Nutrition and Related Factors Affecting Maple Tree Health and Sap Yield

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Abstract

The maple industry is an economically important bioresource for both Canada and the Northeastern United States, with Canada being the world leader in maple products. Maple sap is collected during the natural freeze-thaw cycles which occur in the late winter and early spring. Syrup yield is directly dependent on sap yield which has links to tree health, available nutrients, forest health, environment, soil health, sap components, season length, as well as various other factors. Maple trees can tolerate a wide arrange of soils, but soils in the maple woods are often left alone due to the difficulty with addition and incorporation of the appropriate amendments. Most nutrients come from the nutrient cycling of decomposing litter and mycorrhizal associations. Nutrient deficiencies of K, P and Ca are all linked to maple decline and could be positively influenced by a fertilization program. However, improper nutrient applications could create even greater nutrient imbalances, thus leading to more dieback or decline. This review discusses current maple management practices with an emphasis on the role of soil nutrition on tree health and sap yield.

Keywords

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 [1]. Sugar maple trees contributed $384.4 million to the Canadian economy in 2018 through the production of maple syrup and other maple products, making it a profitable bioresource [1]. Canada is the world's leading supplier of maple syrup

and maple products; annual production volumes of approximately 40 million liters contribute approximately 80% of the world's pure maple syrup [1]. Provinces of Quebec, Ontario, New Brunswick, Nova Scotia, and British Columbia are Canada's main maple producing provinces with Quebec being responsible for roughly 91% of the country's production [2]. In contrast, USA produced approximately 17 million liters in 2017 with Vermont, New York, Maine, Wisconsin, and New Hampshire as the main contributors [3]. Nova Scotia produced around 55,000 gallons of syrup in 2018 [1] accounting for less than 1% of Canada's maple production. Maple syrup production in Nova Scotia has increased from around 32,000 liters in the 1950s to the current 220,000 liters, which is down from a high of 228,000 liters in 2017 [4]. There are approximately 187 Maple farms in Nova Scotia producing sap from around 446,300 taps [5].

There are many factors which affect and are suspected to affect the flow of sap 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, and the location [6] [7]. This paper aims to discuss some of the known factors involved in map sap flow and maple syrup production in relation to Eastern Canada, specifically Nova Scotia.

2. Maple Sap

2.1. Sap Physiology

Maple sap is collected from trees during the freeze-thaw cycle that occurs between February and April in Nova Scotia, where temperatures fluctuate roughly between −10°C and +10°C. Sap flow or 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 [8]. 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 [9] [10]. Ultimately, positive xylem pressure is created, which will push the sap through the tree and out small wounds [11]. 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 [12]. Pressure within the tree(s) can reach up to 40 psi [13].

Sugar concentration might play a role in the magnitude of pressure generated with the various maple species [14]. Sucrose is the main sugar found in sap, with glucose and fructose being present in much smaller amounts [15]. Sap sugar concentration is derived from non-structural carbohydrates stored by trees during previous growing seasons [16] and is positively linked to the pressure and volume of the sapwood cells following the freeze-thaw cycle [14] [17]. Further, there have been significant correlations between sap flow, sugar concentration, and daily temperatures [18]. Experiments showed that exudation occurred only when sucrose was present in the winter months where concentrations are typi-

cally around 2.0% - 5.0% [14]. Conversely, sucrose is found in negligible amounts in summer and exudation does not occur with Maple species. However, the exact role of sucrose in the exudation process is still under debate.

In addition to sugars, maple sap also contains amino acids, minerals, and phytohormones [15] [19]. Major minerals in maple sap include K, Ca, Mg, Na, and Mn [15] [19]. Minerals such as Cu, Fe, P, and Zn all occurred at trace levels in maple sap [MacDonald *et al*. 2016]. Abscisic acid and its derivatives were the major phytohormones found in maple sap, with cytokins, auxins, and gibberellins present at trace levels [19].

2.2. Sap and Syrup Yield

Sap flow and syrup yield are directly linked. It takes approximately 40 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 [20]. The natural variability of sugar levels in sap from a random selection of sugar maples has been well documented through the years, though all the contributing factors and interactions are not completely understood [15] [21] [22] [23]. Sugar maples and black maples generally average between 2.0 and 2.5 percent sap sugar content, though red and silver maples and the boxelder have a much lower average sap sugar content [20]. The average brix of Nova Scotia maple sap was 2.0%, according to a survey of Nova Scotian producers [24] [25].

The duration of sap flow is another important factor in determining yields. Tapping season lengths vary by year and location. In general, a longer tapping season results in greater yields. Latitude and local temperature help to explain some locational variability. For example, a 1°C increase in March temperatures advanced sap collection by 4.3 days [12]. However, there have been cases where a short season has resulted in high yields due to the weather and other factors [25]. There were 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 0.72 L tap^{-1} in Kings County [25]. The highest average syrup yield per tap was found in Vermont (1.5 L tap^{-1}), followed by Maine (1.3 L tap^{-1}), New York (1.2 L tap^{-1}), and Quebec (1 L tap^{-1}), with Nova Scotia accounting for the lowest average at 0.325 L tap^{-1} [24].

There is a lack of information in the literature regarding the influence of stand density, 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 yields 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 [24]. Anatomical variations between trees relating to starch storage capacity accounts for only a minor amount of the variability in sap sugar concentration [26] [27]. 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 [28] [29] [30], but there has been little evidence of a strong impact of light interception on sap yields [25]. The sugar concentration of the sap is directly influenced by the photosynthesis and respiration taking place in the canopy [31]. This is partially 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 [25]. Although there are direct links between the sap and the foliage, the timing of defoliation has shown to have little influence on the sweetness of sap between trees [31] [32] [33].

Since the driving factor for sap flow is temperature, climate change is anticipated to have a significant impact on sap yields. Maple sap currently flows during the late winter and early spring in North American, when temperatures alternate below and above freezing and generate pressure differentials within maple xylem [12]. One model has estimated that by the year 2100 sap harvest will occur one month earlier and sap will decline by 0.7° Brix as result of anticipated climate change [12]. Maximum sap flow is currently observed near 43°N latitude but is expected to shift to 48°N by 2100 [12]. This may result in a shift away from key maple producers (e.g. Vermont, New Hamshire) towards more northern producers (e.g. Ontario, Quebec, New Brunswick). Canada reported record breaking maple harvests in 2022 largely owing to a shift in winter and spring temperatures [1] [2].

3. Maple Management Practices

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 and negative effects on soil quality [34]. Negative effects include soil displacement, waterlogging, compaction, organic matter and nutrient depletion, and acidification. Positive effects include enhanced soil fertility, tilth, water and air availability and organic matter placement [34]. 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 back to a minimum. Sugarbushes are entered at regular intervals to manage undergrowth, thin out the maple trees, check sap lines, to prepare for tapping season, as well as to monitoring the system when the sap begins to flow and to untap the trees when the season is over. [35] states that human activities in the maple woods surpass those of any other managed forest. [34] states 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 (*i.e.* 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 [36].

Most sugarbushes in Canada come from natural mixed forests containing a higher population of maple trees. Sugar maples (*Acer saccharum*, L.) and black maples (*Acer nigrum*, L.) 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 [27]. Even though sugar maples are the best option for tapping, red maples (*Acer rubrum*, L.) are also tapped in Nova Scotia [37]. Silver maple (*Acer saccharinum*, L.) and boxelder (*Acer negundo*, L.) are two other trees that can be tapped for syrup production, but seldom are due to the lower sap sugar content [27]. Sugar, red and silver maples are native to the Nova Scotia region, where the Black maple and Boxelder are native father west [20] [38].

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 [20] [39]. Thinning promotes increased tree growth rate, crown development, and improves the overall health of the stand [39]. It is only recommended to remove up to 10% of the maples in the sugarbush and up to 30% of the non-maple species [39] to maintain some 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 [20] 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 are concerns because sugar maple roots are quite shallow, with fine roots predominately staying in the top 60cm of the soil profile [37]. 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. 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 [20] [39].

3.2. Soil Management

Canadian soils range from deep nutrient rich soils of the Western provinces to shallow acidic soils of Atlantic Canada [40]. These soils may have been in production for many years or may have been freshly cleared or reclaimed. Land can

be reclaimed from the oceans by building barriers such as dykes where flooding and soil salinity may be the main concern. Desert sands can be used as production soils if enough inputs are used [41]. Deserts are considered a "water-controlled ecosystem", where low precipitation, variation of precipitation and randomness of the variation of the precipitation are the main attributes to the ecosystem and controlling factors for all other soil stabilizing processes and factors that would allow for production [41]. Reclaiming land from desert ecosystems production is rarely economically feasible [41].

There are no typical soils for plant production since production depends on the recycling of nutrients within the system and recycling depends on the decomposition of organic matter and the release of contained nutrients [42]. Most soils can be used in some manner for productivity. Whether a soil is to be used to produce a crop is often determined by availability and cost associated with land acquisition and production maintenance. Costs associated with land usage can include, but are not limited to, tile drainage, manure, fertilizers, equipment usage, water, and labor. Producers typically base their decisions on the costs of various inputs and potential profit from the land [43]. In agricultural settings, soils can become abused and suffer from nutrient loss, hardpans, erosion, degradation of structure, as well as various other issues [44]. Many of these soil problems are common. To help combat these issues producers have adopted various management practices. Crop rotations, specialized equipment, nutrient additions, and different versions of tillage are examples of some management practices [44] [45].

Though much focus regarding soil quality relates to 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; 6) accept, hold, and release carbon [34].

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 for forest soils as the result of continuous input of large amounts of woody litter; the C:N ratio is cultivated soils is typically closer to 10 [46]. Despite involving typically less soil management, forest systems must still be monitored and managed to ensure the health and site are not negatively affected by the human interaction [47]. There is increased awareness of the importance of sustainable forest management for non-timber resources, such as maple sap [48].

Sugar maples can have a life expectancy of more than 300 years [49] 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 [50]. As such, there is often very little management

by producers. Maple stands and other forests often do not obtain many human inputs and must rely on the naturally occurring organic matter, leaf litter, and the seasonal dieback of the undergrowth. Up to ten tonnes of leaf litter is deposited annually on the forest floor in highly productive forests, but it offers very poor nutrition to soils [46]. Occasionally some producers do add liming agents and/or 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 considered.

3.3. Liming Maple Stands

Although, sugar maples occur on soils with a wide range of pH and base cation levels, [51] explain that maples often grow poorly in soils with high Al and low Ca, Mg, and 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 [51] [52]. Thus, there is a potential benefit to liming maple stands.

Growth and nutrition of sugar maples are negatively influenced by imbalances of exchangeable basic cations in the soil [53]. The addition of lime to acidic sugarbush soils can have positive effects on tree health and lower levels of tree dieback have been observed in experimental stands when compared to plots that were not limed [54] [55]. Although the exact cause of maple dieback is unknown, soil acidification and low Ca levels are thought to be important factors affecting this process [36]. Long-term application of lime has improved growth and vigor of hardwood stands, including sugar maple [56] [57] [58]. Though both Ca^{2+} and Mg^{2+} have both been cations of interest, it is suggested that Ca is often the limiting factor with respect to tree vigor [52].

Studies on the direct effect of liming on sap productivity and quality have been limited. Most studies have focused on how liming affects tree health with the implication that a healthy tree will have superior sap yield. However, [59] found the addition of 3.4 Mg·ha^{-1} lime improved sugar production by 6% - 11% and [60] found that liming increased sap sweetness by up to 20% and could enhance sap yields in base-poor sugar maple stands. Conversely, several studies have found that lime made no different to sap sweetness or yield [61] [62] [63]. In instances where lime had no effect, it was noted that reports either did not report the initial soil status or that there was no deficiency to indicate the stands would need lime [60].

The practice of liming forest soils has had positive effects in many areas but should be treated with caution according [54]. An increase in pH has shown to 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 through, 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 [64]. There is also a risk that lime could increase the risk of earthworm invasions [52]. The economic feasibility of liming forest stands also must be taken into consideration.

Liming may also have an impact on mycorrhizal fungi. Sugar maples are one of the few tree species of northern hardwood forest known to have symbiotic relationship with arbuscular mycorrhizal fungi [50] [53]. Beech, oak, hemlock and birch have ectomycorrhizae, which differ in cycling-cycling properties than that of arbuscular mycorrhizae [55]. In low P soils, maple seedling nutrient status was improved by the colonization of the fine roots by arbuscular mycorrhizae fungi [53]. 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 [50]. An application lime may reduce the Al-mediated inhibition of Ca uptake by roots [61], but too much lime can decrease the availability of certain nutrients. High lime can cause a high Ca:K ratio leading to foliar K deficiency and can inhibit mycorrhizae [35] [61].

3.4. 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 were to have compromised growth. A healthy tree has higher photosynthetic capacity, which increases C fixation, carbohydrate production, and sapwood growth [60]. An increase in sapwood tissue should promote yields. Conversely, any long-last negative impacts to tree health would adversely impact sap production [65]. For instance, dieback has been shown to be negatively linked to sap volume [54].

A study conducted by [53] 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 poses a risk of negative effects, such as worsening nutrient imbalances if applied incorrectly or the wrong fertilizer is used [35]. 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 several years before the symptoms become apparent making fertilizer recommendation and applications more complex [66]. Trees supplied with K can also exhibit poor root development and are less resistant to frost, pathogens, and pests [67]. 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 [61].

Sampling of the soil and the plant tissue should be completed before nutrients are added to the system. There is great variation in nutrition between plant tis-

sues and season which make it difficult to accurately suggest an appropriate fertilizer plan [25] [35]. There is also evidence that coarse soil fragments may contain important nutrients pools in some forest soils and that standard laboratory procedures for testing soils would not detect these up as the tests are performed on soil that passes through a 2 mm screen [68]. Ultimately, the challenges associated nutrient sampling and limited understanding of nutrition effects on sap flow have resulted in little to no nutrient management in Nova Scotian sugarbush [25]. There is a need to increase awareness in the role of nutrition in maple woods.

4. Nutrient Movement in Maple Woods

4.1. Nutrient Cycling

Nutrient cycling is an important process involved in all ecosystems that describes the use, transformation, movement, and reuse of nutrients in ecosystems [42] Nutrient cycling involves all four spheres of the environment (biosphere, hydrosphere, lithosphere, and atmosphere) and, consequently, includes nutrients in organic forms, inorganic forms, and sometimes multiple physical states. 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 [42].

A typical nutrient cycle on agricultural production land involves additions of nutrients through organic matter and/or commercial fertilizers. Incorporation of these inputs, planting, harvesting, and resulting crop residues help to facilitate the cycle. Organic and inorganic substances enter soils and are removed by plants and other organisms. Nutrient cycles can vary by using green manures, plow-down crops, commercial fertilizers, animal manures, no-till practices, and other forms of management [45]. Variations are also dependent on crops, use of livestock, land, locations, seasons, the producer, and the end goal. Elemental inputs can also come from the environment and have an impact on the cycles in the ecosystem, such as is the case with dust and rain. Rain, which is naturally slightly acidic, combines with the stronger organic acids already present in the soil and can have an effect on the soil pH and the nutrient availability over time [50]. Inputs of nutrients in rain vary with proximity to sources such as the sea, industries, and agriculture [46].

The general model of nutrient cycling in forest as described by [46] has three parts: 1) The inputs of nutrients coming 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; 3) the internal redistribution of mobile nutrients such as nitrogen and phosphorus. Large annual and seasonal fluctuations of soil fertility and root

production are likely and could be strongly affect by extreme climatic events such as drought and soil frost [69]. Rates of mineralization, in particularly nitrification, generally increase after major, single disturbances, such as after forest dieback, logging, the addition of fertilizer or herbicide treatments, fires and any combination of these events [46].

4.2. Decomposition of Leaf Litter

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 [70]. Soil microorganisms decay litter to gain nutrients and energy for their growth and reproduction. The C structures of fresh residues are converted into C products in the soil for the use by plants during this decomposition process [42]. As litter C is lost during decomposition, nutrients such as N and P are immobilized and subsequently released by decomposers [71]. Alternatively, some litter becomes sequestered in soils long-term [72].

There are two major contributors to forest leaf litter: ground vegetation and the herbaceous layer. Litter from trees is generally the largest natural source for the inflow of organic material and nutrients to the forest floor [42]. However, the herbaceous layer can contribute up to 20% of leaf litter to the forest floor. This diversity in leaf litter in important in maple stand nutrition because of differences in C:N ratios, quality of C, N availability, and overall decomposition rates [73].

Litter decomposition rates are 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 [42] [74]. Determination of which factors are most important to leaf decomposition remains in contention. 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 [46] [74]. However, chemical composition is one of the main factors controlling decomposition rate and may be a better determinant of decomposition rates than climate [42]. 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 [42]. It has been suggested 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 [70] [71]. Plant material with chemical compounds that simulate decomposition may interact with litter with chemical compounds that reduce decomposition and, ultimately the diversity of litter species may have more influence that other factors [71]. Understanding decomposition rates is complicated further due to the influence of species diversity on micro-environmental conditions, which has a larger impact than macro-climatic conditions [75].

Low leaf mass per unit area leaves with high nutrient content decompose much faster, leading to increased carbon and nutrient cycling [42] [73]. Cellu-

lose 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 are more susceptible to decomposition and mineralization [42]. 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 [42]. 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; 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 [42] [64]. Litter with high C:N ratio also decomposes more slowly than litter of low C:N or low lignin:N ratios [64] [73].

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 [64]. Virtually all the N in tree leaves is in organic form and N is immobilized during the first stages of the decomposition process [46]. 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 decades to centuries can lead to large differences in organic matter accumulation and the C and N content of the soils [64]. Leaf litter C:N and lignin:N ratios are typically lower in sugar maple, white ash and red maple, than that of beech, red oak and hemlock [64]. Similarly, red maple also tended to populate in soils where nitrate availability was lower [76].

Phenolic compounds may influence rates of decomposition as they bind to the N components in the leaves forming compounds that resist decomposition [42]. 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 [42]. 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 [42]. Allelochemicals including tannins, phenols and volatile terpenoids are capable of inhibiting N mineralization, particularly nitrification, in a wide variety of forest soils [46]. These allelochemicals may come from the decomposing litter or be exuded from the roots growing in the soil [46].

Litter tannins specifically may play an important role in decomposition and nutrient cycling where it has been noticed that in tropical rainforest leaves high in initial condensed tannins seem to decompose slowly in both terrestrial and aquatic ecosystems [42]. 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 [70]. Tannins may limit litter decomposition in five main ways according to by themselves being resistant to decomposition, by sequestering proteins in protein-tannin complexes that are resistant to decomposition, by coating other compounds (*i.e.* cellulose) and protecting them from microbial attack, by direct toxicity to microbes, or by complexing or deactivating microbial exoenzymes [77]. Tannins may also reduce insect predation because they increase the toughness of the leaves [42].

4.3. Interaction with Tree Roots

Trees typically have between four and eleven major woody roots originating from the root collar that grow horizontally through the soil [78]. Fine roots are concentrated in the litter layers and surface soils [46]. Fine root production is associated with two groups of variables: soil fertility (mineralized N and extractable P) and physical soil environment parameters like moisture and temperature [69]. Root growth in general has been widely referenced as responding positively to soil P fertility and negatively to soil N fertility [69]. There is an abundance of evidence that roots of many herbaceous and trees species exude compounds which have the capacity to solubilize compounds containing nutrients [46]. 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 [69]. The "feeder roots" are part of the fine root system that collect the nutrients and water from the soil and deliver it to the rest of the tree [78]. 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 competing for water and nutrients [78]. Surface layers of soils often dry out and are subjected to extremes of temperature, frost heaving as well as other weather. The delicate, non-woody root systems is killed frequently by the fluctuations in the soil environment, but new roots grow back rapidly after injuries [78] 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 [46].

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 "fluffs" the surface layers of undisturbed forest soil so that more than 50% of its volume can be pore space [78]. 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. A comparison of 14 different sites found that the mineral B horizons nutrient concentrations were on average 7 and 17 times lower than the humus nutrient con-

centrations for total N and exchangeable basic cations, respectively [49]. These deeper nutrients, although in low concentrations, would still be available to the trees which had roots deep enough to collect them.

4.4. Nitrate Leaching in Maple Stands

According to studies of northern hardwood forests, sugar maples have a unique characteristic where they do not readily take up nitrate [51]. This is supported by the fact that maple trees were able to grow often in lower nitrate soils [76]. However, this may also increase the risk nitrate leaching in maple stands. 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 [64]. Sugar maple is more often associated with soils of high nitrification rates than other dominate species in northern hardwood forests [51]. When compared to other deciduous tree species, sugar maples do not have unusually high N concentrations in wood or foliage, but sugar maple litter is low in lignin and has a low lingnin:N ratio, leading to high rates of decomposition [51]. 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 [51].

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 [51]. There was also a positive relationship between concentrations of nitrate in soil solution below the rooting zone and the abundance of maple trees in New York, which is an indicator of N loss from the forest ecosystem [51]. 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 and potentially out into the environment [78]. Soils under sugar maples 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 [51]. 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 [51]. Nitrate is the most mobile form of inorganic N in soils and is more readily lost from ecosystems by leaching into ground and surfaces waters [51]. 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 [51].

5. Maple Stand Health and Decline

5.1. Soil Nutrition and Maple Decline

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 [79]. Understanding decline is difficult due to the complex array of stresses of which trees are exposed. Predisposing factors may weaken the trees but may not ultimately be responsible for the dieback and mortality of trees [79]. Symptoms of crown thinning, decreased growth, and nutrient deficiencies have been associated with the maple decline phenomenon [66] [80] [81]. 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 [66]. A combination of climatic factors, forest management, insects, fungi, stand dynamics, poor soil quality due to low nutrient availability, and aluminum toxicity are all included in the many hypotheses regarding maple decline [49] [60] [81]. 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 [49].

Maple decline has been linked to both soil acidification and reduced tissue concentrations of base cations [36] [50]. Stress events such as defoliations, droughts, and extreme weather events have also been common themes among declines [68]. Nutrient deficiencies have 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 [36]. 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 [66]. 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 [67]. The most common deficiencies observed in declining maple stands in Quebec are K, P, Ca and Mg, with N deficiency being diagnosed very rarely [36]. Studies have also shown that poor levels of base cation elements, such as Ca and Mg, are predisposing factors for maple decline [68]. 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 [36].

Excessive Mn may also play a role in observed decline and mortality of sugar maples as seen in northern Pennsylvania [79]. Mn is a common soil element and an essential micronutrient for plants but is highly sensitive to changes in soil acidity and reducing conditions [79]. 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 [79]. Excessive Mn in foliage has been associated with decreased net photosynthesis [82], inhibited chlorophyll synthesis and chlorotic and necrotic spotting [79].

Foliar and soil nutrient imbalances, particularly those of N/Ca and N/Mg, are

considered by some to be the primary cause of tree decline [46]. Foliar 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 [66]. 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 [67]. Maple stands with foliar K levels less than 0.55% in July exhibited high levels of decline, while most stands with K more than that concentration 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 [66]. P deficiency remains an important feature of many declining stands in the deciduous forest of the Quebec St. Lawrence region [66]. Meanwhile, [36] 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 [50]. In a study conducted by [61] 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 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 where notice in the plots where lime was applied despite having a high Ca:K ratio [61]. In a separate study, sugar maple basal area, foliar Ca, and foliar Mg were higher due to long-term liming and the effect persisted in foliage for 21 years after lime application [56].

The presence of mature sugar maples on declining sites indicates that at some point conditions were amenable to colonization, stand establishment, and development [79]. It was suggested that the individual genotypes of trees might affect the tolerance limit to different nutrient deficiencies and stresses [49]. 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 [79].

5.2. Soil Nutrition and Maple Sap Production

Sap flow can ultimately be linked to proper maintenance of basic physiological functions, such as photosynthesis and transpiration. Thus, several logical conclusions can be made regarding the relevance of certain nutrients to sap flow. First, N and P are important for general plant productivity by helping control

Rubisco concentration in chloroplasts. Low levels of nitrogen limit photosynthetic capacity while low phosphorus limits the conversion of ADP to ATP [83]. Second, Ca is required to maintain the structural integrity of the tree and for stomatal control [84]. A lack of soil Ca can increase the risk of embolism due to weaker cell walls and smaller xylem vessels [85]. Third, Si is an important element for proper growth and development and helps regular toxic elements by forming heavy metal silicates [86].

Manipulating soil nutrition has had mixed effects on sap production in many tree species. Application of N increased sap flow in 5 woody savannah species and loblolly pine [87] [88]. Fertilization with a mix of macro and micronutrients increased sap flow in Norway spruce and eucalyptus [89] [90]. However, application of N and P had no effect on sap flow in a temperate hardwood forest [91]. A study investigating the effect of N, P, Ca, and Si also was unable to determine any increase in sap flow in 5 temperate hardwood species [92].

Soil nutrition has had mixed effects on sugar maple yield. Sap yield has generally increased after the application of fertilizer. Combinations of N-P-K fertilization resulted in a short-term increase in sap yield and/or and syrup yield [93] [94]. Inclusion of Ca and Mg with N, P, or K also tended to increase yields [59] [60] [95]. However, there are contradictory studies where fertilization had no effect on yield [62] [92] or even decreased yields [96]. A Nova Scotian study tried correlating soil, leaf, and sap nutrients with sap flow with mixed results [25]. Soil Zn was negative correlated while Cu concentration was positive correlated with yields in 2 years. However, Ca and Mg were positively correlated with yield in one year and negatively correlated in the second year [25].

The same narrative exists with respect to sap sweetness, where soil nutrition had mixed effects. Several studies found fertilization increased sweetness [60] [63] [93] [95] [97]. But several studies also found no effect or a negative effect on sweetness [54] [62] [94] [96]. Higher sweetness was consistently associated with higher concentrations of soil Mg, Ca, and Zn and lower concentrations of Al and S in Nova Scotia [25].

Sap flow is a complex physiological process, which makes it difficult to determine specific role for nutrition. Sap flow is associated with soil water status [25] [92], tree size, sapwood production [65], pH [50], stress [36], leaf litter [42], climate [75], and a variety of other factors. The interaction between nutrition and any of the above variables can make it difficult to identify which factor is most important. Specific genotypic variability also confounds the effect of soil nutrition on sap flow [92]. The relative importance of any individual factor is likely tied to deficiencies. It is possible that proper soil nutrition is required for high sap yields and that we only notice a fertilizer effect in soils that we nutrient deficient [60]. Further, it may take several years before sap flow decreases due to nutrient deficiencies [66] or increases due to better nutrition [60].

5.3. Plant Growth Regulation and Maple Tree Decline

Most maple industries do not take advantage of plant growth regulators (PGRs)

with respect to dieback. Research on PGRs in sugar maple is focuses on very specific needs. For example, at one point it was urgent to develop techniques for successful vegetative propagation of maple, so researchers worked with a variety of auxins to determine which promoted rooting [98]. A second example was a need to promote wound healing due to tapping. Six growth-regulating substances were tested for their abilities to stimulate wound healing in sugar maple with only glutathione found to have a significant effect [99]. Finally, triacontanol may play a crucial role in conversion of starch to sugar in sugar maples and may contribute to spring sap flow [100] [101].

There is a knowledge gap in understanding how PGRs could help reduce maple dieback. The bulk of research regarding maple dieback focuses on nutrition and/or pH challenges [36] [46] [66], which are one of many forms of abiotic stresses. Compounds such as 5-aminolevulinic acid improved nutrient and salt stress in other species [102] [103], Ambiolmitigatedabiotic stresses in other tree species [104] [105], and pyroligneous acid decreased aluminum stress [106]. Though not an exhaustive list of PGRs, the point remains that PGRs are not utilized as effectively by industry as might be possible with additional research.

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 maple stands as closed systems. 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 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 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.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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