

**TREE VARIABILITY LIMITS THE DETECTION OF NUTRIENT TREATMENT
EFFECTS ON SAP FLOW IN A NORTHERN HARDWOOD FOREST**

by

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A thesis
submitted in partial fulfillment
of the requirements for the
Master of Science Degree
State University of New York
College of Environmental Science and Forestry
Syracuse, New York
December 2019

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Acknowledgements

I would like to give my greatest gratitude to my major professor, Ruth Yanai, for taking me on as a graduate student and challenging me to grow as a scientist through her guidance and intuitive gifts. I thank Mark Green, Jamie Harrison, Mariann Johnston, Michele Pruyn, Pam Templer, Matt Vadeboncoeur, and Adam Wild for providing advice on the mechanics of sap flow and guidance on the study design. Thank you to Dr. Briggs and Dr. Stehman for providing invaluable statistical advice. I also thank Christine Costello of the U.S. Forest Service and Mary Hagemann for their constant moral support. I am thankful for the extensive help from high school students, undergraduates, and summer field crews (2013, 2014, 2015, 2017, 2018) as their time spent building probes and instrumenting trees expedited the process of data collection. I give special recognition to my lab mates Yang Yang, Daniel Hong, Gretchen Dillon, Madison Morley, Alexander Young, Jenna Zukswert, and Thomas Mann for their emotional support, incredible advice and guidance.

The Multiple Element Limitation of Northern Hardwood (MELNHE) project was funded by the National Science Foundation and the Long-Term Ecological Research Network.

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Abstract

A.M. Rice. Tree Variability Limits the Detection of Nutrient Treatment Effects on Sap Flow in a Northern Hardwood Forest, 46 pages, 7 tables, 4 figures, 2019. APA style guide used.

Transpiration plays a large role in determining forest water budgets. However, the role of nutrient availability in transpiration rates is not well understood. The objective of this study was to determine whether nutrient fertilization influences sap flow rates in northern hardwood forests. We were unable to detect an effect on sap flow from additions of nitrogen, phosphorus, a combination of nitrogen and phosphorus, or calcium silicate in American beech (*Fagus grandifolia*, Ehr.), red maple (*Acer rubrum* L.), sugar maple (*Acer saccharum* Marsh.), white birch (*Betula papyrifera* Marsh.), or yellow birch (*Betula alleghaniensis* Britton.). Tree-to-tree variability was high, with coefficients of variation averaging 39% within treatment plots. A better study design would include pretreatment data as a covariate. Our data could be used in a power analysis to determine the minimum difference in sap flow rates detectable with our observed variability and study design.

Key Words: sap flow, transpiration, nitrogen, phosphorus, calcium, *Fagus grandifolia* Ehrh., *Acer rubrum* L., *Acer saccharum* Marsh., *Betula papyrifera* Marsh., *Betula alleghaniensis* Britton

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Chapter 1: Literature Review

Why we care about tree water use and sap flow

Understanding tree water use via transpiration under climate change is essential for forecasting changes in hydrological cycling and ecosystem processes (Schlesinger & Jasechko, 2014). Transpiration occurs during photosynthesis, losing more than 100 moles of H₂O per mole of CO₂ gained during this process through the opening of stomata (Hack et al., 2006; Kramer & Boyer, 1995). The opening of stomata is dependent on water availability: if water availability is low, stomata will close to conserve water (Bovard et al., 2004). Transpiration supports the cooling of leaves and the transport of solutes from soil into the roots and through the tree (Nobel, 1999; Tanner & Beevers, 2001). Transpiration rates are affected by the availability of soil water, vapor pressure deficit, and atmospheric CO₂ concentrations (Kirschbaum, 2004; Meinzer et al., 2013).

In a changing climate, transpiration rates can be affected by changes in temperature. A comprehensive study involving long-term evapotranspiration datasets concluded that changes in temperature have had greater effects on tree water use in northern than in southern sections of the northeastern region of the United States (Vadeboncoeur et al., 2018). In Maine, evapotranspiration increased from 18 to 61 years of climate change, whereas to the southwest (PA, OH, WV) evapotranspiration decreased over this time. The increase in transpiration is not as extreme in the southern sections of the region because these sections experience more intense sunlight and a longer growing season than in the northern sections (ME and NH). Lack of sunlight in the northern sections causes the relative increases in air temperature to be more

extreme, creating greater increases in transpiration rates. This finding suggests that the extension of the growing season and increase in temperature due to climate change alleviate an energy limitation in the northern sections of the region (Cleland et al., 2007; Dragoni et al., 2011; Keenan et al., 2014). With this alleviation, tree growth rates increase, thereby increasing transpiration and forest water use. Transpiration is a regulating ecosystem service that is important in hydrological models as it is a major pathway of water loss from an ecosystem. Increasing the accuracy of predictive climate models with improved evapotranspiration estimates is important in predicting water availability as our ecosystems are changing.

Tree water use is also sensitive to elevated atmospheric CO₂ concentrations (Barbour et al., 2005; Meinzer et al., 2004). Tree water use efficiency indicates how much carbon the plant assimilates from CO₂ compared to the loss of water during photosynthesis (Bramley et al., 2013; Farquhar et al., 1989). Through the use of stable isotopes, Jennings et al., (2016) found that increased atmospheric CO₂ has increased tree water use efficiency in eastern black oak (*Quercus velutina* Lamb.) This finding agrees with other studies that have found increased water use efficiency with elevated CO₂ concentrations (Keenan et al., 2013; Kramer et al., 2015; Mastrotheodoros et al., 2017). Higher water use efficiency can be attributed to increased photosynthetic rates and increased stomatal closure (Ainsworth & Rogers, 2007; Franks et al., 2013; Kirschbaum, 2008). Stomata may decrease in aperture or close by increasing H₂O concentrations within the guard cells in response to increasing atmospheric CO₂ (Lawson & Blatt, 2014). This decrease in stomatal aperture decreases water lost from the tree, resulting in increased water use efficiency.

Mechanics of sap flow

Xylem sap is composed of water and minerals that are transported from the roots to the leaves of terrestrial plants through tension generated when stomata open and water is evaporated from the leaf surface (De la Barrera & Smith, 2009). When stomata open during photosynthesis, they create a water potential gradient in the sapwood through tension. This creates a negative pressure in the xylem, pulling water from the soil, through the stem, and to the leaves. The movement of xylem sap through the sapwood is caused by cohesion and adhesion of water combined with a negative pressure gradient when stomates are open during photosynthesis (Dixon & Joly, 1894). The tension pulls sap up the xylem and can be affected by soil water availability, climate, stomatal control in the tree leaves, and humidity (Meinzer et al., 2004).

Ring-porous xylem wood conducts water faster than diffuse-porous wood (Esau, 1965, 1977). Ring-porous species include oak and ash, whereas diffuse species include maple and beech. Diffuse-porous xylem wood has evenly distributed pores throughout the growth layer and ring-porous xylem has larger pores in the spring wood and smaller in summer wood (Esau, 1977). Ring-porous wood has a vessel size of 100 μm , whereas diffuse-porous wood has a vessel size of 20 μm (Nobel, 1974). These size differences explain why sap flux in ring-porous wood is 1.0 cm/s, whereas sap flow in diffuse-porous wood is 0.1 cm/s.

Effects of species and tree size on sap flow

Tree species may be an important factor in forest transpiration rates. A study in four northern Wisconsin forest types--northern hardwoods, conifer, aspen/fir, and forested wetland--found that on average basswood (*Tilia americana* L.) had the highest daily transpiration rate in g H₂O per cm² sapwood per day. The lowest rates were found in red pine (*Pinus resinosa* Ait.) and

balsam fir (*Abies balsamea* (L.) Mill) with trembling aspen (*Populus tremuloides* Michx), white cedar (*Thuja occidentalis* L.), and speckled alder (*Alnus rugosa*) falling in the middle (Ewers et al., 2002). Another study of deciduous trees detected a higher sap flow rate in young white birch than in young American beech and sugar maple (Hernandez-Hernandez, 2014). In England, deciduous species have been found to have 360-390 mm higher annual tree water use than conifers (Harding et al., 1992). In Brazil, a deciduous species (*Cedrela odorata* L.) had higher sap flux densities than a non-coniferous evergreen species (*Carapa guianensis* Aubl.) (Dünisch & Morais, 2002). A more recent study in Minnesota, USA, found that evergreen trees had higher annual transpiration rates than deciduous trees per unit canopy area (Peters et al., 2010). The overall higher annual transpiration rates in evergreen and coniferous species can be attributed to year-long transpiration, whereas deciduous trees only transpire during the growing season while leaves are on. These results suggest that species composition of a forest may play an important role in stand transpiration rates.

Other studies suggest that differences in sap flow among tree species are due to differences in wood density (Dierick & Hölscher, 2009), hydraulic architecture (Bucci et al., 2004), and tree size (Jung et al., 2011; Wullschleger, Hanson, & Todd, 2001). Differences in daily sap flow in deciduous (Herbst et al., 2008; Jung et al., 2011; Wullschleger et al., 2001) and wet tropical forest (Dierick & Hölscher, 2009) suggest that sap flow is influenced more by tree size than species. Tree size is an important factor when scaling single point measurements to stand transpiration rates and is positively correlated to sap flow (Jung et al., 2011; Meinzer et al., 2001). Understanding species differences and size effects on sap flow improves scaling of transpiration in mixed forests.

Importance of Si, Ca, N, and P to sap flow

Calcium is an important plant nutrient because it is responsible for the structural integrity of the tree and stomatal control (Lautner et al., 2007). A lack of soil calcium can increase vulnerability to xylem embolism (Herbette & Cochard, 2010), because calcium affects cell growth by controlling cell wall porosity and as a result decreases xylem vessel size (Lautner et al. 2007). Embolism, also known as vessel blockage, occurs when air enters from outside the xylem cell and the tension within the xylem is lost (De la Barrera & Smith, 2009; Sevanto et al., 2014). It can also occur when gas dissolved in xylem sap degases, creating an air pocket in the xylem vessel. The loss of xylem conductivity can be a result of soil water stress, leading to a failure in water and nutrient transport causing the tree to become susceptible to disease or in extreme cases mortality (Sala et al., 2010).

Nitrogen and phosphorus are important to plant productivity as they control RuBisCo concentrations in leaf chloroplasts. Low levels of nitrogen can limit the photosynthetic capacity of chloroplasts and low phosphorus limits the conversion rate of ADP to ATP, leading to a decrease in sap flow as stomata remain closed (Bigelow & Canham, 2007; Ellsworth et al., 2015). Soil nitrogen and phosphorus influence photosynthetic capacity and potentially increase transpiration rates by increasing RuBisCo concentrations in leaves (Herbert & Fownes, 1995; Warren & Adams, 2002). Some researchers have hypothesized that trees increase nutrient uptake and transport by increasing stomatal conductance above the requirement for optimal carbon assimilation (Ainsworth & Rogers, 2007; Franks et al., 2013; Lu et al., 2018).

Silicon is an important element in plant cell walls and a lack of it can lead to decreased growth and development (Epstein, 1999). Silicon also regulates toxic metals (i.e., Al and Zn) in trees by forming heavy metal silicates (Epstein, 1999; Liang et al., 2007). The uptake of silicon

varies among species and plant groups (Richmond & Sussman, 2003). The transport of silicon is passive through transpiration and has been found to accumulate near stomatal openings (Wiese et al., 2007). Silicon in leaves alleviates drought and temperature stresses because it is highly efficient at emitting midinfrared wavelengths (8-12 μm), resulting in a reduced heat load of the leaf (Wang et al., 2005). An increase in leaf silicon concentrations improves tree tolerance to temperature which is important in regulating transpiration rates in response to interannual temperature fluctuations.

Observations of sap flow response to nutrient manipulation

Multiple fertilization studies have assessed the effects of nutrient availability on transpiration rates. Bucci et al. (2006) observed an increase in average daily sap flow rates with the addition of N in five woody savannah species in Central Brazil. In South Carolina, USA, an increase in sap flow rates was observed in loblolly pine (*Pinus taeda L.*) seedlings (Samuelson et al., 2008). Micro and macronutrient additions have been found to increase sap flow in Norway spruce (*Picea abies*) (Phillips et al., 2001) and eucalyptus (*Eucalyptus saligna*) forests (Hubbard et al., 2004). A study in an abandoned pasture in Amazonia reported an increase in transpiration with the addition of calcium, but not the addition of the limiting nutrient, phosphorus (da Silva et al., 2008). Another study aimed to determine the effects of nitrogen and phosphorus on sap flow in a temperate hardwood forest but was unable to detect a difference (Hernandez-Santana et al., 2015). The inability to detect a treatment effect in the northern hardwood forest may be due to high tree to tree variability and small sample sizes relative to the magnitude of the effects.

Over decades of acid rain, calcium has been leached at a rate that exceeds replenishment through weathering (Federer et al., 1989; Long et al., 2009; Schaberg et al., 2001). The depletion

of calcium can limit forest productivity and cation exchange capacity (Huggett et al., 2007; Likens et al., 1998; Mclaughlin & Wimmer, 1999). A study at the Hubbard Brook Experimental Forest added calcium in the form of wollastonite (CaSiO_2) to examine ecosystem responses to acidification by restoring calcium to preindustrial levels (Cho et al., 2012). An observation of decreased stream flow led to finding that the addition of calcium (or silica) increased transpiration (Green et al., 2013). This increase in water use and relative growth rate of trees could be attributed to an increase in stomatal density (Battles et al., 2014; Juice et al., 2016).

Chapter 2:

Variability in Nutrient Treatment Effects on Sap Flow

in a Northern Hardwood Forest

1. Introduction

Transpiration is affected by vegetation type and coverage and environmental variables such as soil water availability and atmospheric water demand (Aber & Federer, 1992; Foley et al., 2000; Kite, 1998). Deciduous (Ewers et al., 2002; Hernandez-Hernandez, 2014) and coniferous (Harding et al., 1992) forest types differ in transpiration rates due to the length of the growing season. Species may also differ in transpiration rates because of nitrogen or phosphorus limitation (Chapin et al., 1987). Several studies have found evidence that soil nitrogen may regulate transpiration rates (Cramer et al., 2008; Matimati et al., 2014) due to the role of xylem nitrogen concentrations in signaling stomatal opening and leaf growth (Reich et al., 2005; Wilkinson et al., 2007).

In current forest hydrology models, tree transpiration rates do not include the role of soil nutrients due to a lack of knowledge of the role of nutrient availability on sap flow. Northeastern hardwood forests are poorly adapted to water stress due to the abundance of water in this region (Pederson et al., 2014) and species differ in sensitivity (Coble et al., 2017). Models predict that these northeastern areas will experience wetter conditions with more severe dry periods in the near future due to climate change (Hayhoe et al., 2008). Because of these projections it is becoming increasingly crucial to study water cycling in temperate forests and influences on this process. Other studies have suggested a water limitation on tree water use which could become even more important with intensifying summer droughts (Brzostek et al., 2014).

There have been conflicting reports on the effect of nutrient manipulations on sap flow. An increase in sap flow has been observed with the addition of multiple element fertilizers in Norway spruce (Phillips et al., 2001) and eucalyptus forests (Hubbard et al., 2004). Calcium additions have been observed to increase sap flow in Amazonia (da Silva et al., 2008) and may have increased sap flow at Hubbard Brook, based on an observation of decreased stream flow in the first 3 years after treatment (Green et al., 2013). This decrease was suggested to be a response of increased water use efficiency or alleviation of a nutrient limitation. The only experiment to examine the effects of nitrogen and phosphorus additions found no detectable treatment effect on sap flow of northern hardwood species (Hernandez-Hernandez, 2014).

Forest ecosystems on recently glaciated soils have been believed to be nitrogen limited due to the availability of weatherable phosphorus (Walker & Syers, 1976). With chronically elevated nitrogen deposition, the limiting nutrient in some regions may have shifted to phosphorus. Our study takes place in a temperate forest in New Hampshire, USA, which is a glaciated area that at a northeastern regional scale has been found to be primarily nitrogen limited (Naples & Fisk, 2010; Vadeboncoeur, 2010). However, our study sites in the White Mountains show a greater diameter growth response to phosphorus than nitrogen (Gonzales & Yanai, 2019; Goswami et al., 2018).

To investigate the response of tree water use to the addition of nutrients, we examined sap flow rates in trees of five common hardwood species in plots receiving additions of nitrogen and phosphorus in a factorial design. We expected to find an increase in sap flow with the addition of the limiting nutrient as nutrient availability is a driver of productivity and photosynthesis. Additional trees were studied in plots receiving calcium to test the findings of

Green et al. (2013) that increased calcium availability would increase water use within trees for up to 3 years post treatment before returning to ambient rates.

2. Methods

2.1. Site Description

We studied tree water use in five hardwood stands located in three forested sites in the White Mountain National Forest, New Hampshire, USA: two in each of the Bartlett Experimental Forest and Hubbard Brook Experimental Forest, and one in Jeffers Brook (Table 1). The climate is humid continental, with a mean annual temperature of 4.4 °C and precipitation of 140 cm (Bailey et al., 2003; Smith & Martin, 2001). Soils are predominantly moderately to well drained, coarse-loamy Spodosols and Inceptisols developed in glacial drift composed of granitic and metamorphic silicate rocks (Vadeboncoeur et al., 2012; Vadeboncoeur et al., 2014)). Dominant tree species are American beech (*Fagus grandifolia* Ehrh.), sugar maple (*Acer saccharum* Marsh.), and yellow birch (*Betula alleghaniensis* Britton) in mature stands with the inclusion of white birch (*B. papyrifera* Marsh.) and red maple (*A. rubrum* L.) in successional stands (Fatemi et al., 2012; Naples & Fisk, 2010).

These three forested sites are part of a Multiple Element Limitation in Northern Hardwood Ecosystems (MELNHE, <http://www.esf.edu/melnhe>) study that aims to develop an understanding of nutrient limitations. Our design focused on five stands within the MELNHE study. Within each stand there are four plots measuring 50 x 50 m, with the exception of Hubbard Brook Successional (30 x 30 m), which have been treated since summer 2011 with 30 kg ha⁻¹yr⁻¹ of nitrogen as NH₄NO₃, 10 kg ha⁻¹yr⁻¹ of phosphorus as NaH₂PO₃, both nitrogen and phosphorus, or were left untreated. A fifth plot in each stand received a one-time application of

1150 ha⁻¹ of wollastonite (CaSiO₂) in 2011, except that in Hubbard Brook Successional it was applied in 2015 (Table 1).

2.2. Field Methods

Sap flow measurements were taken during the summers of 2013, 2014, 2015, 2017, and 2018 (Tables 2 and 3). In 2013 and 2014, the goal was to examine three tree species in three mature stands in plots that received calcium and control treatments (6 plots total). In 2015, the goal was to assess the effects of nitrogen and phosphorus treatments (4 plots) on one species in one successional stand. During those years, data were collected by a series of summer interns and data were sparse due to gaps in measurements from lack of probe contact to sapwood. Measurements were improved starting in summer 2017 when a graduate student started overseeing data collection and processing. In 2017, one species in a mature stand in Bartlett was examined, and in 2018, three species were examined in a Hubbard Brook successional stand.

Trees were chosen by their dominance in the canopy and their health. The number of trees instrumented per plot ranged from 4 to 9. Probe installation sites chosen were clear of cankers and scars and not directly below decaying limbs. Before probe installation, ~ 4 cm² of bark was removed to the cambium at breast height from the south-facing side of the tree. Once bark was removed, holes 21 mm deep and 2.8 mm in diameter were drilled in the middle of the exposed cambium.

Sap flow measurements were made using the thermal dissipation method (Granier, 1987). This technique used a pair of stainless-steel probes that were 20 mm long and 1.8 mm in diameter. One probe was wrapped with copper constantan wire (Type T) and generated a constant flow of heat (0.2 W). The other was a reference probe that received no heat. Both

probes were coated with heat-conducting paste and inserted into 20 mm long aluminum sleeves for protection during insertion into the tree.

Probes were inserted into the trees 1 to 13 days prior to the collection of measurements. Once probes were inserted, they were protected from precipitation with a plastic cover sealed with acid-free silicone caulk. Closed-cell reflective polyethylene insulation was stapled over the plastic cover to shield solar radiation. The probes were connected to cables no longer than 20 m to minimize loss of power from cable resistance, trampling by humans, and disturbance by wildlife.

In the field, temperature differences between the heated and reference probes in each plot were recorded on a multiplexor and stored on a multichannel data logger (Campbell Scientific CR800) inside an ActionPacker®. To power the data logger and multiplexer, the first study, in 2013, used one battery per plot that was recharged by a solar panel. Late studies used three 12 V deep-cycle marine batteries linked together. Temperature differences were recorded every 15 minutes as an average of thirty 30-second readings. One of the three batteries powering the data logger and multiplexer was charged each week to ensure continuous power supply throughout each collection period.

2.3. Data Processing

Temperature differences were converted into sap flow rates using BaseLiner (version 3.0.10, developed by Ram Oren, Duke University). BaseLiner used the following equation to produce sap flow rates (g H₂O/ m² of sapwood/ day):

$$Sap\ Flow = 119 \times \left[\left(\frac{B}{W} \right) - 1 \right]^{1.23}$$

where the constants, 119 (Watts/°C) and 1.23, were derived using the quantity of heat applied to the probes (P. Lu et al., 2004). B (°C) is the “baseline” value that was manually chosen as the maximum temperature difference between the two probes during the night and was set for each tree and day over the study period. W (°C) is the temperature difference between the probes at each 15-minute observation period.

2.4. Data Analyses

Analyses were conducted by averaging daily sums of sap flow for the best days in each data set (Table 6). Days were excluded from analyses if they did not follow the characteristic diurnal curve or if all probes were not functioning simultaneously. Gaps in usable data were usually due to cable disturbances or improper probe installation; in the first year, batteries were charged from solar panels (which proved insufficient to maintain their charge) and data were very spotty.

The three studies in nitrogen and phosphorus addition plots were analyzed together in a randomized full factorial ANOVA with sap flow as the response variable and species and stand as fixed effects. Three stands were studied in three different years, which precluded distinguishing the effects of stand from the effects of the year of measurement. The five studies of calcium addition were analyzed in an ANOVA type 3 sum of squares test with sap flow as the response variable and stand, species, and the number of years post treatment as categorical fixed effects. The number of years post treatment were nested within two categories: “early” and “late.” These categories were based on the finding that evapotranspiration increased for 3 years after calcium addition and then returned to normal (Green et al., 2013). Treatments were nested within stands and stands were treated as a random effect. The assumption of normality of residuals was met through a logarithmic transformation of sap flow. Finally, coefficients of

variation (CV) across trees were calculated for each treatment by stand and study (year) using the average sap flow rate. These analyses were conducted using the “lme4” package in *R* version 3.5.2 (R Development Core Team 2018).

3. Results

3.1. Characteristics of Sap Flow

Sap flow peaked between 12:30 and 3:00 PM and was lowest between 2:30 and 4:30 AM Eastern Daylight Savings Time (Figure 1).

We used data from days when all the trees in a stand had functioning sap flow sensors (Table 6). The number of days that were used ranged from 1 to 3, depending on the study. After 2013, we abandoned solar panels and invested in more batteries to be charged off site, and data completeness improved.

Coefficients of variation across trees within plots ranged from 9 to 137%. The first year, 2013, had the highest CV among the five studies. CV's averaged 39% within treatment plots (Table 6).

3.2. Nitrogen and Phosphorus Factorial Additions

The effects of nitrogen and phosphorus on sap flow were studied in white birch in Bartlett Successional in 2015, sugar maple in Bartlett Mature in 2017, and red maple, sugar maple, and white birch in Hubbard Brook Successional in 2018 (Table 4). Sap flow differed across these three studies ($p < 0.01$), which could be because sites were different or because conditions differed over the three years in which they were each measured. Sap flow in the Hubbard Brook Successional stand, measured in 2018 after 7 years of fertilization, was 63% higher than in the Bartlett Successional and Mature stands. There was, however, no detectable

difference in sap flow with the addition of nitrogen ($p= 0.50$), phosphorus ($p=0.95$), or their interaction ($p= 0.33$). Species were also indistinguishable in sap flow ($p=0.58$; Figures 2 and 3).

3.3. Calcium Addition

The effect of wollastonite (CaSiO_2) addition was studied on American beech, sugar maple, and yellow birch in Bartlett, Hubbard Brook, and Jeffers Brook Mature stands in 2013 and 2014 (Table 5). Sugar maple was also studied in Bartlett Mature stand in 2017 and white birch was studied in Bartlett Successional in 2015 and Hubbard Brook Successional in 2018. In 2018, we examined red maple in Hubbard Brook Successional (Figure 4).

There were no detectable effects of calcium addition on sap flow ($p= 0.62$). Sap flow rates did not differ consistently between “early” and “late” years ($p=0.37$) nor was there a difference in response to calcium addition over time ($p=0.88$ for the interaction of treatment and time period). The five species were indistinguishable in sap flow ($p = 0.12$)

4. Discussion

Overall, it was difficult to detect an effect of nutrient addition on sap flow with statistical confidence due to high tree-to-tree variation. This was surprising as previous studies reported significant effects of nutrient additions on sap flow. Among these studies, the largest detected difference was an 88% increase in sap flow with the addition of nitrogen ($80 \text{ kg ha}^{-1} \text{ yr}^{-1}$) on loblolly pine (*Pinus taeda L.*) seedlings in South Carolina, USA (Samuelson et al., 2008). Effects of 60% were detected in a study involving the addition of phosphorus ($50 \text{ kg}^{-1} \text{ ha}^{-1}$ of $\text{P}_2\text{O}_5^{-1}$) and calcium (2 t ha^{-1} of CaCO_3) on *Vismia japurensis*, *Bellucia grossularioides*, and *Laetia procera* in Amazonia (da Silva et al., 2008). The use of pretreatment data allowed for the detection of smaller effects (33%) with the addition of macro and micronutrients to a *Eucalyptus saligna* plantation in Hawaii (Hubbard et al., 2004). We were not expecting effect sizes this

large. The effect of calcium addition on water use in a Hubbard Brook watershed was only 25% (Green et al. 2013), based on a decrease in stream flow. Without including pretreatment data, it would be difficult to detect an effect of calcium addition in our study because of the high variability among trees. Pretreatment data would allow the response of individual trees to be monitored.

This study suffered from measurement errors due to improper contact between the probe and the sapwood. This error was reduced in 2017 and 2018 compared to the prior years by the using a smaller drill bit to ensure contact between the aluminum shield around the probe and the sapwood and by using electrical tape over the probe to hold it to the tree. However, even with this decrease in measurement error, there was still high variation from tree to tree in the later years. The number of days of usable data was also improved by more frequent maintenance of wire connections, probes, and batteries.

Future sap flow studies would benefit from incorporating supporting factors such as leaf area, stomatal conductance and soil moisture since these are important influences on sap flow (Green et al., 2013; Hubbard et al., 2004; Phillips et al., 2001). Stomatal conductance is measured per leaf area and can increase transpiration rates by increasing the amount of CO₂ the leaf takes in. Measuring stomatal conductance can determine how nutrient additions affect this mechanism responsible for transpiration rates. Soil moisture also has a direct effect on rates because it is the source of water being transpired by the tree. Low soil moisture can lead to lower sap flow rates. These variables may also explain some of the variability we observed among trees. Environmental variables such as light environment, vapor pressure deficit, and canopy position of the trees may also be of interest since they have also been found to influence sap flow

(Oren et al., 1998a; Oren et al., 1998b), but due to lack of resources, we were unable to incorporate these variables into our study.

Information on the effect of soil nutrient on sap flow could be used when considering what aspects are important in hydrological climate models as well as the effects management practices may have on transpiration. Since we were unable to detect an effect of nitrogen, phosphorus or calcium treatment due to high variability among trees we cannot determine the importance of including nutrients in these models. However, we can suggest that future studies collect pretreatment data for each tree to increase statistical power in detecting treatment effects. By determining the role of soil nutrients in sap flow, we can determine if it is necessary that hydrological models include soil nutrients. Improving these models allows for better management of our forests for productivity.

Chapter 3: Conclusions and Future Directions

With the historical increases in anthropogenic activities leading to acid rain, forest nutrient cycles have the potential to be affected. A shift in soil nutrition due to nitrogen deposition and cation leaching may have an effect on the hydrological cycle in an ecosystem. It is important to understand the role of limiting nutrients in ecosystems that have historically experienced increased nitrogen deposition and the leaching of calcium to increase the predictive power of hydrological models. This study aimed to assess the influence of soil nutrients through the addition of nitrogen, phosphorus, and calcium silicate. Over the five years of study, the effects of these nutrient additions on sap flow were measured on five hardwood tree species across five stands in the White Mountain National Forest, NH, USA. Our results suggest that tree-to-tree variability is too large to detect a small treatment effect with statistical confidence. To improve the ability to detect a treatment effect, future studies should analyze sap flow in the trees prior to fertilization and monitor those same trees for the duration of the experiment.

Prior to the implementation of future studies, a minimum detectable difference should be calculated using values from previous studies in the same area or from the literature (Table 7). The minimum detectable difference in sap flow due to treatment would be calculated using the following equation (Zar 1984):

$$MDD = \sqrt{\frac{2ks^2\phi^2}{n}}$$

where MDD is the minimum detectable difference, k is the number of treatments, s^2 is the sample variance of all the study trees, ϕ^2 is the non-centrality parameter, and n is the sample size. Power would be set at 0.8 and alpha at 0.05.

Determining the MDD for a study would provide insight on the effect size needed to report whether nutrient additions have an effect on tree sap flow. If nutrients have an important effect on water use, incorporating them into hydrological models will provide a more accurate estimate of ecosystem water use.

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Table 1. Site descriptions including coordinates, year of clearcut, elevation, slope, and aspect of the five stands studied in the White Mountains of New Hampshire. Years indicated with an asterisk are approximate, and the older stands may not have been fully clearcut.

Stand	Coordinates	Year of Clearcut	Elevation (m)	Slope (%)	Slope Aspect
Bartlett Successional (C6)	44° 02' N, 71° 16' W	1975	460	13-20	NNW
Bartlett Mature (C8)	44° 03' N, 71° 18' W	1883*	330	5-35	NE
Jeffers Brook Mature	44° 03' N, 71° 88' W	1900*	730	30-40	WNW
Hubbard Brook Successional	43° 93' N, 71° 73' W	1971	500	10-25	S
Hubbard Brook Mature	43° 93' N, 71° 73' W	1910*	500	25-35	S

Table 2. Sap flow studies in control, nitrogen, phosphorus, and nitrogen + phosphorus addition plots showing the number of annual nitrogen and phosphorus applications prior to each study (the year of the study) and the number of trees of each species measured in each treatment.

Years of Treatment (year)	Stand	Species	Number of Trees in Treatment			
			Control	Nitrogen	Phosphorus	Nitrogen + Phosphorus
4 (2015)	Bartlett Successional (C6)	white birch	4	4	5	4
6 (2017)	Bartlett Mature (C8)	sugar maple	5	6	6	5
7 (2018)	Hubbard	red maple	3	3	3	3
	Brook	sugar maple	3	3	3	3
	Successional	white birch	3	3	3	3

Table 3. Sap flow studies in calcium addition plots showing the number of years since the addition of calcium, the year of the study, and the number of trees of each species measured in each treatment. The calcium treatment was applied in 201, except that in Hubbard Brook Successional it was applied in 2015.

# of Years Post Treatment (year)	Stand	Species	Number of Trees in Treatment	
			Control	Calcium
2 (2013)	Bartlett Mature (C8)	American beech	2	3
		sugar maple	3	3
	Hubbard Brook Mature	American beech	2	2
		sugar maple	2	2
	Jeffers Brook Mature	yellow birch	2	1
		sugar maple	4	2
3 (2014)	Bartlett Mature (C8)	yellow birch	3	1
		sugar maple	3	2
	Hubbard Brook Mature	American beech	3	2
		sugar maple	3	2
	Jeffers Brook Mature	yellow birch	3	1
		sugar maple	4	4
3 (2018)	Hubbard Brook Successional	yellow birch	3	5
		sugar maple	3	3
		red maple	3	3
4 (2015)	Bartlett Successional (C6)	white birch	3	3
		white birch	4	4
6 (2017)	Bartlett Mature (C8)	sugar maple	5	4

Table 4. ANOVA table showing type 3 sum of squares for N and P addition plots. The response variable is sap flow and the listed explanatory variables as categorical fixed effects.

	Sum of Square	Df	F Value	Pr(>F)
N Treatment	0.071	1	0.4601	0.4998
P Treatment	0.001	1	0.0038	0.9510
NxP Interaction	0.146	1	0.9442	0.3345
Species	0.168	2	0.5427	0.5835
Stand	4.481	2	14.4777	5.328e-06***
Error	10.987	71		

'Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table. 5 ANOVA table showing type 3 sum of squares for calcium addition plots. The response variable is sap flow with calcium treatment, species, and “Early” vs “Late” as categorical fixed effects. “Early” represents 1-3 years after the calcium addition, and “Late” refers to 4-6 years after the addition.

	Df Numerator	Df Denominator	F Value	Pr(>F)
“Early” vs “Late”	1	333.77	1.2932	0.2563
Treatment	1	6.14	1.2764	0.3008
“Early” vs “Late x Treatment	1	8.45	0.0227	0.8838
Species	4	20.27	1.0287	0.4164

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 6. Coefficient of variation (CV) of sap flow for each treatment plot in each study year. CV's were calculated using the average and standard deviation of sap flow all the trees within a treatment plot. Along with year of study are the dates of days used in analyses.

Year (dates)	Stand	Treatment	CV (%)
2013 (Aug 5)	Bartlett Mature (C8)	Control	137
		Calcium	58
(Aug 5)	Hubbard Brook	Control	36
		Calcium	32
Mature			
(July 19)	Jeffers Brook Mature	Control	34
		Calcium	32
2014 (June 22 - 24)	Bartlett Mature (C8)	Control	36
		Calcium	34
(July 1)	Hubbard Brook	Control	40
		Calcium	45
Mature			
(August 1, 2, and 5)	Jeffers Brook Mature	Control	35
		Calcium	16
2015 (August 1 (Nitrogen and Phosphorus + control); July 22 and 23 (Calcium + control))	Bartlett Successional (C6)	Control	15
		Nitrogen	47
		Phosphorus	30
		Nitrogen + Phosphorus	14
		Calcium	9
2017 (July 31 – Aug 1)	Bartlett Mature (C8)	Control	31
		Nitrogen	29
		Phosphorus	21
		Nitrogen + Phosphorus	67
		Calcium	44
2018 (July 19-21)	Hubbard Brook Successional	Control	30
		Nitrogen	36
		Phosphorus	38
		Nitrogen + Phosphorus	47
		Calcium	31

Table 7. Studies on sap flow that report a difference in sap flow rates among species or nutrient additions.

Forest Type	Species or Treatment Studied (number of trees)	Effect Size and Significance	Source
Mixed Deciduous	<i>Q. mongolica</i> (5) <i>T. amurensis</i> (5) <i>U. davidiana</i> (5) <i>C. controversa</i> (3) <i>A. mono</i> (3)	No Significance	Jung et al. 2011
Mixed Deciduous	<i>Alnus incana</i> (41) <i>Populus tremuloides</i> (79) <i>Thuja occidentalis</i> L. (9)	No Significance	Loranty et al. 2008
Evergreen	Control (9) 50 kg ha ⁻¹ of P ₂ O ₅ (9) 50 kg ha ⁻¹ of P ₂ O ₅ + 2 t ha ⁻¹ of CaCO ₃ (9) 50 kg ha ⁻¹ of P ₂ O ₅ + 2 t ha ⁻¹ of CaCO ₃ + 1 t ha ⁻¹ of CaSO ₄ · 2H ₂ O (9)	P ₂ O ₅ + CaCO ₃ + CaSO ₄ · 2H ₂ O treatment was 35% higher than P ₂ O ₅ + CaCO ₃	da Silva et al. 2008
Tropical	<i>Cedrela odorata</i> (4) <i>Anacardium excelsum</i> (4) <i>Hura crepitans</i> (4) <i>Luehea seemannii</i> (4) <i>Tabebuia rosea</i> (4) <i>Gmelina arborea</i> (4) <i>Tectona grandis</i> (4) <i>Acacia mangium</i> (4) <i>Terminalia amazonia</i> (4)	<i>Luehea seemannii</i> and <i>Terminalia amazonia</i> were 105% higher than <i>Cedrela odorata</i> and <i>Gmelina arborea</i>	Kunert et al. 2010
Coniferous	130 mm H ₂ O yr ⁻¹ (5) 494 mm H ₂ O yr ⁻¹ (5) 0 kg N ha ⁻¹ yr ⁻¹ (5) 80 kg N ha ⁻¹ yr ⁻¹ (5)	90% increase between no N and N addition (<i>p</i> <0.01)	Samuelson et al 2008
Evergreen (Eucalyptus)	Control (9) Micro and micronutrient fertilization (9)	43% increase following fertilization (<i>p</i> =0.04)	Hubbard et al. 2004

Deciduous	<i>Populus fermontii</i> (6) <i>Saliz gooddingii</i> (6) <i>Tamarix ramosissima</i> (6)	<i>Tamarix ramosissima</i> was 94% higher than <i>Populus fermontii</i> and <i>Saliz gooddingii</i>	Nagler et al. 2003
Deciduous	<i>Pinus resinosa</i> Ait. (8) <i>Pinus banksiana</i> Lamb. (8) <i>Acer saccharum</i> Marsh (8) <i>Populus tremuloides</i> Michx (8) <i>Abies balsamea</i> (L.) Mill (8) <i>Thuja occidentalis</i> L. (8) <i>Abies balsamea</i> (L.) Mill (8) <i>Alnus regosa</i> (8)	12% higher than <i>Populus tremuloides</i> Michx (This was the smallest significant effect size)	Ewers et al. 2002

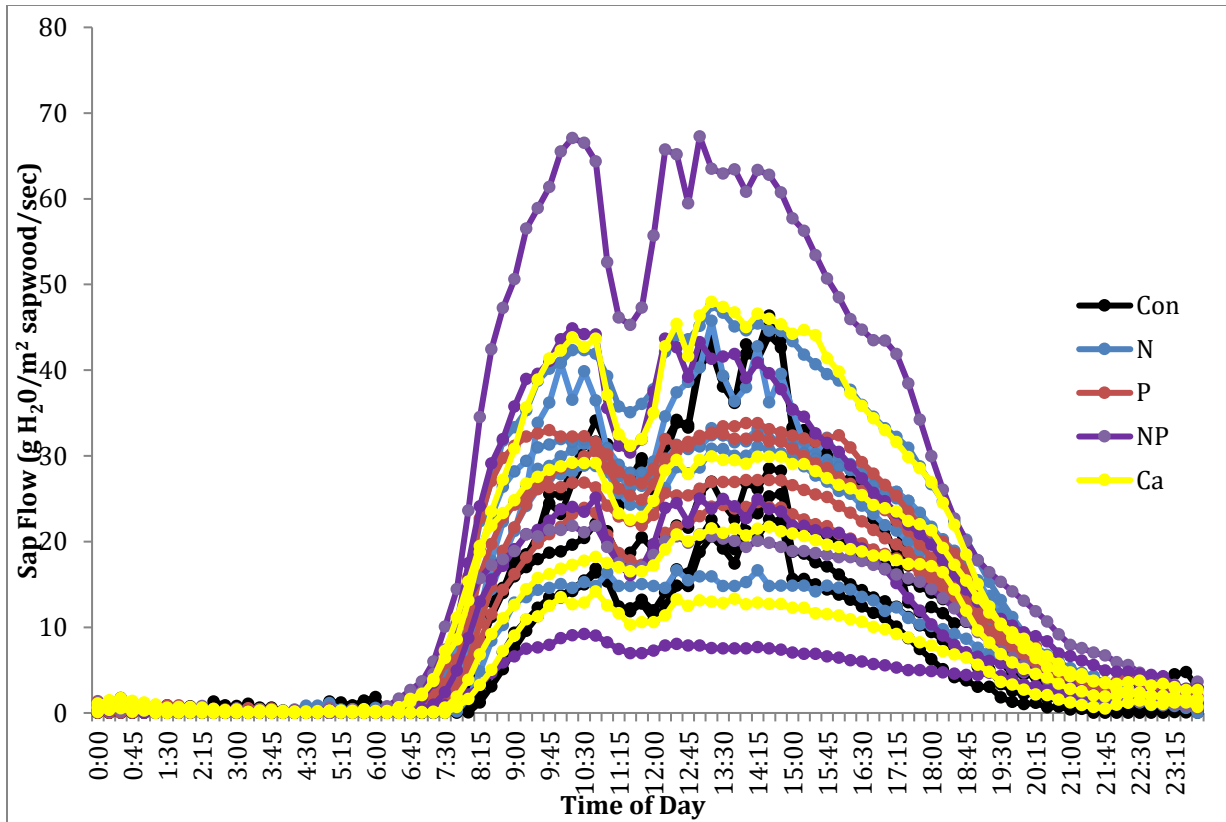


Figure 1. An example of diurnal sap flow patterns in sugar maple in the Bartlett Mature stand on July 30, 2017. Each line represents an instrumented tree and is colored by treatment.

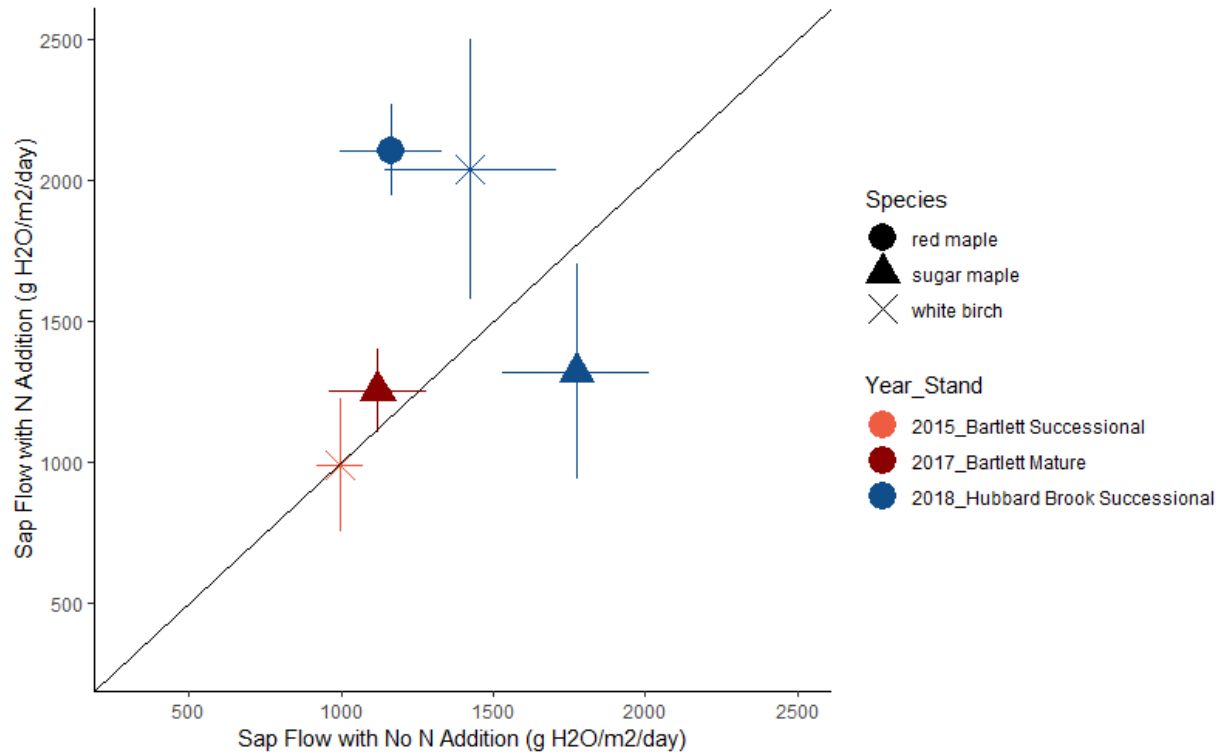


Figure 2. Responses of sap flow to nitrogen treatments. Bars represent the standard error. Species are represented by symbols and stand with corresponding year studied are represented by color. The 1:1 line represents equal sap flow rates in plots that received nitrogen additions and control plots without the addition.

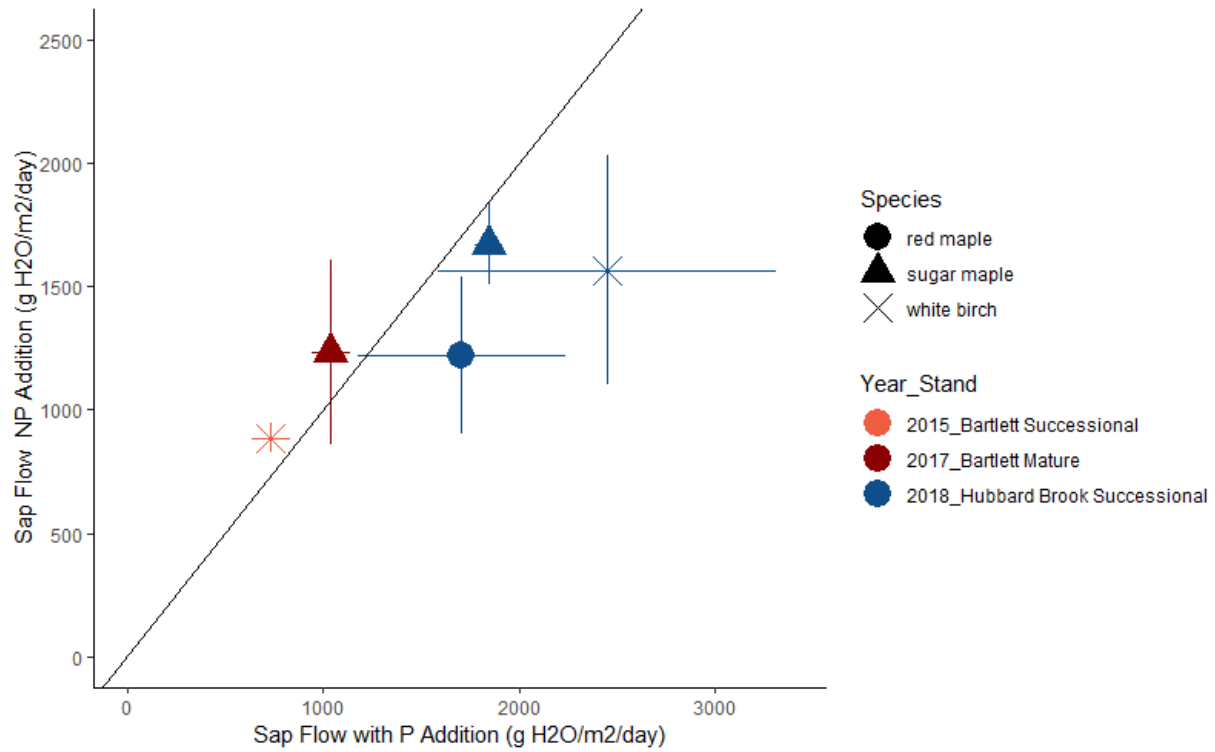


Figure 3. Responses of sap flow to phosphorus treatments. Bars represent the standard error. Species are represented by symbols and stand with corresponding year studied are represented by color. The 1:1 line represents equal sap flow rates in that received phosphorus additions and plots without the addition.

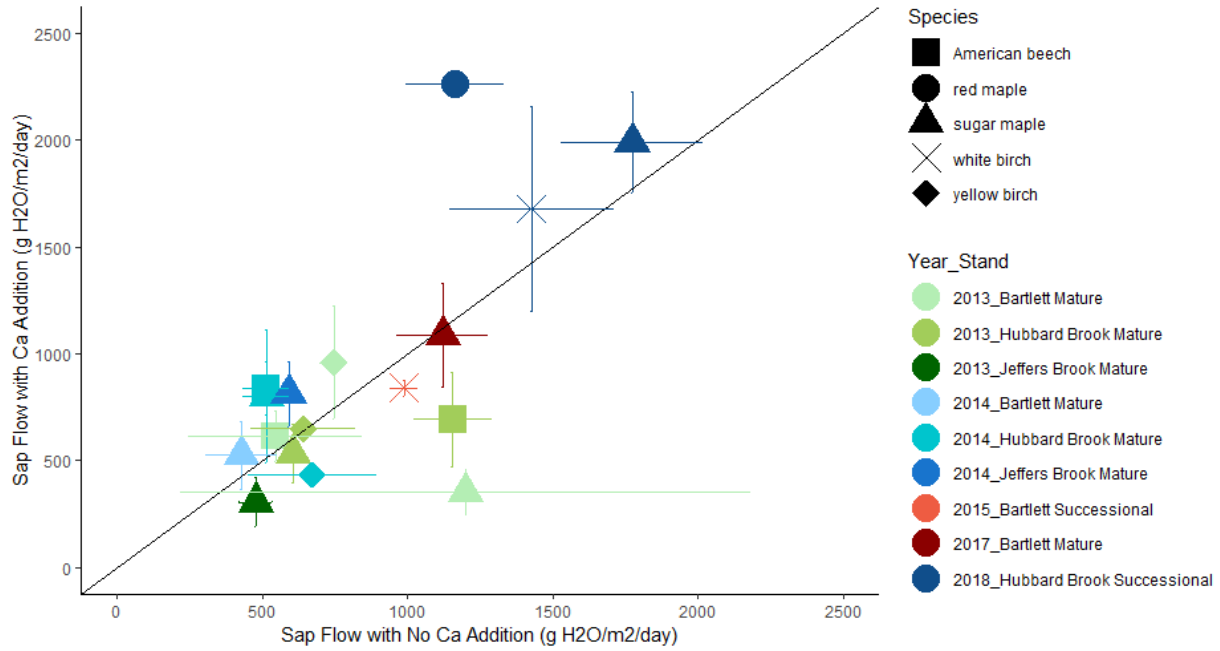


Figure 4. Response of sap flow to calcium treatment. Bars represent standard errors. Symbols represent species and colors represent years with associated stands. The 1:1 line represents equal flow rates in control and treated plots.

Appendix 1

R code for NxP addition design:

```
SF.n.p$TreatYear<-as.factor(SF.n.p$TreatYear)
SF.n.p$NTRT<-as.factor(SF.n.p$NTRT)
SF.n.p$PTRT<-as.factor(SF.n.p$PTRT)

SF.n.p$Site<- as.factor((SF.n.p$Site))
names(SF.n.p)

SF.n.p$Avg<- log(SF.n.p$Avg)
SFnp<-lm(Avg~NTRT*PTRT+Species+Site, data = SF.n.p)
summary(SFnp)
qqnorm(resid(SFnp))
qqline(resid(SFnp))
shapiro.test(resid(SFnp))
skewness(resid(SFnp))
Anova(SFnp,type = 3)
summary(SFnp)
```

R code for Ca addition design:

```
SF.Ca$TreatYear<-as.factor(SF.Ca$TreatYear)
SF.Ca$Dumm<- as.factor(SF.Ca$Dumm)
SF.Ca$Species<-as.factor((SF.Ca$Species))
SF.Ca$Avg<- log10(SF.Ca$Avg)
SF.Ca$Stand<-as.factor(SF.Ca$Stand)
SF.cacon<-lmer(Avg~Dumm*Treat+Species+(1|Stand/Treat)+(1|Dumm/TreatYear),data = SF.Ca )
summary(SF.cacon)
qqnorm(resid(SF.cacon))
qqline(resid(SF.cacon))
shapiro.test(resid(SF.cacon))
skewness(resid(SF.cacon))

# Anova and Tukey HSD
Anova(SF.cacon, "F", type=3,contrasts = list(Dumm=contr.sum, Treat=contr.sum))
```


Curriculum Vita

Alexandrea Rice

Current Address: 900 Shackelton Point Road • Bridgeport, NY 13030
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EDUCATION

Master of Science- Ecosystems and Ecology in Forest and Natural Resources Management

(Dec 2019) State University of New York College of Environmental Science and Forestry,
Syracuse, NY

GPA: 3.82/4.0

Major Professor: Dr. Ruth Yanai

Related Coursework:

- Biogeochemistry
- Ecophysiology of trees and forests
- Experimental Design and ANOVA
- Quantifying Uncertainty in Ecosystem Studies
- Regression Analysis
- Research Management
- Sampling Methods Managing and Archiving Research Data
- Sampling Techniques
- Writing for Scientific Publication
- Uncertainty Analysis

Bachelor of Science- Environmental Science

May 2017

Allegheny College, Meadville, PA

Marine Biological Laboratory

Fall 2015

Woods Hole, MA

Community College of Allegheny County

Fall 2014

Pittsburgh, PA

PROFESSIONAL EXPERIENCE

Teaching Assistant: Introduction to Soils, SUNY-ESF, Syracuse, NY *Dec-Jan 2017, 2018 & 2019*

- Led one lab period each week consisting of a mix of field lectures and laboratory experiments
- Prepared and conveyed field and lab overview lectures on topics such as soil texture, and cation exchange capacity
- Graded weekly lab reports for my lab section, met twice a week for discussion on reports with other TA's; total work equated to 20 hrs/week

Forest Preserve Intern, NYS-DEC, New Paltz, NY

Jun-Aug 2019

- Collected GPS tracks for the 16 trail-less peaks in the Catskill Forest Preserve
- Rated GPS track by condition class and route-finding experience to provide the DEC with baseline data on the informal trail networks currently found on the trail-less peaks
- Produced a report outlining the study findings and recommendations for establishing trails
- Worked 40 hours per week for 13 weeks

Research Assistant, SUNY-ESF, Syracuse, NY

Jan-May 2018 & 2019

- Collected, organized, and analyzed sap flow, sap sweetness, root nutrient uptake and biomass, leaf fall, and woody debris data
- Submitted annual grant reports for projects I collected and analyzed data
- Served as the lab recruiter for undergraduate research assistants
- Mentored high school volunteers and undergraduate students on research projects
- Managed lab meetings, and presented data at conferences
- Worked 20 hours per week on average

Field Crew Leader SUNY-ESF, Bartlett, NH *May-Aug 2017 & 2018*

- Interviewed, hired, organized and over sought 12 intern research projects, working at least 40 hours per week for 13 weeks.
- Coordinated fertilization and sampling procedures as well as daily work schedules
- Mentored projects involving GIS, circuitry, mushroom identification, predatory simulation, stem mapping, soil cations and respiration, and tree photosynthetic mechanisms

Laboratory Manager and Research Assistant, Allegheny College, Meadville, PA *Aug 2013-
May 2017*

- Maintained, collected, and analyzed leaf litter, and soil samples from nutrient addition, and carbon manipulation plots at Allegheny College's Bousson Experimental Research Reserve
- Prepared and presented forest and soil related presentations for middle school and high school students
- Coordinated research projects with community members and organized research assistants
- Worked on average 20 hours per week.

Mushroom Farm Intern, Crawford County Fungi, Cambridge Springs, PA *Jan-May 2017*

- Inoculated fruiting bags with grain spawn and prepared liquid cultures from fruit spores
- Collected mushrooms and packaged for sale at the local farmers market and restaurants
- Designed and produced a mushroom grow kit with detailed growing instructions and recipes to be sold at the local markets.

Research Assistant, Michigan Technological University, Kotzebue, AK *Jun-Aug 2016*

- Assisted in ongoing permafrost thaw research on the effects of nutrient cycling in alpine/spruce forests and tundra landscapes for Robert Stottlemyer
- Collected and analyzed terrestrial and aquatic samples to measure nitrogen and carbon isotope levels, primary productivity, and stream flow to determine if climate change is altering these important cycles
- Worked 40 hours per week in remote areas in Alaska: Selawik National Wildlife Refuge, and the Noatak National Preserve

Independent Research, Marine Biological Laboratory, Woods Hole, MA *Fall 2015*

- Analyzed the effects of long-term nitrogen deposition of ectomycorrhizal fungi between Harvard Forest and Bousson Experimental Forest in collaboration with John Hobbie and Jerry Melillo
- Collected soil, tree leaf, and mushroom samples from Harvard Forest, and Bousson Experimental Research Reserve

Avian Hospital Intern, National Aviary, Pittsburgh, PA

Spring-Winter 2014

- Assisted in procedures such as x-ray's, nebulizations, euthanasia, bandaging, and vaccinations
- Created and distributed diets, maintained cleanliness of cages and hospitalized birds, and constructed enrichments

SKILLS

Scientific Equipment- Hydrolab, Proplus, Van Dorn, Autoclave, LiCorr light meter, LiCorr photosynthesis meter, LiCorr chamber respiration, Wiley Mill, Sonicator, Atomic Mass Spectrometer, inductively coupled plasma spectrometer, Zeiss Discovery v.12 SteREO microscope, Cyclops, HOBO data loggers, CR1000 data logger, muffle furnace, microwave digester

Computer Software- ArcGIS, Microsoft Office (Word, Excel, Powerpoint, Access), R Studio, SAS

Scientific techniques- seining, tree coring, tree diameter, tree height, northeastern tree species identification, soil gas, soil cores, plankton tow, primary productivity, dissolved oxygen, soil respiration, stream flow, soil and water chemistry, sap flow, dry ashing, acid digestion (HCl, HF, HNO₃), sap flow sensor making, public surveying, centrifuge, and soil extractions

POSTERS & PRESENTATIONS

- Rice, A.** "Relating Soil Nutrients to Ecosystem Fluxes". 2019 ASA-CSSA-SSSA International Annual Meeting in San Antonio, TX 2019
- Rice, A.,** and Yanai, R. "Expanding beyond the watershed: the benefits of multi-site comparisons". Hubbard Brook Committee of Scientists Fall Meeting at the Cary Institute of Ecosystem Studies, NY 2019
- Yang, Y., **Rice, A.,** and Yanai, R. "Never Say "There was no difference"- Report the Magnitude of Change You Can Detect in Ecosystem Studies". Gordon Conference 2019
- Rice, A.,** Vadeboncoeur, M., and Yanai, R. "Soil Nutrients Explain Forest Characteristics". Spotlight on Student Research at SUNY-ESF 2019
- Rice, A.,** Vadeboncoeur, M., and Yanai, R. "Which Soil Nutrient Pools Explain Forest Characteristics". New York Society of American Foresters 2019 Annual Meeting in Syracuse, NY 2019
- Libenson, A., **Rice, A.,** Johnston, M., and Yanai, R. "Going with the flow: is tree water use affected by nutrient availability?". Hubbard Brook Ecosystem Study 55th Annual Cooperator's Meeting at the Hubbard Brook Experimental Forest, NH 2018
- Rice, A.,** Vadeboncoeur, M., and Yanai, R. "Filling in the Gaps in Our Soil Data: It's the 2018

- Pits". Hubbard Brook Ecosystem Study 55th Annual Cooperator's Meeting at the Hubbard Brook Experimental Forest, NH
- Rice, A., Johnston, M., and Yanai, R.** "Nutrient Availability Affects Sap Flux in Sugar Maple". NY Society of American Foresters 2018 Annual Meeting in Syracuse, NY 2018
- Rice, A., Johnston, M., and Yanai, R.** "Sap Flux in Sugar Maple Does Not Respond to Nutrient Amendments". 27th Annual Forest Ecosystem Monitoring Conference at the University of Vermont, VT 2017
- Rice, A., Johnston, M., and Yanai, R.** "Do Nutrient Additions Affect Sap Flow in Sugar Maple Trees?". 44th Annual Fall Scientific Paper Session of the Rochester Academy of Science at the St. John Fisher College, NY 2017
- Rice, A., and Johnston, M.** "Effects of Nutrient Additions on *Acer Saccharum* Sap Flow". Hubbard Brook Committee of Scientists Fall Meeting at the Cary Institute of Ecosystem Studies, NY 2017
- Rice, A., Johnston, M., and Yanai, R.** "Nitrogen, Phosphorus, and Sap Flow. And Calcium, Too". Hubbard Brook Ecosystem Study 54th Annual Cooperator's Meeting at the Hubbard Brook Experimental Forest, NH 2017
- Rice, A.** "Long-Term Nitrogen Depositions Decrease Soil Cation Availability in a Mature Hardwood Forest". Sigma Xi 27th Annual Undergraduate Student Research and Creative Accomplishment Conference at Penn State Erie, The Behrend College 2017
- Rice, A. and Schultz, J.** "Identification and Prioritization of Nutrient Loading Contributors into Lake Wilhelm, M.K. Goddard State Park, Pennsylvania". Class project for the PA DCNR in Crawford county, PA. My responsibilities were to digitize maps, created a geodatabase for the project, and provide input on appropriate symbology of the results 2016
- Rice, A. and Moretti, E.** "Improvements and Proposals for Cora Clark Park, Meadville, Pennsylvania". Class project presented to the Meadville mayor, H. Leroy Stearns. My responsibilities were to collect research and analyze the importance of species diversity and protection of species within the park 2016
- Rice, A.** "Effects of long-term nitrogen deposition on ectomycorrhizal fungi communities in forests of the northeastern United States Semester in Environmental Science Independent Research Symposium 2015
- Rice, A., Ludwig, O., and McIntosh, C.** "DIRT". Creek Connections Symposium in Meadville, PA 2015
- Washko, S., **Rice, A.**, and Wind, L. "Forest Education". Creek Connections Symposium in Meadville, PA 2014
- Rice, A., Wang, R., and Chapel, W.** "Small Scale Sustainable Agriculture". Pennsylvania Environmental Research Consortium in State College, PA 2013

PUBLICATIONS

-
- Bowden, R.D., Wurzbacher, S., Washko, S., Wind, L., **Rice, A.**, Coble, A.E., Baldauf, N., Johnson, B., Wang, J., Simpson, M., and Lajtha, K. 2019. Long-Term Nitrogen Addition Decreases Organic Matter Decomposition and Increases Forest Soil Carbon. *Soil Science Society of America Journal* 83: S82-S95.

GRANTS, HONORS AND AWARDS

OIGS Student Travel Grant from SUNY-ESF	2019
Alec Proskine '36 Scholarship from SUNY-ESF	2019
Graduate Student Association Travel Grant from SUNY-ESF	2019
ESF Career Fellowship from SUNY-ESF	2019
Edna Bailey Sussman Foundation Fellowship from SUNY-ESF	2019
OIGS Graduate Student Travel Grant from SUNY-ESF	2019
Albert & Barbara Cline Silviculture Scholarship from SUNY-ESF	2018
Outstanding Student Award and Scholarship by the Allegheny College Env. Sci. Dept.	2017
Arbor Grant from Davey Tree Expert Company	2017
Class of 1939 Senior Research Grant from Allegheny College	2016
Paraskevi (Evi) Mavrogeorgis, Class of 1997, Memorial Fund from Allegheny College Env. Sci. Dept.	2016

ADDITIONAL WORK EXPERIENCE

Server, BRGR, Pittsburgh, PA	<i>May 2015-Jan 2018</i>
<ul style="list-style-type: none">• Opened/Closed the restaurant and provided customer service while on school breaks	
Concession Attendant, Steamship Authority, Woods Hole, MA	<i>Sept-Dec 2015</i>
<ul style="list-style-type: none">• Opened/closed concession stand, and ensured food quality and customer service	
Student Gardener, Allegheny College, Meadville, PA	<i>Aug 2013-May 2014</i>
<ul style="list-style-type: none">• Nurtured crops from seed to harvest, and created potting soil from compost to be sold at the farmers market	
Hostess and Server, Cain's Saloon, Dormont, PA	<i>Aug 2012-May 2015</i>
<ul style="list-style-type: none">• Greeted customers, provided customer service and ensured customer satisfaction	
Admin. Assistant and Car Detailer, Greenwood Automotive, Pittsburgh, PA	<i>Jun 2012-May 2017</i>
<ul style="list-style-type: none">• Detailed interior and exterior of vehicles, ordered automobile parts, and provided final overview before delivery	

LEADERSHIP AND INVOLVEMENT

Outing Club Leader and Treasurer	<i>Jan 2015-May 2017</i>
<ul style="list-style-type: none">• Organized and lead weekend outdoor trips such as backpacking, camping, hiking, kayaking, or biking as well as attend trainings in first aid, CPR, and wilderness first aid• Organized and held skills clinic such as how to plan a backpacking trip, how to tie various knots, and campfire cooking• Handled all club expenses such as participant fees, trip fees, motor pool finances, and club budget	
PJAS Judge	<i>April 2016</i>
<ul style="list-style-type: none">• Volunteered to judge middle school independent science projects	