

**Maple from the Ground Up:
The Role of Place in Distinguishing Sap**

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Research Methods in Vermont Environmental Science
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Table of Contents

Abstract		1
Introduction		2
Background	2	
Maple in Vermont	2	
Maple Syrup Terroir	3	
Maple Sap Terroir	4	
Tree Health Monitoring via Sap	6	
Study Goals	8	
Methods		9
Overview	9	
Site Descriptions	9	
Soil Sampling	13	
Soil Analysis	14	
Sap Collection and Analysis	15	
Statistical Analysis	15	
Results and Discussion		17
Soil Chemistry	17	
Soil-Bedrock Relationships	23	
Sap Chemistry	24	
Sap-Bedrock Relationships	26	
Soil-Sap Relationships	27	
Geographic Distribution of Soil and Sap Chemistry	33	
Evaluation of SSURGO Data	36	
Conclusions and Future Work		37
Acknowledgments		42
Literature Cited		42

Abstract

The relationship between physical location of a maple sugarbush and the sap it produces may have important implications for the use of sap as an indicator of soil fertility, as well as for enhancing current understanding of the concept of *terroir* or “the taste of place” as it pertains to maple syrup. To explore soil-maple sap relationships, during Spring 2009 soil and sap chemistry for nine Addison County maple syrup producers was examined. Soil pH, effective cation exchange capacity (eCEC), and BaCl₂-extractable elements were measured for 28 composited samples, while two sap samples from these sites were analyzed for pH, °Brix, electrical conductivity, and elemental composition. Soil Ca:Al ratios, an indicator of tree health, were above, but close to, the threshold of 1 that has been associated with 50% risk of negative health consequences. Ongoing soil acidification and consequent decrease in Ca:Al ratios would elevate health risks to Addison County sugarbushes and should be monitored. Generally, sap-soil relationships were not statistically significant; however, positive correlations between soil and sap were observed for Ca, Mg, Mn, and Ca:Mn ratios. These concentrations and molar ratios are important indicators of plant nutrition and health; therefore, the observed correlations suggest that sap could potentially serve as an indicator of tree-health at the stand scale. Confirmation of soil-sap trends at additional sites, as well as direct correlation between sap concentrations and tree-health indicators would be required for practical application of this promising approach. A distinct advantage of the proposed sap-based health-monitoring method includes the fact that thousands of VT maple producers are already collecting composite sap samples that would be appropriate for analysis. With regard to the physical basis for the concept of *terroir*, it appears that soil chemistry of a given stand does directly influence sap chemistry, and variation in sap chemistry is readily apparent at the sugarbush scale within Addison County.

Introduction

Background

For the past three years, a group of interdisciplinary scholars at Middlebury College, the University of Vermont, and the Vermont Agency of Agriculture has been exploring the concept of terroir as part of the Terroir Working Group. The concept of terroir, long applied to wines, has recently been expanded to include other foodstuffs that are unique to their locales, such as cheese and maple syrup (1). For wines, terroir is viewed as the combined effect of climate, soil, vine rootstock and cultivar, and production technique on a wine's unique quality and flavor (2). Because maple syrup undergoes relatively few processing steps, it is hypothesized that an important aspect of maple syrup terroir may be derived from maple sap chemistry, which itself may be influenced most importantly by the soil and location where the maple tree grows. In this work, chemical relationships between soil and maple sap were investigated to improve our understanding of the natural science underlying the concept of maple terroir and to assess the usefulness of sap chemistry in monitoring the tree health at the scale of a production sugarbush.

Maple in Vermont

The sugar maple (*Acer saccharum*) embodies a very important part of Vermont's culture and economy. Not only does the sugar maple dominate much of the United States' and Canada's northern hardwood forests, but the species is extensively used for lumber, and its bright orange foliage serves as iconic imagery of a New England autumn. In the fall of 2005, tourism contributed \$363.8 million to the Vermont economy (3). Furthermore, although Vermont is the nation's eighth smallest state, it is the largest maple syrup producer in the U.S. and contributed \$18,624,000 worth of maple syrup to the market in 2007 (4). It is also estimated that the state is

home to more than 2,000 syrup producers (5). The Vermont Agency of Agriculture has recently announced the Taste of Place Initiative (6), the goal of which is to use the concept of terroir to support and promote local food production and marketing, as well as to promote and publicize research into the scientific basis for terroir. Although in its draft form, a proposed Taste of Place “label” explicitly requires objective proof of the place-based uniqueness of a product, including such aspects as the influence of soil type or microclimates on taste. Our examination of soil-maple sap relationships is thus highly relevant to the Vermont maple community.

Maple Syrup Terroir

Although it is widely known in the maple industry that maple syrup from different producers can taste quite different, statistical analysis of maple syrup tastings reveal that the untrained tasters, including the general public, can readily taste differences among multiple syrups placed before them (7, 8). Moreover, it is common for producers to speak about a particular producer they know that produces syrup with a consistent and unique flavor year-to-year. And while the individual flavor compounds (e.g., alkyl pyrazines, furanones, etc.) that may be responsible for differences in flavor have received some attention (9-12), the actual source of this variation, place-based or otherwise, has not. In contrast, others have studied have focused on place-based differences in syrup composition, but examined aspects, such as elemental composition, that may only be indirectly related to syrup flavor. For example, statistically significant differences in the concentrations of Mg, Ca, and K have been observed in maple syrup obtained from different syrup-producing regions of North America (e.g., Vermont, Wisconsin, New Hampshire, Quebec). The authors did not propose a cause of such regional

differences in syrup chemistry, nor whether the chemical variation was related to flavor variation (13).

At its simplest, maple syrup production involves concentrating the natural sugars in the maple sap, either through boiling or a combination of reverse osmosis and boiling. This apparent processing simplicity, however, neglects the wide variation in techniques and materials used during sap collection, evaporation, and bottling, including whether

- galvanized buckets, gravity-fed or vacuum-fed plastic lines are used in sap collection,
- sap is pre-concentrated (and to what sugar content) using reverse osmosis prior to boiling
- wood or oil is used as fuel for the evaporator
- defoaming agent used, what type of defoamer, and how much

For the most part, the impact of various processing steps, methods, and technologies on maple syrup chemistry and flavor are unknown. Because of the large variation in production techniques that may influence syrup chemistry (14-16), we begin our work into the scientific basis for maple terroir by focusing on fundamental relationships between maple *sap* chemistry and place.

Maple Sap Terroir

Maple sap consists primarily of water, and sucrose, with smaller amounts of fructose, glucose, amino acids, organic acids, phenolic compounds, hormones, minerals, and salts. Most research into soil-sap place-based relationships has focused on elemental composition and has focused on the possibility of sap serving as an indicator of soil and maple stand health. For example, Kogelmann and Sharpe (17) focused on correlations among soil and maple foliar,

xylem, and sap Mn concentrations, because of interest in the potential role of Mn toxicity in maple stand decline. Sugar maple (*Acer saccharum*) and red maple (*Acer rubrum*) sap and soil-Mn concentrations were observed to be highly correlated ($p < 0.001$). Ca and Al concentrations in sugar maple sap were also significantly different between the two sites studied (10-15 trees per site), although correlations with associated soil samples were not reported. Similarly, in earlier work designed to examine the feasibility of using sap as an indicator of increased nutrient bioavailability due to acid deposition, McCormick (18) observed qualitative correspondence between soil and sap Ca and Zn concentrations for red maple. For most elements, however, significant within-site variation and temporal (within season, and yearly) variation was observed. Perhaps the earliest work into place-based sap chemistry found that sap concentrations of Na and Cl of roadside sugar maples were significantly higher than those of non-roadside sugar maples as a direct result of the deicing salts (19). These studies suggest that it is plausible that the soil in which maple trees grow directly affects sugar maple sap chemistry, but more work is needed in more locations to determine whether these soil-sap correlations are more generally observed. Importantly, relationships between soil and sap chemistry in sugar maple in these studies have been made primarily at the scale of small number of trees at various sites, for which sap from individual trees and adjacent soil were analyzed. In contrast, we chose to work at a larger scale, with sap samples collected from the main sap holding tanks at each site and soil samples composited from numerous sub-samples collected throughout the site. In this way, we examined the concept of terroir as it may play out at the production scale.

Tree Health Monitoring via Sap

Because of its prevalence throughout the forests of the U.S. Midwest and Northeast and the Canadian east, and because of its economic and cultural importance, the sugar maple health is of high importance. However, several episodes of maple decline throughout its range have occurred over the past four decades, likely due to a combination of natural and anthropogenic forces (17, 20-25). These forces include soil moisture deficiency or excess, highway deicing salts, insects, diseases, harmful management activities, acid deposition, and changes in freeze/thaw cycles, potentially due to climate change (25). Variation in soil acidity, influenced both by surficial geology and acid deposition in the Northeast as an important contributor to maple decline. Mohamed et al. (24) found that more acidic soils with high levels of exchangeable soil-Al were associated with maples in decline. Moreover, soil and xylem wood Al levels were correlated, suggesting xylem wood might be used as a proxy for soil conditions. Similarly, both Kogelmann and Sharpe (17) and Houle et al. (22) found that soil acidity and associated high soil-Mn were associated with declining sites. Mn levels in soil, foliage, and xylem wood were correlated in both studies, while Kogelmann and Sharpe additionally studied and found correlations between soil and sap Mn.

The role of soil chemistry as a contributor to maple decline indicates that our investigation into soil-sap terroir relationships can simultaneously provide information of interest to a larger audience. Moreover, while it is well known that soil chemistry is a critical variable in understanding forest and plant health, soil sampling and analysis can be labor-intensive and difficult to capture representative soil properties over large non-uniform areas. Others have sought to address the large variation in soil properties and associated labor and expense associated with high-density sampling by looking for proxies for soil conditions. For example,

Johnson et al. (26) examined the potential for using GIS-based terrain attributes (e.g., slope, aspect, elevation, soil moisture index, and hydrologic flow accumulation) to predict soil properties, including pH, cation exchange capacity, and base saturation. Terrain attributes failed in this regard, yielding little predictive power.

Because earlier work suggests that maple tissues (xylem, foliage, sap) may reflect soil chemistry and may be correlated with tree health, our study considers the possibility of using maple (xylem) sap composited from an entire sugarbush to serve as a site-wide proxy for soil conditions and indicator of tree health. The use of sap analysis rather than analysis of soil or other tissues boasts the advantage that maple sap is already being collected by maple syrup producers on an annual basis and requires little sample preparation (i.e., no digestion or extraction) prior to analysis. While the ability to use sap analysis to assess the average condition of an entire sugarbush could prove extremely beneficial to maple syrup producers and landowners, potential complications include the fact that stands often overlie multiple soil units of varying size. Specifically, if 25% of trees overlie a given soil unit with its own unique chemistry, it does not follow necessarily that this soil unit produces 25% of the sap collected across the entire stand. Thus, disparities in how soil and sap properties are aggregated via composite sampling may hinder this soil-sap approach.

As a secondary approach to reducing future labor-intensive soil sampling and analysis, we also proposed to examine the use of publicly disseminated soil chemistry data, such as the 1971 Addison County Soil Survey Geographic Database (SSURGO) (27) published by the Natural Resources Conservation Service. This survey was initiated in the 1940s by and completed in the 1960s. Consistency between current soil chemistry measurements and

SSURGO data would lend confidence in the use of SSURGO to understand soil conditions, maple health, and potentially soil-based influence on maple terroir.

Study Goals

In exploring the relationships between soil and sugar maple sap chemistry, this study attempts to understand better both the concept of maple terroir, as well as the potential use of maple sap as a proxy for soil chemistry and an indicator of tree health. Secondly, the use of 1971 Addison County SSURGO data as an estimate of current soil condition was assessed with the motivation of minimizing future requirements for on-the-ground soil sampling and analysis. These goals were addressed by measuring a series of soil and sap chemical parameters on composite samples obtained from nine Addison Country sugarbushes.

Methods

Overview

This study investigated correlations between the chemical compositions of both the soil and sap of the sugar maple on a sugarbush scale. The following sections detail the sugarbush sites studied, the soil sample collection methods, soil analyses, sap sample collection and analyses, soil and sap chemistry analyses, assessment of possible threats to sugarbush health, statistical analyses performed, and evaluation of SSURGO data from the 1971 Addison County Soil Survey.

Site Descriptions

Soil and sap samples were obtained from nine sites in Addison County, VT (Figure 1), chosen based on sugarmakers' past participation in related sap studies and their willingness to have their soil sampled (28). Participating syrup producers reported that they did not blend their sap with sap from other locations nor intentionally lime/fertilize their maple stands.¹ Select SSURGO-reported (27) soil attributes for each site are provided in Table 1. Figures 2a and 2b show the area of tapped trees, SSURGO soil units, and the location of each soil sub-sample collected.

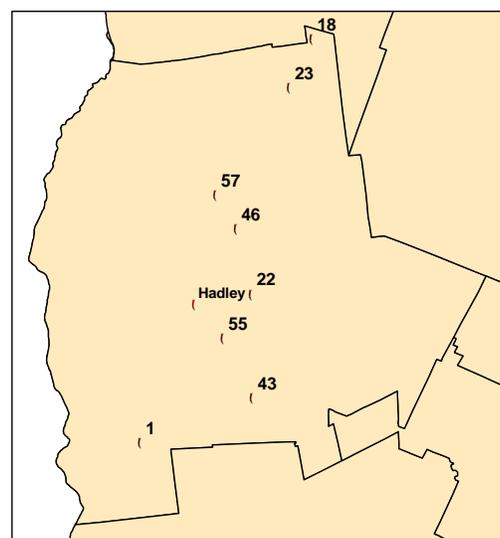


Figure 1. Locations of study sites.

¹ Some participants indicated that nearby quarry operations appeared to deliver air-borne limestone dust to their soil, as indicated to them by above-normal and increasing soil pH values.

Table 1. Site and soil unit properties.

Site ID	Site Properties			Soil Properties ^c							
	Total Area (m ² (acres)) ^a	Ave. Site Elevation (m) ^a	Bedrock Category ^b	Soil Unit	Unit Area (m ²) ^a	Parent Material	Surface Texture	% Organic Matter	% Clay	pH	CEC
1	68753 (17)	168	Not limestone or dolostone	A	6844	N/A	Unweathered bedrock	N/A	N/A	N/A	N/A
				B	55342	Coarse-loamy till	Channery silt loam	≤2.69	≤6.8	5.1 - 5.5	12.3 - 13.5
				C	1005	Coarse-loamy till	Loam	3.3 - 3.86	7.6 - 7.7	5.1 - 5.5	≤9.9
				D	4141	Coarse-loamy till	Loam	3.3 - 3.86	7.6 - 7.7	5.1 - 5.5	≤9.9
				E	662	Coarse-loamy till	Loam	3.3 - 3.86	7.6 - 7.7	5.1 - 5.5	≤9.9
18	18365 (4.54)	320	Not limestone or dolostone	A	17836	Coarse-loamy till	Gravelly fine sandy loam	3.2 - 4	6.5 - 7.5	4.5 - 5.0	N/A
				B	527	Coarse-loamy till	Loam	4.01 - 6.5	6.5 - 7.5	4.5 - 5.0	N/A
22	135192 (33.4)	168	Not limestone or dolostone	A	47817	Sandy and gravelly glaciofluvial deposits	Gravelly sandy loam	3.88 - 3.95	≤4.5	4.5 - 5.0	N/A
				B	3851	Sandy and gravelly glaciofluvial deposits	Gravelly sandy loam	3.73 - 3.88	≤4.5	4.5 - 5.0	N/A
				C	83524	Sandy and gravelly glaciofluvial deposits	Gravelly fine sandy loam	3.23 - 3.73	4.8 - 7	4.5 - 5.0	N/A
23	225992 (55.8)	549	Not limestone or dolostone	A	35040	Coarse-loamy basal till	Gravelly fine sandy loam	3.2 - 3.93	7 - 7.1	4.5 - 5.0	N/A
				B	6468	Coarse-loamy basal till	Gravelly loam	4.47 - 9.28	7.8 - 11	6.1 - 6.5	4.7 - 8.5
				C	59490	Coarse-loamy basal till	Loam	3.93 - 4.32	7.1 - 7.8	5.1 - 5.5	N/A
				D	31276	Coarse-loamy basal till	Loam	3.93 - 4.32	7.1 - 7.8	4.5 - 5.0	N/A
				E	47322	Coarse-loamy basal till	Loam	3.93 - 4.32	7.1 - 7.8	4.5 - 5.0	N/A
				F	39638	Coarse-loamy basal till	Gravelly fine sandy loam	3.2 - 3.93	6.5 - 7	4.5 - 5.0	N/A
43	5985 (1.48)	183	Not limestone or dolostone	A	5288	N/A	N/A	≤3.43	4.9 - 9.7	5.1 - 5.5	≤6.0
				B	697	N/A	N/A	3.43 - 5.48	4.9 - 9.8	4.5 - 5.0	6.0 - 8.7

46	1272 (0.31)	107	Limestone/ Dolostone	A	1272	Clayey glaciolacustrine deposits	Clay	4.07 - 4.53	55.5 - 58.4	5.6 - 6.0	13.9 - 31.6
				B	N/A	Coarse-silty alluvium	Very fine sandy loam	3.14 - 3.4	≤7.8	5.6 - 6.0	≤6.7
55	89025 (22.0)	137	Limestone/ Dolostone	A	64078	Coarse-loamy till	Channery silt loam	3.43 - 4	11 - 17.5	6.1 - 6.5	5.9-6.2
				B	11164	Coarse-loamy till	N/A	N/A	N/A	6.6 - 7.3	N/A
				C	5702	Clayey glaciolacustrine deposits	Boulders	4.1 - 4.53	17.5 - 58.4	5.6 - 6.0	≤5.9
				D	7131	Clayey glaciolacustrine deposits	Boulders	4.1 - 4.53	17.5 - 58.4	5.6 - 6.0	≤5.9
				E	970	N/A	Boulders	4.1- 4.53	17.5 - 58.4	5.6 - 6.0	≤5.9
57	1284 (0.32)	137	Limestone/ Dolostone	A	668	Clayey glaciolacustrine deposits	Clay	3.43 - 5.48	33.0 - 60.0	5.6 - 6.0	23.3 - 132.2
				B	616	Sandy glaciolacustrine deposits over clayey glaciolacustrine deposits	Fine sandy loam	3.43 - 5.48	4.9 - 9.7	6.1-6.5	≤6
Hadley	2279 (0.56)	122	Limestone/ Dolostone	A	2279	Coarse-loamy till	Silt loam	3.3 - 4.1	9.7 - 17.5	6.1 - 6.5	12.3 - 16.6

^a Site areas and average elevation were obtained using GPS tracks and GIS analysis.

^b Bedrock category was determined in consultation with Professor Ray Coish, Geology Department, Middlebury College using the 1961 Digitized version of the Centennial Vermont State Geologic Bedrock Map (29).

^c Soil unit properties were as reported by SSURGO 1971 Addison County Soil Survey, aggregated as average property over 0-15 cm depth (30).

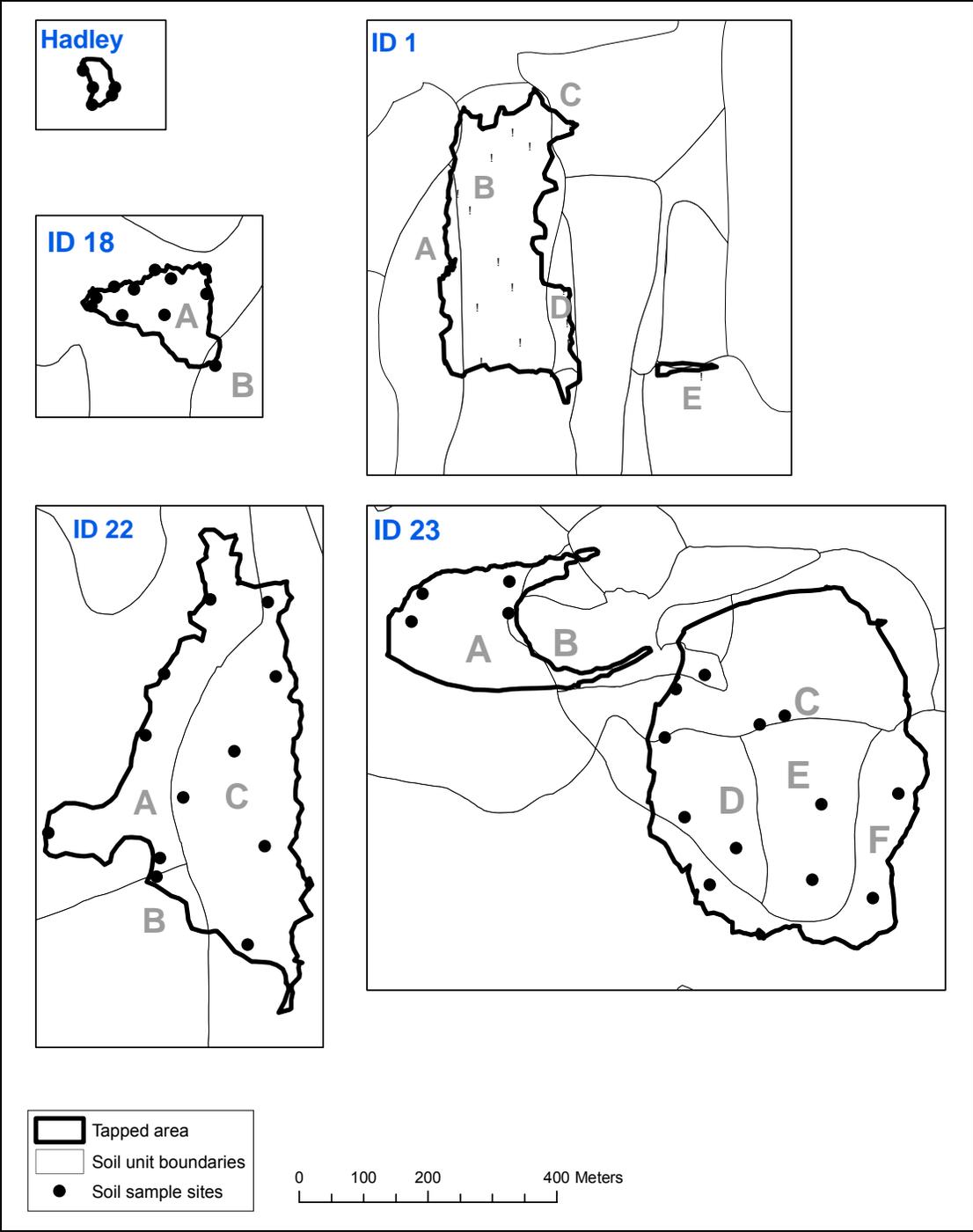


Figure 2a. Maps of soil units and soil sample collection sites for maple producer sites 1, 18, 22, 23, and Hadley.

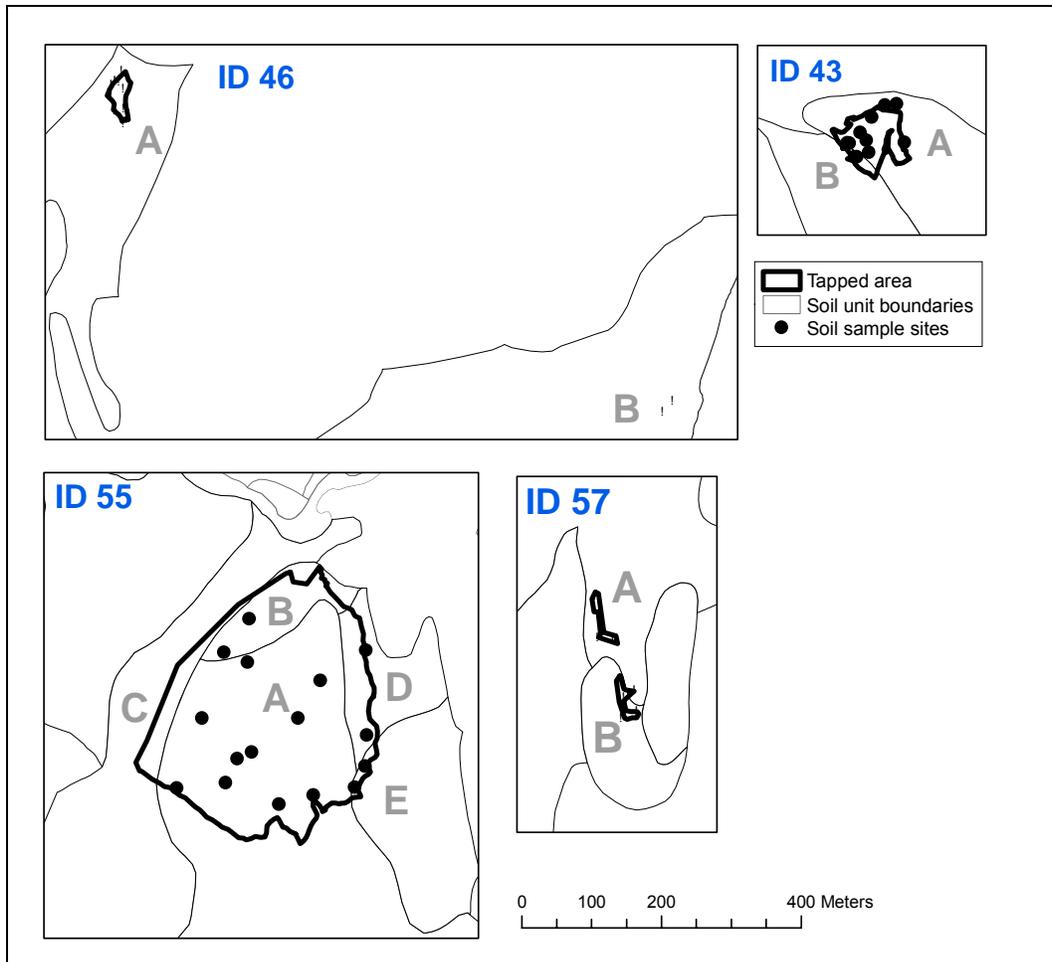


Figure 2b. Maps of soil units and soil sample collection sites for maple producer sites 43, 46, 55, and 57.

Soil Sampling

The tapped area at each site was mapped using Garmin GPSmap 76Cx GPS units. The GPS tracks were overlain on the GIS-based SSURGO soil maps for Addison County (30). The approximate location and number of soil samples collected was determined based on the number of soil units underlying each site. Between 10 and 20 samples per site were collected to capture the heterogeneity of each site's soil units. Actual sample locations were recorded (GPS) (Figures 2a and 2b). For each sample, the top 15 cm of soil was collected using 1-in. i.d. stainless steel soil corers (Oakfield Apparatus, WI). Each sample was stored in a plastic bag, laid out to air-dry,

and, and then sieved to <2-mm. The <2-mm fraction of soil subsamples were composited by soil unit, totaling 28 composite samples representing the 9 sites.

Soil Analysis

The soil sample composites were analyzed for effective cation exchange capacity (eCEC), pH, and extractable elements. All glassware was acid-washed and rinsed with water; all water used was deionized and polished “Pictotech” water. For soil pH measurements, 20 mL water was added to 10 g of soil. The solution was intermittently shaken for 20 min (Stovall Life Science, Inc. The Belly Dancer), allowed to stand for 1 h, then analyzed using the Orion 420A+ pH meter, which was calibrated with pH 4 and 7 buffers. For eCEC and measurement of extractable elements, 1.5 g of soil was extracted with 30 mL 0.1 M BaCl₂·2H₂O. The soil-solution was shaken for 2 h (Burrell Wrist Action Shaker Model 75) and centrifuged at 700 g for 15 min (Beckman GPR Centrifuge). The supernatant was vacuum-filtered through Whatman #2 coarse filters.

Elemental concentrations (Al, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Ni, P, Pb, Sc, Si, Sr, Ti, V, Y, Zn, and Zr) for extractable element and eCEC measurements were determined using inductively coupled plasma atomic emission spectrometry (ICP-AES) (Middlebury College Department of Geology, Middlebury, VT). Elemental concentrations are only reported if they were above the quantifiable limit in either sap or soil. Unfortunately, ICP instrument conditions did not allow accurate determination of Na. Due to the lack of sodium data, CEC reported here is taken as an effective CEC (eCEC). The lack of Na inclusion in CEC would lead to low estimates; however, Na concentrations were expected to be low in the soils studied here. eCEC ($cmol_c kg^{-1}$) is defined as

$$eCEC = \left(Al(\text{cmol}_c L^{-1}) + Ca(\text{cmol}_c L^{-1}) + Mg(\text{cmol}_c L^{-1}) + K(\text{cmol}_c L^{-1}) \right) \frac{0.3L}{\text{SoilMass}(kg)} \quad (1)$$

Where cmol_c refers to centimoles of charge, given the following ionic charges: Al^{3+} , Ca^{2+} , Mg^{2+} , K^+ .

Sap Collection and Analysis

Sap samples were obtained from each participating maple syrup producer during Week 1 and Week 3 of the 2009 sap run. Samples represented a composite of the site's sap by collecting sap from the site's main holding tank. Sap samples were frozen upon collection in polyethylene bottles and later thawed for analysis. For each sample, pH, °Brix, electrical conductivity, and elemental composition were determined. The pH was measured using an Orion 420A+, calibrated with pH 4 and 7 buffers. Conductivity was measured using a digital conductivity meter (Curtin Matheson Scientific) and standardized using a standard 447 μmho NaCl solution. °Brix measurements were made to the nearest 0.1 °Brix using a hand-held temperature-compensated refractometer (ATAGO Master 10 α). In preparation for ICP-AES determination of elemental composition, sap samples were vacuum-filtered through 0.2 μm nylon filters. Trace-metal grade HNO_3 (2.5 mL) was added to 20 mL of filtered sap and brought to reflux on a hot plate. ICP analysis of sap samples proceeded as for soil solutions. An additional 30 mL of each filtered sap sample was frozen for possible use in future studies.

Statistical Analysis

In order to examine correlations between soil and sap properties, average soil data values (e.g., average pH, average extractable-Ca concentration) for each sugarbush were calculated using a weighted average of the areal contribution of each soil unit to the entire tapped area of

the sugarbush. In this manner, the measured properties for the individual composite soil samples (one sample representing each soil unit) at a given site were mathematically averaged to arrive at a site average for each soil property. Pearson's linear or Spearman's (nonlinear) correlations were used to assess the statistical significance of data trends, while non-parametric Mann-Whiney U tests (SPSS 16.0) were used to compare the mean values for soil and sap properties between bedrock categories, while a Wilcoxin Signed Ranks test was used to evaluate pair-wise comparisons of Week 1 and Week 3 sap chemical properties. Correlations and differences in means are reported as notable for $p < 0.10$, significant for $p < 0.05$, and highly significant for $p < 0.01$.

Results and Discussion

Soil Chemistry

Soil pH and exchangeable elemental concentrations were measured for each of 28 composite samples, with each composite representing one soil unit from a given site. Average soil properties for composite samples are shown in Table 2. Sugar maple generally thrives on soils with a pH of 5.0-7.0, while a pH of 5.7-6.0 is thought to be ideal for syrup production (31). The pH of the soil unit composite samples ranged from 3.6 to 6.3, and 13 out of the 28 soil units had a pH < 5.0. A single soil unit was associated with pH < 4, a condition that has been associated with elevated crown dieback and decreased growth rates in a study of northern VT sugar maples (32). Soil pH data indicate that several of the Addison County maple stands examined here are likely operating at sub-optimal pH. Although the potential risks to tree health of soil acidity have been well-documented, its specific effect on sap production or sugar content is not clear.

Table 2. Average chemical properties for soil-unit composite samples.

Property	Average \pm Std (median)	Range of Values
	<i>n</i> = 28	
pH	5.1 \pm 0.6 (5.0)	3.6 - 6.3
eCEC (cmol _c /kg)	9 \pm 5 (8)	4 - 24
% Base Saturation	74 \pm 23 (70)	11 - 100
Exchangeable Elemental Concentrations (mg/L)^a, n = 28		
Al	0.6 \pm 0.6 (0.5)	0 - 1.8
Ca	3 \pm 2 (2)	0 - 9
K	0.2 \pm 0.1 (0.2)	0 - 0.7
Mg	0.6 \pm 0.5 (0.5)	0.2 - 2.7
Mn	0.04 \pm 0.03 (0.04)	0 - 0.1
Molar Ratios^b		
Ca:Al (n = 19)	5 \pm 6 (2)	1 - 27
Ca:Mn (n = 26)	27 \pm 55 (10)	4 - 278
Mg:Mn (n = 25)	113 \pm 179 (52)	10 - 891

^a samples below the quantifiable limit were assigned concentrations of 0.

^b molar ratios were not calculated if one of the elemental concentrations was below the quantifiable limit.

Both soil exchangeable-Al and -Mn were observed to be inversely proportional to soil pH (Figures 3 and 4 respectively), which is expected due to the increased solubility of Al-oxides/hydroxides and Mn-oxides under acidic conditions (17,33). While Mn is a micronutrient essential to plant growth, it can become toxic to plants at higher concentrations, causing deficiency of other nutrients (Ca, Mg, Fe) and impairing photosynthetic functioning (17). Al, on the other hand, is not required for plant health and can cause toxic responses at low concentrations. Our data demonstrate the expected trends. For soil pH > ~5.5, Al is not detectable in soil extracts, whereas below 5.5, extractable-Al concentrations increase significantly (Figure 3). Similarly, Figure 4 shows a highly significant negative correlation between soil pH and extractable-Mn concentration ($r = -0.591$, $p = 0.001$). High Mn levels in soil have been associated with maple decline, although specific concentration thresholds have not been established (17).

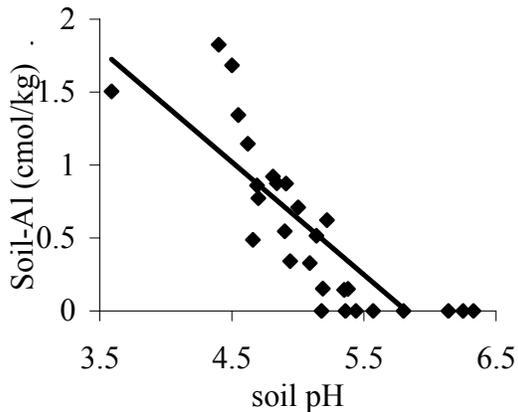


Figure 3. Soil exchangeable-Al vs. soil pH.

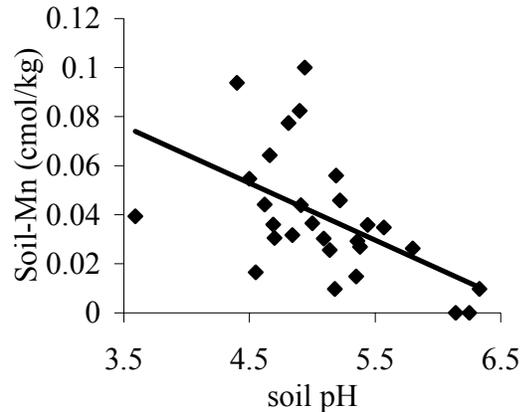


Figure 4. Soil exchangeable-Mn vs. soil pH.

The sparingly soluble macronutrients Ca ($p = 0.002$) and Mg ($p = 0.001$) showed highly significant positive correlations with soil pH (Figure 5). One sample (23F) was below detectable levels with respect to exchangeable-Ca, which is unusual, but consistent with the highly acidic nature (pH 3.6) of that particular soil. More soluble base cations would be leached deeper into the soil profile in highly acidic soils. Extractable-K increased somewhat with pH, but this trend was not statistically significant ($p = 0.894$) (Figure 6).

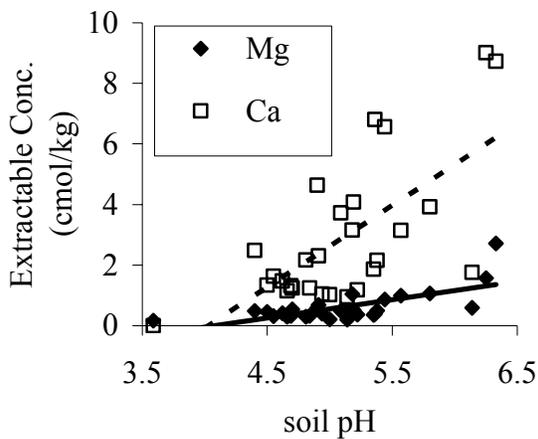


Figure 5. Soil exchangeable-Mg and Ca vs. soil pH.

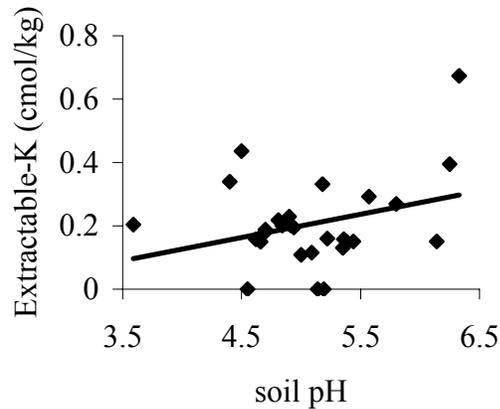


Figure 6. Soil exchangeable-K vs. soil pH.

In contrast to absolute concentrations of individual elements, molar elemental ratios have often been found to be better indicators of tree health (17,33). Molar ratios of relevance as tree health indicators include ratios of base macronutrients (Ca, Mg) to acidic toxic elements (Al, Mn). Accordingly, Ca:Al, Mg:Mn, and Ca:Mn (Figures 7-9) ratios were examined and compared to literature data on health effects. These molar ratios, Ca:Al in particular, are thought to approximate the reduction in nutrient base-cation uptake due to the stronger affinity of the higher-charge Al ions (e.g., Al^{3+} , although other Al species are also found in solution) for the root surface (34). Ratios were not calculated for eight samples for which extractable-Al was

below the quantifiable limit; for two of these samples, Mn was also below quantifiable limits. The low acid-cation levels in these particular samples are consistent with their high pH (6.1-6.2).

A statistically significant positive correlation was found between the molar ratio Ca:Al and pH (Figure 7) (all data: $p = 0.002$; excluding five high points: $p = 0.016$). Despite the strong pH/Ca:Al correlation, Figure 7 shows that there are important factors other than pH that are related to the high Ca:Al values observed in some soils. It is for this reason, that pH alone is insufficient as a sole indicator of plant nutrition.

The literature has suggested that trees growing on soils with a Ca:Al ratio <1 had 50% risk of negative health effects, such as a reduction in root and diameter growth (20,34). Similarly, a comparative study of a declining and a non-declining site found Ca:Al for the sites of 14 and 210, respectively, for the A horizon (approximately equivalent to the 0-15 cm depth sampled here), highlighting that even at Ca:Al > 1 , maple trees are still at elevated risk of negative health consequences (17). A review by Cronan and Grigal (34), suggest that the 50% risk associated with Ca:Al < 1 increases to 75% and nearly 100% risk for Ca:Al of 0.5 and 0.2, respectively. In the current study, Ca:Al ratios for all but one

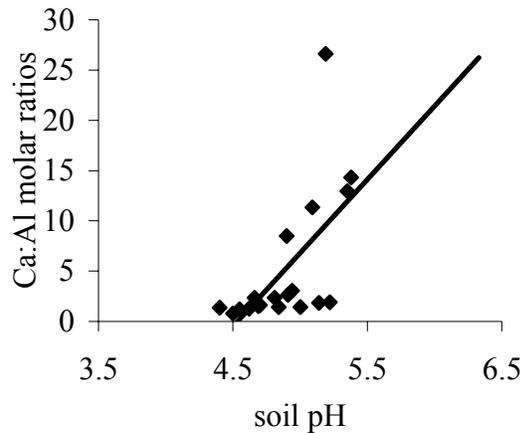


Figure 7. Soil Ca:Al molar ratio vs. soil pH.

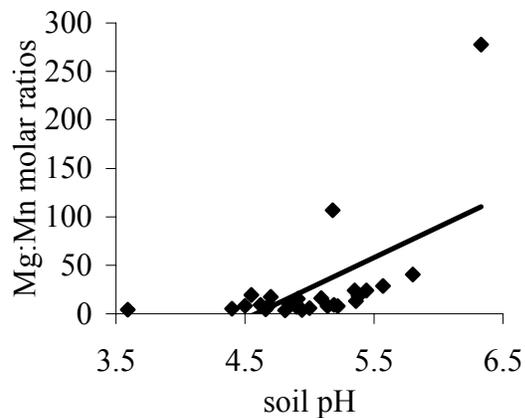


Figure 8. Soil Mg:Mn molar ratio vs. soil pH.

soil-unit composite sample were greater than 1 (Table 2), however 10 of the 28 soil-unit composite samples had relatively low Ca:Al ratios of between 1 and 2, and the median sample had Ca:Al = 1.9. Thus, more than half of the Addison County composite soil-unit samples studied here are close to the threshold for 50% risk of tree health effects, which could increase, for example, as acid precipitation continues to leach Ca and increase the availability of Al. Moreover, these sites may be candidates for fertilization and lime treatments, which have been shown to increase soil pH, tree-available soil-Ca, and annual diameter growth, while decreasing available-Al and the incidence of crown dieback in northern VT base cation-deficient maple stands (35).

Although less established as a forest health indicator, Mg:Mn ratios were also examined. As expected, a highly significant positive correlation was found between Mg:Mn molar ratios and soil pH (Figure 8) (all data: $p = 0.001$; excluding two high points: $p = 0.004$). The two high outlying points represent both of the soil units at site 57, a site that parallels a major road, with all trees located within ~5-10 m of the road. Soil from this site also contained above-average exchangeable-Ca concentrations. It is possible that the soil chemistry at this site reflects the influence of the road, either through road construction material and/or roadway run-off.(19, 36) The comparative study by Kogelmann and Sharpe (17) found A-horizon Mg:Mn ratios for two sugar maple stands, one declining and one non-declining, 1.3 and 30, respectively. There is little work to suggest a specific quantitative threshold for harmful Mg:Mn ratios. Nevertheless, Mg:Mn ratios in the current work were higher than at Kogelmann and Sharpe's declining site, and ranged between 4 and > 200, with a median of 10.

Finally, a highly significant positive correlation was also found between the molar ratio Ca:Mn and pH (Figure 9) (all data: $p = 0.001$; excluding high point: $p = 0.001$). As was observed for Mg:Mn, the highest Ca:Mn ratios were observed for the road-side site (57).

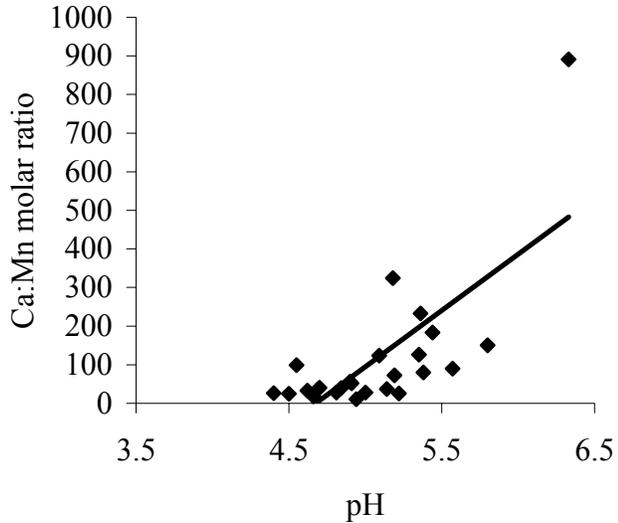


Figure 9. Soil Ca:Mn molar ratio vs. soil pH.

In comparison to the Ca:Mn ratios observed by Kogelmann and Sharpe for A-horizons at declining/non-declining sites (7 and 241, respectively), Addison County values ranged between 10 and 900, with a median ratio of 52.

Based on literature associations between elemental molar ratios and tree health, it appears that most soil units examined in the current work exhibit molar ratios that are more often associated with healthy, rather than declining trees, although many soils had ratios that were only slightly above published thresholds. Because the molar ratios examined were strongly correlated to soil pH, the Addison County soils studied appear to have borderline-high soil acidity that may have the potential for diminished maple stand health. Soil acidification will likely continue due to natural soil development processes, as well as to anthropogenic acid deposition.

Soil-unit composite sample properties were weighted by the area contribution of that soil unit to the total site area in order to arrive at a site-averaged value for each soil property. Site-averaged soil properties are summarized in Table 3.

Table 3. Site-averaged soil chemical properties.

Site	Bedrock categories	pH	Elemental Concentrations (cmol/kg)					Molar Ratios		
			Al	Ca	Mg	K	Mn	Ca:Al	Ca:Mn	Mg:Mn
1	not lime/dolostone	5.0	0.8	2.4	0.7	0.2	0.04	3	57	16
18	not lime/dolostone	4.9	0.6	4.6	0.6	0.2	0.08	8	56	7
22	not lime/dolostone	4.8	0.8	1.2	0.3	0.1	0.04	2	33	8
23	not lime/dolostone	4.2	1.4	1.5	0.4	0.2	0.05	1	31	8
43	not lime/dolostone	4.7	0.5	1.1	0.3	0.2	0.07	2	16	5
46	lime/dolostone	4.7	0.8	1.2	0.5	0.2	0.03	2	41	17
55	lime/dolostone	5.1	0.2	3.9	0.5	0.0	0.05	16	80	10
57 ^a	lime/dolostone	5.4	0.0	5.8	1.8	0.5	0.01	n/a	597	189
Hadley	lime/dolostone	5.4	0.2	2.2	0.5	0.2	0.03	14	80	18
	median	4.9	0.6	2.2	0.5	0.2	0.04	3	56	10
	average	4.9	0.6	2.7	0.6	0.2	0.04	6	110	31
	stdev	0.4	0.4	1.7	0.5	0.1	0.02	6	184	60

^a roadside site, for which soil-Al values were below quantifiable limits (expressed as 0); therefore, Ca:Al ratios could not be calculated for this site.

Soil-Bedrock Correlations

It has been suggested that bedrock-sap chemical correlations exist that may, if only indirectly, contribute to maple terroir. Glacial processes in Vermont have redistributed parent material, such that a soil's parent material and underlying bedrock may be chemically unrelated. In order to better understand the relationships between bedrock and soil, individual soil units and aggregated study sites were divided into two categories: those that overly base-rich bedrock types, defined here as limestone or dolostone, and those that overlie less base-rich (i.e., non-lime/dolostone) bedrock types (Tables 1 and 3). A non-parametric Mann-Whiney U test was performed to determine whether the soil samples within the two bedrock categories had significantly different elemental concentrations (Al, Ca, K, Mn, Mg) and pH. The difference in Mn concentrations and Ca:Mn ratios for individual soil units was highly significant ($p = 0.004$ and 0.005 , respectively), while Ca:Al and Mg:Mn ratios were significantly different between the

two bedrock categories ($p = 0.046, 0.013$, respectively); differences in pH were notable. In all cases, the soil samples from sites overlying lime/dolostone had higher mean elemental ratios and pH, reflecting the higher base (Mg, Ca) concentrations that one would expect from limestone (CaCO_3) and dolostone (MgCO_3)-derived soils. In contrast, mean Mn and Al concentrations were lower at lime/dolostone sites, which is consistent with the low Mn and Al solubility at high pH associated with the more alkaline soil parent material. Interestingly, the differences in average absolute concentrations of base cations and of Al were not statistically significant, while the molar elemental ratios were. This supports the use of base:acid cation ratios as perhaps stronger statistical indicators of differences among soil conditions. The same trends were also apparent when individual soil-unit samples at each site were averaged into a single site value. Specifically, pH and base cation concentration averages were higher and acid cation concentration averages lower at lime/dolostone sites than at the other sites. However, statistical power was lost in reducing the 28 individual soil-unit samples into 9 site averages, and only Mn and Al concentrations were notably different between the bedrock categories ($p = 0.063$ for both). These data are consistent with a bedrock influence on soil chemistry, despite glacial redistribution of bedrock-derived parent material. However, site-averaged correlations have low statistical power due to the small number of sites studied, a factor that may hinder statistical interpretation of sap data, as well.

Sap Chemistry

Sap chemistry was examined during Week 1 and Week 3 of the 2009 run. Average properties for the nine sites are shown in Table 4, and were consistent, where data are available, with ranges reported elsewhere (37). Sap pH, conductivity, °Brix (sugar content), as well as Ca,

K, and Zn concentrations were significantly correlated ($p < 0.05$) between Week 1 and 3, while P correlations were highly significant ($p = 0.006$). For example, a site with a relatively high °Brix sap during Week 1, also had relatively high °Brix during Week 1. Correlations between Week 1 and 3 for Mg and Mn concentrations were notable ($p < 0.10$). Concentrations were greater in Week 3 for Ca ($p = 0.069$) and Mn ($p = 0.018$), but lower for P ($p = 0.012$). K, P, and Mg appeared to increase between Week 1 and 3, although the trend was not statistically significant. A general increase in sap mineral concentration through the season has been observed until immediately preceding bud break when a distinct decrease occurs (17). To our knowledge P content of sap has not been previously examined over the course of the sap season. These temporal changes in sap concentrations suggest that in order to accurately compare sap (and syrup) chemistry from different locations, sap should be collected from as near the same date as possible, a factor that has been neglected in some studies

In addition to direct elemental correlations, Ca:Mn and Mg:Mn ratios were also examined. Ca:Al relationships could not be examined, due to non-detectable levels of Al in sap. Ca:Mn ($p = 0.014$) and Mg:Mn ($p = 0.049$) were correlated between Weeks 1 and 3, respectively (data not shown). Ratios were also examined pair-wise between Weeks 1 and 3. Although absolute concentrations of each of these elements increased over time, the ratios tended to decrease, although notably only for Mg:Mn ($p = 0.091$). Thus, although more temporally stable than absolute concentrations, molar ratios also vary throughout the sap season.

Table 4. Chemical properties of sap from nine study sites. Average \pm 1-standard deviation (median value).

Property	Week 1	Week 3	Range of Values
	<i>n</i> = 9	<i>n</i> = 9	<i>n</i> = 18
pH	6.8 \pm 0.6 (6.8)	6.7 \pm 0.2 (6.7)	6.3 - 7.2
Sugar Content ($^{\circ}$Brix)	2.7 \pm 0.6 (2.6)	2.5 \pm 0.7 (2.4)	1.4 - 3.8
Conductivity (μmho/cm)	445 \pm 85 (472)	487 \pm 98 (495)	311 - 676
Elemental Concentrations (mg/L)			
Ca[*]	44 \pm 18 (41)	57 \pm 15 (53)	23 - 79
K	68 \pm 15 (64)	71 \pm 22 (68)	42 - 104
Mg	5.5 \pm 1.7 (6.0)	6.7 \pm 2.0 (6.1)	2.6 - 10.6
Mn^{**}	1.5 \pm 1.1 (1.1)	2.0 \pm 1.3 (2.0)	0 - 4.5
P^{##}	1.9 \pm 1.0 (1.8)	1.3 \pm 1.0 (0.8)	0.6 - 3.8
Zn	1.9 \pm 1.5 (1.6)	2.6 \pm 2.1 (2.4)	0.2 - 6.1
Molar Ratios^b			
Ca:Mn	34 \pm 20 (33)	34 \pm 22 (32)	10 - 77
Mg:Mn[*]	4 \pm 2 (3.3)	4 \pm 3 (3.4)	1 - 10

^a samples below quantifiable limit of 0.2 mg/L were assigned concentrations of 0.

^b samples for which Mn was below the quantifiable limit (assigned concentrations of 0) were not included in calculations of molar ratio.

** indicates Week 3 levels are significantly higher pair-wise than Week 1

* indicates Week 3 levels are notably higher pair-wise than Week 1

indicates Week 3 levels are significantly lower pair-wise than Week 1

Sap-Bedrock Relationships

Few statistical relationships were observed between sap chemistry and the bedrock categories (lime/dolostone and not lime/dolostone), likely due to the small number of sites investigated, but interesting trends were observed that paralleled those observed for the soil-bedrock relationships. For example, Figure 10 shows Mn concentrations in sap was lower for lime/dolostone sites, a relationship that was notable for Week1 ($p = 0.071$) and significant in Week 3 ($p = 0.036$). Lower concentrations in sap could reflect the lower concentrations of exchangeable-Mn present in soil overlying lime/dolostone bedrock. Mg was also higher in sap samples from sites overlying lime/dolostone, which might be attributable to higher bedrock and soil Mg concentrations. Zn and P were also at higher concentrations in sap samples from sites

overlying lime/dolostone bedrock, although this trend was not statistically significant. In contrast, sap Ca and K showed opposite bedrock trends between Weeks 1 and 3. For example,

sap samples overlying

lime/dolostone had higher Ca levels during Week 1, but lower Ca levels in Week 3. It is possible, that the selective uptake of macronutrients, such as Ca, and leaching of Ca from the parent material by acidic soil conditions complicate any direct relationships between bedrock and sap chemistry. Additional sites should be investigated to increase confidence in these findings.

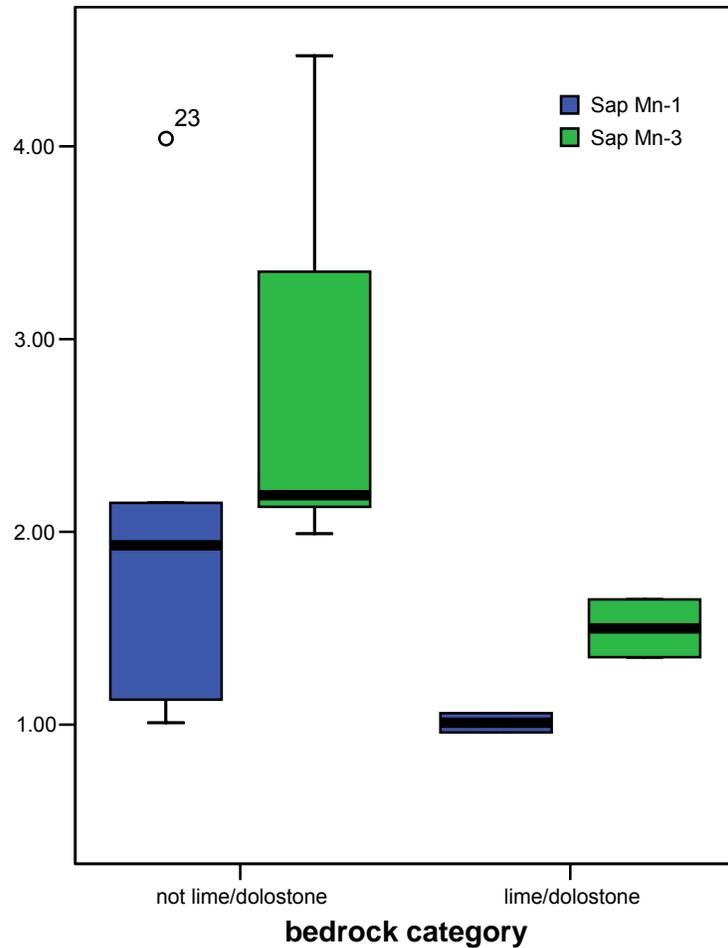


Figure 10. Mn sap concentrations for Week 1 (blue) and Week 3 (green).

Soil-Sap Relationships

Direct correlations between soil and sap chemical properties focused on Ca, K, Mg, and Mn concentrations, because these elements were quantifiable in nearly all soil and sap samples. In particular, Al was not detectable in sap samples by ICP-AES, which is consistent with known defense mechanisms by which toxic Al is sequestered in the roots and not translocated via xylem sap (33). Figure 11 shows observed relationships between sap and soil concentrations for each of

the four elements. As discussed earlier, Week 3 sap concentrations are generally higher than in Week 1. A highly significant correlation was observed between soil- and sap-Ca for Week 3 (Figure 11, $p = 0.002$), while Week 1 showed a positive trend. A positive relationship between soil- and sap-Ca is consistent with the red maple (*Acer rubrum*) results of McCormick (18). Positive relationships were also observed between soil-sap concentrations for Mg and Mn for both Weeks 1 and 3, while K trends (excluding the roadside site 57 samples) were inconclusive and reversed between Week 1 and 3. These K results are consistent with McCormick's red maple study, which found little correlation between soil and sap K. McCormick's study (18), however, found no correlation between soil and sap Mn, which we speculate is due to the well-established species-specific differences in the uptake of Mn. Importantly, at two sugar maple stands, Kogelmann and Sharpe(17) did observe good correlation between soil and sap-Mn. Importantly, both McCormick and Kogelmann and Sharpe compared sap collected from individual trees with adjacent soil samples, while our study examined sap and soil at the scale of a production sugarbush. Thus, although statistical power was not achieved with only nine study sites, the same positive trends in soil- and sap mineral composition are apparent, which suggests that the spatial averaging of soil properties, genetic diversity of the trees in the stand, and other sources of larger-scale variation do not mask relationships between soil and sap chemistry. To increase confidence in these findings, additional sites need to be examined at the larger scale used in this work.

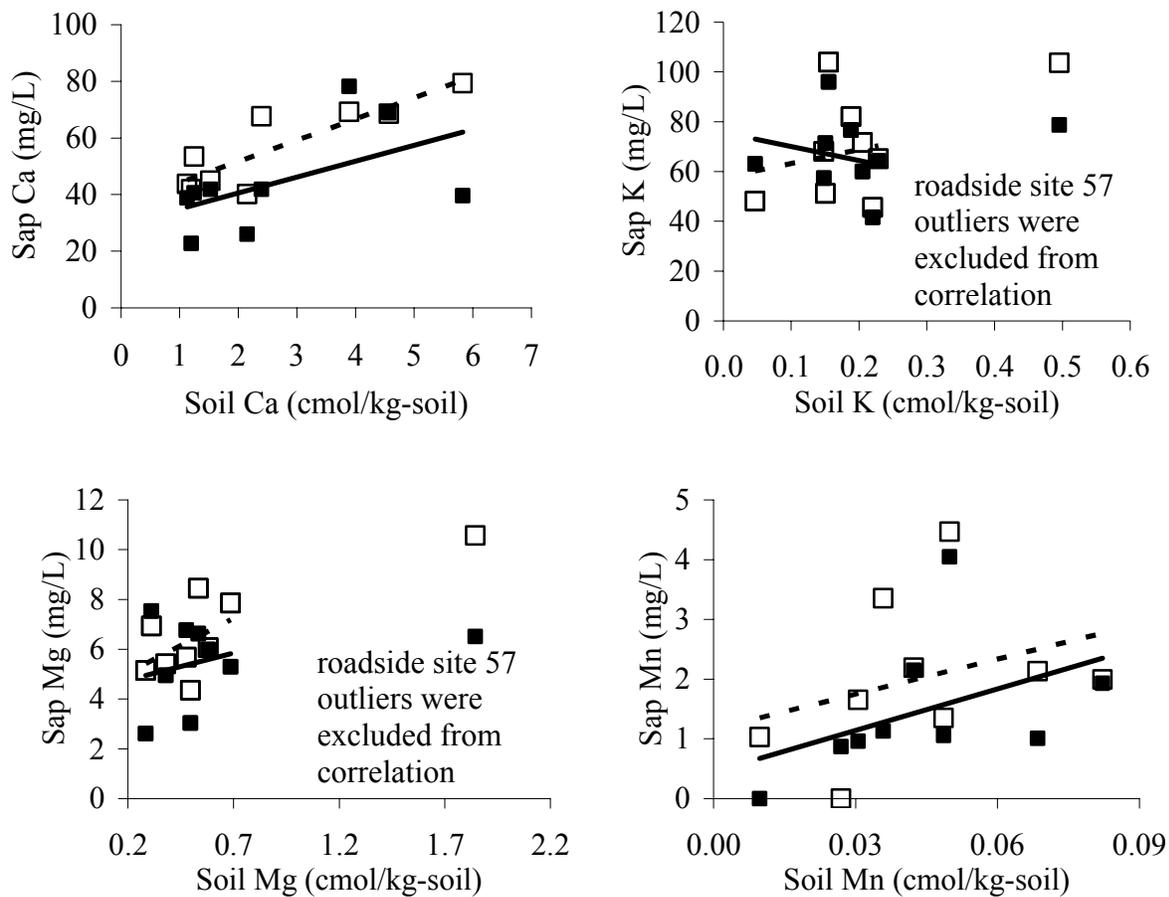


Figure 11. Correlations between soil and sap elemental concentrations. For all plots, filled square and solid lines represent Week 1, and empty squares and dashed lines represent Week 3 sap samples.

Figure 12 shows soil-sap relationships for Ca:Mn and Mg:Mn ratios. The roadside site 57 that contained unusually high *soil* Ca:Mn and Mg:Mn values (see Figures 8 and 9) also exhibited Week 3 *sap* ratios that were approximately double the next closest value (Week 1 ratios could not be calculated because the sap-Mn concentration was below detectable limits), perhaps suggesting a causal relationship between soil and sap ratios. This site was excluded from further statistical analysis. Ca:Mn values for soil and sap were positively related (significantly for Week 3; $p = 0.013$), which supports Kogelmann and Sharpe's suggestion that Ca:Mn ratios are good sap-based indicators of soil conditions. For Week 3, Mg:Mn ratios showed a positive trend

between soil and sap, but no relationship for Week 1. Although Kogelmann and Sharpe suggested sugar maple tissue (xylem, foliar) Mg:Mn ratios as a superior indicator for monitoring changes in soil due to acid deposition, they did not examine this ratio in sap. Thus, while sugar maple xylem and foliar Mg:Mn ratios may be appropriate indicators of soil-chemistry, it appears from the current work that Ca:Mn ratios may provide better sap-based indicators of soil chemistry. Similar positive trends were observed for relationships between sap-ratios and soil-pH, but statistical power was low for all but Week 3 Ca:Mn ratios, which was significantly correlated. Although statistical power might improve with more study sites, it appears, nonetheless, that sap molar ratios provide a better indication of soil molar ratios, than they do more generally of soil-pH.

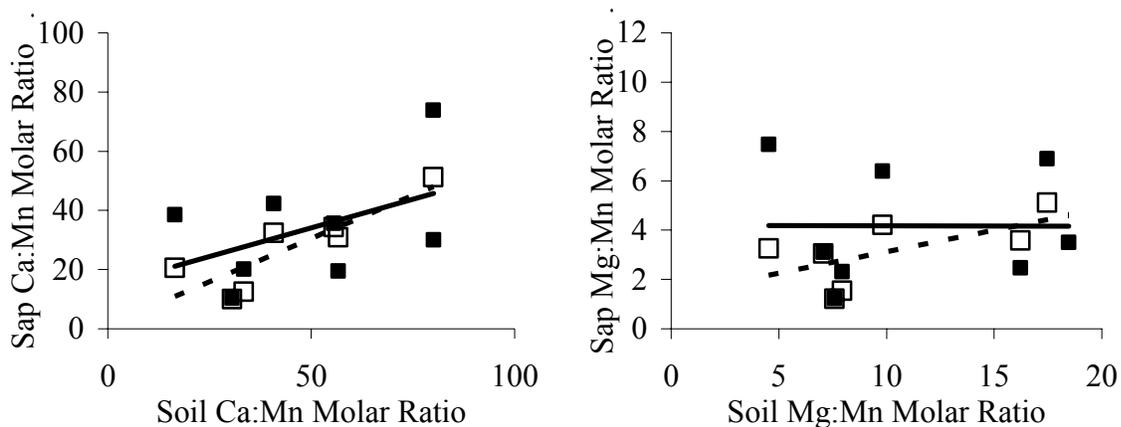


Figure 12. Correlations between soil and sap molar ratios. Filled square and solid lines represent Week 1, and empty squares and dashed lines represent Week 3 sap samples. Extreme outlier roadside site 57 points are not shown.

Although soil-Ca:Al ratios have been most definitively linked to tree health, Ca:Al are unable to be measured in sap; thus, it was of interest to examine whether Ca:Mn or Mg:Mn in sap were reliable indicators of soil Ca:Al. While Week 3 sap-Ca:Mn was correlated to soil-Ca:Al ($p = 0.007$) (Figure 13), sap ratios provided little predictive power for soil Ca:Al ratios. Thus, based

on the current data, it does not appear that sap data can be indirectly linked to maple health via literature soil-based chemistry indicators. Future work is to determine whether sap concentrations and molar ratios can be directly associated with tree health, and whether specific quantitative health thresholds can be developed. Work by Kogelmann and Sharpe (17, 18) and McCormick (18) suggest that this

approach holds promise on the scale of the individual tree, which would need to be further expanded to the stand-scale.

In order to investigate the how individual elements behaved relative to the bulk mineral concentration, elemental concentrations were plotted against sap electrical conductivity, a measure of the total number of ions in solution. As shown in Figure 14, when sap was more

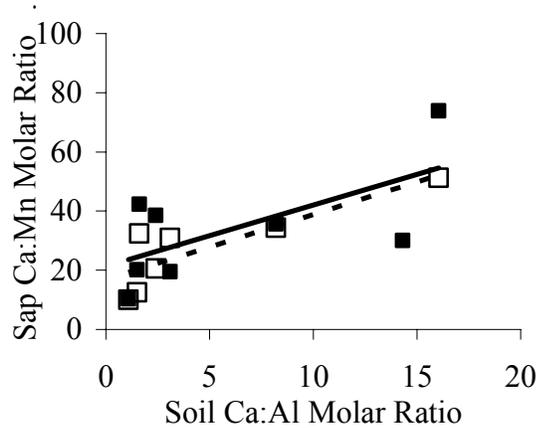


Figure 13. Relationship between sap Ca:Mn and soil Ca:Al molar ratios. Filled squares/solid lines represent Week 1, and empty squares/dashed lines represent Week 3. Site 57 points are not shown.

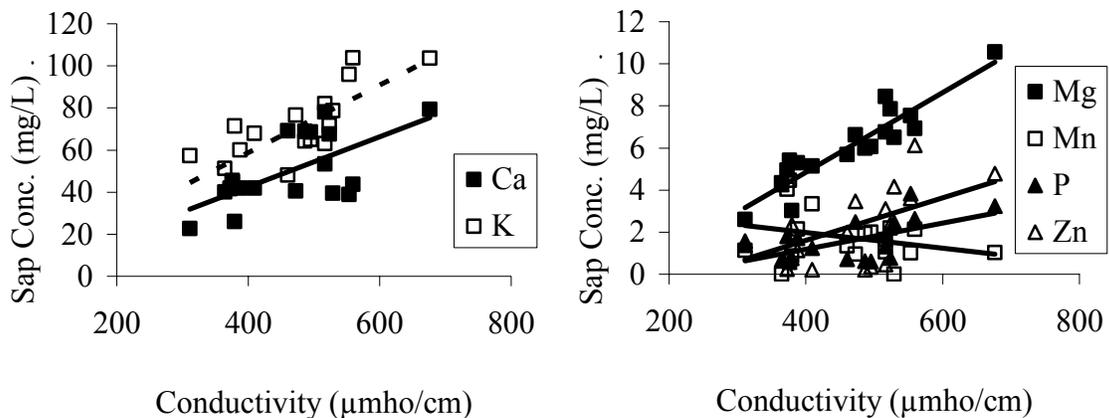


Figure 14. Elemental concentrations of (left) Ca and K and (right) Mg, Mn, P, and Zn in sap versus sap conductivity.

concentrated in ions (higher conductivity), the concentration of Ca, Mg, Mn, P, and Zn also increased. In contrast, Mn was the only element for which the concentration was inversely proportional to overall mineral content of the sap. It is hypothesized that this inverse trend is either due to the ability of the maple to exclude Mn when concentrations of beneficial cations are sufficiently high.

In addition to correlations between elemental concentrations of soil and sap, other correlations between the chemical properties of the two media were investigated. For example, it is a commonly heard claim that Ca-rich soils are thought to produce sweet trees. We investigated this common belief by plotting sap °Brix and soil Ca content for all sites except the roadside site 57, as shown in Figure 15. In fact, no relationship between soil-Ca and sap sugar content was observed.

In general this study did not find many significant correlations between soil and sap chemistry, which may be due to a number of factors. First, this study used a limited number of samples – only 9 for sap compared to 20 in the Kogelmann and Sharpe (17) study – making it difficult to distinguish subtle relationships.

Secondly, this study examined the soil-sap relationship at the sugarbush scale, whereas previous studies, including Kogelmann and Sharpe, focus primarily on individual trees (17). Greater variation would be expected at this larger scale, which may have obscured potential relationships, particularly when coupled

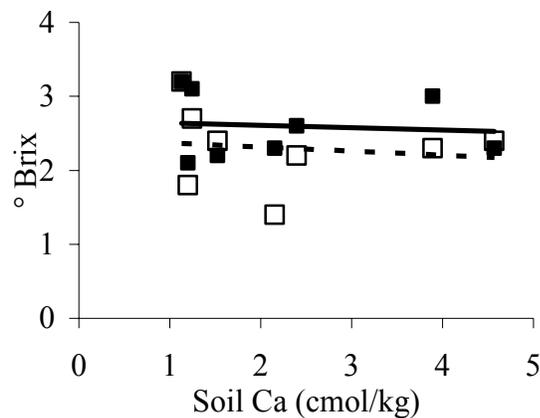


Figure 15. Sap sugar content versus soil-Ca. Filled squares/solid lines represent Week 1, and empty squares/dashed lines represent Week 3. Site 57 data are not shown.

with a small sample size. Additionally, the process used to aggregate properties of individual soil-unit samples into a site average may not accurately represent how the sap is aggregated from across the stand. For example, although a given soil unit may constitute 50% of a site's tapped area, it does not necessarily follow that 50% of the sap volume came from trees growing on that soil unit. This may have had an effect on statistical analysis. Furthermore, it has been suggested that various aspects of sap chemistry, including mineral content and pH, are controlled genetically (18). In light of these important sources of variation, it is striking that consistent and positive relationships were observed between soil and sap mineral concentrations and molar ratios and between sap concentrations and soil pH, a master variable controlling nutrient availability. Thus, the approach used here to aggregate and understand soil and sap relationships at the scale of a production sugarbush appears promising, even as further work is required.

Geographic Distribution of Soil and Sap Chemistry

GIS maps were created to show the location and elevation of each sugarbush in Addison County (Figure 16). Additionally, the values of soil and sap pH, soil and sap elemental concentrations, and sap °Brix for each site are displayed as values relative to the other sites. These maps show the geographical distribution throughout Addison County of the data. Because

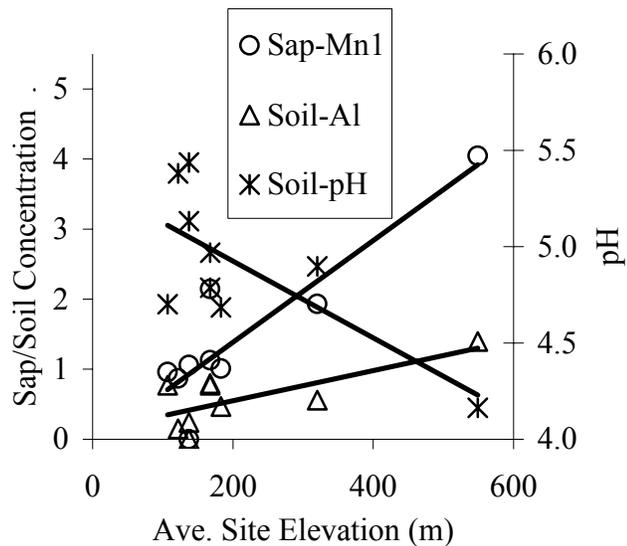


Figure 16. Sap and soil chemistry vs. average site elevation. Sap and soil elemental concentrations are given in mg/L and cmol/kg, respectively.

elevation is often associated with weather and climate differences that may influence soil, and thereby sap, chemistry, the GIS digital elevation model was used to examine relationships between elevation and the chemical data. Significant correlations were observed between sap-Mn (Week 1: $p = 0.001$; Week 3: $p = 0.043$), soil-Al ($p = 0.039$), and soil-pH ($p = 0.036$) and average site elevation, although admittedly, there are relatively few higher-elevation sites in the dataset. Specifically, results showed that soil was more acidic at higher elevation, while concentrations of extractable Mn and Al, elements with highly acid-dependent solubility, were greater in the higher, more acidic locations. This acidity-driven relationship with elevation may be related to the fact that soils situated at higher elevations typically receive greater (acid) precipitation, which could lead to lower pH and consequently higher exchangeable Al and Mn in the soil, although it is not clear that these specific higher-elevation sites do, in fact, receive more precipitation. Underlying bedrock and/or soil parent material would also play an important role in soil acidity. The four sites underlain by lime/dolostone bedrock types have the lowest elevations (< 137 m), while the higher elevation sites (>168 m) have other bedrock types. Thus, it is not clear whether climate, parent material, and/or some other factor cause the observed elevation trend.

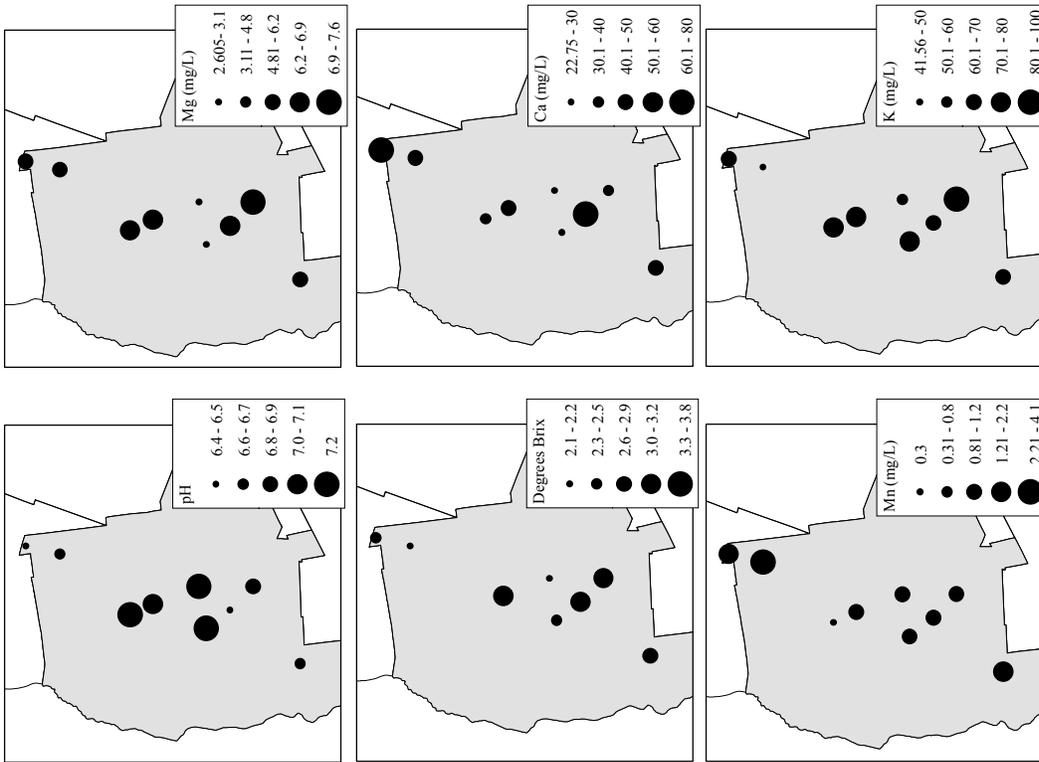


Figure 16a. Maps of sap pH, °Brix, Mg, Ca, Mn, and K by sugarbush location.

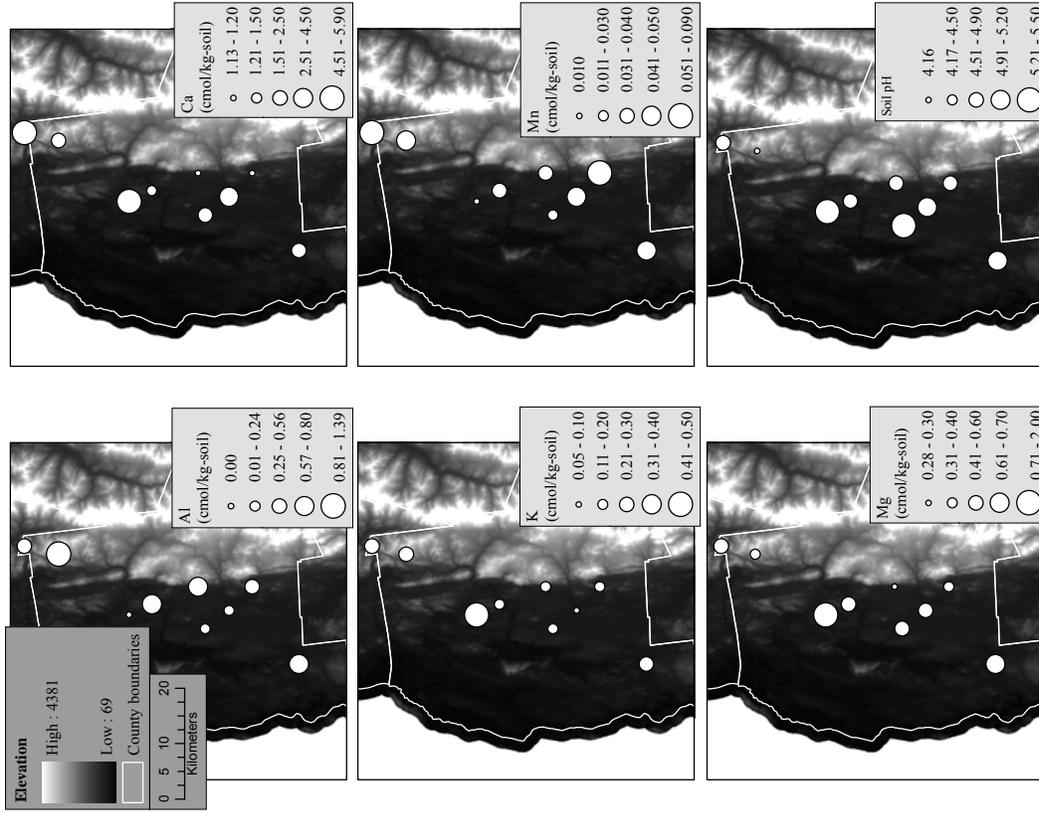


Figure 16b. Maps of soil pH, Al, Mg, Ca, Mn, and K by sugarbush location with elevation.

Evaluation of SSURGO Data

Existing SSURGO data on the soil properties of Addison County were compared to data collected in this study in order to assess the representativeness of the survey data. This comparison focuses on pH (Table 5), because it is the single most important soil chemical property in governing soil and nutrient availability.

Table 5. SSURGO and study pH values by soil unit

Soil Unit	Study pH	SSURGO pH	Study vs. SSURGO ^a
1A	5.2	n/a	n/a
1B	4.9	5.2	L
1C	6.3	5.4	H
1D	5.8	5.4	H
1E	5.6	5.4	H
18A	4.9	4.8	H
18B	4.8	4.8	M
22A	5	4.9	H
22B	5.1	4.9	H
22C	4.7	4.8	L
23A	4.5	4.8	L
23B	5.4	6.2	L
23C	4.6	5.2	L
23D	4.6	4.8	L
23E	4.4	4.8	L
23F	3.6	4.8	L
43A	4.7	n/a	n/a
43B	4.9	n/a	n/a
46A	4.7	5.9	L
46B	6.1	5.9	H
55A	5.1	6.2	L
55B	4.8	6.7	L
55C	5.1	5.9	L
55D	5.4	5.9	L
55E	5.4	6	L
57A	5.2	n/a	n/a
57B	6.3	n/a	n/a
Hadley	5.4	6.2	L

It was hypothesized that, in the event of disparities between SSURGO and study data, the study values would be lower than the SSURGO values due to continued acid deposition that has occurred in the region in the forty years since the survey was conducted. In fact, while not all soils displayed this trend, SSURGO pH values were significantly higher ($p = 0.011$) than the values obtained in current study. This suggests that SSURGO soil chemistry data are not representative of current Addison County soil conditions. Thus, future work in this area cannot rely directly on SSURGO data, but rather, will require on-the-ground soil testing. Nonetheless, the SSURGO data will continue to be quite useful for developing sample collection strategies, as was done in this work.

^a L, M, and H indicate the current study pH values were lower, matching, or higher than SSURGO pH values.

Conclusions and Future Work

The primary goal of this study was to investigate whether relationships exist between soil and sap chemical properties, including elemental composition of soil and sap, sugar content of sap, and site elevation. In addition to these primary investigations, the study also compiled findings on tree health status from previous studies, which are meant to serve as indicators of the state of the sugarbushes studied. The feasibility of using sap analysis to monitor tree health was assessed, because the more traditional method, soil sample analysis, can be time- and labor-intensive. Finally, this study assessed the representativeness of current Addison County soil survey data (SSURGO).

Study soil data demonstrated expected trends in relation to soil pH. In particular, the Ca:Al molar ratio demonstrated highly significant correlation with soil pH. Ca:Al ratio observed in the current work were above, but close to, the literature threshold of 1 that has been associated with 50% risk of negative health consequences. Sites overlying lime/dolostone bedrock types were observed to have higher Ca:Al ratios than other sites, suggesting, perhaps, that the high Ca content or acid-buffering capability of lime/dolostone parent material may provide some protection for those maple stands. Ongoing soil acidification and consequent decrease in Ca:Al ratios, which would elevate health risks to Addison County sugarbushes should be monitored.

Sap chemical properties were within the expected range and demonstrated interesting trends in relation to soil chemistry. While sap-soil relationships were not generally statistically significant, likely due to the relatively few number of sites studied, positive correlations between soil and sap were observed for Ca, Mg, Mn, and Ca:Mn ratios. Soil concentrations of these elements and their molar ratios are important indicators of plant nutrition and health, so these correlations suggest that sap could possibly serve as an appropriate tree tissue to for tree-health

monitoring at the stand scale. Sap-Mn was also observed to be significantly higher on non-lime/dolostone sites, which also were located at higher elevations. It would be interesting to examine sap-Mn trends on a series of non-lime/dolostone sites along an elevational gradient to decouple the potential bedrock and elevation contributions to observed Mn concentrations in sap. Confirmation of bedrock and soil-sap trends at additional sites, as well as direct correlation between sap concentrations and tree-health indicators would be required for practical application of this promising approach. A distinct advantage of the proposed sap-based health-monitoring method includes the fact that thousands of VT maple producers are already collecting composite sap samples that would be appropriate for analysis. Moreover, the annual analysis of sap from sugarbushes across the state could provide a useful data set for monitoring changes in soil conditions due to ongoing soil acidification and global warming. Finally, with regard to the physical basis for the concept of terroir, it appears that soil chemistry of a given stand does influence sap chemistry, and variation in sap chemistry is readily apparent at the sugarbush scale within Addison County. Whether the observed variation in sap chemistry per se or simply the variation in tree nutrition influences syrup chemistry or taste produced from a given stand has yet to be investigated.

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