Bigleaf Maple Sap Flow in Western Washington

Andrew Nicholas Braun

A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Science

University of Washington

2022

Committee:

Gregory Ettl

Indroneil Ganguly

Kent Wheiler

Program Authorized to Offer Degree:

Environmental and Forest Sciences

University of Washington

Abstract

Bigleaf Maple Sap Flow in Western Washington

Andrew Nicholas Braun

Co-Chairs of the Supervisory Committee:
Gregory Ettl
Indroneil Ganguly

School of Environmental and Forest Sciences

Bigleaf maple (*Acer macrophyllum*) is common on well drained soils in mixed conifer forests and along river terraces in Western Washington. Protected riparian buffers often include bigleaf maple stands, and producing syrup from the tree's sap can provide revenue and incentivize maintaining forest cover on land that cannot be harvested for timber. Washington's small forest landowners can face economic difficulties managing their land, and managing forests near streams is often complicated and avoided due to riparian buffer zones and other regulations. Development of forest land accounted for 400,000 acres of deforestation in Washington between 2007 and 2019, much of which resulted from economic pressure on forest landowners. Bigleaf maple sugaring could encourage mixed-species forest ownership and yield an ecological low-impact income from land that might otherwise be a net drain on cash for maintenance and property taxes. Bigleaf maple sap flow is not well documented, and there are key differences between its sap flow and that of eastern North America's sugar maple (*Acer saccharum*) that must be understood if bigleaf maple syrup production is to become commercial in scale.

In this study, tree-level bigleaf maple sap flow data from the University of Washington's Pack Forest near Eatonville, WA was collected for three tapping seasons under high vacuum pressure. A positive correlation between tree diameter at breast height in centimeters and seasonal sap volume in liters was found ($sap\ (l) = 0.22 * DBH\ (cm) + 1.04$). Multi-stem clumps over 30 cm in diameter produced two to three times more sap per tap than individual trees of the same diameter, though taps on clumped stems were more variable. The seasonal sugar content of tapped stems ranged from 0.7% to 1.9%, averaging 1.3%. Sugar content varied with tree diameter but not canopy health, canopy position, or growth form. Sugar content was more similar within stems of the same clump than between clumps or between seasons.

Freeze-thaw events were associated with high sap volume, though sap still flowed in low volumes on warmer days. A linear model relating daily weather from PRISM data at a $4km^2$ resolution to daily sap volume per tap was used to estimate statewide average sap flow potential per tap for each January 1 to March 1 tapping season from 2010 to 2020, and the ten season-long estimates were averaged. The model generally over-predicted sap volumes collected at eight sap collection sites in Western Washington by a factor of two, though harvested sap volume was within 14% of predicted for the most experienced and the only commercial syrup production site. The model therefore probably represents an upper limit on sap harvests achievable with tapping experience and high-power vacuum pumps. If only small, private forest land parcels with electricity are tapped, between 11,693 and 350,785 liters of bigleaf maple syrup could be produced annually in Western Washington depending on the percentage of feasible tapping sites that are utilized. These estimates range between $926,000 and $27.8 million based on 2022 bigleaf maple syrup retail prices. If bigleaf maple sugaring continues to develop, the industry could approach that of some of the Northeastern states' maple harvest in terms of value.

Acknowledgments

I thank the members of my committee for their attention, concern, and humor throughout my time at SEFS, and for helping me make the most of two difficult but rewarding years. I appreciate all of the help, insight, and grace that my co-advisor Dr. Greg Ettl has shared with me. It has been a pleasure learning from his perspectives on ecology, maple syrup, and other heady topics, even while clambering up rocky cliffs at Pack Forest.

I am grateful to my co-advisor Dr. Indroneil Ganguly, who has been consistently patient and good-natured no matter how many times I approached him with statistical questions. He has been invaluable in helping me choose the right approach for each problem at hand, and even while discussing factor analysis for hours was always full of humor.

I would like to thank my committee member Dr. Kent Wheiler for helping me think outside my role as an ecologist, for providing endless forestry knowledge, and for being such an effective and good-natured leader in the maple syrup project. He has been the conduit keeping dozens of maple hobbyists, experts, and researchers connected, and I believe that bigleaf maple syrup makers of the future will owe him much gratitude.

My thanks go to the members of CINTRAFOR, who are all doing inspiring work and many of whom graciously volunteered to help set up partner sites, including Christina Bjarvin, Blaze Burke, Derek Crawford, Lieke Droog, Sarah Pollack, Alec Solemslie, and Shinju Yokoyama.

The Pack Forest staff of 2019-2022 was instrumental in installing and maintaining a 740-tap operation and constructing one of the few dedicated syrup processing rooms in Washington. This work would not have been possible without them. I would like to thank the 2021 Pack Forest summer crew Cristy Fiander, Jamison Mace, Jacob Mobley, Chloe Rabinowitz, and guest star volunteer Nolan Kitts for their help with the project and the excellent company they provided.

I am grateful to NRSIG members Jeff Comnick and Luke Rogers for their work in identifying potential tapping sites in Washington.

The landowners who participated in this study have shown good nature, perseverance, and a remarkable ability to problem solve in this uncharted territory. I am grateful for their time, creativity, and willingness to share their successes and failures. I wish them warm days and freezing nights, clean evaporator pans, and full tanks.

Many thanks to Dr. Mike Farrell for sharing his encyclopedic maple knowledge, his unlimited energy in the field, and his years of dedication that have made the body of maple syrup knowledge so much richer.

I am extremely grateful to my partner Ma'alaea Lawrence for her support and encouragement for the past two years, and for putting up with my many late nights.

Lastly, I want to thank the USDA Agricultural Marketing Service ACER Access and Development program (grant #AM190100XXXXG077) that provided the funding to make this project possible.

Table of Contents

List of Figures

Appendices

List of Tables

Chapter 1: Introduction, Background, Objectives

Land Use Context

A leading cause of deforestation in Washington State is the conversion of forests for residential development, which accounted for over 160,000 hectares of lost forest cover between 2007 and 2019 (Washington Department of Natural Resources, 2021). Population growth in the state has increased the value of real estate relative to that of forested land, and forest ownership has become a less lucrative economic prospect by comparison. Washington is home to some of the most productive softwood forests on Earth, and has some of the United States' most comprehensive forest practices rules to match (Creighton & Baumgartner, 2005). State restrictions protect riparian areas and wetlands by enacting buffers where logging is restricted (Washington Forest Practices Rules, 1975). Low revenue can drive landowners to sell their forested land for development (Rabotyagov et al., 2021). However, non-timber forest products can still be harvested where timber cannot.

Bigleaf maple trees (*Acer macrophyllum*) grow in riparian areas and in mesic forests, often lining fish-bearing streams in Washington (Franklin & Dyrness, 1973). As there is low demand for their timber beyond figured or burled wood, harvested bigleaf maples are typically sent to pulp mills, and they are often eradicated to plant conifers in their place. Producing bigleaf maple syrup could provide forest landowners income from riparian areas that would incentivize forest retention. Additionally, bigleaf maple sugaring could make multi-species timber management systems more attractive. Fifteen percent of Washington's forests are owned by private, non-industrial stakeholders (Rabotyagov et al., 2021), so the potential for producing bigleaf maple syrup to impact land use decisions on a statewide scale should not be overlooked.

Bigleaf maple sap contains half the sugar content of sugar maple (*Acer saccharum*) sap, which has precluded its use in syrup making past the backyard hobbyist scale. Sugar maple, and to a lesser degree red and black maple (*A. rubrum* and *A. nigrum,* respectively*),* are the predominant species used in sugar making in the American and Canadian East. Making syrup is a process of removing water to concentrate sugar content; beginning with half the sugar content requires removing twice as much water, which requires more energy. In the past few decades, several advances in harvesting and processing technology have increased the efficiency of maple sugaring (Farrell, 2013a). Tubing systems have replaced buckets, yielding higher sap volumes per tree with less labor required (Morrow, 1972). Reverse osmosis machines have become cheaper and more accessible, allowing sugar-makers to concentrate sugar content of sap prior to boiling. Vacuum pumps are able to extract significantly more sap from trees than with buckets or tubing alone (Heiligmann et al., 2006). These advances, combined with the public's increased willingness to spend on locally sourced and sustainably produced foods, may be sufficient to turn bigleaf maple sugaring from a hobby-level venture into a substantial economic prospect for small forest landowners. This research addresses the weather and tree-level variables that affect sap volume and sugar content and provides an estimate of potential bigleaf maple sap flow in Washington state for the purpose of sugar making.

History of Maple Syrup

Maple trees (*Acer spp.*) have a long history as a food source in Native American culture. In the Eastern United States, oral tradition holds that the first people learned to tap maple trees by observing squirrels snapping maple branches in late winter to drink the sweet sap (Kimmerer, 2013). Maple sap flow events, known as "runs", coincided with late-winter food scarcity and were a welcome first harvest. Today, maple syrup is the first harvest of the year for many forest farmers and it fills a slow season with activity and revenue. While American maple sugaring is currently on the rise, US production was at its peak a century and a half ago (Farrell, 2013b). During the American Civil War cane sugar became unpopular in the North due to the slave labor involved in its production. Maple sugaring experienced a boom during this time for a few other reasons too: imported sweeteners were expensive, labor was cheap, and it was common to farm one's own land. Even with crude technology, Americans produced the equivalent of 25 million liters of maple syrup in 1860 (Graham, 2016), a staggering amount considering 2019's production was 16 million liters (USDA, 2021). The sap was usually refined into maple sugar to replace cane sugar, and its quality was judged accordingly. The grading of maple syrup changed in 2015 from a somewhat deceptive "A / B" grading to a scale of "Light" to "Robust" (USDA, 2015). The old grading system was a vestige of the past when the most desirable grade of maple sugar resembled white, pure-tasting cane sugar.

The Sugarbush

Early European-Americans adapted Native Americans' sap harvesting and processing methods with a few modifications. Major changes to the process of making of maple syrup did not occur until the middle of the 20th century. In the 1970s, producers started using plastic tubing to transport sap directly from the taps to a central collection tank, freeing them from the daily chore of carrying full buckets of sap through the woods (Farrell, 2013a).

Figure 1.1. A tapped bigleaf maple.

To tap any hardwood, small holes are drilled into the trees and plastic taps are inserted into the holes. The taps connect to lengths of tubing that feed into “lateral lines”, which connect 20-50 trees to the larger diameter “mainline” tubing. The mainline carries sap to the collection point, usually to a tank of up to several thousand liters in capacity. At every point until the sap empties into the collection tank, the connections must be airtight to minimize contamination and maximize vacuum pressure. When tubing is used in the absence of a vacuum pump, it is referred to as a “gravity-driven vacuum system”. Gravity-driven vacuum systems on steep slopes with small diameter tubing (3/16”) create their own vacuum within the tubing as sap moves downslope to a collection tank (Morrow, 1972). Tubing systems have been found to increase yields up to twofold, and connecting a vacuum pump to the lines can pull an additional 50-100% more sap (Heiligmann et al., 2006). The efficiency of 3/16” tubing decreases with multiple seasons of use as wood chips, bacteria, and other debris clogs the lines (Farrell, 2013a). Larger diameter 5/16” tubing is typically used in conjunction with vacuum pumps to avoid this issue.

Sugar content is measured in degrees Brix, equivalent to percent sugar by weight. Sugar maple sap averages between 2 to 4º Brix (Taylor, 1956), while bigleaf maple sap contains only half the sugar. Within a day or two of collection, sap is transferred from a holding tank to a processing room where reverse osmosis (RO) is used to concentrate it to 6-8º Brix with smaller ROs or to over 10º Brix with larger, more expensive ROs. The concentrate is fed into an evaporator fired by oil, gas, or wood, which boils the sap close to its final sugar concentration. A smaller finishing pan allows the syrup maker to more slowly finish the evaporation process and draw off the syrup at the required 66.5% sugar concentration for stable syrup that will neither mold nor crystallize. Syrup is filtered before bottling to remove “sugar sands”, which are accumulated nutrients from the sap.

Trade

As of 2020 the maple syrup market has grown into a billion-dollar industry worldwide, with Canada dominating production and exports. Exports are primarily to the United States, which accounts for 48.5% of the world's syrup imports despite domestic production in the Eastern US (Agriculture and Agri-Food Canada, 2021). Farrell (2013b) found that per capita maple syrup consumption increased by 155% between 1985 and 2009 in the United States. The same study found that people in areas where maple syrup is produced tend to consume more of it. Maple syrup has appeal as a natural forest-sourced sweetener and is a popular, if luxury, ingredient among health-conscious consumers. There remains excess demand for production of maple syrup, and a maple sugaring industry in the Pacific Northwest (PNW) may increase demand further.

History of Bigleaf Maple Sap Utilization in the Pacific Northwest

While syrup can be made from the sap of many tree species, the bulk of maple syrup production comes from sugar maple (*Acer saccharum*) and red maple (*A. rubrum)*. In Western Washington State, bigleaf maple (*A. macrophyllum* Pursh) is the second-most abundant hardwood (behind *Alnus rubra* Bong.) and the Natural Resource Spatial Informatics Group (NRSIG) estimates that the state contains nearly 7 million potentially accessible taps (Niemiec et al., 1995; NRSIG, 2021).

Written accounts of indigenous use of bigleaf maple sap are scarce. Bigleaf maple flowers are edible, and two sources note that both the Clallam and Coast Salish Indians have boiled its sap to produce syrup (Fleisher, 1980; Turner & Bell, 1971). Syrup production from bigleaf maple is first mentioned in writing by an Oregon trailblazer in the mid-1800's (Rucker, 1930), but even the idea of a commercial operation does not appear in the scientific literature until 1972.

The Pacific Northwestern US and Coastal British Columbia have numerous small-scale bigleaf maple sugaring operations but lack the history, organization, and supply chains needed to support commercial production. The Eastern United States has a culture of maple sugaring that predates the nation's founding and a strong maple sugaring industry with well-established supply chains. Producers in the east buy equipment from local suppliers, follow processing laws that evolved with the industry, share best practices with neighbors, and have centuries of maple sugaring knowledge from which to draw. The Pacific Northwest does not enjoy this system partly because of the historical circumstances that made maple sugaring economically significant in the 1800's, but mostly because bigleaf maple sap contains half the sugar of sugar maple sap. Accordingly, twice as much sap must be processed to achieve a given volume of finished bigleaf syrup, burning more fuel, electricity, and time. Sugar maple syrup is readily available and far cheaper, so the higher expense of processing bigleaf maple sap may have kept it at the hobbyist scale until recently. Bigleaf maple syrup is only commercially available from a handful of sources in the Pacific Northwest, including Kleekhoot Gold (kleekhootgold.ca) and Neil's Big Leaf (neilsbigleaf.com). As of 2022 bigleaf maple syrup is in high demand due to its scarcity and local origin. At the time of writing Neil's Big Leaf costs $42 per 350 ml container, or $118 per liter ($448 per gallon) at that volume, and the website is frequently sold out. Sugar maple syrup runs roughly one-quarter of that price, and is far cheaper in bulk (USDA, 2021).

Ruth et al. (1972) documented sap harvest from bigleaf maples in Oregon, collecting between 4 and 30 liters per tap. Sugar maple volumes average around 38 liters per tap per season, and their sap is twice as sweet (Heiligmann et al., 2006). Until the widespread use of vacuum tubing and reverse osmosis machines, bigleaf maple syrup was not economically feasible with low volumes of 0.8 – 2º Brix sap. One collaborator in this study noted that his seasonal sap yield per tap doubled after switching from bucket collection to closed tubing. The increased yield and lower labor inputs of tubing systems, improved sanitation techniques, and reverse osmosis concentration of sap have made bigleaf maple sugaring far more efficient than in 1972. This study addresses the effectiveness of vacuum pumps compared to gravity tubing and traditional bucket collection, though processing techniques are not addressed.

There is an active sugaring community on Vancouver Island in British Columbia, where an annual bigleaf maple syrup festival has been held for twelve years straight with the exception of 2020 and 2021 due to COVID-19. Backlund & Backlund (2012) estimate that British Columbia is home to 10,000 bigleaf maple syrup makers. Bigleaf maple sugaring outreach and workshops led by the Washington State University Extension forester K. Zobrist and Skagit Conservation forester A. Craney helped kickstart landowner interest in the early 2010s (Phillips, 2021). Most maple tapping knowledge in Washington has either been learned on-site through trial and error or shared by sugar-makers from the eastern United States. There is a substantial knowledge gap surrounding best practices, sanitation, weather constraints, and the geographic range of profitable tapping in Washington. This information is more readily shared between maple syrup makers in the Eastern US and Canada through forums (such as mapletrader.com) and conventions, but there is not yet a similar network in the Pacific Northwest.

Bigleaf Maple Geographic Distribution & Site Requirements

Bigleaf maple is a deciduous hardwood tree extending from the more mesic regions of Central California to the central coast of British Columbia. Its high water requirements limit growth to the southern Pacific Coast of the US, whereas its northern and high-elevation borders are limited wherever the deep soil freezes before the first snowfall (Peterson et al., 1999). The bulk of its population is found west of the Pacific Coast and Cascade Mountain ranges in mixed conifer forests, along forest edges and roads, and particularly bordering riparian areas. In Washington State, bigleaf maple grows in upland riparian zones, in mesic forests up to 1000 meters in elevation, and along lowland floodplains (Franklin & Dyrness, 1973). While it thrives in mesic environments and can withstand flooding for up to two months a year, the species grows best in well-drained colluvial and alluvial soils (Eis & Craigdallie, 1980). Bigleaf maple can grow on steep slopes of unconsolidated rock and gravel, and often repopulates previously conifer-dominated patches that have succumbed to root rot (*Phellinus weirii*; Hadfield et al., 1986).

Bigleaf maple provide ecological benefits such as runoff retention, soil stabilization, and nutrient-rich leaf litter (Agee, 1988). It is considered a soil-building species due to the quick nutrient turnover and high volume of its leaf litter (Burns & Honkala, 1990). Its role in nutrient cycling is apparent in its sap chemistry as well. When the sap is boiled, a nutrient-rich sediment called “sugar sand” accumulates in bigleaf maple syrup in higher quantities than in sugar maple syrup. Testing by Bruce (2008) indicates that bigleaf sap contains five times as much calcium as sugar maple sap and significantly higher concentrations in all of the other ten tested minerals. It is possible that nutrient-rich sap is simply the medium between nutrient-rich soil and nutrient-rich leaves. Bigleaf maple bark is also rich in calcium, which probably accounts for its tendency to host abundant communities of moss and ferns (Krajina et al., 1982). On the Western Olympic Peninsula their epiphytic communities that can outweigh a tree’s foliage by a factor of four (Kirk et al., 1992).

Bigleaf maple is an important component of Western Washington's riparian ecosystems. Maples growing in riparian areas offer cooling shade to many salmon-bearing streams, and their dead wood is an important structural component of many streams (Collins & Montgomery, 2002). Dead hardwood branches break down faster than those of conifer species, offering more available nutrition to the macroinvertebrate detritus feeders that form much of base of the aquatic food chain (Piccolo & Wipfli, 2002). In urban areas bigleaf maples provide shade with little upkeep, and the Saanich and Cowichan Coast Salish people incorporate its bark into medicines to heal digestive ailments (Turner & Hebda, 1990). Elk, deer, and rodents browse its foliage, and a variety of animals rely on its seeds in the winter (Burns & Honkala, 1990).

Bigleaf maples establish from seed and resprout when a stem is cut, burned, or killed by herbicide. While this growth pattern allows coppiced stumps to quickly overshadow planted seedlings, it might prove advantageous for tapping. Clumped stems grow close together, making it easier to install multiple taps in the field. These stems share a root system, which could allow sap to flow from one stem to another and would increase the total amount of sap storage accessed by one tap. Clumps also have relatively high growth rates compared to seedlings, as their root system is already established. Resprouting stems can reach up to three meters in height in the first year of growth (Burns & Honkala, 1990). In one study, clump size was found to be positively correlated with parent stump diameter (Tappeiner II et al., 1996). Using coppice management in bigleaf maple stands could provide a relatively fast avenue to convenient, productive tappable stems.

Bigleaf maple seedlings are common in smaller-scale Douglas-fir plantations and naturally regenerated stands, where the juvenile seedlings rapidly release after either commercial thinning or natural mortality allows patches of light to reach the understory (Hadfield et al., 1986). No special management is required to encourage its growth, and more seems to have been written about how to remove its stumps than how to cultivate it (Newton, 1963; Norris & Freed, 1964). The tree is considered a nuisance by many foresters as it resprouts vigorously and competes with planted softwood seedlings for light and water (Peterson et al. 1999). Bigleaf maple stumps have been eradicated to free resources for planted trees in most industrial conifer plantations in Washington, though smaller-scale landowners may not have had the desire nor resources to remove the resprouting hardwoods as thoroughly.

Many of bigleaf maple's characteristics lend it to sugaring. Bigleaf maple stands rarely grow in sufficient density to make commercial harvest profitable, except for pulpwood, so tapping does not degrade its future timber value. Stands growing near fish-bearing streams cannot be harvested per Washington's Forest Practices Rules (1975) protections on fish habitat. In Western Washington, the buffer restricting harvest varies up to 61 meters (200 ft) in width depending on the stream type. Bigleaf maples growing on riparian zones, steep hillsides, rocky slopes, or areas where timber harvest is not feasible can be tapped to yield syrup from land that otherwise generates no revenue. Restoration operations using bigleaf maple, especially in riparian areas, could also include sap harvests without causing the trees substantial harm.

Bigleaf maples establish from seed and resprout when a stem is cut, burned, or killed by herbicide. While this growth pattern allows coppiced stumps to quickly overshadow planted seedlings (Burns & Honkala, 1990; Fried et al., 1990), it might prove advantageous for tapping. Landowners looking to monetize an otherwise unmerchantable life stage of their harvest cycle could thin stump sprouting maples growing alongside planted Douglas-fir and tap them after several years. Clumped stems grow close together, making it easier to install multiple taps in the field. These stems share a root system, which could allow sap to flow from one stem to another and would increase the total amount of sap storage accessed by one tap. Clumps also have relatively high growth rates compared to seedlings, as their root system is already established--resprouting stems can reach up to three meters in height in the first year of growth (Burns & Honkala, 1990). In one study, clump size was found to be positively correlated with parent stump diameter (Tappeiner II et al., 1996). Using coppice management in bigleaf maple stands could provide a relatively fast avenue to convenient, productive tappable stems.

Bigleaf Maple Economic Value & Sugaring

Bigleaf maple lumber is suited for pianos, furniture, and cabinetry, though it is softer than most eastern maples (Northwest Hardwoods, 2022). The trees occasionally form figured wood and burls, which are especially valuable but difficult to locate in the forest. Its stems are relatively short and curved with many limbs, resulting in a poor percentage of volume converted into lumber (Kerbes, 1968). In commercial-oriented operations bigleaf maple trees are typically cleared to make way for more profitable conifer plantations.

While statistics for Washington's bigleaf maple harvest volume are not available, hardwood harvest data illustrates the fact that industrial forest landowners in the Pacific Northwest have nearly eradicated bigleaf maples on their land but small forest landowners have not followed suit. Hardwoods other than red alder comprised 1.8% of all board-feet harvested in Western Washington in 2017. However, this category accounted for 10.8% of harvested board-feet on private lands under 1,000 acres in the same year (Washington State Department of Natural Resources, 2018). These statistics indicate that non-industrial forest land can have high stocking of hardwoods other than red alder, and bigleaf maple is likely a chief component due to its prominence in Western Washington forests.

Bigleaf maple is common enough in the Pacific Northwest that no planting is required to achieve a high density of tappable trees. The factors limiting bigleaf maple syrup production have tended to be the expense and availability of processing equipment, finding labor, and the increased work with sugaring a low sugar content species. The idea of growing maple plantations for their sugar may be gaining traction, but presently nearly all maple syrup of any kind is produced from naturally regenerated trees (Perkins & van der Berg, 2016).

Tapping bigleaf maple trees as a commercial venture has limited ecological impact, provides diversified income to small forest landowners, is highly scalable, and could create seasonal jobs in rural economies. The area of forest where trees are tapped is known as a "sugarbush". Installing a sugarbush requires no heavy machinery, road improvement, or other activity that could compact soils besides the establishment of foot trails. Small tapholes in the trees and plastic tubing installed in the woods are the only signs of harvest, and no material need be left in the woods when the sugarbush is retired. A tubing system accessing one hundred trees can easily be extended to five hundred the next year if a large diameter sap "mainline" is used and a sufficient density of maples is nearby. Copenheaver et al. (2014) found tapping to reduce 10-year growth increment in sugar maples in two of three studied sites by about one-fifth. Tapped trees at the third site did not experience significant changes in growth rate. Research is needed on the impact of tapping bigleaf maple on growth.

Most of the by-products of the maple sugaring process can be repurposed. The trees themselves are burned as evaporator fuel or sold for firewood after their lifetime of use is over. Lumber from tapped maple trees is sold at a markup in Eastern North America for its history and distinctive pattern. Lower quality syrup can be aged to transform it into vinegar, and even unprocessed sap makes a delicious beverage. The byproduct of the reverse osmosis process, called “permeate”, is simply purified tree water. Maple sugaring provides plenty of marketable byproducts beyond syrup, and it is possible to incorporate sugaring into a landowner’s larger forest stewardship plan. How sugaring will come to maturity as a part of forestry in Washington remains to be seen.

Figure 1.2. A bigleaf maple sugarbush near Sultan, WA. At this site, 444 trees were tapped and a tubing system was installed. The only earth-moving required was a 20-ft pipe buried to allow the mainline tubing to transport sap across a dirt road.

Bigleaf Maple Syrup Knowledge Gap

The milder winters of Western Washington, compared to the American and Canadian east, mean that the knowledge of the weather patterns affecting sugar maple sap flow is likely not sufficient for bigleaf maple. The freeze-thaw weather patterns that initiate sap runs occur throughout the winter in Washington, while the Eastern sugarbushes experience a hard winter freeze followed by a period of spring thaw. Winter temperatures are generally warmer in Western Washington, resulting in faster bacteria growth in the tapping equipment and an increased reliance on frequent effective sanitation. Less frequent freezes in Washington may mean that vacuum pumps can be used to pull sap from the trees when it would not naturally be exuded, thereby increasing yields.

The relationship between bigleaf maple tree characteristics such as diameter, height, crown volume, stand social class, and vigor might all affect sap flow and have not been thoroughly studied in Washington. Larger trees with larger canopy volume and sapwood area (Tucker et al. 1993, may produce greater sap flow. It is not clear whether stems growing in the same clump share sap characteristics (sugar content and timing), or whether larger trees produce more sap, or if canopy position and canopy health affect sap flow. Throughout this thesis, "sap flow" will be used to mean the combination of sap volume, timing, and sugar content.

If sap production in bigleaf maple is similar to that in sugar maple, much of the variation in maple sap flow is determined by tree characteristics and weather (Heiligmann et al., 2006; Taylor, 1956). It is important to understand weather and tree characteristics effects and their interaction which may determine which trees should be tapped, and when and where to tap them to increase sap production. Filling in the knowledge gaps on sap flow will contribute to fundamental biological knowledge of bigleaf maple, and will aid bigleaf maple hobbyists and prospective commercial sugaring operations. The benefits of this knowledge will extend more broadly to rural economies should maple tapping continue to expand in Washington.

This thesis examines the potential of bigleaf maple syrup production, however it is important to note that bigleaf maple has been the subject of recent forest health concerns, which are not directly addressed in this thesis. For the past decade, there have been reports of signs of poor tree health and mortality throughout bigleaf maple's range. The affected trees do not display a spatial pattern associated with pathogens, though proximity to developed land and water stress were positively associated with maple decline (Betzen et al., 2021). As climate change is expected to shift Washington's peak river flow dates earlier, soil moisture in the growing season is expected to decline (EPA, 2016). Some landowners have already expressed concern about tapping their bigleaf maples in case the extra stress makes them more vulnerable to decline. A better understanding of bigleaf maple sap flow in response to climate could assist landowners in deciding if and geographically where to tap in anticipation of increased water stress.

Study Goals & Impact

The goals of this research were to:

1) Assess how sap flow varies between bigleaf maple trees of different sizes and growth forms.
2) Create a model of sap flow dependent on daily temperatures.
3) Identify where high bigleaf maple sap flow potential coincides with high potential tap density in Western Washington.
4) Assess whether vacuum pumps improve sap harvest volumes relative to gravity tubing.
5) Estimate annual bigleaf maple syrup production potential in Western Washington.

Understanding how tree characteristics affect sap flow will allow potential syrup producers to estimate yearly sap volumes, appropriately scale their equipment, and decide whether tapping their trees is a worthwhile endeavor. Additionally, it will allow sugar-makers to prioritize their time and equipment by informing them how to tap the most productive trees. Exploring the relationship between daily weather and sap flow will also increase the efficiency of bigleaf maple sugaring. The temperature model of sap flow will help landowners decide when to tap, and to estimate their potential sap per tap yield, which could be combined with an inventory of their trees to yield a more precise estimate of potential stand-level sap yield and calculations of returns on investment. Finding which regions of Washington have the highest potential syrup production would also benefit prospective sugar-makers looking for maple production land. Understanding sap flow timing allows one to clean equipment, re-tap trees, and flush lines when sap flow is unlikely, and prepare for boiling when sap flow is expected.

As bigleaf sugar-makers transition from the hobbyist scale to commercial enterprise, they will need to comply with Washington's food safety codes which are currently far more stringent than the sugaring-specific food production regulations in the Eastern US. A realistic estimate of the scale and location of a potential bigleaf maple syrup industry would give lawmakers the information they need to reevaluate barriers to entry. Requiring small-scale sugar-makers to invest in a dedicated clean room, for example, creates a barrier to selling at local stores and online. While hobbyists will always tap bigleaf maple for non-commercial use, being unable to legally sell their product will dissuade many from expanding their operations.

It is already apparent that sugaring practices vary throughout Washington due to differences in weather. Should a collaborative, community-oriented approach to sugaring become common in the future, factors like population density, topography, road access, and other local idiosyncrasies will become important in determining best practices and eventually regulations for how sap is graded, sold, transported, and processed. Deciding regulations at the local scale would keep each syrup production region flexible to its own needs. Statewide estimates of syrup production will be helpful in identifying where sugaring will be the most productive and could help identify the timing of sap flow in each region. Climate change will require adaptability from sugar-makers as temperatures become less predictable, and local autonomy helps in keeping agricultural producers flexible (Sauchyn et al., 2010). Provenance and terroir are important selling features for most wines and many cheeses, honeys, and other agricultural products. If early marketing of bigleaf maple syrup includes the same concepts, terroirs or climate regions could emerge as base marketing or regulatory units. The spatial predictions of sap flow in Chapter 4 would be of use here.

Developing a bigleaf maple syrup industry in Washington could provide small forest landowners with income from parts of their land that are not economically productive. Riparian areas, steep rocky hillsides, hardwood forest, and wetlands all have legal or economic barriers to timber harvest, and they are all common habitat for bigleaf maple. Tapping maples in these unutilized areas may be an environmentally low-impact way to tip the economic scales in favor of keeping their land forested versus selling it for development

Study Design

Canister Tree-level Sap Measurements

While most sugar-makers collect sap using a tubing system for its convenience and labor savings, in such operations sap measurements can only be taken at the level of the "sugarbush" – the collection of trees whose sap feeds into one collection tank. Determining how tree characteristics affect sap flow requires an individual-tree-level measurement approach. An experiment was established at the University of Washington's Pack Forest, near Eatonville, Washington, wherein sap was collected and measured from individual bigleaf maples spanning a range of diameters, number of stems, and canopy positions. Each tree had an attached canister that collected sap for measurement, and a high-power vacuum pump pulled full and continuous vacuum pressure on the taps.

Figure 1.3 The canister sap collection site at Pack Forest, near Eatonville, WA. Photo used with permission from Kiyomi Taguchi (UW News).

The canister data were analyzed in two ways. In Chapter 2, the relationships between individual tree characteristics and season-total sap flow are explored by summarizing the data at the level of individual tree and unique season. Diameter, growth form, canopy position, and canopy health were analyzed as independent variables of the dependent sap production. In Chapter 3, the canister data are summarized by unique date and several daily weather variables were analyzed to determine how the sum of all of the trees' sap flow varies with changes in daily weather.

Regional, Stand-level Sap Measurement

Landowners at eight study locations agreed to share their data and experiences tapping bigleaf maple trees in return for assistance procuring equipment and establishing their tapping operations. Sap collection sites varied in climate, topography, forest structure, and number of trees per lateral line (ranged from 80 to 700 taps). Low-power vacuum pumps were used at three sites, a high-power vacuum pump was used at one site, and there were gravity-driven vacuum systems at seven sites. Three sites served as a replicated comparison of gravity-vacuum and gravity vacuum assisted with a small diaphragm pump (Bosworth Co. model number GE-0401N). These three locations have separate vacuum pump and gravity systems, which allowed a comparison to be made between the two systems under the same weather conditions. Daily sap volume, Brix, and weather variables were measured at each site. All tapped trees were inventoried at four of these sites.

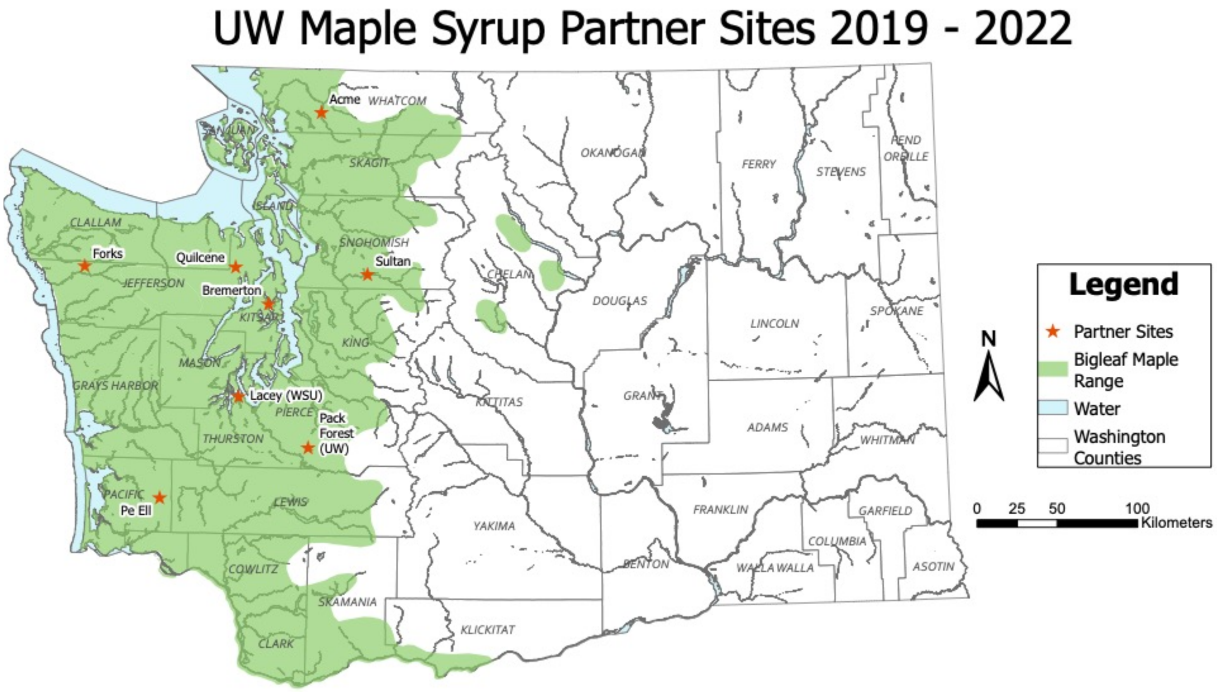


Figure 1.4. The locations of the eight partner sites. The range of bigleaf maple was adopted from Thompson et al. (1999). Note that some higher-elevation sites shown here, such as the Olympic mountains, are too high for bigleaf maple to grow.

Weather Model of Sap Volume

A hurdle model of daily sap volume per tap based on daily weather data was constructed using the daily sap flow data in the canister dataset. A selection of fifteen daily weather variables were screened for cross-correlation and five daily weather variables were chosen to represent daily and lagged temperature and freeze-thaw occurrences. A three-day lagged sum of freeze-thaw occurrence was the most effective predictor variable for daily sap volume. This freeze-thaw indicator was used as the independent variable in a model of daily sap volume per tap, to which two hurdles were applied to filter out days where temperatures were too cold for sap to flow.

The sap volume model was used to predict sap flow per tap for a 2-month tapping season (January 1 – March 1) on a 4 km^2 grid in Western Washington using publicly available weather data (PRISM Climate Group, 2022). A comparison was made between model predictions and season totals from the partner sites to illustrate a range of realistic sap collection and to compare this more variable production to that collected under ideal, controlled conditions of the canister experiment. This prediction layer was combined with a map of potential bigleaf maple taps per acre created by the Natural Resource Spatial Informatics Group to yield potential sap volume per acre (NRSIG, 2021). The resulting estimate is potential sap volume per year at a 4 km^2 spatial resolution informed by daily weather patterns, potential bigleaf maple tap density per acre, access to roads, and electricity availability. Tap utilization rates from the Eastern US provided by Farrell (2013b) were used to convert estimates of sap volume per unit land area to conservative estimates of potential annual syrup production in Western Washington, should bigleaf maple syrup continue its development.

References

Agriculture and Agri-Food Canada. (2021). Statistical Overview of the Canadian Maple Industry (p. 16). Crops and Horticulture Division, Government of Canada.

Backlund, G., & Backlund, K. (2012). Bigleaf Sugaring: Tapping the Western Maple. Backwoods Forest Management Publishing.

Betzen, J. J., Ramsey, A., Omdal, D., Ettl, G. J., & Tobin, P. C. (2021). Bigleaf maple, Acer macrophyllum Pursh, decline in western Washington, USA. *Forest Ecology and Management*, 501, 119681. https://doi.org/10.1016/j.foreco.2021.119681

Bruce, D. (2008). Production and quality of sap from bigleaf maple (*Acer macrophyllum* Marsh) on Vancouver Island, British Columbia. University of British Columbia.

Burns, R., Honkala, B. (1990). Silvics of North America: Conifers (Volume 1). United States Department of Agriculture (USDA), Forest Service, Agriculture Handbook 654.

Collins, B. D., & Montgomery, D. R. (2002). Forest Development, Wood Jams, and Restoration of Floodplain Rivers in the Puget Lowland, Washington. *Restoration Ecology*, *10*(2), 237–247. https://doi.org/10.1046/j.1526-100X.2002.01023.x

Copenheaver, C. A., McCune, R. C., Sorensen, E. A., Pisaric, M. F. J., & Beale, B. J. (2014). Decreased radial growth in sugar maple trees tapped for maple syrup. *The Forestry Chronicle*, *90*(06), 771–777. https://doi.org/10.5558/tfc2014-149

Creighton, J., & Baumgartner, D. (2005). Washington State's forest regulations: Family forest owners' understanding and opinions. *Western Journal of Applied Forestry*, *20*(3), 192–198.

Eis, S., & Craigdallie, D. (1980). Shore and landscape analysis of the western section of the Capital Regional District of British Columbia (BC-X-208; p. 43). Canadian Forestry Service, Pacific Forest Research Centre.

EPA. (2016). What climate change means for Washington (No. 430-F-16–049; p. 2). United States Environmental Protection Agency.

Farrell, M. (2013a) The Sugarmaker's Companion. Chelsea Green Publishing.

Farrell, M. (2013b). Assessing the growth potential of the maple syrup industry in the United States: A multi-disciplinary approach based on ecologic, socio-economic, and public policy factors. Cornell University.

Fleisher, Mark. (1980). The Ethnobotany of the Clallam Indians of Western Washington (14 (2); Northwest Anthropological Research Notes, pp. 192–210).

Franklin, J. F., & Dyrness, C. (1973). Natural Vegetation of Oregon and Washington (p. 417) [General Technical Report]. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station.

Fried, J. S., Boyle, J. R., Tappeiner II, J. C., & Cromack Jr., K. (1990). Effects of bigleaf maple on soils in Douglas-fir forests. *Canadian Journal of Forest Research*, 20(3), 259–266. https://doi.org/10.1139/x90-038

Graham, G. (2016). Maple Syrup Production Statistics, an Updated Report to the North American Maple Council (p. 31). Ohio State University Extension.

Hadfield, J., Goheen, D., Filip, C., Schmitt, C., & Harvey, R. (1986). Root diseases in Oregon and Washington conifers (No. R6-FPM-250–86; p. 27). USDA Forest Service, Pacific Northwest Region.

Heiligmann et al., R., Koelling, M.R., & Perkins, T.D. (2006). Maple Sap Production—Tapping, Collection, and Storage. In: *North American Maple Syrup Producers Manual,* (pp. 81-118). (2nd ed.). Ohio State University.

Kerbes, E. L. (1968). Broadleaf maple in British Columbia (VF-X-38; p. 23). Forest Products Laboratory.

Kimmerer, R. W. (2013). Braiding sweetgrass: Indigenous wisdom, scientific knowledge and the teachings of plant*s* (First paperback edition). Milkweed Editions.

Kirk, R., Franklin, J. F., & Kirk, L. (1992). The Olympic rain forest: An ecological web. University of Washington Press.

Krajina, V., Klinka, K., & Worrall, J. (1982). Distribution and ecological characteristics of trees and shrubs of British Columbia. University of British Columbia.

Morrow, R. R. (1972). Natural vacuum and the flow of maple sap. *New York's Food and Life Sciences Bulletin*, *14*(18).

Natural Resource Spatial Informatics Group. (2021). Identifying Potential Sites for Big Leaf Maple Syrup Production. University of Washington, Precision Forestry Cooperative.

Newton, M. (1963). Success in Douglas-fir plantations as related to site and method of removal of bigleaf maple overstory. Research Progress Report, 17–18.

Niemiec, S. S., Ahrens, G. R., Willits, S., & Hibbs, D. E. (1995). Hardwoods of the Pacific Northwest (Research Contribution No. 8; p. 125). Forest Research Laboratory, Oregon State University College of Forestry.

Norris, L. A., & Freed, V. H. (1964). The absorption, translocation, and metabolism characteristics of 4-(2,4-dichlorophenoxy) butyric acid in bigleaf maple. *Weed Research*, *6*(4), 283–291.

Northwest Hardwoods. (2022). Pacific Coast Maple. Western Species and Grades. https://northwesthardwoods.com/products/western/pacific-coast-maple/

Perkins, T., & van der Berg, A. (2016). Sap Collection from Small-Diameter Trees (p. 9). University of Vermont Proctor Maple Research Center.

Peterson, E.B., Peterson, N.M., Comeau P.G., & Thomas K.D. (1999). Bigleaf maple managers' handbook for British Columbia. British Columbia, Ministry of Forests Research Program.

Phillips, R. (2021). Bigleaf belief. Washington State University Magazine. https://magazine.wsu.edu/2021/11/08/bigleaf-belief/

Piccolo, J. J., & Wipfli, M. S. (2002). Does red alder (Alnus rubra) in upland riparian forests elevate macroinvertebrate and detritus export from headwater streams to downstream habitats in southeastern Alaska? 59, 11.

PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu, data created 20 March 2022, accessed 1 April 2022.

Rabotyagov, S., Rogers, L., Danley, B., Comnick, J., Cooke, A., Chowdhury, P. K. R., & Diaz, D. (2021). Washington's Small Forest Landowners in 2020. Status, trends, and recommendations after 20 years of Forests & Fish. University of Washington School of Environmental and Forest Sciences.

Rucker, M. (1930). Recollections of my boyhood. In the Oregon Trail and some of its blazers. Walter Neale.

Ruth, R. H., Underwood, J. C., Smith, C. E., & Yang, H. Y. (1972). Maple sirup production from bigleaf maple. USFS Research Note, Pacific Northwest Research Station, 12.

Sauchyn, D., Diaz, H., & Kulshreshtha, S. (2010). The New Normal: The Canadian Prairies in a Changing Climate. University of Regina Press.

Tappeiner II, J. C., Zasada, J., Huffman, D., & Maxwell, Bruce D. (1996). Effects of cutting time, stump height, parent tree characteristics, and harvest variables on development of bigleaf maple sprout clumps. *Western Journal of Applied Forestry, 11*(4), 120–124.

Taylor, F. H. (1956). Variation in Sugar Content of Maple Sap (Bulletin No. 587; p. 21). University of Vermont Agricultural Experiment Station.

Tucker, GF., Lassoie, JP, and Fahey, TF. (1993). Crown architecture of stand-grown sugar maple (Acer saccharum Marsh.) in the Adirondack Mountains. *Tree Physiology 13*(3), 297-310.

Turner, N. C., & Bell, M. (1971). The Ethnobotany of the Coast Salish Indians of Vancouver Island, I and II. *Economic Botany,* 25(1), 63–104.

Turner, N. J., & Hebda, R. J. (1990). Contemporary use of bark for medicine by two salishan native elders of Southeast Vancouver Island, Canada. *Journal of Ethnopharmacology*, *29*(1), 59–72. https://doi.org/10.1016/0378-8741(90)90098-E

United States Standards for Grades of Maple Syrup, 7 U.S.C. 1621-1627 7 (2015).

USDA. (2021). Northeastern Region Maple Syrup Report (p. 2). USDA National Agricultural Statistics Service.

Washington Forest Practices Rules, WAC Title 222 § 30 (1975).

Washington State Department of Natural Resources. (2018). 2017 Washington Timber Harvest Report (p. 45).

Washington State Department of Natural Resources. (2021). Commissioner Hilary Franz Introduces “Keep Washington Evergreen” Plan for Forest Conservation and Reforestation.

Chapter 2: Bigleaf Maple Size, Growth Form, and Sap Flow

Background

Sap exudation in maple trees is triggered by freezing nights and warm days (Tyree, 1995). Native Americans have used the timing of sap exudation in sugar maples (*Acer saccharum*) to their advantage since well before European colonization (Kimmerer, 2013), and while the process is still not completely understood the evidence indicates that multiple mechanisms cause pressure variations within maple xylem (Tyree & Zimmerman, 2002).

Several models of maple sap exudation have been studied. Maple tree xylem contain hollow libriform fibers which transport gas separately from the sap-carrying vessels. Separate vessels for sap and gas prevent cavitation within the sap vessels as sap moves vertically throughout the tree under pressure (Cirelli et al., 2008). Cirelli et al. (2008) found that the microscopic holes, known as "pits", connect the sap-carrying vessels to the libriform fibers. This study found that the pits will allow water and gas to flow between the sap vessels and the fibers, but sucrose molecules are too large to pass and thus remain in the sap vessels. When the tree thaws, the sap-filled fibers contain sap (which contains sucrose) while the libriform fibers contain only water and gas. The osmotic gradient between the fibers and the vessels creates substantial pressure (Wiegand, 1906; Cortes & Sinclair, 1985; Ameglio, 2001). These mechanisms contribute to negative pressure

Figure 2.1. An emerging bigleaf maple bud signals the end of the sap harvesting season. Taps have been pulled and secured in the T - connections on the blue drop lines.

within the xylem during a freeze, which can draw water in through the roots if the ground is sufficiently insulated (typically by snowpack in the Eastern US and Canada; Tyree & Zimmerman, 2002).

Sachs (1860) examined how internal sap pressure in maple trees could be driven by thermal expansion of compressed gas. When the tree freezes, water and gas from the sap vessels is drawn into the libriform fibers and the water freezes on the inside of the fiber wall (Graf et al. 2015). Gas in the fibers is compressed during this process. When the trees thaw, the compressed gas in the fibers expands and creates a positive internal pressure (Schenk et al. 2021).

During a thaw, the expansion of gas in the libriform fibers, the osmotic gradient within the xylem, and possibly even the weight of the sap within the tree combine to create a positive internal pressure (Heiligmann et al., 2006). The precise amount of pressure that each of the aforementioned mechanisms contribute remains unresolved. If a taphole is drilled or even a branch is broken, sap will be exuded through the wound when the tree thaws. The timing of sap flow events, or "runs", depends on daily weather fluctuations, but individual tree-level characteristics like diameter, health, and light access appear play a role in how much sap volume can be extracted from sugar maples (Heiligmann et al., 2006) and bigleaf maples (Bruce, 2008). Anecdotal evidence from sugar-makers in Washington suggests that there is high variability in sap volume and sugar content even between neighboring trees. Studies on individual sugar maples have shown high variation between neighboring trees (e.g. Taylor, 1956), as have the few published results of bigleaf maple tapping (Bruce, 2008; Ruth et al., 1972). While site-level characteristics like soil type, aspect, and elevation likely affect sap flow, the variation between neighboring trees is clearly a separate phenomenon. Several tree-level characteristics were explored in this study to determine their effects on sap flow.

The amount of sap a tree can store is directly related to its diameter, in particular the cross-sectional are of active xylem or sapwood. Larger trees have a greater volume of xylem and a larger root mass from which to draw groundwater (Heiligmann et al., 2006). However, older trees have thicker bark and are more likely to have rotten patches of sapwood that do not yield sap. The ideal diameter range for tapping bigleaf maple is still not clear and may be better described by tree vigor. Bruce (2008) found a significant positive correlation between January sap volume and diameter at breast heigh (DBH) in 18 bigleaf maples, though the largest trees were removed from the dataset due to low sap volumes. Bruce's trees were tapped using 7/16" plastic spiles connected to 20-liter plastic collection tanks by plastic tubing approximately one meter in length. No artificial vacuum was used, and the vertical drop of the tubing was unlikely to initiate gravity-induced vacuum because the tubing was too wide for the trickling sap to fill it completely and create and airtight sap "plug". The present study provided the first record of individual bigleaf maple sap flow using a high-powered vacuum pump.

Bigleaf maple trees often grow with multiple main stems, or as resprouting clumps after a tree is cut, burned, or treated with herbicide (Peterson et al, 1999). Clumps naturally thin over time -- a resprouting clump may begin with over one hundred sprouts the year after the main stem was cut, but these typically thin by half in the following season (Roy, 1955). Stems in a resprouting clump grow from the same root system, and it is unknown if sap may be able to flow from an untapped stem through the roots to a tapped stem when vacuum pressure is applied to a taphole. In this case, the diameter of the tapped stem would under-represent the amount of sap storage accessed by that tap.

A study from British Columbia suggests that bigleaf maples growing on the edges of a stand have higher sugar content (Bruce, 2008). This is likely due to the increased levels of light reaching the canopy at such edges, allowing larger crown volume and more carbohydrate production. In the Eastern United States this trend has been known for some time: Heiligmann et al. (2006) reports that faster-growing trees on stand edges yield higher sap volumes compared to trees in a stand's interior. The trees tapped for the canister experiment were classified by canopy position, which is determined by the amount of light reaching the crown as per Kraft's (1884) classification scheme. This measurement was analogous to edge vs. interior position with respect to crown size and light availability. Canopy health, measured by the percentage of dead crown volume, may also affect sugar production by determining the amount of leaf area able to effectively photosynthesize. Canopy health was measured in 10% increments in terms of percent live crown.

The eight collaborator sites provided insight into how real landowners are making syrup on their land, and they helped to illustrate what knowledge and techniques may help bigleaf maple sugaring transition from the hobbyist to the commercial scale. The collaborators were at the vanguard of this new industry and they offered critical information on best practices and local knowledge. However, their sap flow data is limited to a spatial scale of several hundred trees, as the sap was collected in tanks before being measured (discussed Chapter 5). A finer, more controlled spatial scale was needed to determine how sap flows in individual trees without the variation and idiosyncrasies of an entire sugarbush. Two individual-tree-level experiments was performed at Pack Forest that provided an opportunity to measure sap flow rate and sugar content at a fine spatial scale. A bucket study allowed sampling along an elevation gradient from (161 m – 608 m), and a set of canisters on individual trees connected to high vacuum allowed consistent vacuum pressure in a controlled setting.

Methods

Bucket Sap Collection

Bucket sap collections were performed at four sites spanning a range of elevations within Pack Forest in the 2019-20 tapping season (Table 2.1). Six bigleaf maple trees were tapped at each site from 12/27/2019 to 02/25/2020. This collection method was a low-cost way to explore how much sap could be harvested across the four sites at Pack Forest and determine where sap collections should be installed. The Nisqually River site was a mesic, low-elevation site near a major river. The Camp site was located near the canister collection site near the entrance to Pack Forest, Big Ponds was halfway up a small mountain but on a flat bench of land next to two large water collection pools, and the Emmons site was located near the top of a ridge. Sap collection was not regular enough to establish daily trends, but sap volume, sugar content, and tree diameter were measured and summarized for the entire two-month season.

Table 2.1. Site-level summary data for the bucket collections at Pack Forest.

Site	Elevation (m)	Site Topography	Volume-weighted Brix	Liters per tap
Emmons	608	Ridge	1.6	1.9
Big Ponds	402	Bench	0.8	9.0
Camp	285	Flat	1.2	2.0
Nisqually River	161	Floodplain	0.4	0.2

Canister Sap Collection

A series of twenty airtight PVC canisters were connected to tapped bigleaf maples along a roughly 100m stretch of forest at Pack Forest for the ‘19/’20, ‘20/21, and ’21/’22 winter seasons. Trees were tapped with 3/16th inch diameter plastic spiles that ran through approximately 50 cm of vertical 3/16th inch diameter tubing before entering the canisters. The canisters were connected by 5/16th inch tubing, in series, to a vacuum pump that ran continuously for each season. Thus, vacuum pressure was consistent between each taphole, and each tree's sap flow was collected in a separate container that could be measured and emptied independently of the others. Sap volume was measured in a graduated pitcher in 10-ml increments. Sugar content was measured using an electronic portable refractometer, and sap quality was assessed visually and by smell. High quality sap ("1") was clear and odorless, medium quality sap ("2") was cloudy but with no off-flavors, and low-quality sap ("3") was yellow, milky, or with off-flavors and was not considered fit for boiling. The diameter, growth form, and canopy position of the canister trees were recorded in order to determine the individual tree-level factors affecting sap flow.

Due to weather constraints and staffing limits, the canisters could not be measured at consistent intervals and collection intervals range from a few hours to a week. Additionally, there were twenty-three total bigleaf maples tapped during this time period but not all of them were tapped for all three seasons (Table 2.2). One red alder and one black cottonwood were tapped but not included in this analysis, and one tapped tree was found to be dead and thus omitted. Heavy sap flow from some stems required multiple canisters to prevent overflow into the dry vacuum line. The study area was cleared in 1980 and planted with red alder, which now dominate the site. Bigleaf maples are present that resprouted from cut stumps during the 1980 treatment, or that had established as seedlings and were released by the treatment. It is a flat stand that collects water during precipitation events and receives only afternoon sun in the winter tapping season.

Table 2.2. Seasonal summary data for the canister collections.

	2019/20	**2020/21**	**2021/22**
Number of tapped trees	15	9	19
Date tapped	Feb 11	Jan 28	Jan 31
Average liters/tap	15.5	24.8	11.8
Volume-weighted Brix	1.02	1.07	1.24

Note: Some trees required more than one canister due to high sap volumes, so fewer than twenty trees could be tapped with the twenty canisters available.

Statistical Design

Sap volume totals were not normally distributed and were heavily left-skewed as most tapped trees produce moderate to poor amounts of sap while some produce very high amounts. The mean seasonal sap volume was tested between two groups of growth form (individual and clumped stems) and three diameter classes (<30 cm, 30-48 cm, and > 48 cm). Two permutational analysis of variance tests (PERMANOVA) were used to detect differences in seasonal sap volume and sugar content by tree size (three diameter classes), growth form (clumped stems or individual stems), canopy classification (dominant, codominant, intermediate, or suppressed), and percent live canopy (to nearest 10%). Sap volume and sugar content were shown to have no correlation and were thus kept in two separate tests for better interpretability. PERMANOVA allowed statistical comparisons given the non-normal, categorical structure of the data, and is interpreted for data which were not suited for the nested analysis of variance nest.

The statistical power of the PERMANOVA allowed for an additional diameter category, though pairwise comparisons of mean sap volume were not possible.

Based on the results of the sap volume PERMANOVA, a nested ANOVA test was performed to determine the correlation between tapping season and sap volume, and within tapping season how diameter class (<35cm or >35cm) correlates with sap volume. Tukey's post hoc analysis was used to find which pairwise differences were significant. Two linear regressions were constructed, one for each growth form, to determine the level of heteroscedasticity present in the relationships between diameter and sap volume. For every statistical test, the threshold of alpha < 0.05 was used to determine statistical significance.

The explanatory tree physiology variables were diameter at breast height (DBH), growth form (clumps of stems or individual stems), canopy health, and canopy position. The response matrix was planned to include sap volume, Brix, quality, number of flow days per season, and flow season midpoint, but only volume and Brix were analyzed. There was almost no variation in sap quality – only five samples were not of good quality out of several hundred – so it was omitted from the response matrix. Each season's initial tapping date is determined by the sugar-maker and is decided when weather forecast first shows a period of freezing weather followed by a thaw sometime after mid-November. This discretion in tapping date affects the season start date and thus its length and number of possible sap flow days. This start date is the same for every tree within seasons but is not comparable between seasons. For the 2021 season, sap collection notes and data collection frequency were not sufficient to determine on which days sap was actually flowing, so the "number of flow days per season" variable was also omitted. Sap volume and sap sugar content were not found to be correlated in this study, and the two variables were analyzed in separate tests.

PERMANOVA

The experimental design of the canister sap collection was unbalanced as a different set of a different number of trees was tapped each year. A permutational test was used to correlate tree characteristics with differences in sap volume, using season-average data from only the nine canister trees that were tapped for all three seasons. The PERMANOVA test requires no distributional assumptions and permutations can be restricted to accommodate an unbalanced experimental design. The “Adonis2” function in the Vegan package was used to run the PERMANOVAs (Oksanen 2020). For the distance matrix, the “plots” are each of the nine canister trees that were tapped for all three seasons for a total of 27 measurements.

Permutations were restricted to within-seasons because “season” itself introduces variation that was not captured by the explanatory tree characteristic variables. In the restricted design, “blocks” were the seasons and “plots” were trees, and shuffling was not allowed between blocks, only within blocks. That is, tree numbers within seasons were shuffled. Variance was calculated for each term sequentially (*by = “terms”*), as the growth form and diameter of the tree were expected to account for the bulk of the variation in sap flow. The amount of sapwood present in a tree, measured indirectly by DBH, was presumed to be the most important tree characteristic in determining sap volume. As the explanatory variables were correlated (trees with larger diameters are likely to be taller and have higher canopy positions, for example) all explanatory terms were included in each of the two PERMANOVA analyses. The 2020-2022 responses were univariate, and volume-weighted Brix and sap volume were kept separate. The Euclidean distance measure was used to calculate the distance matrix because both sap variables are continuous. Neither response variable was relativized because they were each the only response variable in their respective analyses.

Tree diameters were binned into three categories: <30 cm, 30-48 cm, and > 48 cm. Three categories were chosen to give some distinction along the range of DBH while keeping at least two trees per growth form type in each category. The categories were chosen by converting tree diameters to basal area, which relates to how much live sapwood is potentially present in a tree, and then by using the Jenks natural breaks method to find two natural breaks in the basal area data. These breaks were then re-converted to diameter. Using the PERMANOVA allowed for a greater number of groups and additional specificity in analyzing sap volume and volume-weighted Brix by diameter class because the test's statistical power is more robust to having few measurements within groups than an ANOVA.

Nested ANOVA

Using the average seasonal sap volume for each of the 21 trees tapped in the canister experiment, a nested ANOVA was used to determine: 1) whether seasonal sap volume differed between trees of different growth form; and 2) whether within those growth forms if sap volume varied by diameter. This order was chosen because growth form affects tree diameter to a certain extent; a comparison of 472 bigleaf maple trees measured at six different partner sites for this study showed that the average diameter of tapped coppiced trees was 28.4 cm while that of tapped individual trees was 33.3 cm. Individual trees had an average of 30% greater basal area as a result of this difference. An interaction plot was created using seasonal sap volume per tap as the response variable and DBH category as the predictor variable. Two diameter groups were established, split at the median measurement to create equally sized groups (*n* = 10 under 35 cm, *n* = 11 over 35 cm).

Results

Sap Volume

The canister trees produced between 100 ml and 64 liters of sap each season, averaging 16.3 liters/tree. Averaged values across all three seasons were between 5.3 and 45 liters of sap, with a mean of 15.6 liters/tree. The bucket trees produced between 30 ml and 36 liters of sap each season, averaging 3.3 liters/tree. Three of the bucket trees and one of the canister trees produced no sap. According to a two-sample Student's t-test, the canister trees far outperformed the bucket trees in terms of sap volume for the 2019-2020 tapping season even though the bucket trees were tapped for a longer period of time (*p* = 0.002).

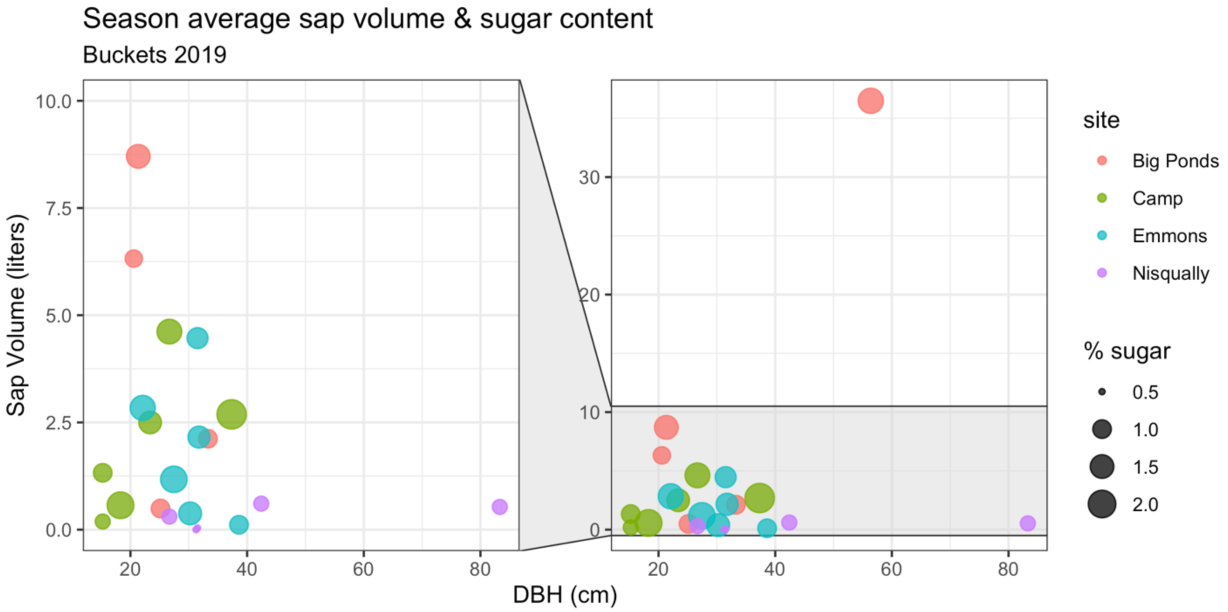


Figure 2.2. Bucket sap collection results. Three of 24 trees produced no sap at all.

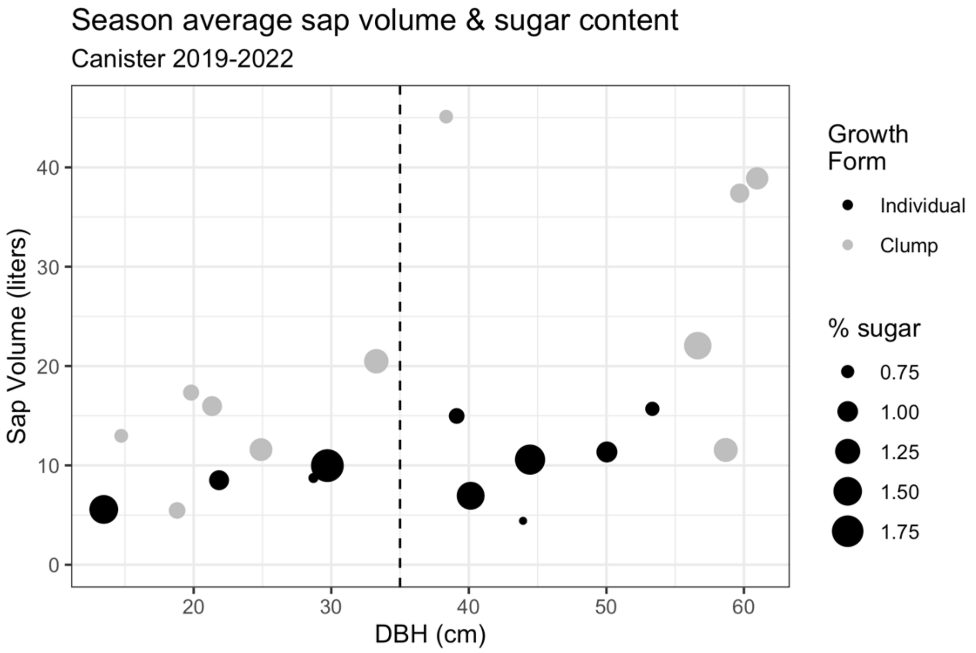


Figure 2.3. A graph of tree averages across three seasons of canister data shows a positive relationship between sap volume and tree diameter. Individual stems follow a closer linear trend than do clumped stems. The vertical line at 35cm shows the cutoff points for the two diameter classes used in the statistical analysis.

The PERMANOVA results indicate that differences in tree diameter class were significantly associated with differences in sap volume ($p = 0.001$). Neither growth form ($p = 0.08$), canopy position ($p = 0.12$), nor canopy health ($p = 0.98$) had significant effects on sap volume (Table 2.3).

Table 2.3. PERMANOVA results comparing sap volume measurements between tapped canister trees.

Predictor variable	Degrees of freedom	Sum of squares	R-squared	F-statistic	P-value
DBH category	2	226.10	0.49190	13.2955	**0.001**
Growth form	1	27.24	0.05926	3.2036	0.076
Canopy class	2	36.24	0.07883	2.1307	0.121
Canopy health	1	0.01	0.00002	0.0013	0.975
Residual	20	170.06	0.36998		
Total	26	459.65	1.00000		

Notes: Permutations were free within each of the three tapping seasons, while between-season permutations were restricted. Terms were added sequentially.

The nested ANOVA showed seasonal sap volume was significantly different between trees of different growth forms ($p = 0.002$). Mean sap volume per season for individual trees was 9.8 liters, while taps on clumped trees achieved a seasonal average of 21.6 liters. Seasonal sap volume also varied with different combinations of growth form and diameter ($p = 0.007$). Mean sap volume per season for the largest diameter class of coppice trees was 28.8 liters, which was significantly greater than that of individual stems of all size classes and for the smallest clumped trees (Table 2.4

Table 2.4. Nested ANOVA results grouping the canister measurements first by growth form (clump stem vs. individual tree), then by diameter class, compared to seasonal sap volume.

Predictor variable	Degrees of freedom	Sum of squares	F-statistic	P-value
Growth form	1	758.7	12.839	**0.00229**
Growth form : DBH	2	805.7	6.817	**0.00670**
Residual	17	1004.6		

A moderate interaction effect was found between diameter and growth form in seasonal sap volume averages. Trees of both growth forms produced more sap per season at larger diameters, though this difference was more pronounced for the clumped stems (Figure 2.4). A post hoc Tukey's HSD test showed the following pairwise differences at the 95% confidence threshold: clumped stems greater than 35 cm DBH had higher sap volume than clumped stems under 35 cm and both size classes of individual stems.

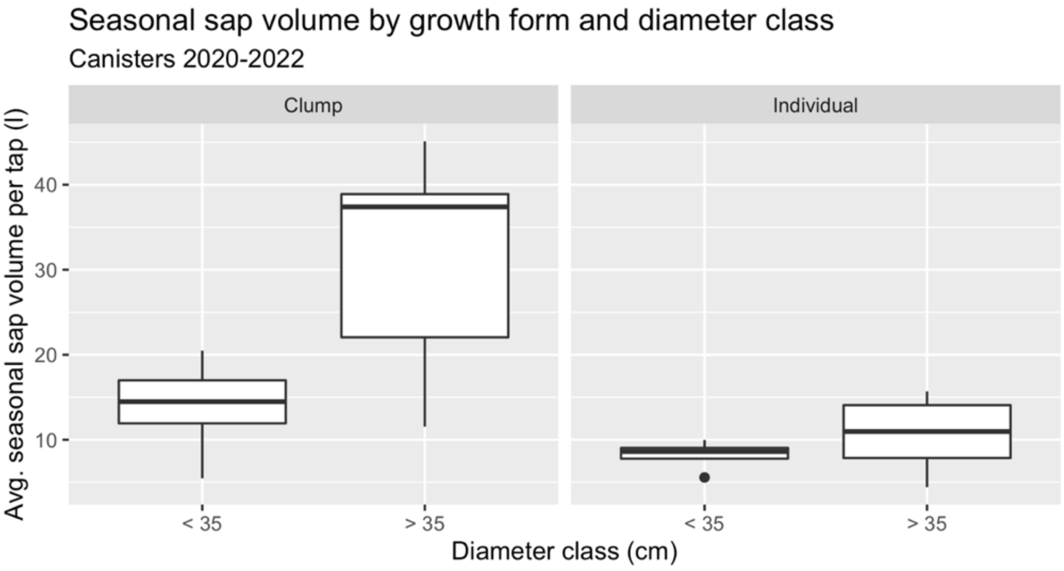


Figure 2.4. A boxplot depicting how season average sap volume varies by the growth form and diameter of the tapped stem.

The linear regression analysis showed that tree diameter explained 16% of the variation in seasonal sap volume averages per tap ($sap = 0.22 * DBH + 1.04$; $p = 0.038$; Appendix 2.3). Linear model residuals were uniformly distributed for the individual trees, but variance from the fitted model increased with diameter for the clumped trees. By contrast, the linear regression analyses where the canister trees were separated by growth form did not have sufficient statistical power (low *n*) to identify a linear relationship between diameter and seasonal sap volume (Tables 2.6 & 2.7) These results corroborate Bruce's (2008) study, in which the diameters of 18 stems 19 to 58 cm DBH were positively correlated with the stems' total January sap volumes ($r^2 = 0.12$). That study also found model residuals to increase with tree diameter, though growth form was not reported for each stem. Bruce removed several larger trees, averaging 93 cm DBH, from the dataset due to very low sap volumes, so there may be a diameter at which sap volumes decrease. That upper limit was not found in the present study, but future work including a wider range of tree diameters would be useful.

Table 2.5. Linear regression results comparing stem diameter to seasonal average sap volume per tap at the canister site.

Predictor variable	Estimate	Std. Error	t - value	P-value
(Intercept)	1.04172	1.55210	0.671	0.5102
DBH	0.21976	0.9899	2.220	**0.0388**

Table 2.6. Linear regression results comparing stem diameter to seasonal average sap volume per tap of the *clumped stems* at the canister site.

Predictor variable	Estimate	Std. Error	t - value	P-value
(Intercept)	1.8843	2.0794	0.906	0.3885
DBH	0.2643	0.1286	2.055	0.0701

Table 2.7. Linear regression results comparing stem diameter to seasonal average sap volume per tap of the *individual stems* at the canister site.

Predictor variable	Estimate	Std. Error	t - value	P-value
(Intercept)	1.14750	0.89707	1.279	0.237
DBH	0.09811	0.05931	1.654	0.137

Table 2.8. PERMANOVA results comparing Brix measurements between tapped canister trees.

Predictor variable	Degrees of freedom	Sum of squares	R-squared	F-statistic	P-value
DBH category	2	1.4738	0.26011	4.5542	**0.018**
Growth form	1	0.0246	0.00434	0.1520	0.721
Canopy class	2	0.9089	0.16042	2.8088	0.094
Canopy health	1	0.0229	0.00400	0.1399	0.745
Residual	20	3.2360	0.57114		
Total	26	5.6660	1.00000		

Sugar Content

The results of the PERMANOVA indicated that tree diameter class was associated with differences in seasonal sap volume-weighted sugar content (*p* = 0.018). Growth form, canopy position, and canopy health were not found to have significant effects on sugar content, so they were not analyzed further (Table 2.8).

The mean of the < 30 cm was 1.75º Brix, the mean of the 30 – 48 cm group was 1.20º, and the mean of the > 48 cm group was 1.16º. Due to the nature of the PERMANOVA test, a pairwise comparison of volume-weighted Brix between the three DBH groups was not possible so it is not clear which of these mean differences are significant. A nested ANOVA of season and clump unit showed that average total sugar content for the clumped stems did not vary significantly between seasons, but within seasons there was significant variation between clumps (*p* = 0.03; Table 2.9; Figure 2.5). A two-sample Student's t-test showed that differences in volume-weighted Brix between the bucket trees and the canister trees (subset to only include the same season as the bucket trees) were not statistically significant (*p* = 0.72).

Table 2.9. Nested ANOVA results grouping the canister measurements first by season of collection, then by which unique clump the stem was growing in, compared to seasonal sap volume.

Predictor variable	Degrees of freedom	Sum of squares	F-statistic	P-value
Season	2	0.1023	1.116	0.3594
Season : Clump	5	0.8557	3.734	**0.0286**
Residual	12	0.5500		

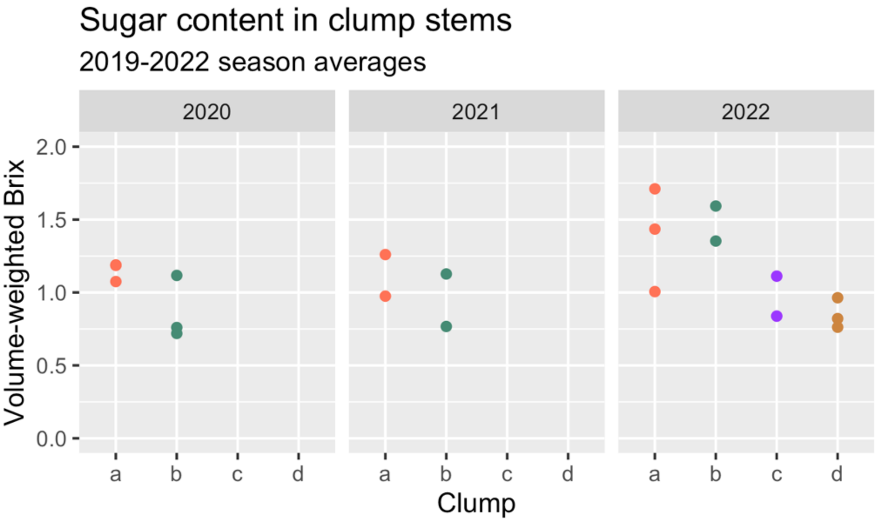


Figure 2.5. Sugar content variation for several tapped stems within the same clumps. Each letter indicates a different clump, and each point is a different tapped stem within one of those clumps. Sugar content was more similar within clumps than between clumps.

Discussion

Sap Volume

The 21 trees tapped for the canister experiment ranged from 13.5 cm to 61.0 cm DBH. This diameter range encompasses 93% of trees from the 1264 measured tapped trees at the six partner sites that were surveyed (Figure 2.6). At the partner sites, only 5% of trees were larger than the range of canister trees, with the largest reaching 148.0 cm DBH, and only 2% of trees were smaller. Trees are typically only tapped above 20 cm DBH (Heiligmann et al., 2006). The surveyed sites extended from the Eastern Olympic Peninsula to the foothills of Mt. Rainier. In terms of diameter range, the canister trees appeared to be representative of the majority of tapped bigleaf maples in Western Washington.

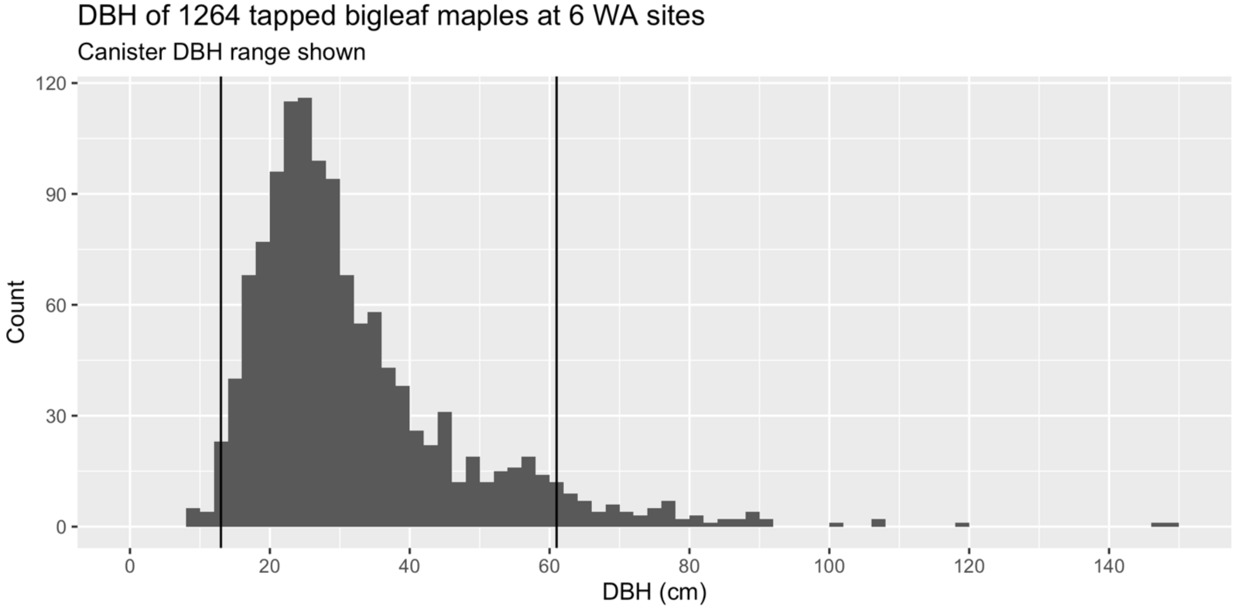


Figure 2.6. The diameter distribution of tapped bigleaf maples at six surveyed partner sites.

Notes: The vertical lines encompass the diameter range tapped in the canister experiment, which encompasses 93% of tapped trees at the surveyed partner sites. The general rule is to tap trees above 20 cm DBH.

The results of the PERMANOVA indicated that seasonal sap volume varied with tree diameter (*p*=0.001), and growth form clumped vs. individual stems had a marginal but not significant effect (*p*=0.076). The canopy position and canopy health measurements were not found to have significant effects on sap volume or sugar content (Table 2.3).

The nested ANOVA confirms this relationship and offers more clarity regarding the role of growth form on sap volume. When the data is grouped by growth form a clear positive linear relationship between DBH and seasonal sap volume emerges in the individual trees, while a more variable positive relationship is present for clump trees (Figure 2.3).

Heteroscedasticity for both clump trees and individuals was found to increase with increasing values of diameter, i.e. variation in sap volume increased with increasing values of diameter. Conversations with maple hobbyists in Washington have revealed split opinions on whether larger diameter trees are strong or weak choices for tapping. Larger trees could produce more sap due to their larger cross-sectional sapwood area, crown area, and root mass, or less sap due to their thick bark and higher likelihood of rotten sapwood at old age. Data on this subject have been sparse to this point. The present analysis illustrates that larger trees have higher variability in sap flow, so both opinions may be equally true. This result corroborates findings from Bruce (2008), who reported that variation in sap volume increased with diameter along a similar range of tree sizes. The linear model of stem diameter and seasonal sap volume could be used to refine predictions of sap flow where tree diameters have been measured.

The relationship between DBH and seasonal sap volume is still positive but much more variable for clumped trees. As clumped stems share root systems, the diameter of the tapped stems is not necessarily indicative of the amount of sap storage available to the tapped stem. It is unknown if sap may be able to travel between stems, but if this were the case the entire clump's canopy, root system, and sapwood would affect the amount of sap available to each tapped stem. Sap transfer between stems could explain the increased heteroscedasticity in clumped tree sap volume, or it may be a function of overall variability increasing with mean sap production.

For the 2020-21 winter season, six stems of clump growth were in the top seven sap producers out of fifteen tapped trees. The two clumps containing these six stems produced about 4.2 liters of syrup equivalent, which is double the rest of the nine single stems. These results track with speculation in the maple sugaring community that vacuum pressure can draw sap from the entire clump system through just a few taps – further research is needed.

At partner sites in this study, typically only one-half to one-third of the healthy stems over 15-20 cm DBH in a clump are tapped. When maple syrup producers re-tap midway through the season, the second taphole may be drilled in the previously untapped stems to make use of all the available sapwood and minimize stress on each stem. The canister experiment did not involve re-tapping midway through the season, as the seasons were relatively short.

Sugar Content

Four unique clumps were measured over the course of three seasons, for a total of eight clump-season combinations. A nested ANOVA showed that sap averages were not significantly different between seasons, but sugar content differed between clumps within each season. That is, sap sugar content was more similar within clumps than between clumps. The cause of this tendency is not clear. It is possible that sap transfers between stems, resulting in similar Brix values throughout a clump. However, stems in a clump share the same genetics, and perhaps a common pool of stored carbohydrates produced during the growing season, which could also result in similar sugar production. Additionally, the root-to-shoot ratio and other allometric properties of the stems tend to be similar as each stem has nearly identical life history and growing conditions. Sap transfer between stems would neatly explain the higher variability in sap volume with diameter for clumped stems, the similarity in sugar content between stems of the same clump, and the higher overall sap production of clumped stems. Further research including bucket collections on a mix of individual and clumped stems would be useful in determining whether the same trends suggesting sap transfer between stems are found in a system without vacuum pressure. Several studied methods of tracing sap flow within trees could be of use (e.g. Kalma et al., 1998; Goulden & Field, 1994). It could also be helpful to compare sap volume in clumped stems to the *total* basal area of each clump. Sap volume in clumped stems may be more directly related to total clump basal area than to the diameter of the tapped stem.

The analysis of sugar content between the bucket and canister collections showed no difference in volume-weighted sugar content for the 2019-2020 season. Within only the bucket trees at the "Camp" site, near the canister experiment, the mean volume-weighted Brix was higher (1.48%), but with only six trees tapped there was not enough statistical power to conclude a meaningful difference. Based on the data available from the bucket collections, it cannot be concluded that sugar content varies with under high vacuum pressure. However, it is worth noting that the bucket trees averaged just 3.3 liters of sap per tree while the canister trees averaged 16.0 liters, so any differences in sugar content are more than offset by the gain in sap volume, in terms of equivalent syrup volume.

Implications & Recommendations

Within the bulk of the diameter range of bigleaf maple trees, clumped stems appear to produce more sap than individual stems. Variation is very high between trees. On average, trees of greater diameter have greater sap flow but more variability between trees. It would be advantageous for bigleaf maple tappers to seek stands with clumped trees above 30 cm in diameter or manage their forests to produce such stands, though it is not clear if sap volumes continue to increase or decline above the studied range of diameters. Due to high variability between trees, it is recommended to note which trees produce sap most consistently, either by using buckets or in a tubing system, by noting how often each tree's spout has sap flow. In this experiment, one 13.5 cm clump tree produced more sap per season than 80% of the individual stems, and more than a 58.7 cm clump stem produced. In a standard tubing system without individual-level sap measurements this difference in production would be easy to overlook. Such measurements have the potential to save labor and equipment. Each additional tap in a tubing system is an opportunity for vacuum leaks and contamination, so it may not be beneficial to tap unproductive trees. It is also possible that low sap flow from a tree is due to tapping into damaged xylem and care should be taken to make sure no obvious reason for low sap flow is apparent.

Bucket collections were performed with 24 trees on four sites within Pack Forest in the 2019-20 tapping season. Of those, eight trees (33.3%) produced under 0.5 liters of sap for the entire season, and three (12.5%) produced no sap at all. The best producing stem was an individual tree 56.4 cm DBH which yielded 36.5 liters of 1.7 º Brix sap, which is equivalent to 1.1 liters of finished syrup. The variation in sap volume was much higher and a higher proportion of unproductive trees were found in the bucket collections than under high vacuum in the canister experiment. This indicates that nearly all living bigleaf maples will exude sap under vacuum pressure, but without vacuum pressure one in three will produce very little sap and one in eight will produce nothing. No experiment was done to collect individual-level tree sap volume data using gravity tubing, and this would be required to conclude whether gravity tubing is sufficient to induce unproductive trees to flow or whether a vacuum pump is the best option. Further research on gravity lines would be very useful in this regard.

Given that one cannot control the weather that initiates sapflow, and maple tapping location is determined by property ownership, the choice of which maple trees to tap is one of the few site-level variables landowners control. The prevailing rule of thumb is to only tap trees over 20 cm in diameter. While this study does not present a clear lower or upper diameter cutoff point, it is clear that larger trees produce more sap, as do clumped stems.

If bigleaf maple syrup production were a major forest management goal, it could be advantageous to thin existing coppiced clumps of bigleaf maple to just the largest, healthiest stems, and to release naturally regenerated seedlings. One collaborating landowner has suggested planting bigleaf maple stumps that have been removed from softwood plantations in order to grow tappable xylem faster than by planting a single seedling. Researchers at the University of Vermont's Proctor Maple Research Center have shown that 5 cm diameter clumped stems can be cut and capped under vacuum to produce modest sap yields per stem at a very high tree density per acre (Perkins & van der Berg, 2016). This approach could be used to produce sap from coppice thins or young bigleaf maple plantations.

References

Ameglio, T., Ewers, F., & Cruiziat, P. (2001). Winter stem xylem pressure in walnut trees: Effects of carbohydrates, cooling and freezing. *Tree Physiology,* (*21)*387.

Bruce, D. (2008). Production and quality of sap from bigleaf maple (*Acer macrophyllum* Marsh) on Vancouver Island, British Columbia. University of British Columbia.

Cirelli, D., Jagels, R., & Tyree, M. T. (2008). Toward an improved model of maple sap exudation: the location and role of osmotic barriers in sugar maple, butternut and white birch. *Tree physiology*, *28*(8), 1145–1155. https://doi.org/10.1093/treephys/28.8.1145

Cortes P.M, Sinclair T.R. (1985). The role of osmotic potential in spring sap flow of mature sugar maple trees (Acer saccharum Marsh.). *Journal of Experimental Botany, 36*(1), 12 – 24. https://doi.org/10.1093/jxb/36.1.12

Goulden, M. L., & Field, C.B. (1994). Three methods for monitoring the gas exchange of individual tree canopies: ventilated-chamber, sap-flow and Penman-Monteith measurements on evergreen oaks. *Functional Ecology*: 125-135.

Graf, I., Ceseri, M., & Stockie, J. M. (2015). Multiscale model of a freeze–thaw process for tree sap exudation. *Journal of The Royal Society Interface*, *12*(111), 20150665. https://doi.org/10.1098/rsif.2015.0665

Heiligmann, R., Koelling, M.R., & Perkins, T.D. (2006). Maple Sap Production—Tapping, Collection, and Storage. In: *North American Maple Syrup Producers Manual,* (pp. 81-118). (2nd ed.). Ohio State University.

Kalma, S.J., Thorburn, P.J., & Dunn, G.M. (1998). A comparison of heat pulse and deuterium tracing techniques for estimating sap flow in Eucalyptus grandis trees. *Tree Physiology, 18*(10): 697-705.

Kimmerer, R. W. (2013). Braiding sweetgrass: Indigenous wisdom, scientific knowledge and the teachings of plants (First paperback edition). Milkweed Editions.

Kraft, G. (1884). Thinning, felling rules and intense thin of stand. *Klindworth's Verlag*.

Oksanen, J. F.; Blanchet, G.; Friendly, M; Kindt, R; Legendre, P; McGlinn, D.; Minchin, .P R.; O'Hara, R. B.; Simpson, G. L; Solymos, P; Stevens, M. H. H; Szoecs, E.; Wagner, H. (2020). vegan: Community Ecology Package. R package version 2.5-7. https://CRAN.R-project.org/package=vegan

Perkins, T., & van der Berg, A. (2016). Sap Collection from Small-Diameter Trees (p. 9). University of Vermont Proctor Maple Research Center.

Peterson, E. B., Peterson, N. M., Comeau P G., & Thomas K. D. (1999). Bigleaf maple managers' handbook for British Columbia. British Columbia, Ministry of Forests Research Program.

Roy, D. (1955). Hardwood sprout measurements in northwestern California (Forest Research Notes No. 95; p. 6). USDA Forest Service, California Forest and Range Experiment Station.

Ruth, R. H., Underwood, J. C., Smith, C. E., & Yang, H. Y. (1972). Maple sirup production from bigleaf maple. USFS Research Note, Pacific Northwest Research Station, 12.

Sachs J. 1860 Quellungserscheinungen an Holzern. Bot. Zeit. 18, 253 –259.

Schenk, H. Jochen, Steven Jansen, and Teemu Hölttä. "Positive pressure in xylem and its role in hydraulic function." *New Phytologist* 230.1 (2021): 27-45.

Taylor, F. H. (1956). Variation in Sugar Content of Maple Sap (Bulletin No. 587; p. 21). University of Vermont Agricultural Experiment Station.

Tyree M. T. (1995) The mechanism of maple sap exudation. In *Tree Sap: Proceedings of the First International Symposium. on Sap Utilization,* 37 –45. Bifuka, Japan: Hokkaido University Press.

Tyree M. T, Zimmermann M.H. (2002) Xylem structure and the ascent of sap, 2nd Ed. Springer Series in Wood Science. Berlin, Germany: Springer.

Wiegand K. M. 1906 Pressure and flow of sap in wood. *American Nature, (40)*, 409 –453. https://doi.org/10.1086/ 278634)

Chapter 3: Weather and Sap Flow

Background

This chapter will discuss the role of daily weather in driving the volume of sap that can be collected from any given bigleaf maple tree. As the sap exudation process in sugar maple is driven by freeze-thaw cycles (Graf et al., 2015), clearly air temperature plays an important role and likely is critical to bigleaf maple sap flow. For any given sap run in a sugar maple, there are optimal minimum and maximum temperatures where the sap flow is highest (Rapp et al. 2019). It is not known if these temperature optima are the same for bigleaf maple. Each sugar maple sap flow event, or "run", may last one to approximately four days, with the sap flow rate peaking early and then tapering off (Heiligmann et al., 2006). Season total sap volume for any given tree is limited by the number of freeze – thaw cycles that occur, their intensity, and their timing. The more often a tree freezes completely and then thaws, the more runs can be harvested in a season. The volume of sap that flows from a tap on a given day is affected by the preceding weather as well; freezes lasting multiple days before a thaw typically resulted in the best sap runs at the partner sites in this study. Bruce (2008) found that temperature variation, quantified by the temperature difference between minimum and maximum on days when there was a freeze-thaw event, was positively and strongly correlated with sap volume at a 4-day time window ($r^2 = 0.68$).

In this study, sap volume was measured for individual trees under artificial vacuum for three winter seasons. Measurements were not taken at regular intervals due to staffing and weather constraints but were taken when sap runs were expected to be active. Sapflow is similar enough between bigleaf maples and sugar maples that it is safe to assume that sap does not flow when daily highs are above 10ºC or when temperatures stay below freezing all day. During periods below freezing it is reasonable to assume that sap cannot flow out of a frozen taphole or tubing line. Measurements were not taken outside of this range in order to prioritize employees' time. For these reasons there is a sampling bias towards collecting on colder days, but this is not expected to affect the completeness of the sap flow dataset. Additionally, several lagged weather variables were analyzed to account for the fact that each sap measurement represents sap that has flowed prior to the collection time, and possibly several days in advance.

Sap volume during a given day is affected by that day's weather and the previous days' weather (Heiligmann et al., 2006). Thus, two lagged temperature variables were synthesized to account for preceding weather conditions. The first, "freeze-thaw moving lag sum" or "FT_{sum3}", was calculated as the number of days in the previous three days where a freeze-thaw event occurred, ranging from zero to three, not including the day of collection. The second synthetic variable was the number of days since the last freeze-thaw day. Daily freeze-thaw occurrence was calculated and set to "1" where temperatures were both below and above freezing during a given day, and "0" when they were only above or only below freezing. Temperatures were collected using Thermocron iButtons installed on site.

The maple tapping season in the Eastern US and Canada lasts between four and six weeks during the freeze-thaw cycles of early spring (Heiligmann et al., 2006). Washington's bigleaf maple tapping season is much longer, spanning from December to March, though sap has been collected as early as November (Ruth et al., 1972). Whether it is beneficial to tap early or wait until midwinter depends partly on the sugar content of the sap, which varies over the course of the season. The value of sap is determined by its volume and sugar content-- a 1890-liter (500-

gallon) tank full of 2º Brix sap can be processed into 42 liters (11 gallons) of syrup, while the same tank of 0.7º Brix sap can only yield 15 liters (4 gallons). It may not be worth the time and energy to collect, concentrate, and boil sap with especially low sugar content, especially considering trees need to be re-tapped roughly every four weeks. Investing in a reverse osmosis machine may offset the lower sugar content by concentrating the sap before evaporation, and tapping could be worthwhile for an expanded season.

Bigleaf maple sap averages from 0.7º to 1.5º Brix, about half of sugar maple's 1-3º. Individual bigleaf maples may reach as high as 2.6º (Ruth et al., 1972) or as low as 0.4º (Table 2.1), but these measurements are uncommon. Ruth et al. (1972) found that bigleaf maple sap in Corvallis, Oregon started the season with a low sugar content, which averaged 0.6% Brix in December 1970, peaked in mid-January at 1.6%, and declined until late March reaching 0.6% Brix again. The canister experiment and the collaborating landowners provided a range of Brix measurements throughout three winter tapping seasons that were tracked and compared to Ruth et al.'s data.

Methods

Brix Variation Over Time

In order to visualize seasonal variation in Brix a volume-weighted Brix was calculated for each date, pooled by year, and plotted for each collection site. This metric gives the Brix reading that would result if all of the sap was pooled into one collection container and then measured. For example, if sap was collected on January 10, 2020 and January 10, 2021, the two measurements would be combined to give one January 10 measurement. The resulting dataset contained every unique day of the year where sap was collected. The range of sap collection was different for each site, and none matched the length of season obtained by Ruth et al. (1972). The three Pack Forest sites were combined because there were not enough collections at any one of them to give a full season view of sugar content variation. As the Pack Forest data was the most consistently collected, it was kept separate from the rest of the partner sites. The partner site data was combined because records of Brix were missing numerous measurements for each site.

Data Exploration

While the collaborating landowners provided sap flow data, these operations did not have the same level of consistent data collection or power of vacuum pressure as the canister experiment and their data was not used to build the weather-sap volume model. Minimum temperatures were categorized into four groups, and daily sap volume was categorized into three groups to visualize how sap volume varies by temperature. Data points were not grouped by measurement date, as above, but were kept separate at the level of tree and date. This data was used to determine the probability of picking a random tapped tree and measuring its sap volume on any date with a given minimum temperature.

Volume was binned into three categories to track the experiences of collaborating bigleaf maple tappers. A low volume of sap is more of a nuisance than an asset, as it is often not worth the energy to store or process it before it spoils. Moderate volumes can be saved for a day or two for processing, but this invites bacteria growth and reduces syrup quality. Large volumes are easier to process immediately, limiting the chance for spoilage. Larger sap runs, while obviously providing more value and quality in syrup, also require less labor per liter of finished product.

Minimum temperature was binned into four categories: below -2ºC, between -2ºC and freezing, between freezing and 2ºC, and above 2ºC. These categories were chosen to account for microsite variation in temperature. Below -2ºC, it is likely that all trees in a hobbyist-scale sugarbush (a few hundred trees) are frozen. Between -2ºC and 0ºC, most trees are likely frozen, though microsite variation in temperature may mean that some trees are not. The converse is true for daily lows between 0ºC and 2ºC, and above 2ºC.

Fifteen weather variables were originally considered in this analysis: daily precipitation (mm), T_{min} (ºC), T_{max}, T_{mean}, T_{min} moving average (1-4 days), freeze-thaw, freeze-thaw lagged sum (1-4 days), days since last freeze-thaw. An initial factor analysis was performed to explore the correlation between these variables for each day that the canister experiment was running. A biplot of the initial factors, with the aid of a correlation table, was used to identify which variables were not highly correlated. Most of the variables showed a high degree of correlation with one another and adding little explanatory power. Five variables with cross-correlation values less than 0.7 (and greater than -0.7) were retained in order to make the factors in the second factor analysis more interpretable (Figure 3.5).

Factor Analysis

A factor analysis was used to reduce the number of weather variables for subsequent use in the model of daily sap flow, and to identify correlation between weather variables. A scree plot was constructed using the Psych package in R to determine whether a principal components analysis or a factor analysis would be more effective at data reduction (Revelle, 2022). The results of the scree plot suggested a factor analysis which was performed using the maximum variance rotation ("rotation = varimax").

Weather data was downloaded from the publicly available PRISM dataset was subset into dates between December 5 and March 15 for 2018 through 2022 (PRISM Climate Group, 2022).

December 5 was chosen because it was the date of the latest first winter freeze in the dataset examined, and thus the earliest common feasible tapping date for all five years. Maple sap collection typically ends in mid-February to early March depending on the timing of tree bud break, which is a reliable indicator of reduced sap quality (Heiligmann et al., 2006). The latest occurrence of sap flow measured in this study was March 9 (2020), so a buffer was added to March 15.

Sap runs last for several hours to several days, and limited staffing prevented regularity in sap collection. Multiple measurements were taken for some sap runs, and it is not easy to distinguish the end of one run from the beginning of another when they are consecutive. A previous study of bigleaf maple sap flow and daily weather found that a variable combining the 4-day lagged sum of temperature variation and freeze-thaw occurrence correlated with 4-day summed sap volume (Bruce, 2008). The inclusion of the lagged temperature and freeze-thaw variables accounts for the fact that sap flow on any given day is determined by prior days' weather, and not just weather on the day of collection.

A factor analysis was performed to explore correlation between the explanatory weather variables and create a new set of non-correlated predictor variables. This analysis helped to show the direction of correlation between weather variables. The resulting "factors" did not provide much utility in data reduction, but they were helpful in visualizing how the explanatory weather variables related to each other and to daily sap volume. Linear regression analysis was used to determine whether variation in daily sap volume per tap could be explained by either of the two factors. The canister data was summarized by date, so that all taps were pooled for each date using the sums of sap volume and the volume-weighted mean of Brix.

Weather Model of Sap Volume

A linear model was constructed using FT_{sum3} as the explanatory weather variable to predict daily sap volume. Half of the canister data was randomly selected, without replacement, to train the linear model, and the other half of the canister data was used to test the accuracy of the model's predictions (R Core Team 2020).

Results

Brix Over Time

Plotting the results of volume-weighted Brix by day of the year shows a clear inverted U-shaped trend from early December to early March for the Ruth et al. (1971) data from Corvallis, OR, while a less pronounced curve is shown in the Pack Forest data, and no clear trend is present in the rest of the pooled partner site data (Appendix 3.2).

Data Exploration

The bulk of sap volume collections were either zero or under 1 liter (0.25 gallons) per tap per day (Figure 3.1). There were very few occasions where flow exceeded 8 liters (2 gallons) per tap per day, and the measurements above 12 liters (3 gallons) per tap per day represented collection intervals shorter than one day when sap flow was very high. A simple categorization of sap flow by minimum temperature shows that days where minimum temperature was between -2ºC and 0ºC had the best chance of high volumes of sap, with half of those days still resulting in poor flow (Figure 3.2). Days that stay above 2ºC had a low probability of yielding high sap volumes. Days with minimum temperatures between 2ºC of freezing show improved odds, with about one-quarter of days resulting in flow above 1 liter per day. Days with lows below -2ºC had the highest chance of sap volume above 1 liter per day.

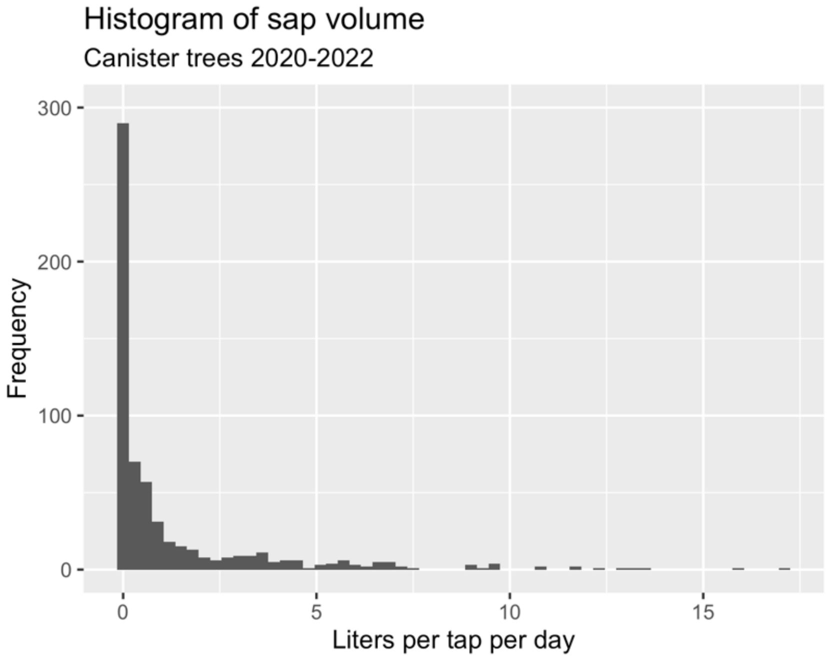


Figure 3.1. Histogram of all canister sap collection data. Each data point is a unique combination of tree number and date.

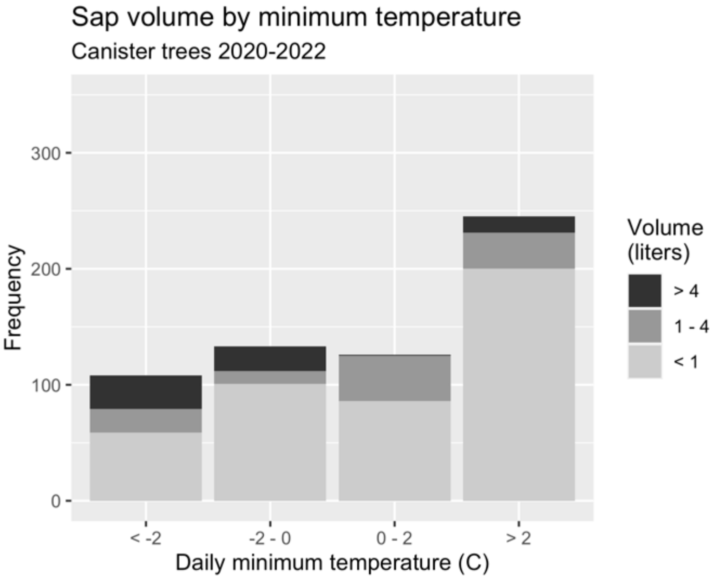


Figure 3.2. A categorization of sap flow days by minimum daily temperature from the canister experiment.

Factor Analysis

The factor analysis showed that the temperature minima, maxima, and means were highly correlated. Precipitation and the synthetic freeze-thaw index (FT_{sum3}) were not highly correlated with other weather variables or each other (Table 3.1). The proportions of explained variance, with the visual aid of a scree plot, were used to determine how many factors to include in the linear model (Figure 3.3). The first two factors explained 58% of the variance in the weather variables while reducing the number of components from five to two.

Table 3.1. Correlation between the tested weather variables.

	T_{mean}	Freeze-thaw	FT_{last}	FT_{sum3}
Freeze-thaw	-0.6331			
FT_{last}	0.3381	-0.3338		
FT_{sum3}	-0.4219	0.4171	-0.4273	
T_{diff}	0.0520	0.3513	-0.0951	0.1512

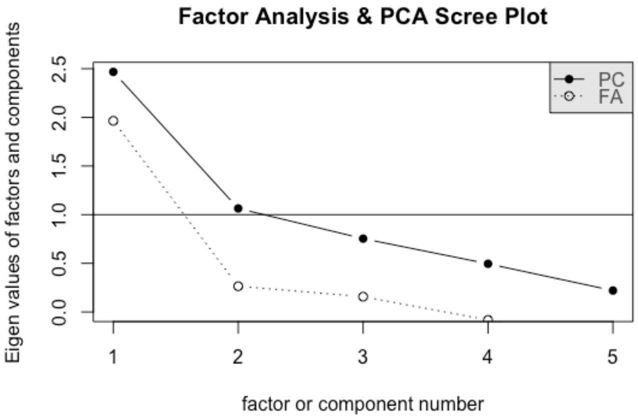


Figure 3.3. A scree plot of both the PCA and the factor analysis shows the difference in variance explained by the resulting loadings. The first two factors represent 58% of the variation in the five explanatory variables.

The results of the factor analysis are visualized in Figure 3.5, where the temperature variables are oriented in the positive direction along the x-axis. The days (dots) to the right of the x-axis had warmer daily temperatures, and those to the left were colder (more likely to include a freeze-thaw event and have recent cold weather). Sap flow events increase in frequency and intensity of sap flow as Factor 1 decreases (left side of the x-axis). Sap flow does not show any distinction along Factor 2. A linear regression analysis showed that the two factors did not significantly explain any difference in sap volume (Factor 1: $p = 0.08$; Factor 2: $p = 0.23$).

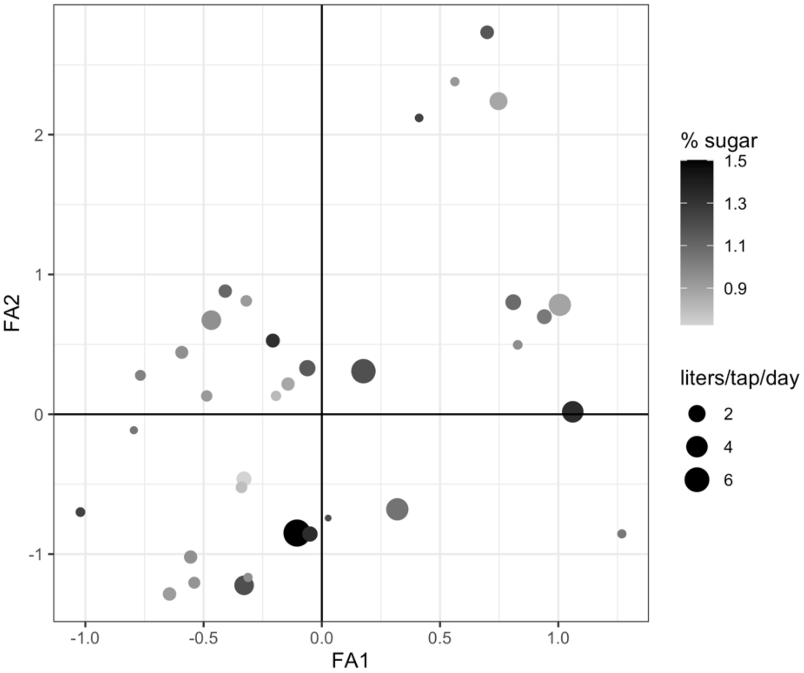


Figure 3.4. Sap volume and volume-weighted Brix totals, summarized by date, for the two weather factors from the factor analysis

Linear Regression

A categorical linear regression analysis was done to explore whether variance in daily sap volume per tap was explained by any of the five daily weather variables. Only the FT_{sum3} variable had a significant effect ($p = 0.007$; Table 3.2). An ANOVA test showed that daily sap volume varied significantly with the FT_{sum3} variable ($p = 0.0006$; Table 3.3). A Tukey's post-hoc HSD test showed that the days with three prior freeze-thaw days ($FT_{sum3} = 3$) had higher sap flow than all other days, but freeze-thaw on the day of collection had no effect on daily sap volume per tap.

Table 3.2. Linear regression results testing the daily weather variables against daily sap volume per tap at the canister site.

Predictor variable	Estimate	Std. Error	t - value	P-value
(Intercept)	0.325661	0.497046	0.655	0.51769
Temperature difference	0.001608	0.027659	0.058	0.95404
Temperature mean	-0.068319	0.064652	-1.057	0.29967
FT_{last}	0.039047	0.037874	1.031	0.31138
FT_{sum3}	0.268007	0.092170	2.908	**0.00705**
Freeze-thaw day of collection	-0.048599	0.207450	-0.234	0.81648

Table 3.3. One-way ANOVA results of the freeze-thaw variables and sap volume.

Predictor variable	Degrees of freedom	Sum of squares	F-statistic	P-value
FT_{sum3}	3	3.415	8.046	**0.000591**
Freeze-thaw day of collection	1	0.057	0.404	0.530728
FT_{sum3} : Freeze-thaw day of collection	3	0.611	1.439	0.254184
Residual	26	3.679		

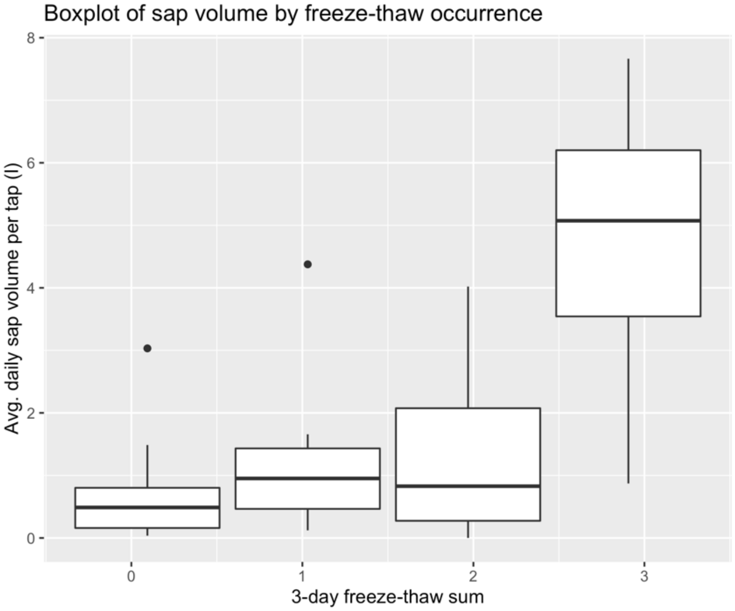


Figure 3.5. A boxplot of average daily sap volume for the tapped canister trees. The x-axis distinguishes the number of days in the 3 days prior to collection where a freeze-thaw event occurred (FT_{sum3}).

Discussion

The loadings from the factor analysis show that Factor 1 was primarily determined by daily temperature mean and freeze-thaw occurrence, and Factor 2 was determined by temperature difference (Figure 3.6). The most sap runs were recorded on days where Factor 1 was low, meaning where mean temperature was low and freeze-thaw events were likely, though the relationship was not statistically significant and variation was high (Figure 3.4). There was less distinction in sap volumes and flow occurrence along the Factor 2 axis, which was an indicator of temperature difference. Overall, there were not enough relevant explanatory variables for a factor analysis to provide much data reduction, and a simpler approach using linear regression was more effective in identifying which weather variables are significantly correlated with sap volume. In fact, the FT_{sum3} variable was the only significant predictor of sap flow (Table 3.2). This variable was used in Chapter 4 to model potential sap flow by region.

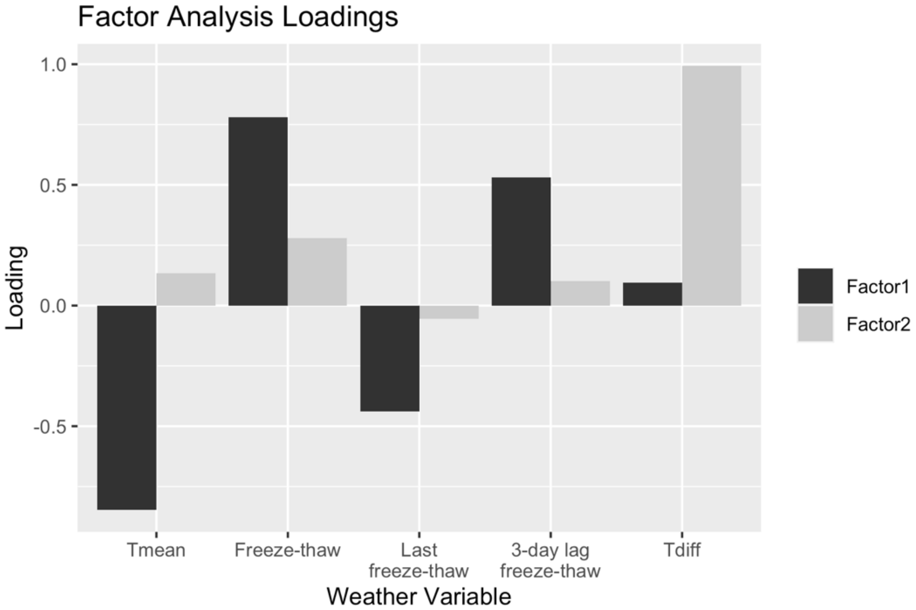


Figure 3.6. The factor analysis loadings. Factor 1 was primarily determined by mean temperature (T_{mean}) in the negative direction and freeze-thaw event in the positive direction, such that a high Factor 1 value indicates a low mean temperature and a high probability of a freeze-thaw event. Factor 2 was positively determined by temperature difference (T_{diff}).

The FT_{sum3} variable was significantly and positively associated with sap volume. This thesis comes to a similar conclusion as Bruce's (2008) analysis of a 4-day-scale temperature and sap volume model. The present analysis confirms a relationship between temperature fluctuations around freezing and sap flow occurrence and volume in bigleaf maple, but the result leaves the timing uncertain. Sap was collected at irregular intervals, and sometimes three or more days passed in between collections. Each collection was the sum of all sap flow since the last collection, so it follows that the lagged freeze-thaw variable is the main predictor of sap flow for this dataset while the day-of-collection freeze-thaw had no effect. The fact that three days was the most significant time window found here may reflect the timing of sap collection. Additionally, freeze-thaw days were not necessarily warm enough to initiate sap flow. Western Washington is cloudy during the winter, and measured air temperatures of 1ºC may not mean that every tree thawed completely without direct sunlight; this might be common on north facing aspects. Heiligmann et al. (2006) notes that temperatures slightly above freezing may not be enough to thaw the tap holes after particularly cold weather. If future research includes consistent, daily measurements using the canister method, it is expected that freeze-thaw events on the day of collection and the day prior will emerge as the most significant predictors.

The FT_{sum3} variable was an effective predictor of seasonal sap volume, though its temporal specificity was limited by the consistency of data collection. There was high variation in predictive accuracy between seasons, likely because there were only 11, 9, and 14 different sap collection days for the 2020, 2021, and 2022 seasons, respectively. Thus, the linear model of sap volume was only trained on half of those days, or just 5 days for 2021. Variation in model predictions can be reduced by using it primarily for multi-year volume predictions or for combining multiple site predictions into a larger spatial unit of interest. Both of these actions were taken when applying the model to statewide sap volume predictions for Washington.

Ruth el al.'s 1971 study found a peak in sugar content around the 18th of January during the 1970-71 winter, with weaker sap during the early and late season (Ruth et al., 1971). The data from Pack Forest partially support this trend, though with a much weaker relationship (Appendix 3.2). This could be because the Pack Forest data includes collections from three sites: the canisters (lower elevation), and two adjacent higher-elevation sites, one with a diaphragm vacuum pump and 3/16" tubing and one relying on only natural gravity vacuum with 3/16" tubing. The canister site was approximately 4 km from the higher-elevation sites, and thus experienced slightly warmer weather. The difference in weather patterns likely meant that each site's sugar content curve was slightly different, and when combined resulted in a weak pattern with noise (Appendix 3.2). There was even higher variation in weather patterns between the partner sites, which were spread out across Western Washington (Figure 1.4). The partner site Brix data shows no trend over the season. For a more complete picture of bigleaf maple sap Brix variation over the tapping season in Washington, it will be necessary to take sap measurements more frequently and consistently. Further data collection would also allow for a more complete comparison of sap flow timing between 1970 and today. More long-term data collection could give insight into how climate change is affecting Washington's tapping season, though with little historical data a baseline would be difficult to establish. Hobbyist sugar-makers could help in this task by keeping records of their Brix measurements over each season.

Implications & Recommendations

The relationship between daily weather and sap flow can help prospective maple tappers find the best climate to establish their sugarbush, and can assist current maple tappers in manipulating the layout of their sugarbush to maximize sap flow.

Pack Forest, the location of the canister experiment, does not experience particularly cold weather during the winter compared to other parts of Washington that contain bigleaf maples. At Pack Forest and all of the partner sites, sap flow was generally limited by the occurrence of cold weather. While sap flow tended to be better on colder days, there appears to be a lower ideal temperature limit. Sap volumes were lower on days with the very coldest temperature minima compared to days with lows within 2ºC of freezing (Figure 3.3). As sap flow events are more likely to occur and be larger when temperatures have fluctuated around freezing for several days, the ideal bigleaf maple sugarbush would have as many days above freezing and as many nights slightly below freezing as possible.

If a sugarbush has already been chosen, sugar-makers can take steps to optimize sap flow without having to relocate to the ideal climate. In the Northern Hemisphere, the south side of a tree heats up more quickly than the shaded side (Reid et al., 2020). In locations with below-freezing temperature averages during the tapping season, it would be sensible to tap the warmer south side of the tree to increase the number of freeze-thaw cycles. In warmer locations, the opposite is true. Hillside aspect would also have the same effect, with northern slopes staying cooler during the day. In the Eastern US, a generally continuous snowpack throughout the season insulates the soil and ensures that the ground stays near freezing. Maple tappers in the Pacific Northwest have to contend with warmer and more variable temperatures during tapping season.

In climates that have only borderline sap flow potential, the choice of microsite and tapping aspect could facilitate more sap runs per season.

Other factors not explored in this study likely also affect how much sap a given tree will produce. Landowner anecdotes suggest that bigleaf maples in riparian areas produce more sap than those on slopes or ridges, which may be due to differences in soil moisture availability. In Washington, the temperate climate seems to limit the number of sap flow events per winter season, especially in coastal areas. However, even coastal locations have had success using vacuum pumps. As many hobbyist sugar-makers already record sap volume, Brix, and weather, there is great potential in using citizen science to create a far more thorough dataset of bigleaf maple sap flow in Washington. Standardizing and sharing this data would give a more precise understanding of sap flow trends and allow sugar-makers to make the most informed decisions possible. It is important to note that on partner sit near Forks produced almost no sap on a gravity system and was decommissioned after two seasons. Appendix 3.1 contains a sample sap collection data sheet.

References

Bruce, D. (2008). Production and quality of sap from bigleaf maple (*Acer macrophyllum* Marsh) on Vancouver Island, British Columbia. University of British Columbia.

Graf, I., Ceseri, M., & Stockie, J. M. (2015). Multiscale model of a freeze–thaw process for tree sap exudation. *Journal of The Royal Society Interface*, *12*(111), 20150665. https://doi.org/10.1098/rsif.2015.066.

Heiligmann, R., Koelling, M.R., & Perkins, T.D. (2006). Maple Sap Production—Tapping, Collection, and Storage. In: *North American Maple Syrup Producers Manual,* (pp. 81-118). (2nd ed.). Ohio State University.

PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu, data created 20 March 2022, accessed 1 April 2022.

Rapp, J. M., Lutz, D. A., Huish, R. D., Dufour, B., Ahmed, S., Morelli, T. L., & Stinson, K. A. (2019). Finding the sweet spot: Shifting optimal climate for maple syrup production in North America. *Forest Ecology and Management*, *448*, 187–197. https://doi.org/10.1016/j.foreco.2019.05.045

Revelle, W. (2022) psych: Procedures for Personality and Psychological Research, Northwestern University, Evanston, Illinois, USA, https://CRAN.R-project.org/package=psych Version = 2.2.3.

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Reid, S., Driller, T., & Watson, M. (2020). A two-dimensional heat transfer model for predicting freeze-thaw events in sugar maple trees. *Agricultural and Forest Meteorology*, *294*, 108139. https://doi.org/10.1016/j.agrformet.2020.108139

Ruth, R. H., Underwood, J. C., Smith, C. E., & Yang, H. Y. (1972). Maple sirup production from bigleaf maple. *USFS Research Note, Pacific Northwest Research Station*, 12.

Chapter 4: Modeling Bigleaf Maple Sap Flow in Washington

Background

Many factors influence the profitability of a maple sugaring operation. Sap volume and Brix are obviously important, but labor costs, familiarity with installing lateral lines, topography, availability of processing equipment, and access to market also affect one's bottom line. This study was limited to exploring sap flow in bigleaf maple trees and did not examine processing or sales. There is no guarantee that a forest with high potential sap flow will be profitable to tap, but all else being equal, an accessible, dense stand of tappable bigleaf maple stems in a favorable climate would be the best place to start.

This chapter builds on relationships between daily weather and sap flow analyzed in Chapter 3, and here a linear model is used to predict seasonal bigleaf maple sap volume in Western Washington using daily weather data. Several assumptions were made regarding the length of tapping season, percentage of all potential taps that are utilized, average sugar content, ratio of sap harvested to syrup produced, and price of syrup. In each case conservative assumptions were used in order to accommodate the fact that most potential commercial producers in Washington will be coming from the hobbyist scale, and as a result will tend to achieve less than the maximum potential sap volume. The conservative assumptions result in estimates of sap volume that I assume will more closely match actual revenue for each sugar-maker. The results presented here offer greater specificity to the NRSIG potential tapping sites in terms of seasonal potential sap production (NRSIG, 2021).

The relationships between diameter, growth form, and sap volume from Chapter 2 were not included in sap volume predictions, as the diameter distribution of potential taps from the

NRSIG dataset was not known. Typically no more than two taps per maple stem are used, even for the largest stems (Heiligmann et al., 2006). However, the NRSIG study defined one tappable stem as being 20-38 cm DBH, and each additional 13 cm over 38 cm was assigned another tap. This may have resulted in an overestimation of the number of taps on the landscape. The Forest Inventory and Analysis (FIA) data collection procedures stipulate that each stem of a multi-stemmed clump that splits below 1.4m (4.5ft) off the ground is measured as a separate stem (US Forest Service, 2021). Trees are generally tapped at comfortable working height, between 1 and 1.5m, so the number of stems indicated in the FIA should match closely with the number of actual tappable stems. Bigleaf maples commonly have multiple stems or are grown from coppice stumps: two of the partner sites had over 90% of their taps on clumped stems (Table 5.1).

Methods

In the previous chapter, several different explanatory weather variables were tested for the strength of their relationship to daily sap volumes within the canister experiment at Pack Forest. A linear model of bigleaf maple sap volume per tap per season using the 3-day freeze-thaw lagged sum (FT_{sum3}) variable as the sole predictor was constructed. This model was tested against a randomly selected half of the available canister data and was found to predict three-year total sap volume within 6% of measured values. Seasonal predictions were more variable (between -9% and +65%), so in order to estimate potential sap flow per acre on the statewide scale ten seasons of sap flow were predicted and then averaged.

The model was applied to Washington state on the scale of $4km^2$ pixels, which was the spatial unit of the statewide weather data (PRISM Climate Group, 2022). Data collection in the canister experiment spanned January 28 to March 4, with sap quality and quantity tending to decline for the last week of collection. Ten seasons of winter weather data from January 1 to March 1 were downloaded for 2010 – 2020. The dataset was modified to include three day lagged freeze-thaw sum for each measurement date and pixel. The “terra” package in R was used for raster manipulation (Hijmans, 2022). The linear model was used to predict seasonal sap volume per tap for every 4km^2 pixel for each of the ten years.

The NRSIG dataset includes 19,000 1.6-hectare (4-acre) sites where at least 123 taps per hectare (50 taps per acre) and 250 total taps are predicted to be present. On each 1.6-ha site, the tapping density averages at least 156 taps per hectare. Farrell’s (2013) classification used 74 taps/ha as a lower cutoff for “feasible” tap density, and 147 taps/ha as the “optimal” cutoff. Sites identified in this study were not categorized further by tap density, as the 156 taps/ha threshold exceeded Farrell’s optimal tap density. Farrell’s classification distinguished potential sites less than 0.8 km to the nearest road as being optimal and less than 1.6 km being feasible. Of all non-industrial private forest (NIPF) potential tapping sites identified by the NRSIG, only 0.2% were more than 0.8 km from the nearest road. Thus, the sites were not further categorized by distance to road, as mainlines make it straightforward and typically not cost-prohibitive to transport sap at a 2% grade for 0.8 km. Sap lifters can be used on flat sections of mainline with a generator or battery station. Tapping sites were distinguished by access to electricity, for which the Washington State Forestland Database’s land use development code was a proxy (NRSIG 2021).

The number of taps at each site was multiplied by the ten-year average sap predictions to give an estimate of potential sap production at each 1.6-hectare site. The predictions were compiled by calculating the mean ten-year sap volume per tap per Watershed Administrative Unit (WAU), and by calculating the standard deviation of ten-year sap volumes per WAU. The resulting map was clipped to exclude visible surface water using data from the Washington

Geospatial Open Data Portal (WA Department of Fish and Wildlife, 2022). The potential sites were distinguished by private, federal, state, municipal, and tribal land ownership. Further classifications were made within privately-owned land, following the classification scheme presented by Rabotyagov et al. (2021). NIPF is owned by private owners of at least two acres, of which one acre must be forest cover. Other large private landowners including real estate and ranchers are listed as “Other”. Privately owned conservation land, real estate property, utility-owned land, and protected watershed areas were also identified.

Summary statistics were calculated by first converting potential sap volume to potential syrup assuming an average Brix of 1%. The conversion ratio of sap to syrup at Pack Forest in 2020 was 107:1, which is poorer than expected but representative of hobbyist / small-scale commercial operations (see Chapter 5 for detail). Summary statistics were reported for the entire set of predictions by ownership class for three different utilization rates of tappable maple trees (Farrell 2013).

On average, 0.39% of all red and sugar maples in the Eastern United States are tapped for their sap. Vermont taps 2.59% of their red and sugar maples, and in the Midwest the lower end of utilization is at 0.15% (Farrell, 2013). Farrell distinguished four categories of potential sugarbushes in which the most optimal sugarbush contains over 147 taps per hectare within 0.8 km of a road and on private land. Vermont utilizes 27.0% of all potential sugar and red maple taps in this category, while Connecticut’s utilization rate is 0.9%. The average utilization rate for that category of sugarbush for the ten states reported was 5.1%. These utilization rates were used to estimate statewide syrup production using the low, average, and high rates described above.

The daily weather and sap volume linear model was formulated as:

$$Sap\ volume\ (l) = 0.5227 + 0.8620 * FT_{sum3}$$

where FT_{sum3} is the integer sum of the number of days in the past three days where a freeze-thaw event occurred, excluding the day of collection and beginning on the previous day (i.e. temperatures were both <0º C and >0º C on that day). Several adjustments were made to the daily weather model predictions of sap volume to reflect observations from the canister experiment and from the collaborating sugar-makers. The canister dataset had relatively few days below freezing compared to partner sites, and it was observed at many sites that sap does not flow when temperatures are below freezing. Thus, days that stayed below freezing ($T_{max} < 0$) were assigned zero sap flow. Additionally, days where maximum temperature did not exceed 2ºC and minimum temperature was under -2ºC were assigned zero sap flow. These days typically did not thaw sufficiently for sap to flow at the partner sites.

Lastly, of the twenty-one trees tapped in the canister experiment, one was dead and did not flow. It was assumed that similar odds of tapping unproductive or dead trees would apply to larger scales, and a 4.7% reduction (1 in 21) was applied to the sap volume outputs before mapping.

Results

The majority of 1.6-ha sites fell on private land, while state, municipal, federal, and tribal land accounted for 38% of all identified sites. Only 1% of the 19,514 potential sites fell on tribal land. Of the privately-owned sites, 78% of them fell on non-industrial private forest (NIPF) land. Slightly less than half of the NIPF sites identified have electricity available (Figure 4.1).

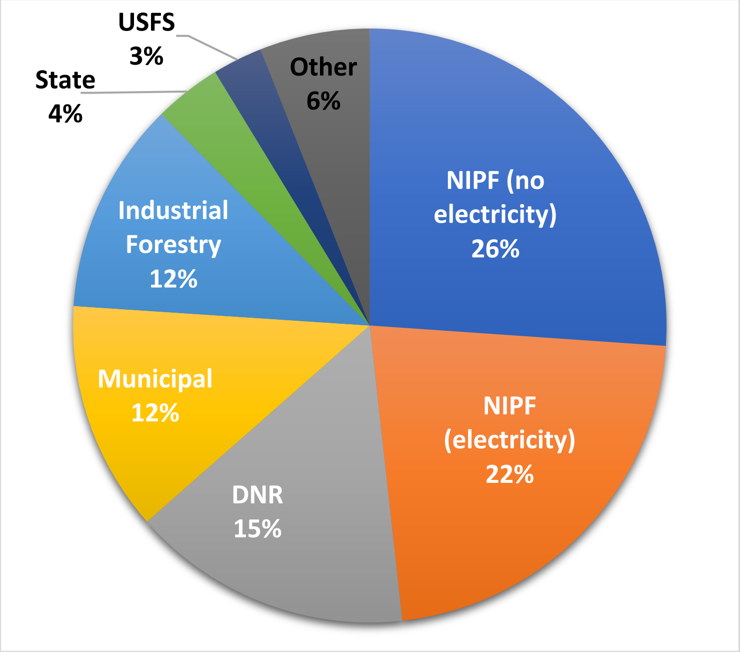


Figure 4.4.1. Proportion of potential tapping sites by ownership class.

The range of predicted seasonal sap per tap at 4 km^2 pixel in Western Washington spans from zero, along the coasts and on high mountain peaks, to more than 150 liters (Appendix 4.1). Several regions with high tap densities and predicted sap flow above 100 liters per season were identified, including on the eastern coast of the Olympic Peninsula, the Skagit Valley, and between Arlington and Mt. Vernon. Non-industrial private forest lands accounted for the majority of potential bigleaf maple tapping sites, and potential syrup production for January and February combined was estimated to be over 400 million liters at NIPF sites.

Table 4.4.1: Conservative summary statistics for potential bigleaf maple syrup value in WA, categorized by ownership class.

Ownership Class	Total area (ha)	Syrup (High) (liters)	Syrup (Mid) (liters)	Syrup (Low) (liters)	Value (High) 1000's USD	Value (Mid) 1000's USD	Value (Low) 1000's USD
NIPF (total non-tribal)	**36,676**	**783,480**	**147,991**	**26,116**	**$62,098.80**	**$11,729.77**	**$2,069.96**
NIPF (electricity)	**16,840**	**350,785**	**66,259**	**11,693**	**$27,803.34**	**$5,251.74**	**$926.78**
NIPF (no electricity)	**19,836**	**432,694**	**81,731**	**14,423**	**$34,295.46**	**$6,478.03**	**$1,143.18**
DNR	11,604	272,026	51,383	9,068	$21,560.83	$4,072.60	$718.69
Municipal	9,528	212,460	40,131	7,082	$16,839.62	$3,180.82	$561.32
Industrial Forestry	8,788	198,434	37,482	6,614	$15,727.92	$2,970.83	$524.26
State	2,788	61,477	11,612	2,049	$4,872.65	$920.39	$162.42
USFS	2,072	46,604	8,803	1,553	$3,693.81	$697.72	$123.13
Federal	1,992	45,234	8,544	1,508	$3,585.26	$677.22	$119.51
Watershed Protection (Municipal)	1,920	39,356	7,434	1,312	$3,119.38	$589.22	$103.98
Private Conservation	640	15,109	2,854	504	$1,197.55	$226.20	$39.92
NIPF (Tribal)	632	12,411	2,344	414	$983.73	$185.82	$32.79
Real Estate	444	9,559	1,806	319	$757.66	$143.11	$25.26
Private (Other)	420	10,066	1,901	336	$797.86	$150.71	$26.60
Forestry (Tribal)	300	6,544	1,236	218	$518.70	$97.98	$17.29
Utility (Private)	204	4,624	873	154	$366.47	$69.22	$12.22

Notes: "NIPF" stands for non-industrial private forest. Upper, average, and lower tap utilization scenarios (27%, 5.1%, and 0.9%, respectively) are shown. Syrup equivalent was calculated assuming a conversion ratio of 107 liters of sap to 1 liter of 66.5° Brix syrup. Prices were calculating assuming retail value of $79 per liter ($300 / gal), or roughly three-quarters of 2022 retail prices.

Discussion

Potential bigleaf maple syrup production at just the NIPF sites with electricity equates to \$926,000 to \$27.8 million USD annually, depending on the tap utilization rate (Table 4.1). For context, Washington farmers produced \$3 million worth of apricots in 2021 and \$22 million worth of pumpkins (USDA, 2022). Calculations of syrup value are limited by the fact that bigleaf maple syrup is in such high demand and short supply that no accepted bulk prices exist, as they do for sugar maple syrup. As the industry grows, prices are expected to fall. Neil's Bigleaf (operated in Acme, WA) consistently sells out of their syrup, even at retail prices of over \$106 / liter (\$400 / gallon). A price of \$79 per liter (\$300/gal) was used to reflect that the price should fall once enough product reaches the market, and if a bulk price is established in the coming years then statewide production potential value should be recalculated. The calculations of syrup value do not include bottling, sales, marketing, or any other cost to get finished syrup to market.

Sites without electricity can still be tapped if one relies on a mobile sap processing station, like those operated by UW and Oregon State University. Sap can be transported from sites without electricity in insulated steel dairy tanks, though road improvements and other investments may make the transport of unconcentrated sap cost prohibitive at distances over a few kilometers. Of all NIPF potential tapping sites identified by the NRSIG, only 0.2% were more than 0.8 km from the nearest road. Road access makes it easier to move supplies, install heavy equipment, transport sap or its concentrate, and maintain tubing systems frequently. While sap can be transported a kilometer or more using mainline tubing, sap lifters, and other equipment common in the East, it is much cheaper to minimize the distance between the sugarbush, the collection tank, and the processing facility.

The modelled predictions portray an optimistic potential for bigleaf maple sugaring in Western Washington, but it must be noted that the model was trained using data from a sugarbush that was not completely representative of typical sugaring operations at the 100-500 tree scale. The canister experiment included a maximum of only twenty tapped trees at a time, so special attention was given to ensure that every fitting, connection, and tap was installed correctly. In larger operations it is harder to detect leaks and clogged lines, which reduces one's sap harvest. A high-powered vacuum ran continuously throughout the canister experiment, though Neil's Bigleaf Maple, in Acme, is the only operation in Washington known to use a high-powered vacuum system.

An important difference between maple sugaring in Eastern North America and in the Pacific Northwest is the milder winters of the latter region. Collaborating landowners have speculated that in the absence of hard freezes lasting multiple weeks, as is the norm in the Eastern US and Canada, sap could potentially be harvested for a much longer period. The model was only run for a January 1 to March 1 tapping season scenario, and it is not clear whether the model would predict sap volumes with equal precision for the months of November and December. Tapping earlier could result in lower sugar content (Appendix 3.2) and may only be a worthwhile use of fuel and labor if one uses an efficient evaporator and reverse osmosis machine.

Winters in Western Washington are expected to grow warmer in the coming years (EPA 2016). The outputs of this model would be useful in determining which bigleaf maple sugarbushes are in marginal climates and may risk a decline in sap production. High-powered vacuum pumps may be able to extract sap in sufficient quantities to boil even when temperatures remain above freezing, which would be useful in marginal climates with a high density of tappable stems. However, there is no lack of potential sites in colder regions and if one has the ability to choose one's tapping location, Appendices 4.1 through 4.5 could provide some guidance. Leasing access to bigleaf maples from landowners in optimal sites would allow those in marginal sites to still participate in sugaring, though either sap would need to be transported or a mobile sap processing station would have to be used. Leasing taps from nearby landowners is especially appropriate for sugar-makers looking to increase their sap harvest but who have no more trees to tap.

Bigleaf maple tapping is still in its early stages, and Washington's syrup industry will not realistically approach that of Vermont in the near future. Syrup volume and value projections were calculated to illustrate the availability of tappable bigleaf maples in favorable climates in Washington rather than to provide projections of future production. The distance in sap yields per tap between a hobbyist sugarbush and the high-vacuum canister experiment can be narrowed through experience and attention to detail, but it is unlikely that a novice sugar-maker will achieve the sap yields shown here without substantial investment in time and equipment. Fortunately, even with a fraction of the sap volumes predicted here it is still possible to produce quality bigleaf maple syrup without investing in a vacuum pump. Chapter 5 explores the effectiveness of gravity-driven systems and vacuum-pump systems and compares modeled sap harvests to measured sap harvests at eight different partner sites in Western Washington.

References

EPA. (2016). What climate change means for Washington (No. 430-F-16–049; p. 2). United States Environmental Protection Agency

Farrell, M. L. (2013). Assessing the growth potential of the maple syrup industry in the United States: A multi-disciplinary approach based on ecologic, socio-economic, and public policy factors. Cornell University.

Heiligmann, R., Koelling, M.R., & Perkins, T.D. (2006). Maple Sap Production—Tapping, Collection, and Storage. In: *North American Maple Syrup Producers Manual,* (pp. 81-118). (2nd ed.). Ohio State University.

Hijmans. R.W. (2022). terra: Spatial Data Analysis. R package version 1.5-17. https://CRAN.R-project.org/package=terra.

Natural Resource Spatial Informatics Group. (2021). Identifying Potential Sites for Big Leaf Maple Syrup Production. University of Washington, Precision Forestry Cooperative.

PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu, data created 20 March 2022, accessed 1 April 2022.

Rabotyagov, S., Rogers, L., Danley, B., Comnick, J., Cooke, A., Chowdhury, P. K. R., & Diaz, D. (2021). Washington's Small Forest Landowners in 2020. Status, trends, and recommendations after 20 years of Forests & Fish. p. 384. University of Washington School of Environmental and Forest Sciences.

Thompson, Robert S.; Anderson, Katherine H.; Bartlein, Patrick J. 1999. Digital representations of tree species range maps from "Atlas of United States trees" by Elbert L. Little, Jr. (and other publications), [Online]. In: Atlas of relations between climatic parameters and distributions of important trees and shrubs in North America--GIS files of tree species range maps. U.S. Geological Survey Professional Paper 1650 A&B. Reston, VA: U.S. Geological Survey, Geology and Environmental Change Science Center, Earth Surface Processes (Producer). Available: http://esp.cr.usgs.gov/data/atlas/little/ [2011, June 8]. [82831]

USDA. (2022). *2021 Washington State Agriculture Overview*. National Agricultural Statistics Service. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=WASHINGTON

US Forest Service. (2021). *Field instructions for the annual inventory of California, Oregon, and Washington*, pp. 189-190. US Department of Agriculture.

Washington Department of Fish and Wildlife (2022). Visible Surface Water GIS Feature Layer. https://geo.wa.gov/datasets/wdfw::visible-surface-water/about

Chapter 5: Partner sites

Background

The maple tapping season in the Eastern US and Canada lasts between four and six weeks during the freeze-thaw cycles of early spring (Heiligmann et al., 2006b). Washington's bigleaf maple tapping season is much longer, spanning from December to March, though sap has been collected as early as November. Whether it is beneficial to tap early or wait until midwinter depends partly on the sugar content of the sap, which varies over the course of the season (Ruth et al. 1972; Appendix 5.1). The sugar content of bigleaf maple sap generally ranges from 0.7% to 2.0%, with some outliers, and sugar content dictates how much energy is required to concentrate sap into a final product. It may not be worth the time and energy to collect, concentrate, and boil sap with especially low sugar content, particularly considering trees need to be re-tapped roughly every four weeks. Investing in a reverse osmosis machine may offset the lower sugar content of early- and late-season sap by concentrating the sap before evaporation, thus expanding the tapping season.

Vacuum Pumps

Gravity-driven sap collection systems are a convenient method of sap collection that lies between bucket collection and vacuum pumps in terms of both investment and sap production. In a gravity system, sap flows through the tubing downhill to a collection tank, relying on the natural slope of the sugarbush. As sap flows downhill through the airtight system, it exerts vacuum pressure on the line above it which draws more sap from the uphill taps. This system requires a slope sufficient for the sap to reach its collection point and pull adequate vacuum pressure. Using a vacuum pump to pull sap from the trees can increase yields, but there is some question regarding whether pumps make economic sense where a gravity-driven system could also be used. The pumps are useful in pulling sap from trees on flat ground towards a collection point where slope is insufficient for sap to flow downhill. Vacuum pumps extend the range of possible tapping locations, but it is not yet clear whether they increase sap yields by enough to make the investment worthwhile. There is also some worry of vacuum pumps diluting the sap by drawing more groundwater through the trees' roots, though Smith and Gibbs (1970) found no difference in sugar content between sap from vacuum and gravity stems.

In order to assess differences between vacuum pump systems and gravity systems, data from the collaborating landowners was adjusted to liters of sap per unit basal area per day. Every tapped tree was measured at Murphy, EBR, Quilcene, Pe Ell, Lacey (2020-21 season only), and the canister site, and total tapped basal area was calculated for each collection point. However, the inconsistencies in vacuum pump use meant that a paired comparison would not be statistically sound and no formal analysis was possible.

Model Comparison

While the model described in Chapter 4 shows the higher range of attainable sap harvests across Washington, nearly all bigleaf maple sugaring operations in the state are using smaller diaphragm vacuum pumps or no vacuum pumps at all. Most sites also do not have the level of quality control in tapping and connections as the canister site. Comparing modeled sap volumes to actual collections at the partner sites illustrates the difference that experience and investment can make in a bigleaf maple sugaring operation, and it gives some perspective that is useful in interpreting the statewide economic potential and evaluating one's prospects in maple tapping.

Methods

Within-Site Temperature Variation

Temperatures were collected using H2O Innovations Smartrek vacuum sensors and Thermocron iButtons installed at each of the partner sites. Where the collected temperatures did not span the entire range of the tapping season, daily PRISM data was used instead such that each site's temperature data was from one consistent source for each season. Temperature readings from different sensors installed at the same sites were compared to determine the level of temperature variation present at the spatial scale of the sugarbush.

Model Comparison and Adjustments

The model described in Chapter 4 was run using the weather data for the duration of each of the partner sites' tapping seasons, and the results were compared to the actual volumes of sap collected at those sites. Bucket collections were performed with 24 trees on four sites within Pack Forest in the 2019-20 tapping season. Of those, eight trees (33.3%) produced under 0.5 liters of sap for the entire season, and three (12.5%) produced no sap at all. The best producing stem was an individual tree 56.4 cm DBH which yielded 36.5 liters of 1.7º Brix sap. While no partner site used bucket collection and gravity tubing is known to increase yields substantially, it was assumed that a similar ratio of unproductive trees would be found at each site as were found in the bucket collections at Pack Forest. Thus, a 12.5% reduction in projected sap volume was applied to each site that did not use a vacuum pump. A 4.8% reduction was applied to sites that did use vacuum pumps, as only 1 in 21 tapped trees in the canister experiment did not produce sap. These reductions were informed by a limited number of tapping observations, and future sap measurements would give greater specificity to these adjustments.

Results

Partner Sites

Seasonal sap collection at the eight collaborator sites ranged from 7 to 124 liters per tap (Table 5.1). Sugar content was also variable, ranging from 0.75º to 1.26º Brix. The timing of tapping varied by site and season due to differences in weather, and collection periods ranged from 9 to 111 days. Average sap collected per day that taps were installed was 0.6 liters, with a low of 0.15 liters (Pack Forest gravity 2021) and a high of 2.2 liters (Quilcene gravity 2022). A full tree inventory of each site was not possible, so some tap counts were reported by the landowners and there may be some associated error.

There was substantial variation in minimum and maximum temperatures found at the level of each individual sugarbush (Figure 5.1). Daily differences in minimum temperature averaged 0.47ºC within all sites with a maximum of 4ºC. Temperature measurements that were available for multiple points within each site and spanned the entirety of the tapping season are shown in Figure 5.

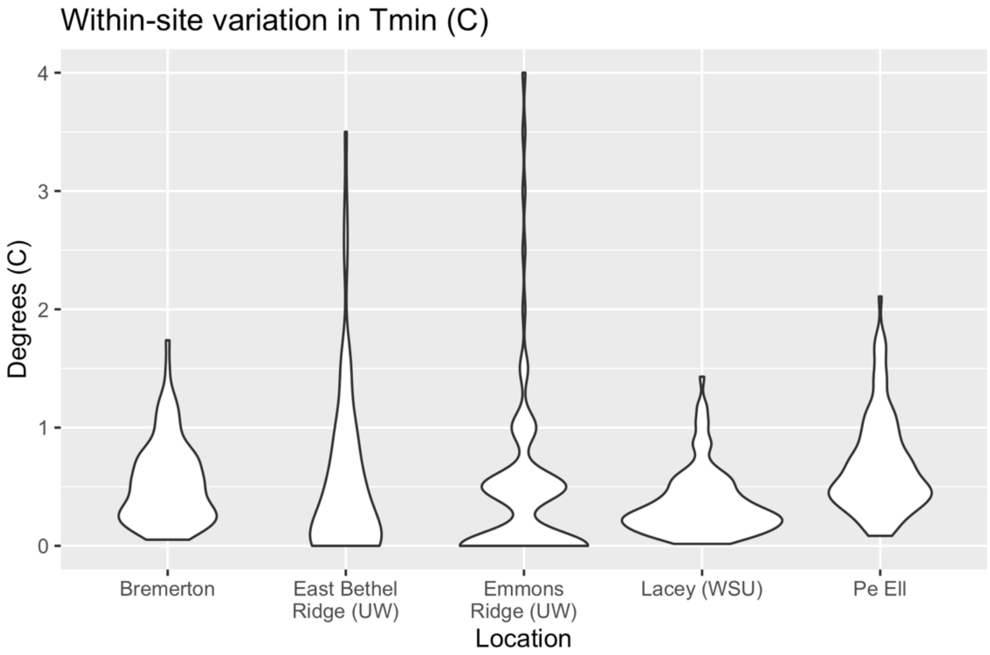


Figure 5.1. A violin plot of the differences in daily minimum temperature (C) recorded by multiple sensors within five partner sap collection sites with complete on-site records.

Table 5.1: Partner site summaries by season

			2020				*2021*				*2022*			
Site name	**Vacuum**	**% clumps**	**Taps**	**Sap (liters)**	**L / tap**	**Brix**	**Taps**	**Sap (liters)**	**L / tap**	**Brix**	**Taps**	**Sap (liters)**	**L / tap**	**Brix**
Pack Forest (UW)	Gravity	54%	410	4921	12.0	NA	410	2986	7.27	1.02	410	2839	6.93	1.05
Pack Forest (UW)	Low-power pump	60%	330	7369	22.3	1.23	330	3032	9.20	0.93	330	2638	7.99	0.89
Lacey (WSU)	Gravity	97%	-	-	-	-	150	1616	10.8	0.96	-	-	-	-
Lacey (WSU)*	Low-power pump		-	-	-	-	-	-	-	-	264	8668	32.8	1
Bremerton*	Gravity	-	-	-	-	-	300	3702	12.3	1.26	-	-	-	-
Pe Ell	Low-power pump	87%	-	-	-	-	175	2725	15.6	1	175	2877	16.4	1
Pe Ell	Gravity	77%	-	-	-	-	78	1669	21.4	0.75	98	1582	16.2	1
Quilcene	Low-power pump	83%	-	-	-	-	198	5734	29.0	0.84	-	-	-	-
Quilcene	Gravity	100%	-	-	-	-	200	6809	34.1	0.83	74	1942	25.9	1
Sultan*	Gravity	-	-	-	-	-	-	-	-	-	444	-	23.5	NA
Forks*	Gravity	-	-	-	-	-		Trace	Trace	NA		Trace	Trace	NA
Acme*	Hi-power pump	-	700	32267	124.0	1.03	700	25295	136.8	-	-	-	-	-

Notes: Asterisks indicate sites with landowner-reported tap counts that were not surveyed by the author. Sites listed twice have separate collection points or seasons for vacuum pump systems and gravity systems. At Forks, sap volume was not reported in detail.

Model Predictions

The model overestimated average sap volume per tap across partner sites by an average of 38% in 2020, 204% in 2021, and 254% in 2022. Model predictions averaged 14% higher than recorded for Acme, which was the only site with a high-powered vacuum pump. Predictions averaged 208% higher for sites with low-powered vacuum pumps, and 224% higher for sites not using vacuum pumps (Table 5.2).

Table 5.2: Modelled and observed sap volume at eight partner sites.

Year	Site	Vacuum	Observed liters/tap	Predicted liters/tap	% Difference
2020	Acme*	High	124.0	147.9	+19.3
	Pack Forest	Gravity	12.0	21.8	+81.7
	Pack Forest	Low	22.3	24.9	+11.5
2021	Acme*	High	136.8	147.9	+8.1
	Bremerton*	Gravity	12.3	54.7	+345.0
	Lacey	Gravity	10.8	40.9	+279.2
	Pack Forest	Gravity	7.3	37.3	+411.9
	Pack Forest	Low	9.2	42.8	+365.7
	Pe Ell	Gravity	34.8	53.4	+53.4
	Pe Ell	Low	15.6	61.9	+297.3
	Quilcene	Gravity	34.0	42.2	+24.1
	Quilcene	Low	29.0	44.9	+55.0
2022	Lacey*	Low	32.8	84.8	+158.2
	Pack Forest	Gravity	6.9	35.4	+411.8
	Pack Forest	Low	8.0	38.8	+384.8
	Pe Ell	Gravity	16.1	98.4	+509.8
	Pe Ell	Low	16.3	46.7	+185.9
	Quilcene	Gravity	25.9	17.7	-31.7
	Sultan*	Gravity	23.5	60.4	157.7

Notes: Only Quilcene in 2022 outperformed model predictions, and this collection period only lasted 9 days. Asterisks indicate sites with landowner-reported tap counts that were not surveyed by the author. "High" vacuum indicates a vacuum pump operated with a sap releaser that pulls over 85 kPa (25" Hg) consistently. "Low" vacuum indicates a diaphragm-style pump that pull up to 55 kPa (16 "Hg) and require less power.

Vacuum Pumps

Small Bosworth vacuum pumps (model number GE-0401N) were installed at East Bethel Ridge, Pe Ell, Lacey, and Quilcene to determine whether their ability to increase production for sugar-makers at the 100-500 tap scale. These pumps pull up to 55kPa (16" Hg) of vacuum pressure, while larger, the more expensive pumps at Pack Forest's canister experiment and the Acme site pull close to full vacuum though they do require purchasing a releaser. A steep learning curve and lack of experience hampered the effective usage of the Bosworth pumps for the first season of their use in each location. Thus, the experimental design was not consistent enough between or within sites to identify the difference in seasonal sap output by small vacuum pump versus gravity-driven systems. The more powerful vacuum pump at the Acme site was able to pull a consistent 85+ kPa (25” Hg) when running. When measured, the low-power pumps were actually able to pull similar pressures, approaching 95 kPa (28” Hg) near the vacuum pump but losing pressure at the ends of the lateral lines due to leaks.

Discussion

Vacuum Pumps

Several inconsistencies between sites and tapping seasons made it difficult to quantify any benefits of using low-power vacuum pumps. Initial tapping date was based on local weather forecasts and thus different for every site. Additionally, some sites did not have the same level of quality control in tapping trees and establishing mainlines and lateral lines, resulting in leaks and sagging lines in some cases. This seemed to be typical of the transition from the < 100 -tap sugarbush using bucket or bag collection to the 100-500-tap scale sugarbush using tubing, and vacuum pumps steepened the learning curve. The vacuum pumps themselves required some troubleshooting to incorporate into existing mainlines, and the pumps often required repair during the middle of a sap run or at other inopportune times. While these setbacks prevented a paired experimental design in which the effect of vacuum pumps could be rigorously tested, important lessons were learned. Vacuum pumps of any size require thoughtful planning to install on a mainline, and they can actually worsen sap quality if the mainline is not properly installed.

In one instance, a sag in the mainline collected sap for several warmer days while the vacuum pump exerted a churning effect on the sap, creating very bacteria-friendly conditions and resulting in fermented sap.

The Acme sugarbush was installed and upgraded over a decade by people who are now experienced maple tappers, while all of the other sites had tubing systems installed by people with varying levels of experience using tubing systems. It was common to find leaks in the tubing, disconnected taps, and wood chips blocking tubing connections. Each air leak reduces vacuum pressure and allows bacteria to enter the lines, reducing sap volume and quality, and clogged lateral lines create a bottleneck that blocks sap. Vacuum gauges often showed a discrepancy between vacuum pressure near the pump and pressure at the top of the lateral lines, though some sites were more consistent than others. Falling branches, and human and animal damage also created leaks and all partner sites improved their ability to manage the leaks through time.

The Acme site was not comparable to the other partner sites for these reasons, but it did show that larger-scale operations are able to extract much more sap per tap through high-powered vacuum and tapping experience. The Acme site achieved 124 liters of sap per tap in 2020, though it must be noted that the number of taps was reported verbally by the landowner and the author was not able to confirm this due to time constraints. This is a very high average yield, though several individual bigleaf maples have exceeded it. Bruce (2008) reported a bigleaf maple stem on Vancouver Island that produced 168 liters over a 90-day season. That experiment used plastic tubing connected to collection jugs with only about one meter of vertical drop, and the trees were re-tapped every 4 weeks. Ruth et al. (1972) reported 64 liters of sap for the highest producing tree over a 120-day season using a simple bucket setup with no tubing. A site in

Oregon reported 136 liters per tap using a low-power diaphragm pump and 5/16” tubing during the 2021/22 tapping season. The Acme sugarbush features large-diameter trees growing on stream banks with frequent flooding and uses a high-powered vacuum pump, so the 124 liters per tap average could well be accurate and may represent an upper bound for sap collection during a 3-month season.

At the Washington State University site near Lacey, the installation of a low-power vacuum pump was followed by a threefold increase in sap volume per tap. In this instance, the vacuum pump helped to overcome difficult topography, though it is unclear what marginal effect the artificial vacuum pressure had on sap volume per tap. The site featured a mainline that traversed a flat area some 300 meters wide, and the pump was installed to pull sap through the flat section of tubing. The additional volume capacity from the pump, mainline, and upgraded tank allowed the addition of a hundred new taps.

Installing vacuum pumps in a sugarbush comes with challenges due to the remote nature of many tapping sites. Pumps using alternating current require a generator or must be connected to the power grid, while direct current pumps need a large battery power source to operate. Either way, if grid power is not accessible a substantial investment is required to change batteries or fuel a generator every few days. Where topography allows, gravity systems have been successful and the marginal benefit of using a small vacuum pump is not yet clear. The step between gravity / low-power vacuum pump systems and high-power vacuum pump systems may be substantial in terms of sap yields, though the extra cost must be considered. At the Sultan partner site, the processing room was installed in an existing structure. The site’s topography allowed a ¾”-diameter mainline to carry sap directly from the lateral lines to a tank in the processing room without the use of a vacuum pump. This scenario appears to be the least costly and most convenient, though it is not possible in every location.

The canister data, which informed the model, was collected from a highly controlled version of a bigleaf maple sugarbush and represents the upper bound of possible sap harvests using high-powered vacuum pumps. Actual collections tended to be lower than predicted for a few possible reasons. The vacuum pump utilized in the canister experiment may have boosted sap volumes compared to the partner sites, which would explain the success of the Acme site relative to model predictions. The canister experiment was only tapped for a total of between 16 and 25 days each season, though sap volumes averaged between 0.69 and 1.00 liters of sap per tap per day. If the experiment was run for the full 60 days that the model uses, between 41 and 60 liters of sap may have been harvested.

The within-site variation in temperature could have also had an impact on discrepancies between the modelled sap flow and the partner site collections. Temperatures varied several degrees Celsius at different elevations and aspects on the same hillside at the same collection time (Figure 5.1). As maple sap exudation is triggered by freeze-thaw cycles and sap cannot flow when tapholes are frozen, a difference of even half a degree Celsius could be sufficient to prevent a taphole from thawing while nearby tapholes are thawed. The 4km^2 resolution of the PRISM weather data used to model sap flow could not account for the level of fine-scale spatial variation in temperature present at the tapping sites. This variation could have meant frozen lines or tapholes on days when the model indicated sap flow. The model would likely produce estimates closer to measured values using temperature data at a finer resolution.

Partner Sites

The eight collaborating landowners ranged from veteran sugar-makers to complete novices, and all were able to produce good quality syrup from bigleaf maples on their land. Records from the Forks site are unavailable due to very low sap volumes that were barely sufficient to process. This site is in the lower-elevation Hoh Rainforest, near the west coast of the Olympic Peninsula, where winters are mild and temperature fluctuations minimal. Additionally, the tapped trees at this site were very large and old, while most of the other sites contained younger stems frequently growing in clumps.

Processing low volumes of sap is an inefficient use of both labor and fuel. Additionally, small quantities of sap spoil quickly because they reach ambient temperature faster than a full tank of sap, which has more thermal mass. At Pack Forest, only 4.3% of sap volume collected in 2022 was in quantities that were too small to process. In 2021, a full 43% of sap collected had to be dumped due to insufficient volume for processing. In 2021 only 3.8 liters of syrup were produced due to lack of sufficient labor, resulting in a sap to syrup ratio of 900:1. The 5,242 liters that were processed in 2022 yielded 49 liters of syrup for a 107:1 sap to syrup ratio. Based on sugar content alone, only 89 liters of sap should have been required to make 1 liter of syrup during that year. Inefficiencies in processing reduced syrup yield by 20% of expected volume in this instance.

Scaling up the amount of sap processed is one way to reduce this loss. A poor sap flow day can still result in processable quantities of sap with enough taps in the field, especially if reverse osmosis is used and the resulting sap concentrate is refrigerated or frozen. Pre-syrup is unavoidably left behind in the evaporator when boiling is finished, syrup gets caught in filters and sugar sands, and some spillage is inevitable. The more sap that moves through this system, the higher the ratio of finished syrup to wasted sugar. Evaporators also work best when a constant, slow stream of concentrated sap can be fed in while the tray boils.

Bigleaf Maple Sugaring: Moving Forward

With a much longer tapping season, it appears that one can harvest more sap per season from a bigleaf maple than from a sugar maple. Sugar maples average around 38 liters per tap per season (Heiligmann et al., 2006a), and several of the collaborating bigleaf sugar-makers achieved over 34 liters per tap without a vacuum pump and without tapping the entire possible range of the season. The one partner site that used techniques similar to industrial-scale sugaring on the East Coast was able to consistently harvest over 1 liter per tap per day of tapping, yielding 124 liters over the course of the 2020 season (Table 5.1). The additional volume of bigleaf maple sap may offset its lower sugar content in larger-scale operations. Though trees must be re-tapped every 4 weeks and the sap takes more energy to concentrate, one could produce bigleaf maple syrup in quantities that approach sugar maple yields per tap.

While bigleaf maple sap volumes are sufficient to produce quality sap, sugar-makers are still faced with high costs to transition from small-scale bucket sugaring to a commercial scale. A community sugaring approach, similar to small-scale dairy farming, would use a shared processing facility to reduce the fixed cost per participant. Several other methods of collaboration would reduce barriers to entry.

Some bigleaf sugar-makers do not have the funds, time, or desire to process sap, but still enjoy collecting it. Likewise, some enjoy cooking syrup or wish to get more use out of their evaporator, but do not have any more trees they can easily tap. Buying and selling sap is common practice in eastern North America, and it is facilitated by standard bulk sap and syrup prices by grade. Pricing consistency does not yet exist in Washington, though a good starting point may be splitting the syrup produced from the seller's sap 50-50 between sap seller and sap buyer, as is common in the East (Farrell, 2013). The economies of scale enjoyed in the east may be out of reach for Washingtonians for some time unless a cooperative approach to processing sap is taken. Larger-scale processing equipment is more efficient, and efficiency makes processing each unit of finished syrup cheaper. The sap buyer can then pass some of the savings on to the sap seller.

Mobile sap processing operations, like those used by the University of Washington and Oregon State University, also help to reduce barriers to entry for sugar-makers and do not require hundreds of liters of raw sap to be driven to a central facility. One catch to community sugaring is timing. Sap runs tend to happen during the same few days in each region, so processing equipment is in high demand during those runs or no demand at all when sap is not running. Freezing concentrated sap may help spread out demand over time. Further investigation into sap concentration and storage is needed to facilitate shared processing equipment. At minimum, collaboration between sugar-makers would help reduce high shipping costs from suppliers in the East by ordering in bulk.

Bigleaf maple sugaring can facilitate the use of other non-timber forest products (NTFPs). Tapping a sugarbush requires one to spend hours clearing trails, stringing lateral lines, and walking their lines for leaks. The establishment of foot trails in one's sugarbush facilitates collecting NTFPs for personal use, barter, or sale at farmer's markets. Shifts in weather between November and March become more salient to a sugar-maker. As bigleaf maple grows in most forest types in Western Washington below 1000m in elevation, plenty of consumable forest products grow alongside it. Edible mushrooms, salal, edible forbs and ferns, medicinal plants, and a wide variety of berries grow alongside bigleaf maple (Burns & Honkala, 1990), and the tree's flowers are delicious lightly fried.

Over the duration of the study, we observed widespread public interest in sugaring in Western Washington. Stories about bigleaf maple sugaring have been featured on NPR, the Seattle Times, King5 News, and others (King, 2020; Bush, 2020; Wright, 2020). The Pacific Northwest's inaugural Bigleaf Maple Syrup Conference was hosted at Pack Forest in May 2022, where a network of 57 scientists, experienced and novice sugar-makers, industry professionals, and interested small forest landowners met for two days to discuss the progress, potential, and best practices of bigleaf maple sugaring. The first-ever Bigleaf Maple Syrup Festival held the same weekend drew over 200 attendees. Events centered around specific agricultural products, like the Skagit Tulip Festival, are an effective way to market niche products and draw interest for tours and demonstrations. Bigleaf maple sugaring operations are currently unique in the Pacific Northwest and could host tours, tastings, and guided foraging trips, which can provide substantial income for landowners.

Hobbyists still form the heart of Pacific Northwest sugaring and while its economic potential appears to be substantial, there will always be value in keeping forests forested and connecting people to the land. Over the course of this study, it has become clear that selling syrup is only one of many reasons people get involved in bigleaf maple sugaring. Landowners are excited to find that a much-maligned tree can give them such a unique and delicious product. People share stories of tapping sugar maples as children in New England and wish to try it in their new home. Others enjoy another excuse to spend time in the woods. And many just have a desire to reconnect with the land in another way, to make the changing of the seasons a little more meaningful, and to bring some joy to cold weather in the forecast.

References

Burns, R., Honkala, B. (1990). *Silvics of North America: Conifers* (Volume 1). United States Department of Agriculture (USDA), Forest Service, Agriculture Handbook 654.

Bush, E. (2020, April 26). Northwest maple syrup? UW testing local bigleaf maples for sweet industry. *The Seattle Times*.

Farrell, M. (2013). *The Sugarmaker's Companion*. Chelsea Green Publishing.

Heiligmann, R., Koelling, M.R., & Perkins, T.D. (2006). Planning a Maple Syrup Operation In: *North American Maple Syrup Producers Manual,* (pp. 25-30). (2nd ed.). Ohio State University.

Heiligmann, R., Koelling, M.R., & Perkins, T.D. (2006). Maple Sap Production—Tapping, Collection, and Storage. In: *North American Maple Syrup Producers Manual,* (pp. 81-118). (2nd ed.). Ohio State University.

King, A. (2020, January 6). Bigleaf Maple Syrup Flows as Profits Drip from Once-Maligned Northwest Tree. *National Public Radio.*

Ruth, R. H., Underwood, J. C., Smith, C. E., & Yang, H. Y. (1972). Maple sirup production from bigleaf maple. *USFS Research Note, Pacific Northwest Research Station*, 12.

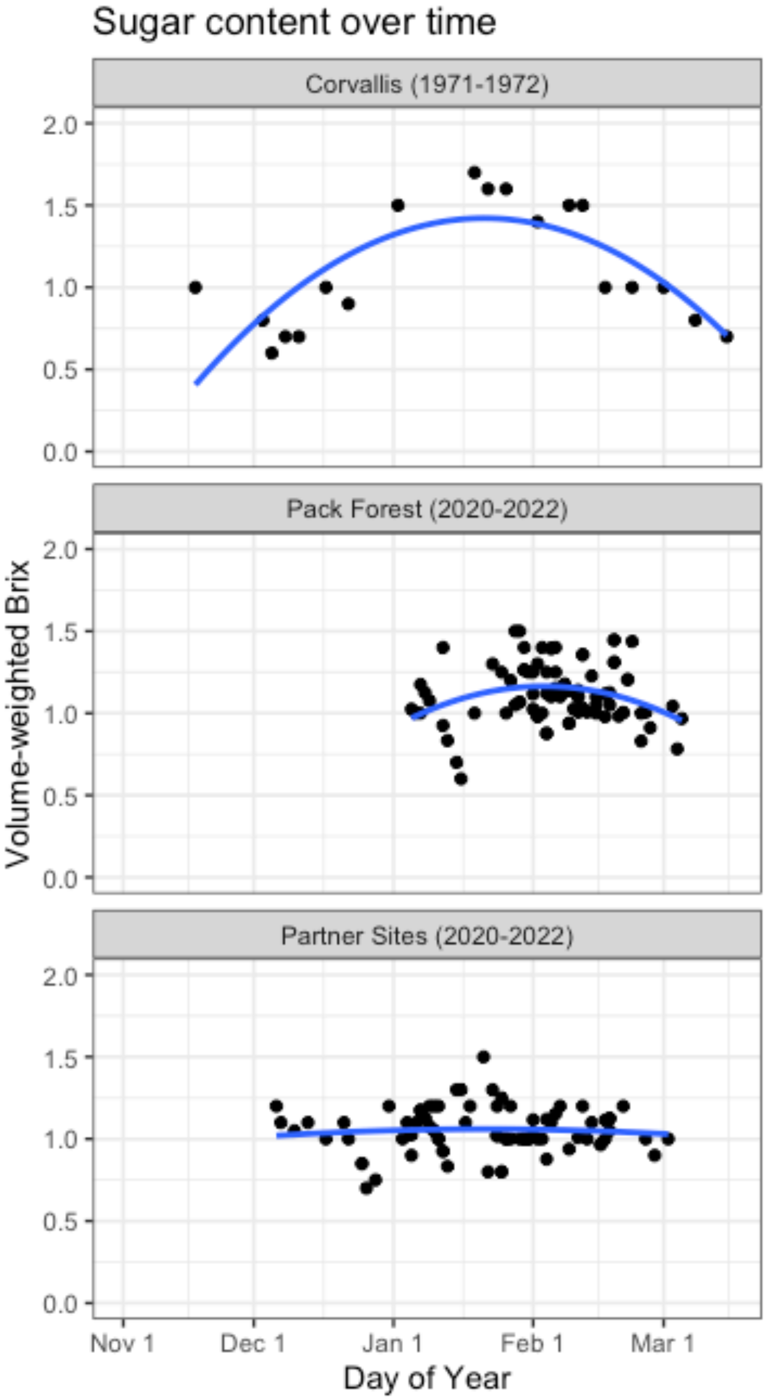
Smith, H. Clay; Gibbs, Carter B. 1970. Comparison of vacuum and gravity sap flows from paired sugar maple trees. Research Note NE-122. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 4p.

Wright, M. (2020, February 11). The rarest maple syrup in American could be made right here in Washington. *King 5 News.*

Appendix

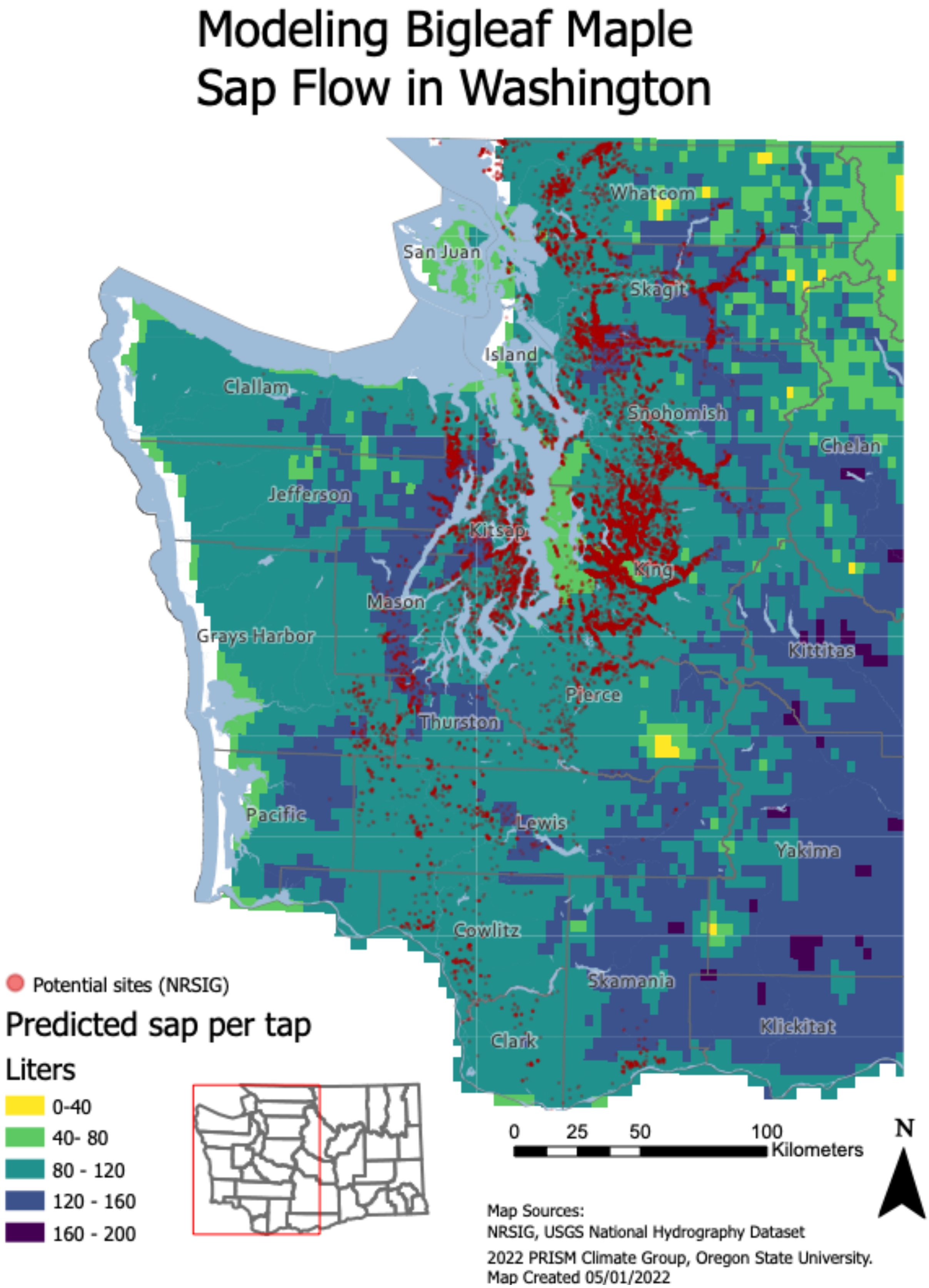
Appendix 3.1. A sample sap collection data sheet. Sap quality is measured on a three-point scale as described in on page 31.

Location (lat – long)	*Number of taps*	*Date*	*Vacuum pump on?*	*Sap volume (liters)*	*Brix*	*Sap Quality*	*Did sap flow today?*	*Days since tank emptied*	*Daily Low (C)*	*Daily High (C)*	*Comments*
47.777, 120.000	200	1/1/22	No	20	1.1	1	yes	1	2	5	Vac. Pump just arrived
“	“	1/2/22	No	0	NA	NA	No	1	-2	0	
“	“	1/3/22	Yes	450	1.1	1	yes	2	-1	4	
“	“	1/4/22	Yes	250	0.9	2	yes	1	1	5	Made 7L good syrup



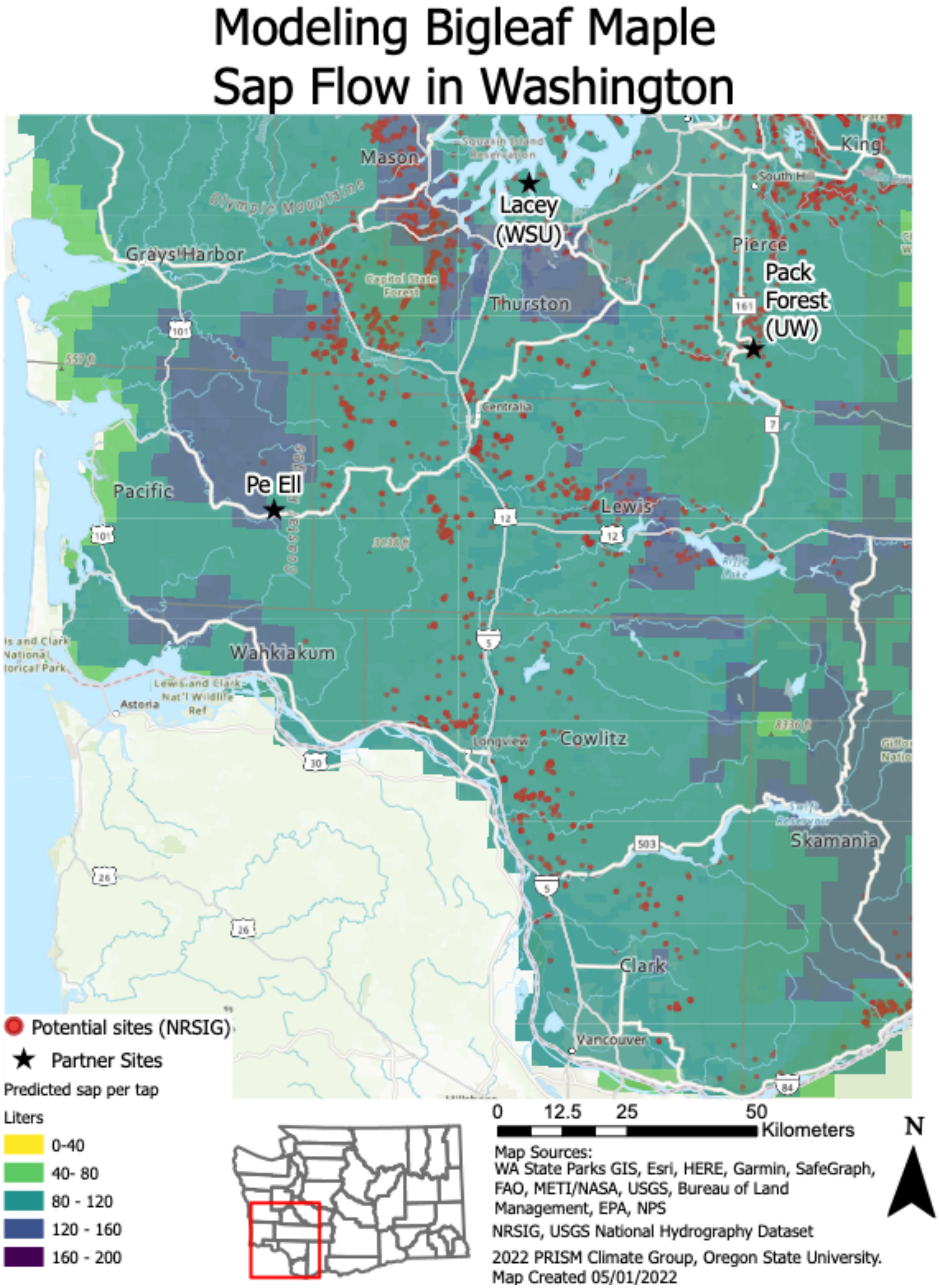
Appendix 3.2. The variation in sugar content from Ruth et al.'s 1971 collection period, Pack Forest's data (including canisters), and the rest of the partner sites.

Notes: Points represent collections that were each a pooled measurement since the last time sap was collected. This is analogous to volume-weighted Brix. A second-order polynomial line of best fit is shown for each set of sites.



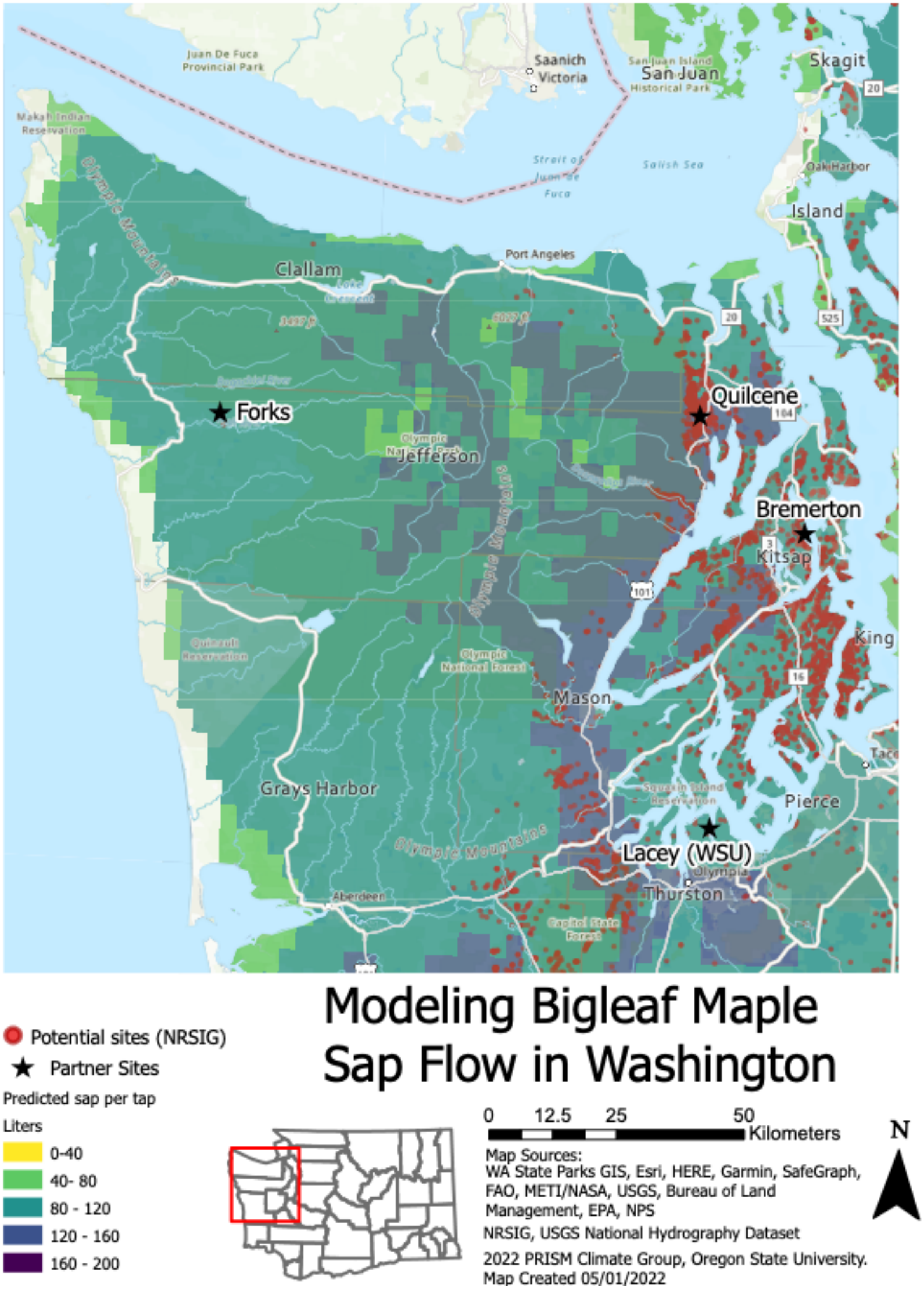
Map Sources:
NRSIG, USGS National Hydrography Dataset
2022 PRISM Climate Group, Oregon State University.
Map Created 05/01/2022

Appendix 4.1. Season-average bigleaf maple sap projections for Western Washington.

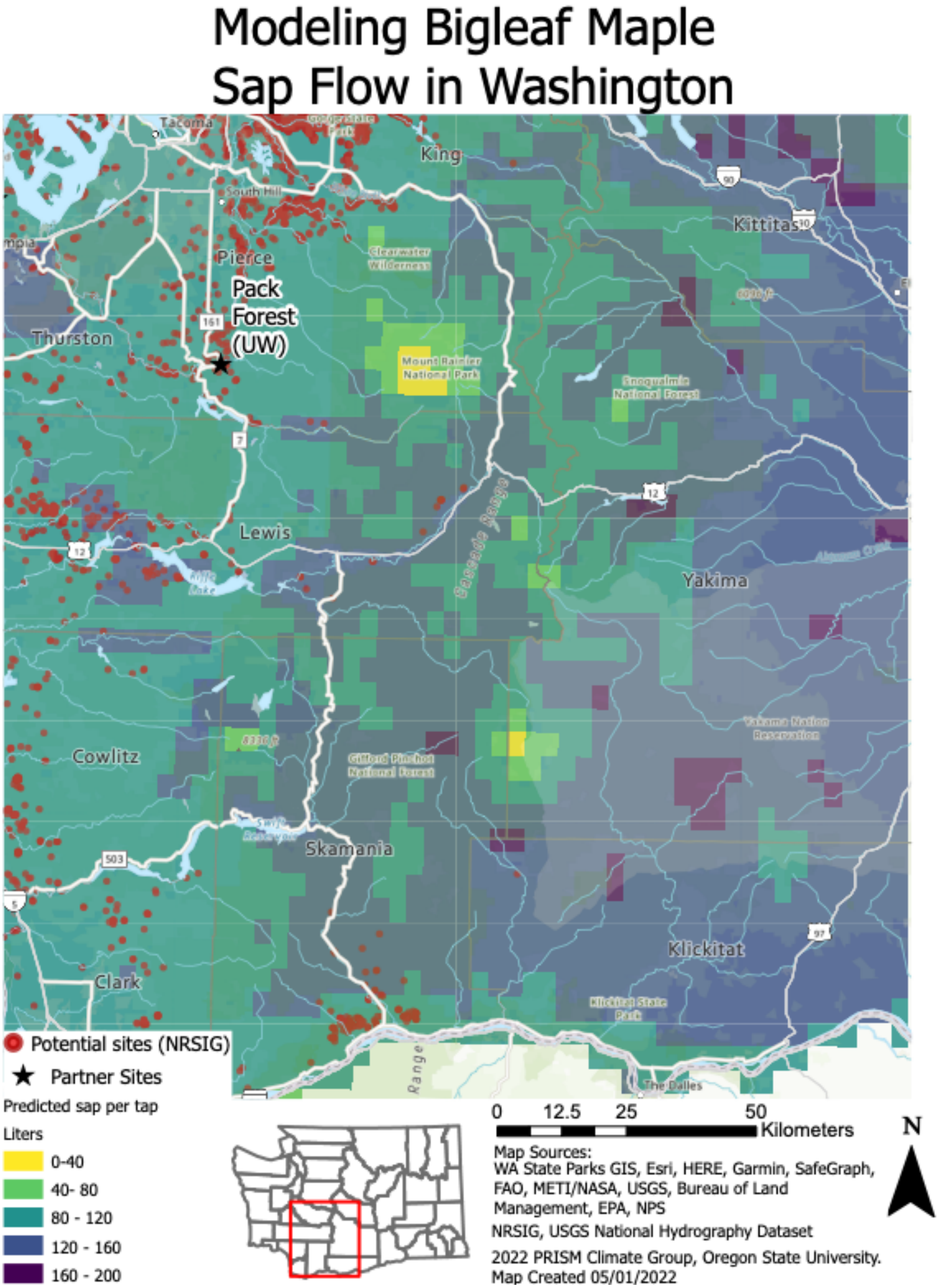


Map Sources:
WA State Parks GIS, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, Bureau of Land Management, EPA, NPS
NRSIG, USGS National Hydrography Dataset
2022 PRISM Climate Group, Oregon State University.
Map Created 05/01/2022

Appendix 4.2. Season-average bigleaf maple sap projections for Western Washington.

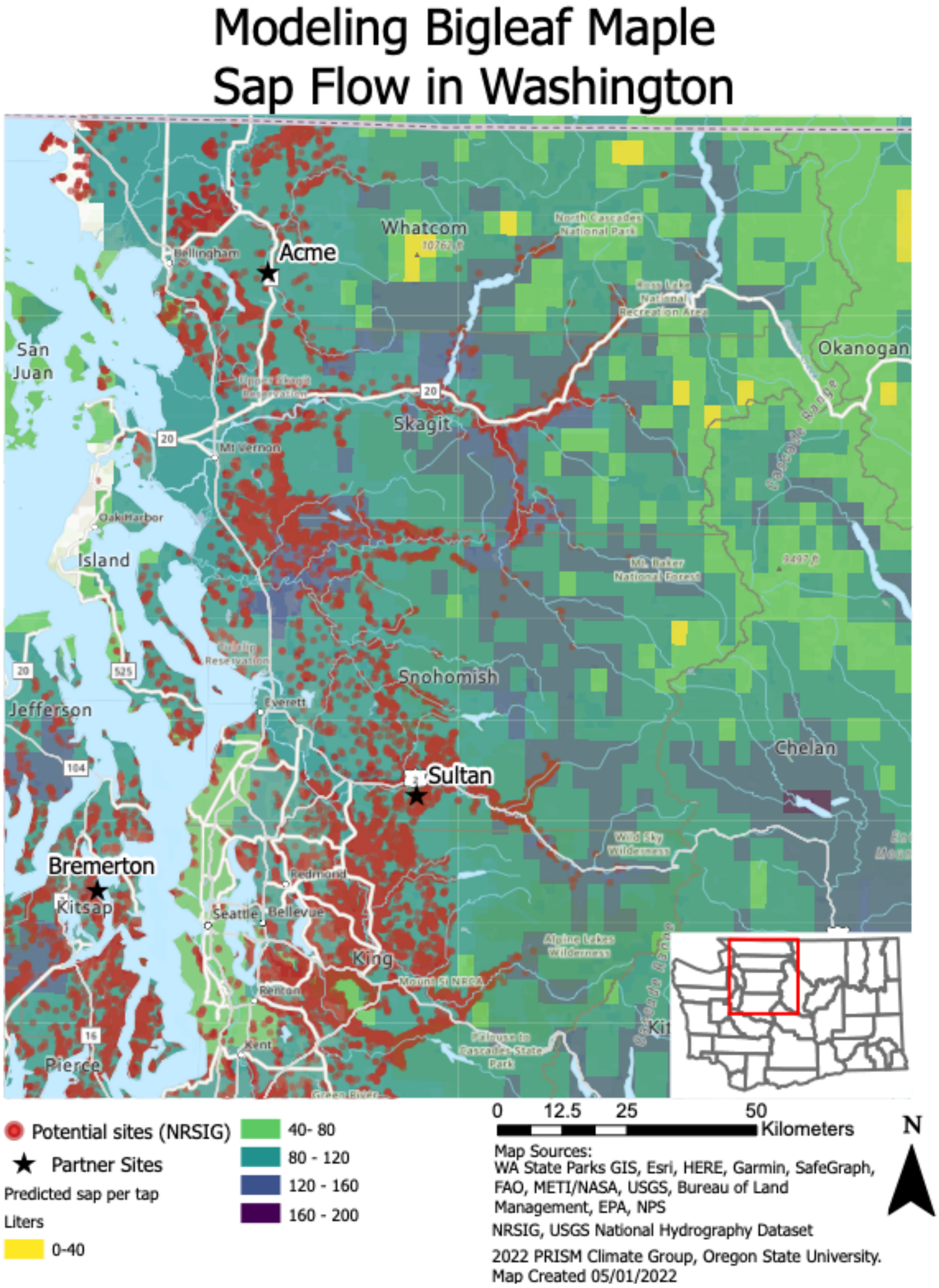


Appendix 4.3. Season-average bigleaf maple sap projections for Western Washington.



Map Sources:
WA State Parks GIS, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, Bureau of Land Management, EPA, NPS
NRSIG, USGS National Hydrography Dataset
2022 PRISM Climate Group, Oregon State University.
Map Created 05/01/2022

Appendix 4.4. Season-average bigleaf maple sap projections for Western Washington.



Map Sources:
WA State Parks GIS, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, Bureau of Land Management, EPA, NPS
NRSIG, USGS National Hydrography Dataset
2022 PRISM Climate Group, Oregon State University.
Map Created 05/01/2022

Appendix 4.5. Season-average bigleaf maple sap projections for Western Washington.