactions between experimental year, research site and sap run on sap brix ($p < 0.001$), pH ($p < 0.001$) and P ($p < 0.031$). Significant interactions were also noted between research site and run on sap Ca ($p < 0.006$), K ($p < 0.005$), Mg ($p < 0.032$) and Zn ($p < 0.011$), research site and year on sap Ca ($p < 0.046$), K ($p < 0.001$), Mg ($p < 0.014$), Mn ($p < 0.035$) and Zn ($p < 0.001$) and experimental year and run on sap Ca ($p < 0.015$), K ($p < 0.007$), Mg ($p < 0.039$), Mn ($p < 0.036$) and Zn ($p < 0.001$).

7.2 SAP FLOW & YIELD

Sap flow varied amongst the sites and between the two years. Year one showed Pictou and Cumberland 3 had the highest average sap flow, whereas Pictou and Colchester 1 had the highest average sap flow in year two (Fig 9). Antigonish and Colchester 1 saw the sites

greatest change between years one and two, where the Antigonish location had a large decrease in flow rate and Colchester 1 had a large increase (Fig 10). There was a significant interaction between site and year on average flow rate ($p < 0.001$). The significant interaction was caused by the fact that sap flow in year two decreased in all sites except Colchester 1 and Cumberland 2. A significant interaction effect was noted between research location and experimental year on average flow rate ($p < 0.025$).

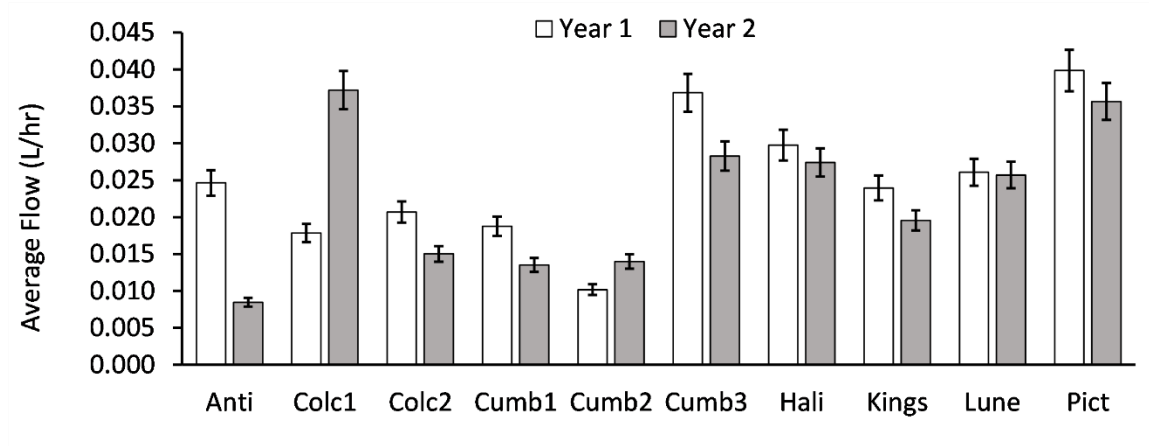


Figure 9. Average flow across research sites. Error bars represent standard error.

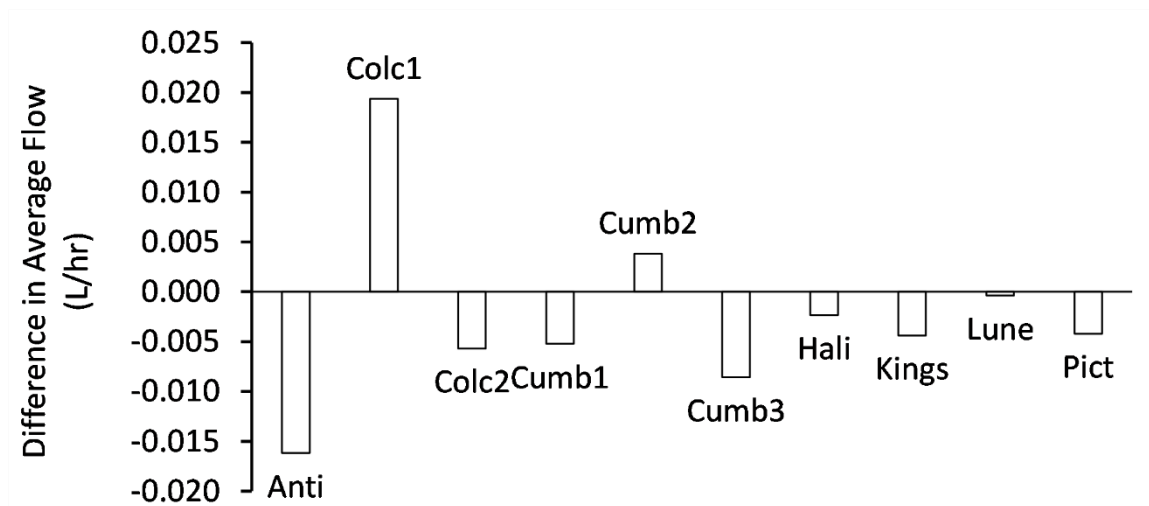


Figure 10. Difference in average flow at research locations between study years (year 2 minus year 1). A positive difference denotes a greater yield in year 2, whereas a negative difference shows higher sap flow in year one.

There was no significant correlation between recorded flow days (days of data collection by producer) and yield or flow. The number of days data were collected by the producers for this study on sap flow and yield was fairly consistent between the two years. However, seven of the ten locations had fewer data collection days in year two (Fig 11). Generally, Halifax, Pictou and Antigonish locations had the lowest number of flow days, with Cumberland and Colchester counties having higher flow days. Across all sites, it was reported that most of the production trees were tapped earlier than those included in the study and were untapped later than those in the study. Thus, the trees included in the study had a shorter sap flow season than the other trees in production in the maple bush. This was most likely due to producer comfort and time availability with data collection.

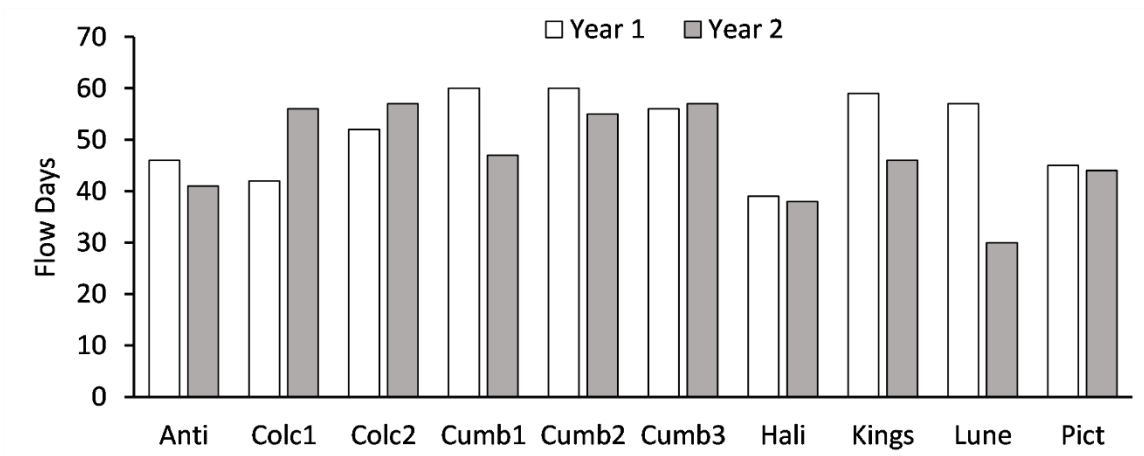


Figure 11. The number of sap flow days at each location from the time the sap collection unit was installed to when it was removed, for each year of study.

The largest difference in tapping days was noted in Lunenburg, Cumberland 1 and Kings locations with a drop in days and an increase in days at Colchester 1 (Fig 12). Although, total flow days recorded did not play a significant role in this study, sap yield had a significant positive correlation with average sap flow (Table 19).

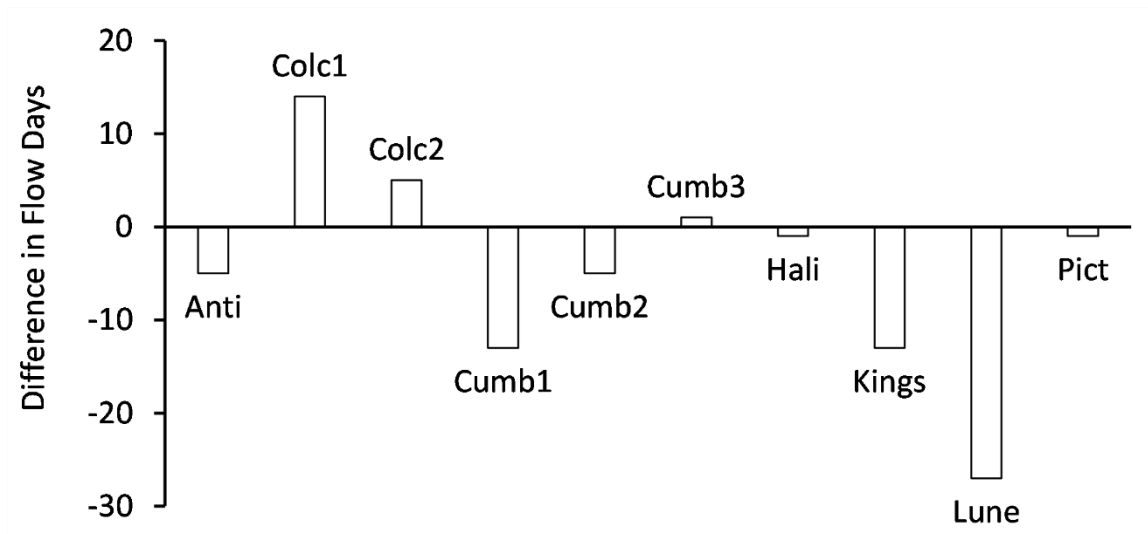


Figure 12. Difference in sap flow days between 2016 and 2017 tapping seasons.

Sap yield was also quite variable among the sites and between the two years of study. In general, the sap yield was 35% lower in year 2. Figure 13 shows the highest yields in year one coming from Cumberland 1 and 3, with the lowest in Colchester 1. Yields in Cumberland 1 and 3 were 123% and 146% higher, respectively, than Colchester 1. However, in year two, Cumberland 1 and Antigonish had the lowest yields while Kings and Cumberland 3 had 191% and 235% higher yields, respectively (Fig 13). There was an overall drop in yield, with the experimental trees at all sites between the yield in year one and that of year two, with Cumberland 1 seeing the most significant change and Cumberland 2 seeing relatively little drop in yield (Fig 14). There was also a significant interaction effect between research location and year on yield ($p < 0.001$).

Table 19. Correlation coefficients between average sap flow and yield in Year 1 and Year 2. Both values are statistically significant ($P < 0.05$). There were no correlations of marginal significance ($0.05 < P < 0.10$).

Factor	Flow (Year 1)	Flow (Year 2)
Yield	0.498	0.299

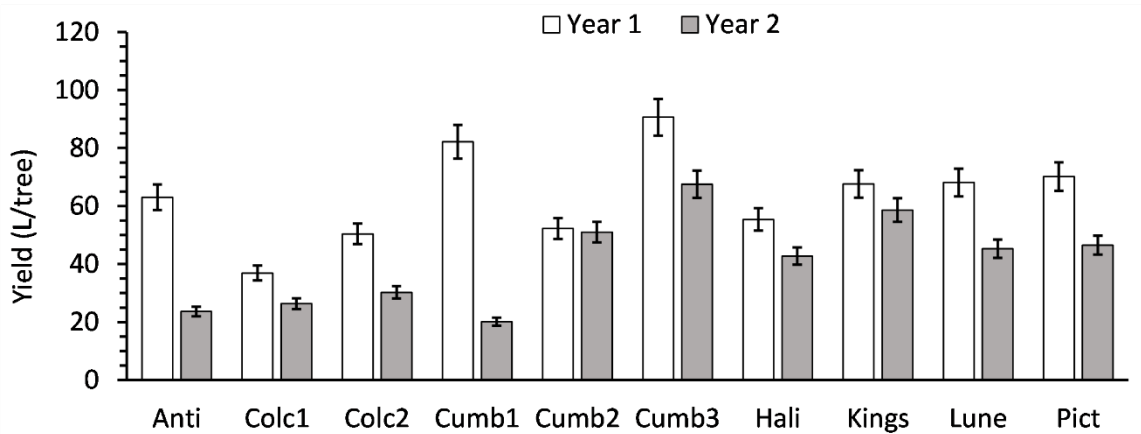


Figure 13. Comparison of total sap yield (L) collected from the research trees, at each site, from the two study years. Bars represent the average yield of the 6 research trees at each location and error bars represent the standard.

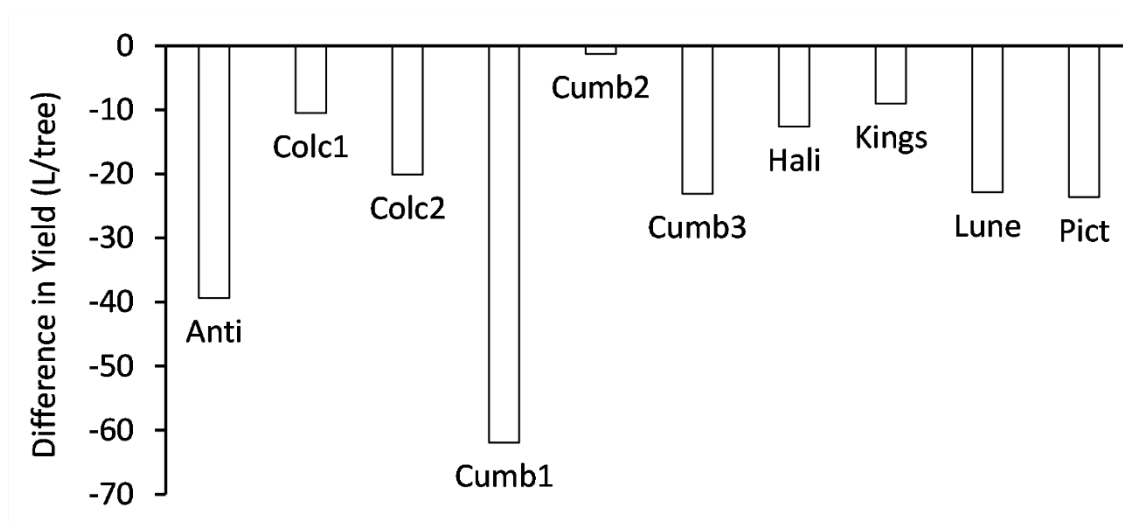


Figure 14. Difference in sap yield (L) between the 2016 and 2017 tapping seasons.

7.3 SAP NUTRITION

Maple sap is a complex and variable solution containing various concentrations of different nutrients and displaying different characteristics, which may be dependent on tree physiology, location, soil nutritional status, soil moisture status, and weather. More research is required to discover the exact link. However, out of all the sap characteristics only the pH of the initial sample, or the first run sample, showed significance over the two years (Table 20). There was a significant negative correlation between yield and the pH of

the initial sap sample collected in the tapping season of each year. The greater the pH for the initial sample, the lower the yield. With the average pH of samples being 7.23 in year one and 6.80 in year two, then becoming more acidic as the season progressed. No nutrients, brix, CEC or final pH demonstrated significant correlations over both years (Table 20).

Table 20. Correlation coefficients between sap nutrients, average sap flow and yield. Significant values ($P < 0.05$ are highlighted in grey), marginally significant values ($0.05 < P < 0.1$) are not highlighted, and non-significant values ($P > 0.10$) are indicated with a dash.

Sap Nutrients	Year 1 (2015-16)		Year 2 (2016-17)	
	Flow	Yield	Flow	Yield
pH (1st)	-0.330	-0.254	--	-0.521
K (1st)	--	0.285	--	--
P (1st)	--	--	--	0.296
Zn (1st)	--	0.302	--	--
Brix (2nd)	--	--	--	-0.261
EC (2nd)	--	--	--	-0.254
Mg (2nd)	--	--	--	-0.254

CHAPTER 8 – INFLUENCE OF ASSOCIATED VEGETATION ON MAPLE FLOW & YIELD

8.1 SAP FLOW

In a shared environment interactions exist between organisms for nutrients, moisture, light, space, etc. that influence growth and physiological processes. The maple bush is home to many species of plants and animals related to its region. Significance was discovered between sap flow and density of other plants sharing the same land, in relation to year 2 (Figure 15) as measurements were only taken in the 2016 summer season due to project timeline. Interestingly, there was a positive relationship where the greater density of trees resulted in higher sap flow. This could be an indication of environmental health or ideal growing conditions in the maple trees habitat. Understanding that healthy trees produced greater amounts of product, healthier trees grow best in healthy environments, and typically greater amounts of plants grown in healthy environments which are suited to meet their physiological needs. Another possible explanation would be plant-to-plant interactions by way of small trees signaling greater growth.

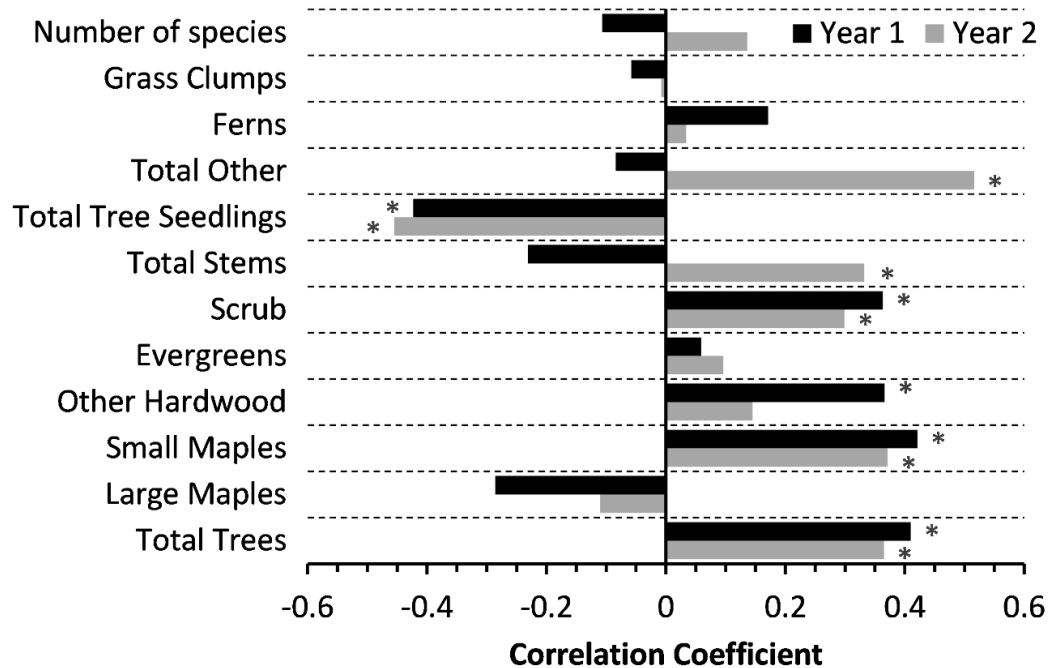


Figure 15. Correlation coefficients for several species growing in the sugar bush versus sap flow. A * indicates significance at $P \leq 0.05$.

There does appear to be an upper limit to this positive feedback, as there was a significant negative relationship found between total tree seedlings and sap flow (Figure 15 and 16), a possible indication of too much competition for resources, thus stressing the production trees resulting in lower flow. Although not significant, it is worth noting that the greater number of large maples follows this same negative trend (figure 15) and could prove significant given more data collection years.

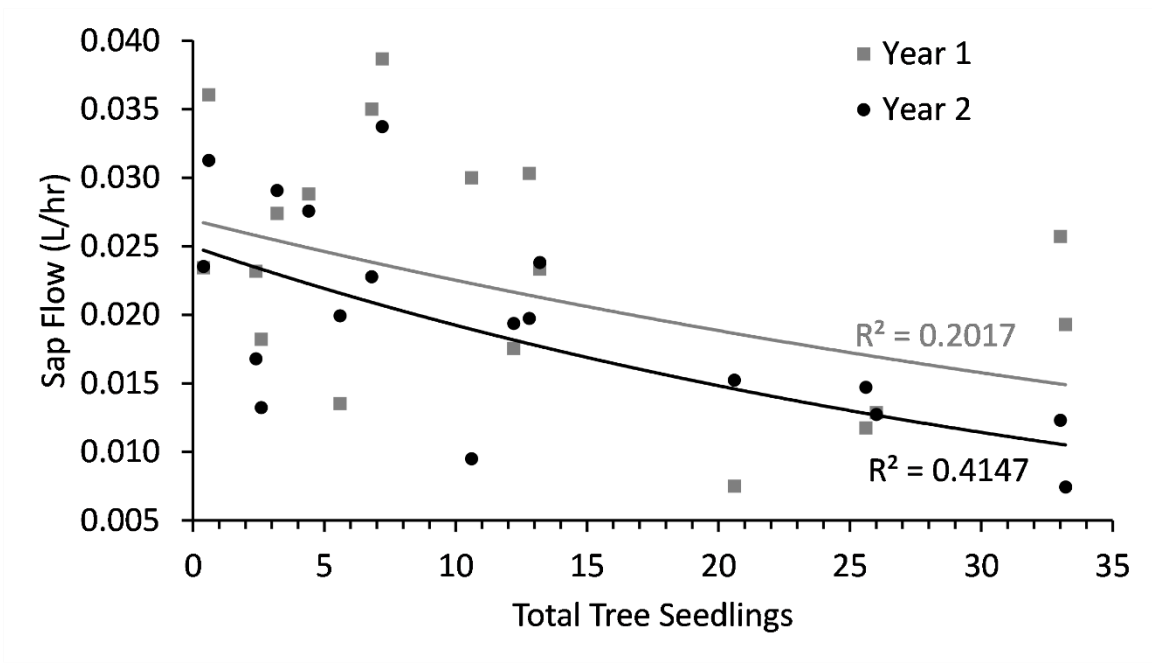


Figure 16. Relationship between tree seedling density and average sap flow in maple trees.

8.2 SAP YIELD

Sap yield is directly linked to sap flow and often follows the same trends as can be seen in figure 17 where other hardwoods, small maples and total trees has a significant positive correlation with yield. There were fewer significant relationships between yield and vegetative competition than with flow rate. This could be due to how the data on these two variables was collected. Due to the geographical location of all the sites and how frequently the data needed to be collected, the producer was made responsible at each study location. Each producer was provided with identical spreadsheets, instructions, and sap collect setups. However, length of time between days yield data was collection varied, as did run

length and who collected the data. Some sites also shut down sooner than others due to regional microclimate, perceived end of season and other characteristics of the “last” run.

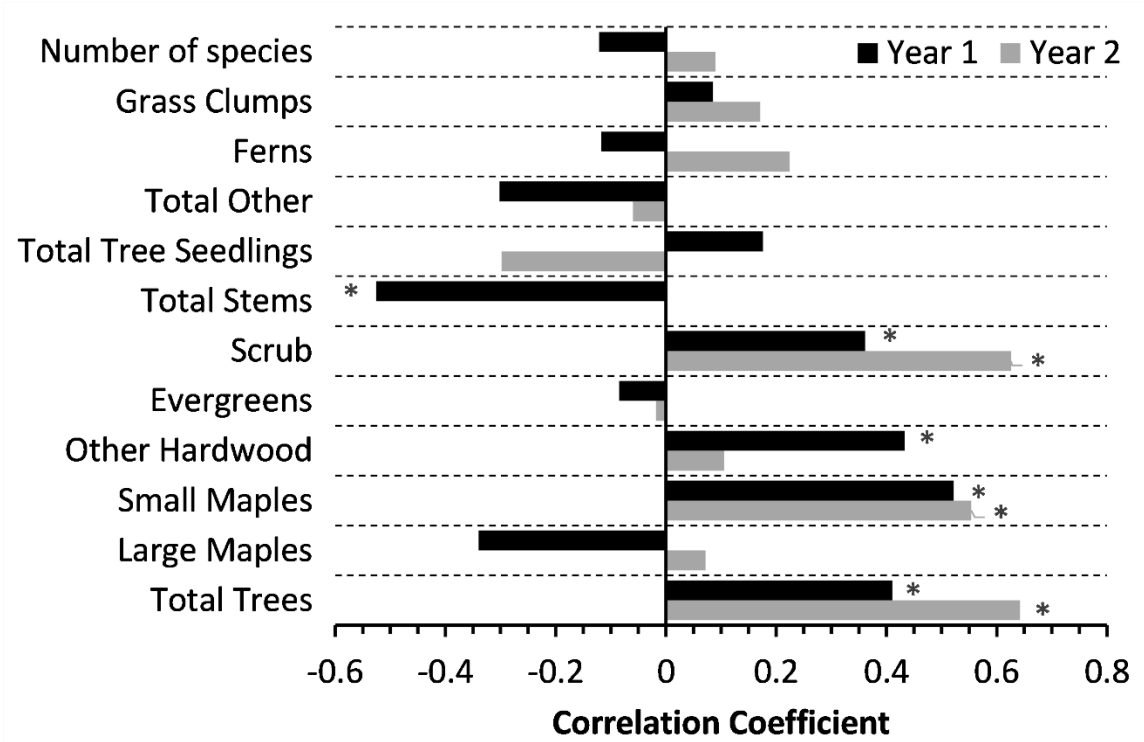


Figure 17. Correlation coefficients for a variety of species growing in the sugar bush versus yield. A * indicates significance at $P \leq 0.05$.

CHAPTER 9 – GENERAL DISCUSSION AND CONCLUSIONS

9.1 DISCUSSION

Over the two years of this study in the Nova Scotia sugar bush, various factors and dynamics were studied with numerous significant correlations noted. There were significant relationships between soil nutrients and research locations and months. Tree core nutrients displayed significant differences with month between years and research sites. Leaf nutrients had significant differences with year, month and site as well as between year and month and year and research site. Sap nutrients also had a significant three-way interaction between experimental year, research site and sap run, as well as significant interaction effects between research site and run, research site and year, and year and sap run. LAI had significant interaction effects between month and location, location and year, as well as year and month.

Maple sap flow and yield is a complex process with numerous influences of various magnitudes. Influences can be environmental, ecological and physiological (Cirelli et al. 2008). Sap flow and yield both displayed significant differences between research site and experimental year. However, sap yield was the one which display the most significant correlations consistently over both years of the study. Of all the significant linkages, Zn concentrations, Fe concentrations, soil moisture from August to September, competition of trees/woody plants, April max temperature, snow present December through March, longitude, and sap pH (initial or 1st run) had the strongest consistent correlations over the years of this study (Table 21).

Table 21. Summary of factors with the strongest correlations ($r > 0.33$) to sap yield consistently in year 1 and 2. Each was significant at $P < 0.05$. The r-values were averaged between years 1 and 2, as well as between months when the same relationship spanned multiple months.

Factor Type	Factor	Yield
Soil	Moisture (Aug - Sept)	-0.39
	Fe (Jun - Oct)	-0.44
	Zn (Jul - Oct)	-0.43
Core	Zn (Aug)	-0.39
	Zn (Dec)	-0.41
Leaf	Fe (Jun)	-0.37
	Zn (Jun)	-0.40
Vegetative Interactions*	Scrub brush	0.49
	Small Maple	0.54
	Total Trees	0.53
Environmental	Max Temp (Apr)	0.36
	Snow (Dec - Mar)	0.39
Other	Longitude	0.36
	Sap pH (1st)	-0.39

* Vegetative interaction data was only collected in year 2, so could not be averaged. However, it was included since they had some of the highest correlations in the study.

Zn and Fe each had a consistent, significant, negative relationship with sap yield. It is speculated that with the consistent presence of a negative significant relationship between Zn present in soil, core and leaf tissue with sap yield, over numerous months, that Zn was the greatest indicator of low sap yield in NS. There is little literature that directly compares Zn to sap flow, but high Zn was identified as a contributor to poor maple tree health and higher dieback rates (Watmough 2010). Since tree health is positively correlated with sap flow (Moore et al. 2020; Wilmot et al. 1995), it is a logical that Zn could also affect sap flow. This could lead to high soil Zn being used as a predictor of low sap yield when choosing future maple producing sites, especially if soil Fe is also high. Understanding that Fe and Zn are more available in more acidic soils (Boguta et al. 2019; Reddy et al. 1995) and move more freely in moist soils (Li et al. 2015; Kashem and Singh 2006), it would stand to reason that higher moisture in August and September would allow for the tree to uptake more of these elements in a time where the tree is starting to prepare for dormancy and store nutrients. Producers could potentially use liming to increase pH and reduce the available Zn and Fe, while simultaneously making other macronutrients more available.

Increasing the pH of the soil could also influence the pH of sap, which also had a negative correlation to yield (Table 21). Cutter and Guyette (1989) found that the pH of the soil was positively correlated with the sap pH in eastern red cedar. It would also stand to reason that a tree grown in an acidic environment would take on the more acidic characteristics, much like it absorbs nutrients from its environment. In general, the availability of micronutrients such as Zn and Fe are high in acidic soils, thus it was not surprising that there was a negative relationship with soil Zn and sap yield (Keddy et al. 1995).

Vegetative interactions in the sugar bush overall could be seen as a positive factor where number of total trees, scrub brush (i.e. other types of large woody plants that were not easily classified due to health, stage of life cycle, abundance, etc.) and small maples showed significant positive relationships with yield (Table 21). A positive relationship between competing species was surprising because competition was identified as one of the most important factors limiting deciduous tree growth (Soubeyrand et al. 2024). This could possibly be linked to overall environmental health which would allow for good growing conditions for the larger woody plants, like a type of social disjunctive symbiosis as discussed by MacDougall (1922). Another possibility is that maple trees have a beneficial mycorrhizal fungus that may be shared among trees (DeBellis et al. 2019).

Surprisingly, only two of the environmental factors had strong relationships with yield consistently: 1) April maximum temperature and 2) snow cover from December to March. April maximum temperature could be indicative of greater temperature fluctuations, helping the root pump process. The April maximum temperature could also be a sign of a longer growing season as a higher day time temperature may be an indication of the tree “waking up” and starting to grow sooner. The second environmental factor, and the one with the stronger correlation, was the presence of snow on the ground from December to March. This factor may be a positive influence for a few reasons. First, since the influence spans from December to March, this indicates that the ground was frozen or cold enough to keep snow on the ground thus keeping with the traditional cold or dormancy period of a maple tree (Figure 18) (Stern et al. 2022). Second, snow acts as an insulator protecting the tree roots from extreme temperature fluctuations which, if too warm, could initiate the processes of breaking dormancy too early using up tree resources or if too cold, exposed

roots could be damaged (Stern et al. 2022) and thus not contribute to the root pump action needed for sap movement. Third, snow present on the ground specifically in tapping season from February to April (Figure 18) would also act as a reflecting surface. Sunlight could be reflecting onto the trunk like a heliostat field (Merchan et al. 2022), which could cause a greater heating of the trunk tissue, thus increasing the root pump activity.

In addition to the afore mentioned correlations, there was also evidence which suggested that environmental factors (specifically weather) could influence sap flow/yield for various years into the future. This was not explored in depth during this study, but would possibly be linked to overall tree growth, health, and energy/nutrient stores that came from that season. Potentially comparable to how growth rings work, where good growing years have large growth rings and poor growth years have small rings. These relationships would need to be studied in greater detail to understand their significance to the maple producing sites.

Another factor that would require greater study would be the positive influence longitude had on yield. Longitude, a factor that cannot be manipulated via human means, could be used in consideration with other factors to determine future sites for maple production. It would need to be determined if it is directly due to the more westerly location or if it was confounded by another factor, such as more westerly sites being located further inland. Understanding this relationship could be helpful in the determination of future sites.

With the large variability in locations, weather, and factors both in a single year and between the two years of this research study, there is still a great deal to understand about what exactly influences sap flow and yield in the Nova Scotian sugar bushes. However, this study did identify some very promising factors that would lend themselves to be the basis for additional studies to focus on. Sadly, most of these strongly correlated relationships would be difficult to change or adjust via human means. Vegetative interactions within the maple stand and increasing the pH of the soil would be the only factors that could truly be influenced by producer interaction, both of which would still be difficult due to the nature of natural stands.

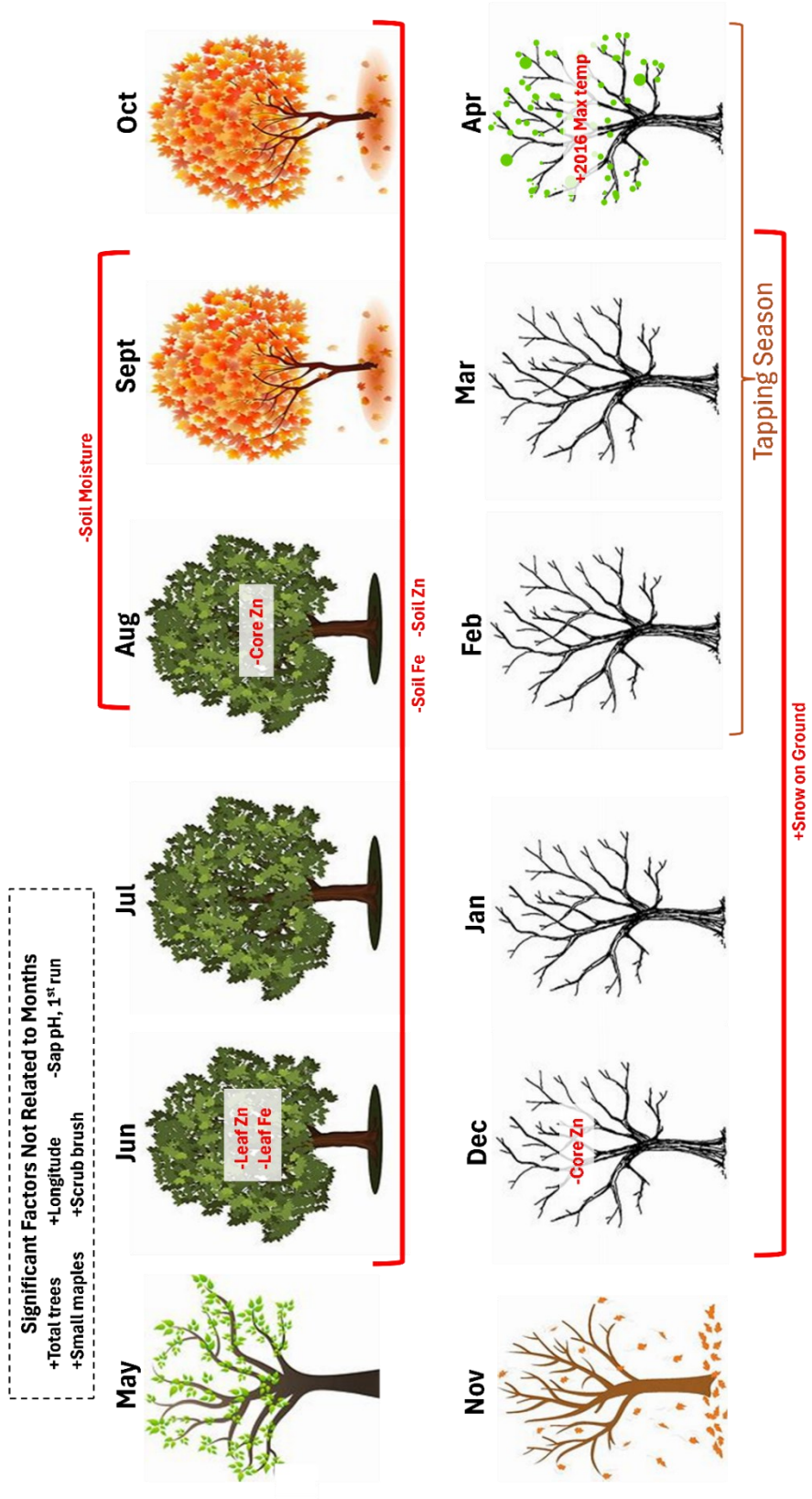


Figure 18. Graphical representation of most significant factors affecting sap yield displayed over the 12-month period.

9.2 CONCLUSIONS

There were 6 hypotheses in this study. The first hypothesis regarding variability among maple producing sites was accepted. However, the second hypothesis regarding similarities between sites geographically close to one another was rejected. Spatial variation of nutrition was high, even within a site. The third hypothesis suggested that soil moisture and nutrition status would positively affect sap yield, while heavy metal concentration would negatively affect sap yield. Soil moisture and nutrient status had no consistent effect on sap yield, but heavy metals Zn and Fe did have a negative effect on sap yield. The fourth hypothesis suggested competition would have a negative effect on sap yield, but the opposite occurred. It was found that an increase in density of total trees, small maple trees, and scrub brush displayed a positive relationship between vegetative interactions and sap yields. The fifth hypothesis suggested that climate effects could be good or bad for sap yield dependant on the factor, which was not rejected. Snow cover from December to March and high maximum temperatures in April were consistently associated with high sap yield. Lastly, the sixth hypothesis suggested geography would have no effect on sap yield, which was rejected. Longitude had a consistent relationship with sap yield where more westerly sites had higher sap flow. It must be noted that the effect of longitude is likely confounded by another yet unknown variable.

9.3 SIGNIFICANCE TO INDUSTRY

This project could significantly benefit the Nova Scotian maple industry in many ways:

- 1) Understanding of the relationship between soil-tree nutrition, soil moisture status and the sap and syrup yield in the various maple growing regions of Nova Scotia.
- 2) Differentiating and bench marking soil-tree nutrition, soil moisture and sap and syrup yield in other maple producing provinces in Canada and Vermont, USA.
- 3) Establish the relationships between soil, tree nutrient and sap and syrup yield that would help to assess the tree health and would allow development of Best Management Practices.

- 4) Development of innovative, region-specific soil, tree nutrition-based syrup yield and sap sugar forecast models.
- 5) A possible scientific reason for low syrup yields in Nova Scotia.

Optimizing tree and site health is the essential first step in maximizing sap and syrup yield. This project was developed to satisfy an information need by the Maple Producers of Nova Scotia. Prior to this research project there was limited or no information on the linkages.

REFERENCES

Agriculture and Agri-Food Canada (2020) Statistical Overview of the Canadian Maple Industry. 2020. Accessed March 2, 2023. <https://agriculture.canada.ca/en/canadas-agriculture-sectors/horticulture/horticulture-sector-reports/statistical-overview-canadian-maple-industry-2020#a1.1>

Agriculture and Agri-Food Canada (2021) Statistical Overview of the Canadian Maple Industry. 2021. Accessed March 2, 2023. <https://agriculture.canada.ca/en/sector/horticulture/reports/statistical-overview-canadian-maple-industry-2021>

Agriculture and Agri-Food Canada (2023) Statistical Overview of the Canadian Maple Industry. 2023. Accessed February 17th, 2025. [Statistical Overview of the Canadian Maple Industry, 2023 - agriculture.canada.ca](#)

Attiwill P and Adams M (1993) Tansley Review No. 50 Nutrient cycling in forests. *New Phytologist*. 124: 561-582.

Bailey S, Horsley S, Long R, Hallett R (2004) Influence of edaphic factors on sugar maple nutrition and health on the Allegheny Plateau. *Soil Science Society of American Journal*. 68: 243-252.

Baligar VC, Fageria NK, He ZL (2001) Nutrient use efficiency in plants. *Communications in Soil and Plant Analysis*. 32: 921-950.

Bernier B and Brazeau M (1988a) Foliar nutrient status in relation to sugar maple dieback and decline in the Quebec Appalachians. *Canadian Journal of Forest Research*. 18: 754-761.

Bernier B and Brazeau M (1988b) Nutrient deficiency symptoms associated with sugar maple dieback and decline in the Quebec Appalachians. *Canadian Journal of Forest Research*. 18: 762-767.

Blum BM (1971). The association among sap and sugar production competition, and physical characteristic of individual sugar maple (*Aster saccharum Marsh.*) trees. Ph.D. diss., SUNY, Syracuse. New York. 197p.

Blum BM and Gibbs CB (1968) Variation of sugar maple sap yield and its influence on experimental design. USDA Forest Service Research Paper. NE-108.8 p.

Boguta P, D'orazio V, Senesi N, Sokolowska Z, Szewczuk-Karpisz K (2019) Insight into the interaction mechanism of iron ions with humic acids. The effect of the pH and chemical properties of humic acids. *Journal of Environmental Management*. 245: 367-374. <https://doi.org/10.1016/j.jenvman.2019.05.098>.

Burger J and Kelting D (1999) Using soil quality indicators to assess forest stand management. *Forest Ecology and Management*. 122: 55-166.

Chen Y, Sun J, Xie F, Wang X, Cheng G, Lu X (2015) Litter chemical structure is more important than species richness in affecting soil carbon and nitrogen dynamics including gas emissions from an alpine soil. *Biology and Fertility of Soils*. DOI 10.1007/s00374-015-1025-0.

Cirelli D, Jagels R, Tyree MT (2008) Toward an improved model of maple sap exudation: the location and role of osmotic barriers in sugar maple, butternut and white birch. *Tree Physiology*. 28: 1145-1155.

Comerford DP, Schaberg PG, Templer PH, Socci AM, Campbell JL, Wallin KF (2013) Influence of experimental snow removal on root and canopy physiology of sugar maple trees in a northern hardwood forest. *Oecologia*. 171: 261-269.

Cote B, Hendershot W, Fyles J, Roy A, Bradley R, Biron P, Courchesne F (1998) The phenology of fine root growth in maples- dominated ecosystem: relationships with some soil properties. *Plant and Soil*. 201: 59-69.

Cornell University (2017) What causes the sap to flow out of the trees? Cornell Cooperative Extension Monroe County. Accessed March 1, 2018. <http://monroe.cce.cornell.edu/agriculture/seasonal-produce-highlights/what-causes-the-sap-to-flow-out-of-the-trees>

Cortes PM and Sinclair TR (1985) The Role of Osmotic Potential in Spring Sap Flow of Mature Sugar Maple Trees (*Acer saccharum* Marsh). *Journal of Experimental Botany*. 36: 12-24.

Coughlan A, Dalpe Y, Lapointe L, Piche Y (2000) Soil pH-induced changes in root colonization, diversity and reproduction of symbiotic arbuscular mycorrhizal fungi from healthy and declining maple forests. *Canadian Journal of Forest Research*. 30: 1543-1554.

Cutter BE and Guyette RP (1989) A Note on Sap pH in Eastern Redcedar (*Juniperus Virginiana* L.). *Wood and Fiber Science*. 22(1): 109-112.

DeBellis T, Kembel SW, Lessard J (2019) Shared mycorrhizae but distinct communities of other root-associated microbes on co-occurring native and invasive maples. *PeerJ*. 7: 7295.

Donald, G. and Harnish, J.B., 1993. Refinement and calibration of soil organic matter determination for the NS soil testing laboratory. Technology development programme (TDP1-70). Nova Scotia Department of Agriculture and Marketing, Truro, NS.

Duchesne L, Ouiment R, Houle D (2002) Basal Area Growth of Sugar Maple in Relation to Acid Deposition, Stand health, and soil Nutrients. *Journal of Environmental Quality*. 31: 1676-1683.

Finzi A, Van Breemen N, Canham C (1998) Canopy tree-soil interactions within temperate forests: species effects on soil carbon and nitrogen. *Ecological Applications*. 8:440-446.
Gregory RA and Wargo PM (1986) Timing of defoliation and its effect on bud development, starch reserves, and sap sugar concentration in sugar maple. *Canadian Journal of Forestry Research*. 16: 10-17.

Heiligmann R, Koelling M, Perkins T (2006) *North American Maple Syrup Producers Manual*, 2nd Edition. Ohio State University Extension. pp. 329.

Houston D, Allen D, Lachance D (1990) *Sugarbush Management: A guide to maintaining tree health*. United States Department of Agriculture: Forest Service. Northeastern Forest Experiment Station. Radnor, Pennsylvania, USA.

Johnson RW, Tyree MT, Dixon MA (1987) A requirement for sucrose in xylem sap flow from dormant maple trees. *Plant Physiology*. 84: 495-500.

Jones CH, Edson AW, Morse WI. (1903) The maple sap flow. *Vermont Agricultural Experiment Station Bulletin*. 103.

Karus T, Yu Z, Preston C, Dahlgren R, Zasoski R (2003) Linking chemical reactivity and protein precipitation to structural characteristics of foliar tissues. *Journal of Chemical Ecology*. 29: 703-773.

Kashem MA and Singh BR (2004) Transformations in solid phase species of metals as affected by flooding and organic matter. *Communications in Soil Science and Plant Analysis*. 35: 1435-1456. <https://doi.org/10.1081/CSS-120037556>.

Keddy KJ, Wang L, Gloss SP (1995) Solubility and mobility of copper, zinc, and lead in acidic environments. *Plant and Soil*. 171: 53-58.

Kogelmann W and Sharpe W (2006) Soil acidity and manganese in declining and nondeclining sugar maple stands in Pennsylvania. *Journal of Environmental Quality*. 35: 433-441.

Kolb TE, McCormick LH, Simons EE and Jeffery DJ (1992) Impacts of pear thrips damage on root carbohydrate, sap and crown characteristics of sugar maples in a Pennsylvania sugarbush. *Forest Science*. 38: 381-392.

Kozlowski TT and Pallardy SG (1996) *Physiology of woody plants*. 2nd Edition. Academic Press. 411p.

Kurokawa SYS, Silvestro R, Khan A, de Lima Santos G, Delagrangé S, Rossi S (2025) The divergent advancements of sap phenology in maple under warming conditions can shorten the sugar season. *Trees, Forest and People*. 19: 100779.

Lada R and Nelson K (2013) Nova Scotia maple production informatics and maple syrup chemical analysis. Maple Research Programme Report. Dalhousie University.

Lada RR (2014) Maple Tree Nutritional Physiology: Proposal for Research Acceleration Fund - Growing Forward 2 Program. Dalhousie University.

Li Z, Wu L, Zhang H, Luo Y, Christie P (2015) Effects of soil drying and wetting-drying cycles on the availability of heavy metals and their relationship to dissolved organic matter. *Journal of Soil and Sediment*. 15: 1510-1519. <http://doi.org/10.1007/s11368-015-1090-x>.

Lovett G and Mitchell M (2004) Sugar maple and nitrogen cycling in the forest of eastern North America. *Frontiers in Ecology and the Environment*. 2: 81-88.

MacDougall WB (1922) Symbiosis in a deciduous forest. *Botanical Gazette*. 73: 200-212.

Marvin JW, Morselli MF, Laing FM (1967) A correlation between sugar concentration and volume yield in sugar maple – an 18-year study. *Forest Science*. 13: 346-351.

McIsaac D (2012) Characteristics of a Good Sugar Maple Stand. Accessed March 23, 2018. <http://www.perennia.ca/wp-content/uploads/2016/04/Characteristics-of-a-Good-Maple-Stand.pdf>

Mehlich A (1984) Mehlich 3 Soil Test Extractant. A Modification of Mehlich 2 Extractant. *Communications in Soil Science and Plant Analysis*. 15: 1409-1416.

Merchan RP, Santos MJ, Medina A, Hernandez AC (2022) High temperature central tower plants for concentrated power: 2021 review. *Renewable and Sustainable Energy*. 155:111828.

Moore JD, Duchesne L, Ouimet R, Duschenes M-L (2020) Liming improves sap characteristics of sugar maple of the long term. *Forest Ecology and Management*. 464: 118044.

Moore JD and Ouimet R (2006) Ten-year effect of dolomitic lime on the nutrition, crown vigor, and growth of sugar maple. *Canadian Journal of Forest Research*. 36: 1834-1841.

Moore HR, Anderson WR, Baker RH (1951) Ohio maple syrup: Some factors influencing production. *Ohio Agriculture Experiment Small Bulletin*. 718: 3-53.

Morrow RL (1955) Influence of tree crowns on maple sap production. *Cornell Agricultural Experiment Station Bulletin*. 916: 3-30.

Morselli M, Marvin LW, Laing FM (1978) Image-analyzing computer in plant science: more and larger vascular rays in sugar maples of high sap and sugar yield. *Canadian Journal of Botany*. 56:983-986.

MPANS (2016) Best Management Practices for Maple Syrup Producers in Nova Scotia. Maple Producers Association of Nova Scotia. Accessed March 23, 2018. <http://www.novascotiamplesyrup.com/wp-content/uploads/2016/09/Best-Management-Practices-for-Maple-Syrup-Producers-in-Nova-Scotia.pdf>

Noy-Meir I (1973) Desert Ecosystems: Environment and producers. Annual Review of Ecology, Evolution and Systematics. 4: 25-51.

NS Department of Natural Resources (2012) Trees of the Acadian Forest. Government of Nova Scotia. Accessed September 8, 2016. <http://novascoita.ca/natr/forestry/treeid/>

Ouimet R and Camire C (1995) Foliar deficiencies of sugar maples stands associated with soil cation imbalances in the Quebec Appalachians. Canadian Journal of Soil Science. 75: 169-175.

Ouimet R, Camire C, Furlan V (1996) Effect of Soil K, Ca and Mg Saturation and endomycorrhization on growth and nutrient uptake of sugar maple seedlings. Plant and Soil. 179: 207-216.

Ouimet R and Fortin JM (1992) Growth and foliar nutrient status of sugar maple: incidence of forest decline and reaction to fertilization. Canadian Journal Forest Research. 22: 699-706.

Perkins TD and van den Berg AK (2009) Maple Syrup – Production, Composition, Chemistry and Sensory Characteristics. Advances in Food and Nutrition Research. 56: 101-143.

Perry T (1982) The ecology of tree roots and the practical significance thereof. Journal of Arboriculture. 8: 197-211.

Rahman M, Tsukamoto J, Tokumoto Y, Shuvo A (2013) The role of quantitative traits of leaf litter on decomposition and nutrient cycling of the forest ecosystems. Journal of Forest Science. 29: 38-48.

Reddy KJ, Wang L, Gloss SP (1995) Solubility and mobility of copper, zinc, and lead in acidic environments. Plant and Soil. 171: 53-58.

Statistics Canada (2017) Maple Products, 2017. The Daily. (2017). Accessed March 3, 2023. <https://www150.statcan.gc.ca/n1/daily-quotidien/171213/dq171213e-eng.htm>

Statistics Canada (2018) Maple Products, 2018. The Daily. Accessed April 3, 2019. <https://www150.statcan.gc.ca/n1/daily-quotidien/181212/dq181212f-eng.htm>

Statistics Canada (2022) Maple Products, 2022. The Daily. Accessed March 2, 2023 <https://www150.statcan.gc.ca/n1/daily-quotidien/221214/dq221214e-eng.htm>

St. Clair S and Lunch J (2005) Element accumulation patterns of deciduous and evergreen tree seedlings on acid soil and its implications for sensitivity to manganese toxicity. *Tree Physiology*. 25: 85-92.

Stuckel JG and Low NH (1996) The chemical composition of 80 pure maple syrup samples produced in North America. *Food Research International*. 29: 373-379.

Stern RL, Schaberg PG, Rayback SA, Hansen CF, Murakami PF, and Hawley GJ (2023) Growth trends and environmental drivers of major tree species of the northern hardwood forest of eastern North America. *Journal of Forestry Research*. 34:37-50.

Taylor FH (1956) Variation in sugar content of maple sap. *Vermont Agricultural Experiment Station Bulletin*. 587.

Tyree MT (1983) Maple sap uptake, exudation, and pressure changes correlated with freezing exotherms and thawing endotherms. *Plant Physiology*. 73: 277-285.

United States Department of Agriculture (2022) New York Ranked Second in 2022 Maple Syrup Production. Accessed March 3, 2023. https://www.nass.usda.gov/Statistics_by_State/New_York/Publications/Latest_Releases/2022/New-York-2022-Maple-Production.pdf

University of Vermont (2022) North American syrup Producers Manual, 3edu. Accessed November 15, 2024. <https://mapleresearch.org/wp-content/uploads/NAMSPM3sm.pdf>

United States Department of Agriculture (2017) United States Maple Syrup Production. National Agricultural Statistics Service. Accessed March 22, 2018. https://www.nass.usda.gov/Statistics_by_State/New_York/Publications/Latest_Releases/2017/2017_Maple_Syrup.pdf

Wallner WE and Gregory RA (1980) Relationship of sap sugar concentrations in sugar maple to ray tissue and parenchyma flecks caused by *Phytobia setosa*. Canadian Journal of Forest Research. 10: 312-315.

Watmough SA (2010) Assessment of the potential role of metals in sugar maple (*Acer saccharum* Marsh) decline in Ontario, Canada. Plant Soil. 332: 463-474.

Wilmot TR, Brett PW, Tyree MT (1995) Vigor and Nutrition vs. Sap Sugar Concentration in Sugar Maples. Northern Journal of Applied Forestry. 12: 156-162.

Wilmot T, Ellsworth D, Tyree M (1996) Base cation fertilization and liming effects on nutrition and growth of Vermont sugar maple stands. Forest Ecology and Management. 84: 123-134.

Zhang S, Jiang L, Liu X, Zhang X, Fu S, Dai L (2016) Soil nutrient variance by slope position in a mollisol farmland area of northeast China. Chinese Geography Science. 26: 508-517.