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Maple syrup production is both an economically and culturally important industry in the northeastern U.S., and the commercial harvest of the temperature-sensitive sap has occurred for several centuries. A significant decline in maple syrup yield has been associated with warming spring temperatures during the critical sugaring period, and increases in summer drought frequencies. What is unknown, however, is how this current decline compares within the range of variability expected for a broader range of crops. Few sugar maple tree-ring chronologies from the northeastern U.S. exist, yet the potential utility of this species is high.

This project will be the first to incorporate and employ dendrochronological techniques to develop maple syrup yield reconstructions. This project is designed to investigate correlations between statewide tree growth and maple syrup production using data collected from multiple sites in New York State and determine if these relationships can be modeled to reconstruction historical yields. Thus, this project will help promote the effectiveness of using tree-ring data to predict agricultural yields, which will ultimately provide farmers additional information about crop yield cycles. This knowledge will in turn help determine appropriate management methods for sugarbush operators during less optimal climatological conditions.

THE UTILITY OF USING SUGAR MAPLE TREE-RING DATA TO RECONSTRUCT
MAPLE SYRUP PRODUCTION IN NEW YORK

by

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CHAPTER I

INTRODUCTION

[1.1] Background

Since the mid-20th century, maple syrup production in the northeastern U.S. has declined despite improved collection techniques and sugarbush management strategies that have allowed maple producers to collect sap when ambient conditions are suboptimal. A suite of explanations for the decline have been identified including forest pests (Fig.1.1) and diseases, nitrogen leaching, elevated carbon dioxide, ice storms, summer and fall droughts, decreased snow cover, and increased springtime minimum and maximum temperatures.

Additionally, the mid-20th century rise of interest in non-timber forest products has created an impetus in understanding the impact of extraction and the long-term sustainability of sugar maple. How trees adapted to environmental conditions varies in their growth and survival response to changes in temperature and precipitation shifts. Therefore, it is important to determine to what extent such within-species climate adaptation affects the physiological processes that contribute to growth. Mid-20th century declines of sugar maple trees have been attributed primarily to the strong demand and high prices for maple lumber, which promoted many owners to cut and sell their trees. Young trees grow slower, but are sleek and sturdy and are particularly valuable for such

uses as mine props, while older trees are used in the manufacturing of furniture, flooring, certain types of musical instruments, heels for women's shoes, and other items.



Figure 1.1. The favored hosts of this insect, the forest tent caterpillar (*Malacosoma disstria* Hubner), are broadleaved trees, especially the sugar maple in the northeastern U.S.

The production of maple sugar and syrup is entirely a North American industry. Maple sugar appears to have been the first kind of sugar ever produced in the Americas. Sugarbushes are usually owned and cared for by individual farmers and in some cases, remain in the same family for over two centuries. The production of maple sugar was a large-scale social event in the 19th and early-20th centuries that welcomed the breath of spring with accompanying music, dancing, and courting. The craft of collection, processing, and celebration of maple products has been of interest to many artists. The 19th century American Artist Eastman Johnson produced 25 oil sketches that depicted the

seasonal February New England (NE) event including the celebratory season-ending sugaring-off party (Fig. 1.2).



Figure 1.2. *Sugaring Off at the Camp, Fryburg, Maine, ca. 1861–1865* by Eastman Johnson. Sugaring off is the celebratory gathering of farmers and villagers during the first production batch of molten maple sugar (syrup) and signifies the start of spring.

The influence of recent climate variability on crop productivity and quality has been the subject of considerable investigation including studies on grapes (Jones et al., 2005), rice (Peng et al., 2004), soybeans (Lobell and Asner, 2007), and cherries (McGlashen, 2009). Although few studies (e.g., Kairiukstis and Dubinskaite, 1986; Therrell et al., 2006) have directly employed tree-ring data to examine crop variability, tree-ring data obtained from sugar maples may provide another promising opportunity to determine crop yield.

Despite the status of the maple syrup industry in the Northeast, considerable uncertainty exists about its future health given the possible trend toward unfavorable climatic variability. Few studies have addressed this problem from a holistic approach integrating climatology, physiology, ecology, and dendrochronology to investigate and quantify the environmental variables associated with the decline of maple syrup production. The New York maple syrup data are particularly valuable as they represent the longest, most-detailed dataset available in the northeastern U.S. Further, as the New York syrup data parallel trends in data sets for other New England states, results from New York will serve as a proxy for the cause(s) for declines in NE.

Additionally, long-term models predict a shift in Northeast forest composition with a loss of the maple–beech–birch dominate forest type. Accordingly, my study will couple tree-ring data with meteorological data to examine maple syrup production declines in New York State. I will address the following objectives:

- 1) Determine the growth-climate relationships of sugar maple tree growth throughout the state of New York;*
- 2) Model meteorological variables that have affected syrup yields and tree-ring growth since the early 1900s; and*
- 3) Determine the effectiveness of using sugar maple tree-ring data to predict and reconstruct maple syrup yields during the past two centuries.*

[1.2] Sugar Maples and Maple Syrup

Sugar Maples

The maple family (Aceraceae) is composed of two genera with 113 species of trees and shrubs. All but two species (*Dipterònia*) found in China occur in the genus *Acer*. The genus *Acer* consists of ca. 110 species in the Northern Hemisphere. Fourteen maples are indigenous to North America, in which seven are important components to forest ecosystems. Hybridization and introgression, a natural movement of the gene(s) from one species or population to another through hybridization and repeated backcrossing, can occur among sympatric species. The sugar, rock, or hard maple (*Acer saccharum* Marshall) is an economically and biologically important hardwood species in the forests of the northeastern and midwestern U.S. and eastern Canada (Horsely et al., 2002), and is the state tree of New York, Vermont, West Virginia, and Wisconsin.

Sugar maple is a major component of six northern hardwood forest types, where it accounts for $\geq 50\%$ of the basal area in these forests (Horsely and Long, 1999), and mature sugar maples can reach ages of 300–400 years with an average longevity of 150–200 years (Godman et al., 1980). Within these forests, sugar maple is commonly associated with American beech, yellow birch, basswood, black cherry, red spruce, oaks, and eastern hemlock. It flourishes in regions with annual precipitation of 70–120 cm and January temperatures within the distribution range between -10° to -20°C . The northern limit of sugar maple roughly parallels 47° N, which corresponds with the 0°C annual isotherm, extending eastward from the extreme southeast corner of Manitoba, through central Ontario, the southern third of Quebec, and all of New Brunswick and Nova Scotia

(Figs. 1.7–1.9), although there is a lack of agreement on the precise boundaries of the species. Additionally, relict stands of sugar maple exist west of their contiguous range (Fig. 1.10).

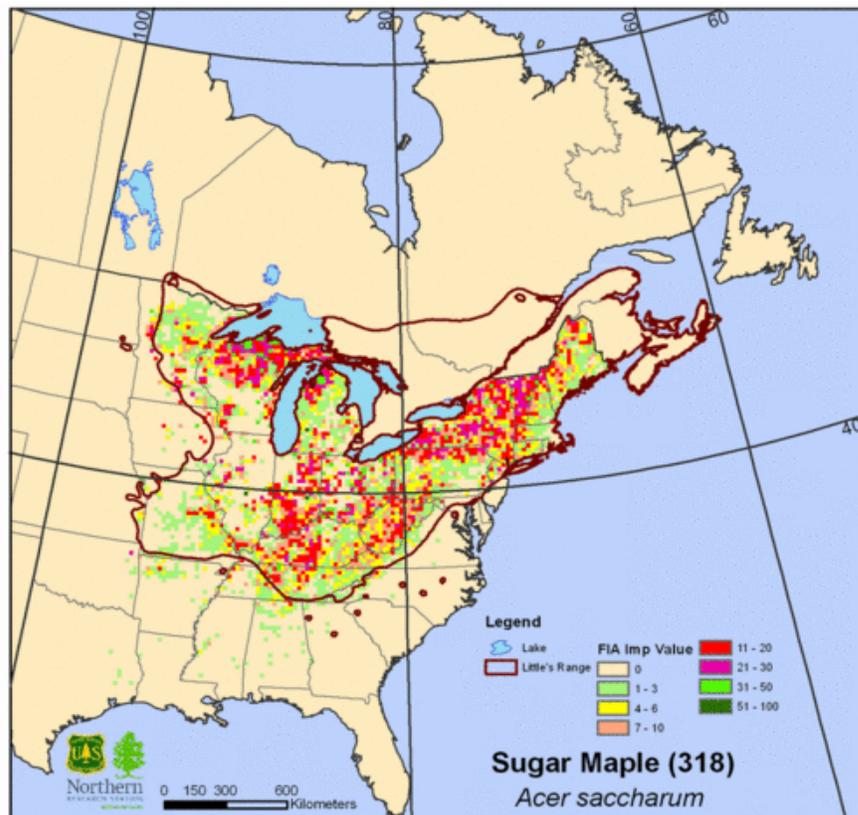


Figure 1.3. The niche space of The Forest Inventory and Analysis' (FIA) eastern U.S. range as well as the Little's range of the sugar maple is mapped (Source: Prasad et al., 2007).

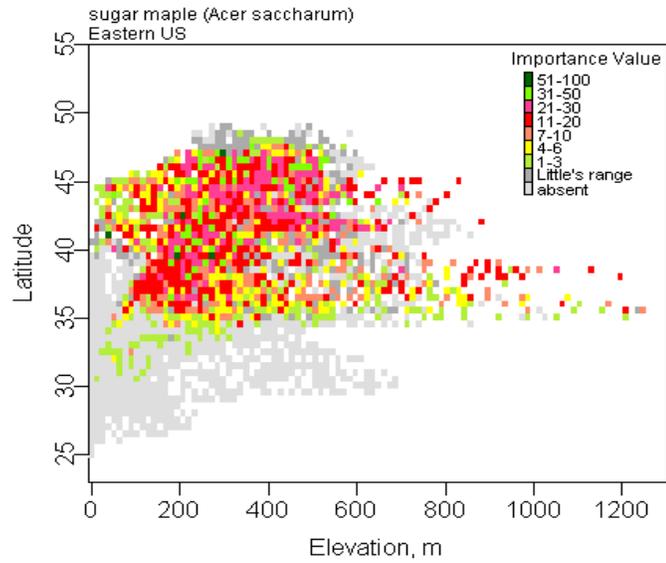


Figure 1.4. Niche map display the species Importance Value plotted to elevation and latitude (Source: Prasad et al., 2007).

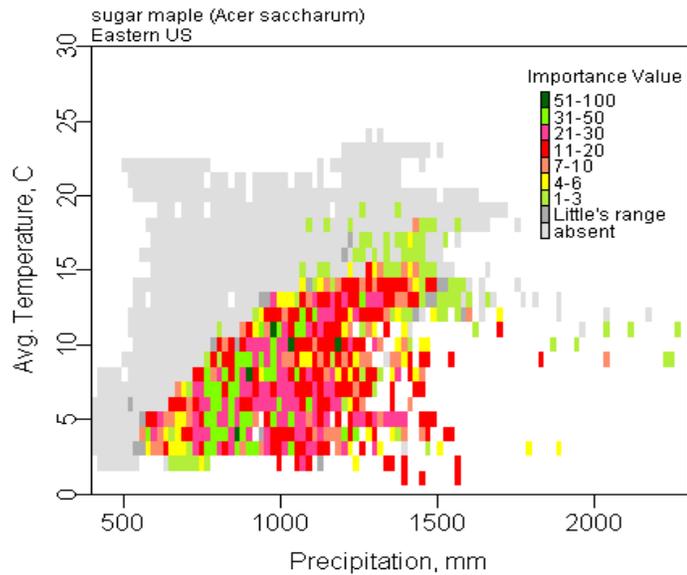


Figure 1.5a. Niche maps display the species Importance Value plotted to climate (Source: Prasad et al., 2007)

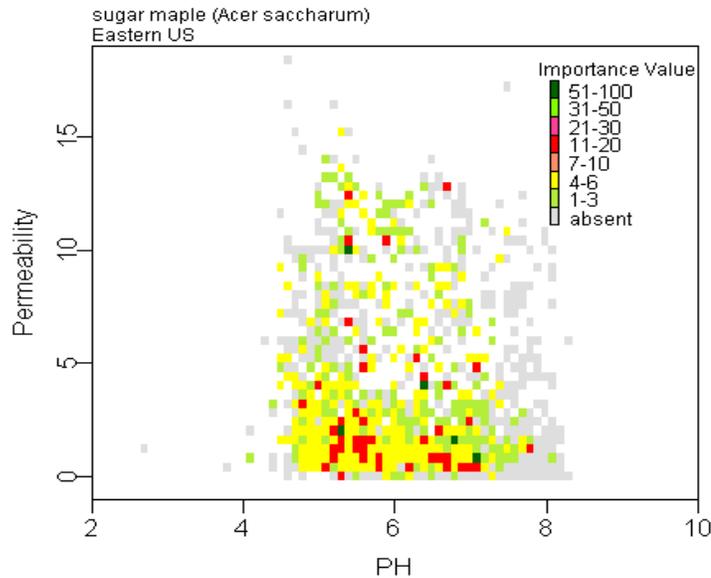


Figure 1.5b. Niche maps display the species Importance Value plotted to soil characteristics (Source: Prasad et al., 2007)

In the United States (U.S.), the species occurs throughout New England, New York, Pennsylvania, and the Mid-Atlantic States, extending southwestward through central New Jersey to the Appalachian Mountains, and southward through the western edge of North Carolina to the southern border of Tennessee. The western limit extends through Missouri into a small section of Kansas, the western one-third of Iowa, and the eastern two-thirds of Minnesota.

Relict populations of sugar maple persist in the Wichita Mountains and Caddo Canyon area of western Oklahoma, the Black Hills of western South Dakota, and along the southern escarpment of the Edwards Plateau in central Texas. This broad region has a generally cool and moist climate, growing season of 80–260 days, with no well-defined

seasonal precipitation maxima or minima. Two physiological ecotypes exist, with populations west of approximately the Mississippi River considered a separate subspecies by some authorities and being better adapted to high temperatures and drought than their eastern U.S. population counterparts (Dent and Adams, 1983). No differences in winter hardiness have been detected between the populations (Kallio and Tubbs, 1980).

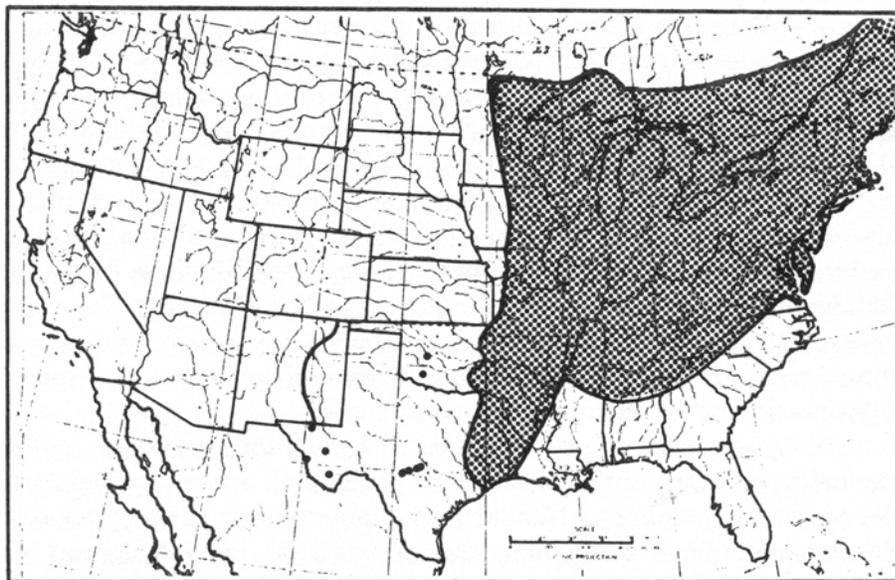


Figure 1.6. Sugar maple natural range (Hubbs and Lagler, 1958).

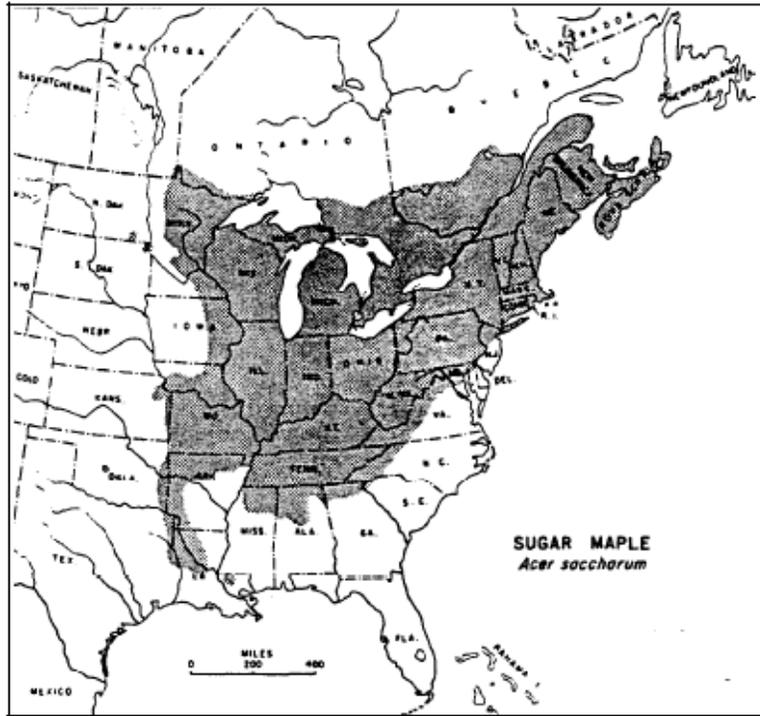


Figure 1.7. Natural range of sugar maple (Kallio and Tubbs, 1959).

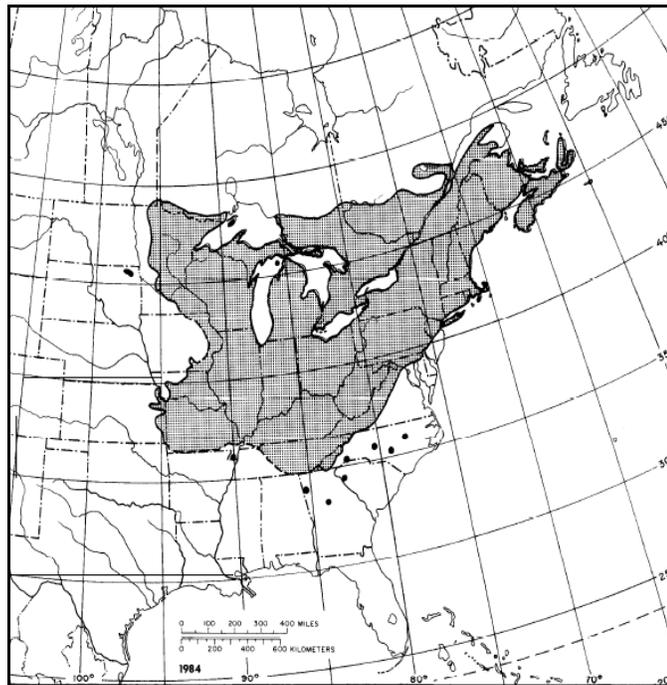


Figure 1.8. Natural range of sugar maple (Burns and Honkala, 1990).

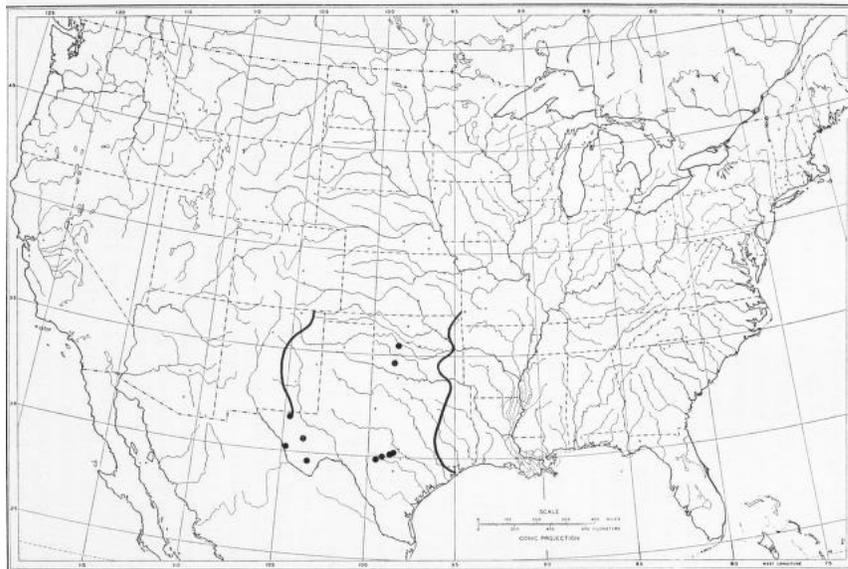


Figure 1.9. Relict populations of sugar maple found outside their current contiguous range (Blair, 1958).

Throughout much of sugar maple's range, the species occupies elevations from sea level to ~762 meters, although in the southern Appalachians the species occurs at ~915–1,675 meters. Sugar maple is critical to carbon sequestration, and helps regulate nitrogen cycling and leaching from forested watersheds (Lovett and Mitchell, 2004). In addition to producing a sweet sap, the sugar maple provides several additional amenities including a desired wood source for American furniture and cabinetmakers since early Colonial days, baseball bats, railroad ties, musical instruments, butcher's blocks, clothespins, ladder rungs, surveying rods, tool handles, excellent landscaping specimens, heating fuel, and materials for hardwood flooring. Maple veneer is used to make drums, guitar panels, bowling pins, auditorium seats, and golf club drivers. Further, two fancy grains exist for woodwork. Bird's-eye maple (Fig. 1.11A), believed to be produced by fungal growths or bark-bound buds, and curley maple (Fig. 1.B), are used in the

manufacturing of gunstocks and backings of fine fiddles.



Figure 1.10a and 1.10b. Bird's eye maple (top) and curley (tiger) (bottom) maple (Photo by author).

[1.3] Maple Sap and Syrup

Industry standards use English units of measurement, and therefore from this point forward, units are expressed as English units (e.g., gallons). Production of maple syrup in the U.S. is concentrated in the Great Lakes area and the Northeast. Roughly, 75% of domestic maple syrup is produced in New England; New York and Vermont account for ca. two-thirds of the U.S. production. In Canada, syrup is produced in the eastern provinces of Nova Scotia, New Brunswick, Quebec, and Ontario with Quebec producing >90% of the total.

Maple sugar and syrup has long been a source of a pure and natural sweetener for cooking and condiment use. Sugaring is a proud tradition for many North Americans (Fig. 1.0) and ownership operation of sugarbushes and sugarhouses are often transferred from one generation to another. Maple syrup has been described as a fine food, like that of balsamic vinegar or Tuscan olive oil and American syrup buyers tend to favor toffee

accents while French importers prefer syrup with vanilla aromas (Chipello, 2000).



Figure 1.11. Pure maple syrup or genuine maple syrup is made from the sap of maples, with sugar maple being the most productive (Photo by author).

Maple sap is a dilute solution of water and sugar, coupled with traces of non-sugar solids including organic acids, nitrogenous waste, and inorganic salts. The proportions of sap are variable; the sugar content, which is 99.9% sucrose, can range from 1–10%, with 2–6% being common. Maple syrup production occurs by boiling the sap to evaporate excess water and increase the solids fraction of the sap. Boiling continues until the syrup contains 35% water and 65% solids, at which point the proportion of water and solids brings the weight of the syrup to 11 pounds per gallon as required by the USDA (Heiligmann and Winch, 1996).



Figure 1.12. The above sign is located roadside throughout the maple syrup production regions of New York and is part of the agrotourism initiative of New York (Photo by author).

Sap with a high concentration of sugar can be brought to the syrup stage with less boiling time than less sweet sap and is preferred because of reduced labor and energy

costs. For example, 86 gallons of sap containing 1% sugar are required to make 1 gallon of syrup. Jones' Rule or the *rule of 86* (Fig. 1.15) is an industry standard expressed as

$$sap(gal.) = 86(x^{-1})$$

where x = sugar percentage of sap. The doubling of the sugar content to 2% halves the amount of sap required to 43 gallons, whereas a sugar concentration of 5% requires only 17 gallons. Finally, sweet sap results in lighter-colored, more delicately flavored syrup such as *Grade A Light* that commands premium wholesale and retail prices.

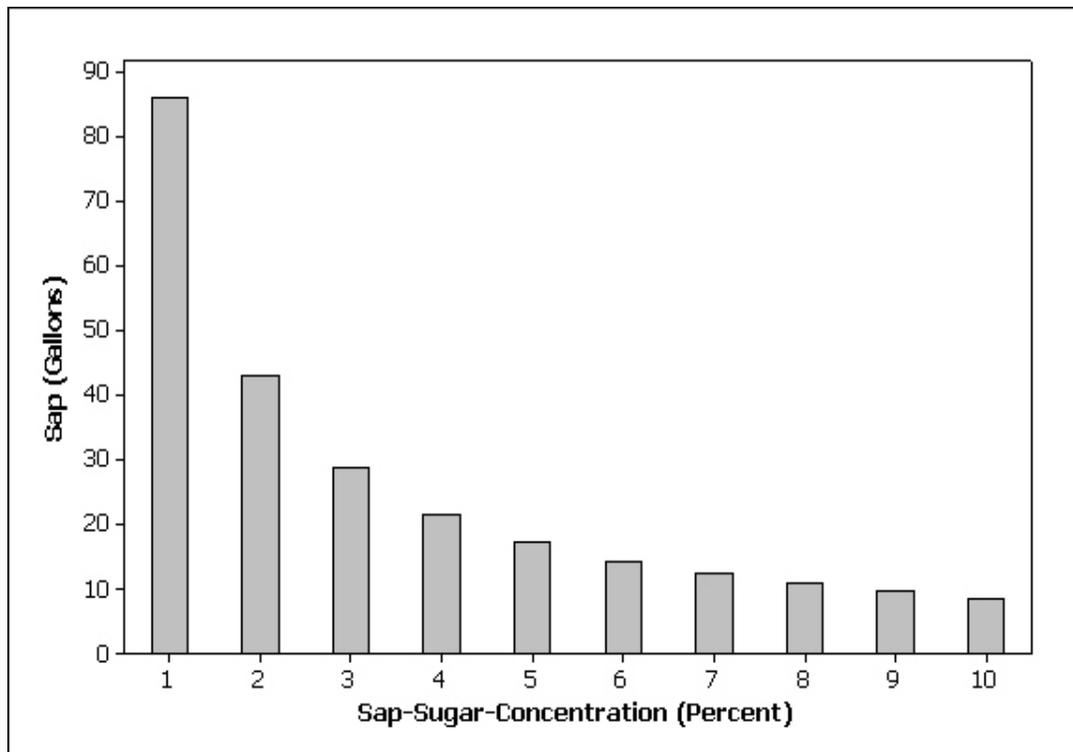


Figure 1.13. A graphical representation of the rule of 86 (Taylor, 1956).

[1.4] The History of Maple Syrup Production

The production of maple sugar and syrup is among the oldest industries in the northeastern U.S. (Gabriel, 1972). Maple sugar and syrup products have been important cash crops to North American farmers during the 18th and 19th centuries (Whitney and Upmeyer, 2004) and appropriately, many settlers and farmers referred to the extracted sap of maples as white gold (Koelling et. al., 1996). Several regional and cultural lexicons exist for describing maple sap and its products: Canadian, American, or Indian sugar or molasses; *melasses*, or *syrrup* of maple; and maple *sirup*. French explorers first documented the sugaring process occurring along the St. Lawrence River in 1609 after observing American Indians tapping maples trees to obtain a sweet, edible sap (Fig. 8; Nearing and Nearing, 2000; p. 22). Jesuit Missionary, Paul Le Juene, traveling through New France¹ in 1634 noted: “When they are pressed by famine, they eat the shaving of bark of a certain tree, which they call Michtan, which they split in the Spring to get from it a juice, sweet as honey or as sugar.

It is believed that American Indians discovered the sweetness of maple trees by eating sap icicles (as the ice forms, the sap concentrates) that formed at the end of broken branches or frozen sap from a wounded maple. Early explorers’ journal entries also indicate the sap was used to boil meats; thereby leaving the meats with a sweet maple flavor. Interestingly, red squirrels (*Tamiasciurus hudsonicus*) have been observed methodically harvesting sugar and syrup from sugar maple trees in western Maine

¹ The possessions of France in North America from the 16th century until 1763. New France included much of southeast Canada, the Great Lakes region, and the Mississippi Valley.

(Heinrich, 1992).



Figure 1.14. A heritage product, maple syrup production is of great pride to a large population of New Yorkers (Photo by author).

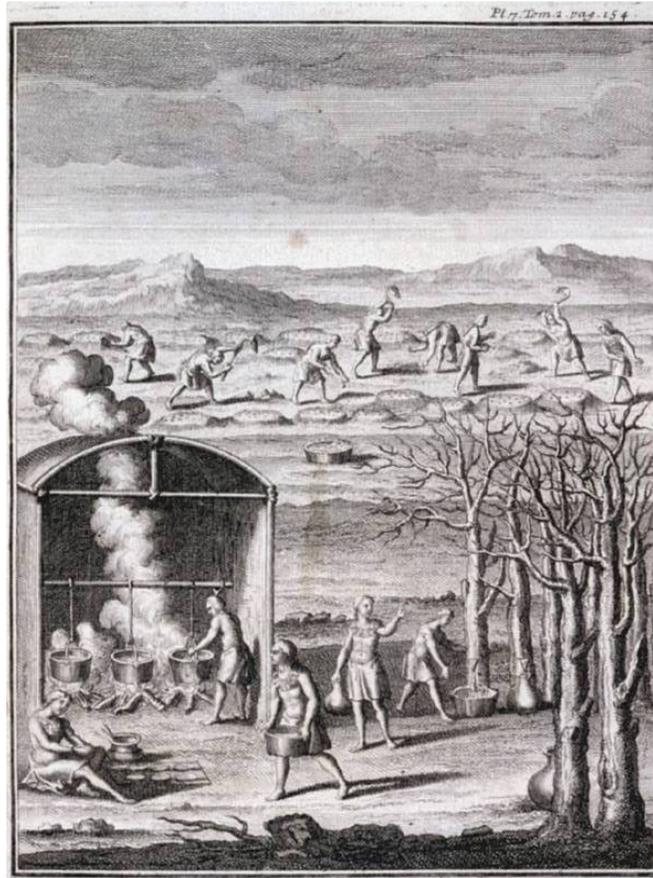


Figure 1.15. Native Americans collecting sap and cooking maple syrup. Josep Fancois Lafitau, 1724 (Library of Congress).

The storage of liquids posed several problems, and hardened dry maple sugar could easily be stored. With a stable sugar product, Native Americans of New England often used the sugar for trading with European explorers presented in the form of a gift. The popularity of maple products to the early settlers evoked a need to produce these products for themselves. English settlers were slower to adopt the native's sugaring process compared to their French counterparts. The process of sugaring was passed from Native North Americans to the European explorers and settlers (Heilmann, et al., 2006). In the mid- to late-1700s, the production of maple products became an important

economic source to many colonists of the Massachusetts Bay Colony, especially where high transport costs limited the use of imported cane sugar.

The financial capital required to produce sugar was minimal. Therefore, the advantage maple sugaring offered New England farmers was that it supplied work and income during the least agriculturally productive season of winter through early spring. The English scientist William Fox Talbot noted, that maple sugaring can “afford an ample compensation for the farmer for little more than half a month’s labour.” Families often made more maple sugar than they could use, and traded the excess for either other food items or supplies with local merchants. The popularity of the locally-made maple sugar also highlighted their objection to the sugar cane harvesting by slaves in the West Indies.

It was not until the 1700s that Europeans developed a need for granular sugar, as sugar was considered a medicine and luxury item for the wealthy. The blockage of passage on the St. Lawrence River by the British in 1703–1705, facilitated the need and production of maple sugar in the Quebec region. During the Napoleonic Wars (1803–1815), sugar was produced from maple trees in the historical region of Bohemia in central Europe. The industry received substantial means of encouragement from the Bohemian government and large groves of maple trees were planted and cultivated. However, because of the low yields of sugar and the long interval of time required before trees can be retapped, the industry was short-lived.

[1.5] Commercial Aspects of Maple Sugar and Syrup: 1800–Present

Thomas Jefferson was an advocate for the U.S. to produce its own supply of sugar (i.e., maple sugar), and established a maple plantation at Monticello. The commercial aspect of the maple sugar and syrup industry did not begin in earnest until the 1800s (Tyree, 1983), at which time maple products were an inexpensive substitute to offset the cost of escalating cane sugar prices. With the presence of the American Civil War, many Northerners saw the consumption of maple sugar as a statement of their abolitionist beliefs. The rise of the maple sugar industry was short-lived; however, as the increased availability of sugar derived from sugar cane (*Saccharum* spp.) post-1803 in Louisiana and sugar beets (*Beta vulgaris*) after 1830 created a decrease in the demand for maple sugar (Whitney and Upmeyer, 2004). Retail prices from Vermont for 1800–1849 show that maple sugar was consistently less expensive, while during 1850–1859 prices became approximately equal to that of cane sugar. However, shortages in the supply of cane sugar during the Civil War (1861–1865) significantly increased prices and cane sugar did not undersell maple sugar until 1880. With more efficient cane sugar production at the end of the 19th century, prices fell and the consumption of maple sugar fell while maple syrup consumption increased (Whitney and Upmeyer, 2004).

New York, Vermont, Michigan, and Ohio were the center of the North American maple syrup industry from the late-1800s through the mid-1900s. Prior to the 1920s, 80% of worldwide maple syrup production occurred in the U.S. and included several southern and midwestern states (i.e., North Carolina, Virginia, Kentucky, Tennessee, Missouri, and Kansas) that have few commercially viable operations. In the 19th century,

approximately two-thirds of all Vermont families engaged in maple sugar production and unlike today, sugar maple was heavily exploited in the Ozark bottomlands of Missouri.

During the later half of the 20th century, the location of peak syrup production shifted northward with 93% of maple syrup production now occurring in the province of Quebec, Canada (MacIver et al., 2006). This shift has occurred despite New York alone having more maple trees than Quebec, and reflects the immense economic support of their government to underwrite production costs. The Canadian government recognized early the potential of the industry and made the necessary investments to support its growth and latter dominance. However, the U.S. has the potential to regain a section of the international market with investments from federal and state agencies.

Despite this shift, maple production remains an important crop in the northeastern U.S. Currently (2008), New York produces 20% of the U.S. maple supply, ranking second to Vermont's 31%. Further, the economic influence of the industry is significant. In upstate New York, the total farm cash receipts approach 3 billion dollars on an annual basis, and maple syrup accounted for greater than 14 million dollars in revenue for 2008 (Keough, 2008). Beyond the economic component of maple syrup, the maple syrup industry represents a cultural aspect of New England-associated tourism and a way of life for many long-term residents of the region (Figs. 1.14–1.17).



Figure 1.16. *American Forest Scene: Maple Sugaring* (Currier & Ives, 1856). It was common for artists to use images of "sugaring off" to cleverly comment on the political implications of cane sugar (i.e., slavery). Interestingly, Currier & Ives focused on the community facet of maple sugaring. The firm's 1860 catalogue investigates the social context of maple sugar by describing the image as: "*An agreeable picture of a peculiarly American character, showing a maple grove in early springtime. A light snow has apparently fallen over night, and the ground is thinly covered with a mantle of white. On the logs, near the fire where the sap is boiling, are seated two ladies with a male companion, apparently city folks come out to taste the sweets of the country. In the distance, an ox- cart is approaching with another party of the same sort. On the left, two "natives" seem engaged in a discussion, either on the sugar trade or the next election. A number of boys and girls are tending the kettles, bringing up the sap in the buckets, or having a good time generally at the sugaring off.*" (Springfield Museum, Michele & Donald D'Amour Museum of Fine Arts, Springfield, MA)

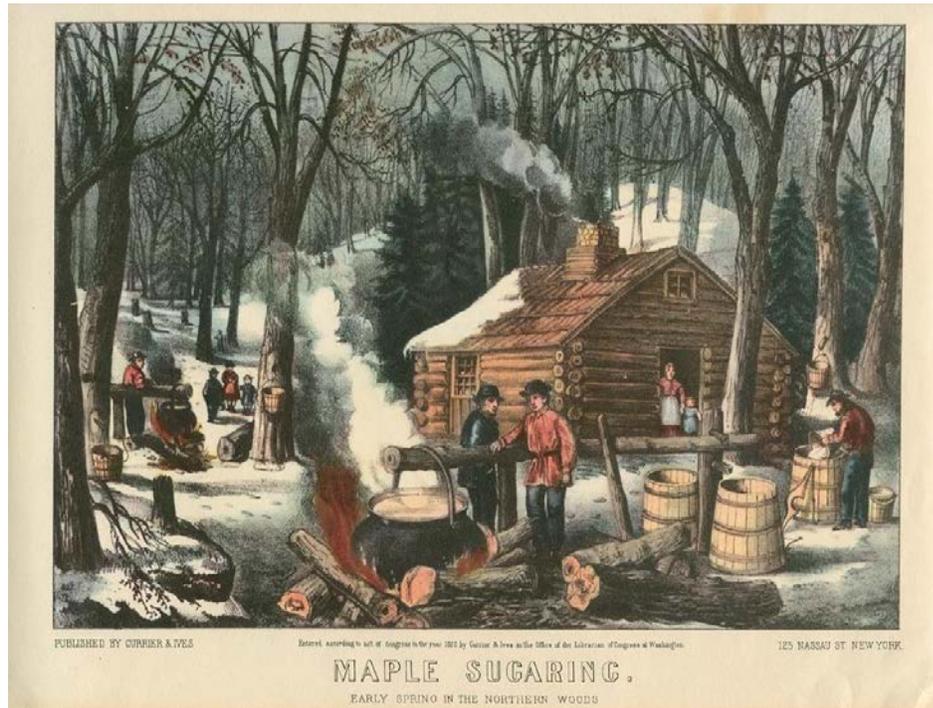


Figure 1.17 *Maple Sugaring: Early Spring in the Northern Woods* (Currier & Ives, 1872).

[1.6] Harvesting Maple Syrup

Collection

The minimum suggested tree diameter for tapping sugar maples is 10–12 in. (25.4–30.5 cm) measured at ~breast height (i.e., DBH). Typically, for trees up to 15 in. (38 cm) in diameter 1 tap is required, 15–20 in. (38–51 cm) 2 taps, and 25+ in. (64 cm) 2–4 taps; some research indicates that using fewer taps-per-tree can substantially increase the volume of sap-yield-per-tap (Fig. 1.20).



Figure 1.18. A sugar maple with two spiles (i.e., taps) inserted into its stem and connected to the associated tubing (lateral lines) necessary for sap collection. Down lines then bring the sap to a collection tank (Photo by author).

When air temperature is above 32°F (0°C), tapholes are drilled 1–3 in. (2.5–7.5 cm) upward (to facilitate sap flow) into the sapwood (the lighter colored wood) of the tree trunk with a 7/16- or 5/16-in. diameter bit. New tapholes are drilled each year in areas free of wood deformation caused by scars and old taps. Once the taphole is free of debris, a sanitized spile called a spout and seat are inserted. At the end of the maple season, the spiles are removed and the tapholes are left uncovered to begin the internal repair process.



Figure 1.19 The tree is not harmed from the year-to-year tapping; however, the tree's response causes staining to the wood which can encompass 3 ft. (~1 meter) vertically up the stem from the taphole (Photo by author).

Traditionally, a metal bucket with a cover, to prevent rainwater and debris contamination, is hung from the spile with the sap dripping into the bucket. However, modern collection systems and producers with large operations use plastic tubing and dark colored pipelines. Sugarhouses and collection tanks are often found at a lower elevation than the sugarbush and the elevation gradient produces a natural vacuum within the tubing. However, if a small or no gradient exist, commercial vacuum systems can be added. Sap is collected daily to help prevent sap from bacterial fermentation and spoiling and is filtered and stored in large holding tanks (Fig. 1.22). A single tap on average produces one-quart of syrup; this amount depends strongly on the sugar concentration of

the sap. Thus, to produce 200 gallons (53 liters) of syrup, 400–800 tapholes would be required.

The highest-quality syrup is normally produced soon after the sap is harvested. Sap from the holding tanks is filtered to remove bark and any other large contaminants. The sap is then subjected to reverse osmosis to remove large quantities of water before the costly evaporation process. Next, the concentrated sap enters the wood- or oil-fired evaporator where the remaining water is evaporated (i.e., boiled off) until the sap (now, syrup) density is between 66–67% Brix². This level of density ensures the syrup will neither ferment nor crystallize.

Annual forecasts of maple syrup production are highly uncertain (Morrow, 1973), because sap flow (Fig. 1.23) is dependent upon critical changes in temperature during a relatively short period of alternately freezing and thawing diurnal temperatures. Maple sap is collected for approximately six to eight weeks each year under specific weather conditions that occur in northeastern North America from February through April. Optimal climatic conditions include a combination of nighttime temperature minima $\leq 32^{\circ}\text{F}$ ($\leq 0^{\circ}\text{C}$), contrasting warm, sunny days 44°F ($\geq 4^{\circ}\text{C}$) (Marvin, 1957, 1958), and sub-freezing soil temperatures that delay budding onset as bud break produces a sour sap and ends the sugaring season. Producers and researchers have explored the feasibility of fall (i.e., November) sap collection as similar meteorological conditions could be met and sap

² Brix is a unit representative of the sugar content of an aqueous solution. One degree Brix corresponds to 1 gram of sucrose in 100 grams of solution.

could be obtained. However, for tapped trees, both the amount and the sap-sugar content of the sap were lower than that obtained in the spring (Koelling, 1968).

Additionally, when springtime yields were compared between trees that were and were not tapped in the fall, trees tapped in the fall and spring produced significantly less than trees only tapped in the spring; conversely, no changes in sap-sugar content were found. These observations provided a strong case for the continuation of springtime sugaring and the cessation of counterproductive fall tapping.



Figure 1.20. A wounded (i.e., tapped) maple in early spring. Note the darker, wet bark from sap flow (Photo by author).

[1.7] Sugarbush Characteristics

Climatic conditions required for prodigious maple sap production limit the geographical range of the maple syrup industry. Sap used commercially is gathered from four of the 13 native maple species because of their unique physiology and high sap yields. In addition to sugar maple, silver maple (*A. saccharinum* L.), black maple (*A. nigrum* Michx. f.), and red maple (*A. rubra*) are used in the maple industry because of their high sap-sugar concentration and long sap collection season (Heiligmann and Winch, 1996).

Interestingly, maple syrup can be produced from the sap of bigleaf maples (*A. macrophyllum*) in the Pacific Northwest for noncommercial use. A preliminary study on bigleaf maple syrup production by Ruth et al., (1972) concluded that commercial production may be viable; however, syrup produced from bigleaf maples in Corvallis, Oregon, was of lower quality, with lower sugar content and comparatively less flavor than the Eastern U.S. standard. Despite the utility of other maple species, no maple species is as commercially viable as sugar maple. Sugar maples have one of the latest budbreaks and produce the largest yields of sap with the highest sugar concentrations of all maple species (Gabriel, 1972).

The maple syrup industry of northeastern North America has historically used wild sugar maples growing along roadsides, fencerows, or in stands of native forests, while more recently, sugarbush management has moved toward thinning, phenotypic stand selection, and cloning of maple saplings selected for high sap concentrations (Staats, 1994). Maple stands, called sugarbushes, often consist of mature trees.

Phenotype variation may also influence sap production as Taylor (1956) observed that phenotypes within the same sugarbush may have sap-sugar differences of more than 100%, although year-to-year yields of sap-sugar remain consistent (Marvin, 1957).

While many sugarbushes remain in an organic state year-round, as they are free of chemical treatment(s), commercial fertilizer use can result in a significant increase in sap-sugar concentrations during the concurrent sap-flow season (Perkins et al., 2004 and 2004). Sugarbush fertilization, however, can decrease the following sugar season's sap-sugar concentrations (Watterston et al., 1963), and thus chemical treatments are not widely used in the northeastern U.S.

Sugar-makers have long recognized the inter-tree variation of the sugar content and amount of sap produced from their sugarbushes, while often making a point to stop at a "sweet tree" for a drink. In other words, some trees are significantly more prodigious in their production of a high sugar content sap. Thus, understanding this variation is important when trying to reduce the amount of labor required in producing maple syrup from a dilute maple sap.

Anatomical differences among trees relating to starch storage capacity account for a minor portion of observed variability in sap-sugar concentrations (Marvin et al., 1967). The total solids in maple sap vary considerably daily and seasonally for individual trees and between trees, indicating that optimal conditions for two trees from the same sugarbush can vary. Thus, it is important to understand the degree of variation between trees and seasons. Additionally, understanding the influence of environmental factors

such as rainfall, light, and temperature that contribute to these variations is important to maple producers.

Taylor (1945) found that it is difficult to assign a sugar content (percent) value to a single tree. From the sugar maker's view, yield of syrup depends on sugar content of sap and sap flow volume. Early farmers and investigators have been aware of the fact that maple sap flows occur only following a rise in temperature. However, early efforts to correlate sap flow rate and volume with temperature were complicated by understanding which temperature parameter(s) to measure including air, soil, branch, bark, and trunk (Cortes and Sinclair, 1985). Further, crown health and size, and light interception are linked to phenotypical differences in sap-sugar concentrations.

In mature stands, maples that produce high-sap-sugar concentrations also produce the highest sap yields (Marvin et al., 1967). Additionally, the physical characteristics of a maple tree may provide a diagnostic feature in finding sweet- and high-yield trees. Specifically: 1) maples with sweeter sap have larger xylem rays than do trees with less sweet sap (Morselli et al., 1978); 2) maple trees with large crowns such as roadside and open-field trees tend to produce more and sweeter sap than forest-grown trees (Anderson 1951; Morrow, 1953; Morrow 1955); 3) faster growing mature trees usually are good sap producers, and sap sweetness increases with tree size (Moore et al., 1951); and, 4) crown size with trees having a broad healthy canopy is an important positive factor (Anderson, 1951).

Ray parenchyma cells (ray tissue) serve as essential vegetative storage tissues in which starch, sugars, and protein accumulate seasonally; additionally, is the primary

storage areas for sugar in trees (Kramer and Kozlowski, 1979). Attempts to correlate ray tissue, as a percentage of total-wood volume with sap-sugar concentration to aid in identifying “sweet” trees has been difficult. Morselli et al., (1978) and Gregory (1981) report that ray area is strongly correlated with sap-sugar; conversely, Wallner and Gregory (1980) report that no relationships exist between sap-sugar concentration and the amount of ray tissue, and that factors other than storage space are involved in regulating sap-sugar concentrations. Further, both Garret and Dudzik (1989) and Wallner and Gregory (1980), found a lack of correlation between the amount of sugar storage tissue (ray cells) and sap-sugar concentrations in sugar maple trees. Annual sap yields are correlated to the DBH of individual trees, although no relationships were found between sap sweetness and DBH. Additional studies by Marvin et al., 1967; Blume, 1973; Laing and Howard, 1990; and Larochelle et al., 1998, support a weak and non-significant relationship between DBH and sap-sugar concentrations. Crown ratios also are weakly related to sap and sugar yields in short-term studies (Marvin, 1957).

Conifers in a sugarbush may compete with sugar maples for soil moisture and nutrients (Walters, 1978). The competition effects can reduce sap flow and lower sap-sugar concentrations. Studies have shown that a closed sugarbush, with a coniferous understory composed of hemlock and white pine, consistently produced less syrup equivalent per-tap than those in an adjacent open, park-like bush. When the understory was removed, the two sugarbushes produced comparable amounts of syrup equivalent. Increased availability of nutrients, moisture, and growing space via selective-cutting can increase tree-growth rates and produce trees with large crowns and higher sap yields

(Walters, 1978). The influences of fast growth, increased tree vigor, and large crown effects on sap and total sugar production were also documented by and Jones et al., (1903), Moore et al., (1951) and Blum (1973),

[1.8] Physiology

The success of the sugar maple industry is associated with minor climatological variations (MacIver et al., 2006) that strongly affect sap production via physiological responses. Sugar diffusion from the roots into the tree occurs during cold springtime nights. As air temperatures drop, the branch extremities freeze as does the sap inside of them, attracting the unfrozen sap from the trunk into the extremities of the branches. Even though water volume expands upon freezing, maple wood properties provide the explanation for the unique absorption process.

In sugar maples, unlike in other species, the wood fibers are composed of dead cells, and those cells contain gas rather than water. These gases contract as temperature decreases creating space for water to expand upon freezing. In turn, sufficient space remains for more sap to be drawn by capillary forces from the roots to the branches through the xylem, creating positive pressure in the stem and thus sap flow (Corte and Sinclair, 1985).

Positive xylem pressure (sap flow) in sugar maples during early spring has been recognized and exploited for sugar and syrup production for centuries. The fundamental phenomenology of this process is well documented (e.g., Jones et al., 1903; Marvin, 1957, 1958; Morrow, 1952, 1955), but the exact mechanism of sap exudation is not completely understood (Cortes and Sinclair, 1984; Kramer and Kozlowski, 1997; Tyree

and Zimmermann, 2003; Cirelli, 2005). In addition to generating hydrostatic xylem sap pressure, sugar maples also produce a large concentration of sugar in the xylem. The sap is a dilute solution of water and sugar, along with traces of other non-sugar solids including organic acids, nitrogenous waste, and inorganic salts. The proportions of sap are variable and the sugar content, which is 99.9% sucrose, can range from 1–10%, with 2–6% being common. The diurnal behavior of the xylem sap osmotic potential nearly parallels that of sap hydrostatic pressure, but the connection between these two measures in sugar maples is indirect (Cortes and Sinclair, 1984). Therefore, the role played by the concentration of sucrose in the sap in generating hydrostatic pressure may be auxiliary.

[1.9] Meteorological and Climatological Conditions

Because of the known meteorological conditions associated with optimal syrup production, it is important to understand the relationship between changes in atmospheric circulation patterns such as the North Atlantic Oscillation (NAO) and seasonal temperature and precipitation trends. Several studies have found climatological trends relevant to northeastern U.S. agriculture including: 1) a greater rate of warming (+1.61°C) during December–February (Keim and Rock, 2001); 2) an average 8-day increase in growing season length (Easterling, 2002); 3) a decrease in annual and winter snow-to-total precipitation ratios (Huntington et al., 2004); and 4) an increase in the frequency of extreme precipitation events (Wake, 2005).

In addition, the NAO, which is a prominent winter teleconnection pattern that, when positive, produces stronger than average westerlies across the mid-latitudes bringing mild winters to the Northeast, has been in a positive phase over the past 30

years. The magnitude of the positive phase has been unparalleled in the observational record, with record anomalies occurring since the winter of 1989 (Visbeck et al., 2001). Because the positive (negative) phase of the NAO can produce winter and early spring temperatures that are above (below) the long-term mean, this teleconnection may supply additional warming to an already above-average winter and spring.

Sustainability of a climatically-sensitive industry such as maple sugaring depends on the ability of farmers to adapt to variable climate conditions. Warmer temperatures, the frequency and magnitude of insect outbreaks, changes in forest composition, and invasive plants all threaten the long-term sustainability of the sugar maple industry in Canada and the U.S. Thus, the decisions of producers to plant seedlings in their aging sugarbushes may be affected.

The recent decline in maple syrup production parallels the migration of the sugar maple range and a persistent increase in winter temperatures in this region. Climate scenarios show a possible shift of two degrees north latitude (from 45°N to 47°N) in the sugar maple's current geographical range over the next 100 years with the replacement of maples with oak, hickory, and pine (Iverson and Prasad, 1998; Beckage et al., 2008; Fig. 1.24).

Even with the use of current technological interventions such as reverse osmosis, ventless tubing, and vacuum pumping, the production of maple syrup continues to decline in the northeastern U.S. As ideal meteorological conditions (i.e., number of days with daily minimum and maximum temperatures 32°F ($\leq 0^{\circ}\text{C}$) and 44°F ($\geq 4^{\circ}\text{C}$) respectively) continue to decrease in frequency, the production of maple syrup may become

economically unviable for commercial producers. In general, the effects of springtime warming have been hypothesized by many sugarmakers and extension programs (MacIver et al., 2006), but no long-term studies have shown empirically how fluctuations in spring temperatures affect interannual yield.

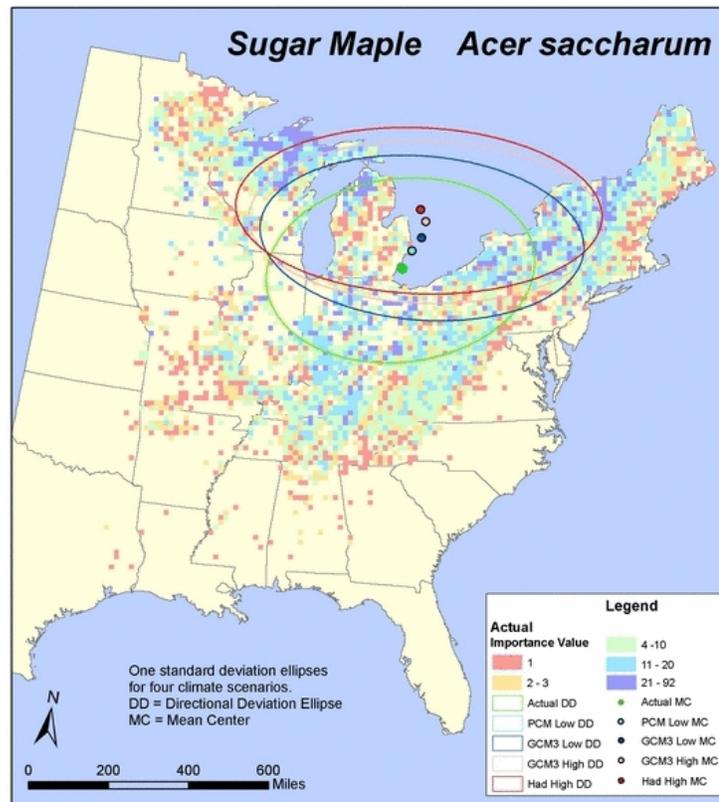


Figure 1.21. Current mean center and the potential changes in mean center of distribution for sugar maple (Source: Prasad et al., 2007).

The timing of ideal conditions has changed as maple producers throughout New England report that they are tapping their trees in February and ending the tapping (i.e., season) in March. Thus, the sugar season now ends approximately when it began in the late 19th to mid 20th century (Perkins, 2007). Additionally, producers express concern

that the optimal locations for the sugar maple industry will move northward as the frequency of freeze cycles become increasingly unpredictable. Sugarbushes will also produce less and lower-quality syrup, while warmer conditions may provide ideal conditions for the sap to ferment and spoil. Further, above-average winter temperatures affect the production costs, and during 2003–2007, the price per gallon of syrup increased 58% from \$26.80 in 2003 to \$42.40 in 2008 (Table 1; Keough, 2009).

Table 1. Average maple syrup prices for New York, 1916–2008. Prices are adjusted to 2009 dollars.

Year	Price/Gal.	Year	Price/Gal.	Year	Price/Gal.
1916	17.52	1947	48.46	1978	39.03
1917	18.24	1948	42.31	1979	38.21
1918	21.19	1949	37.39	1980	39.32
1919	20.09	1950	35.26	1981	41.01
1920	26.54	1951	33.50	1982	37.96
1921	21.99	1952	33.17	1983	36.14
1922	20.30	1953	35.29	1984	34.45
1923	21.19	1954	34.33	1985	33.64
1924	22.39	1955	34.86	1986	37.84
1925	21.84	1956	34.73	1987	43.42
1926	24.03	1957	31.64	1988	42.07
1927	24.50	1958	31.18	1989	40.83
1928	22.59	1959	32.75	1990	38.41
1929	23.33	1960	33.67	1991	36.24
1930	23.29	1961	31.92	1992	35.34
1931	21.07	1962	30.52	1993	27.42
1932	21.78	1963	30.85	1994	35.01
1933	19.67	1964	31.14	1995	32.76
1934	20.61	1965	30.62	1996	34.52
1935	20.88	1966	28.77	1997	33.41
1936	21.44	1967	31.77	1998	35.73
1937	22.18	1968	31.70	1999	34.82
1938	23.36	1969	33.56	2000	35.77
1939	24.45	1970	35.52	2001	35.82
1940	24.21	1971	35.62	2002	37.78
1941	25.22	1972	41.08	2003	31.18
1942	29.29	1973	41.54	2004	29.51
1943	35.58	1974	41.30	2005	34.53
1944	36.20	1975	38.64	2006	33.69
1945	37.15	1976	40.62	2007	34.63
1946	36.41	1977	38.84	2008	42.23

With these warming trends, maple syrup production may be inhibited and, in addition, have a higher sap-to-syrup ratio. Interestingly, when maple producers were asked to describe the 2005 maple season, which was a low-production year, their major concerns were: 1) insufficient cold weather; 2) shift toward increased cold in the early season followed by insufficient late-season cold; and 3) fickle weather that was poor for sugaring (USDA, 2005). From these observations, it might be hypothesized that maple syrup production strongly depends upon a balance between the daily minimum and maximum temperatures. Therefore, diurnal temperature ranges during early spring may be the central variable in maple yields.

Field studies have examined the short-term effects of daily temperature fluctuations on pressure formation in dormant maple trunks, which in turn influences sap yields (Jones et al., 1903; Marvin and Erickson, 1995). Further, the influence of temperature on sap flow has been examined in controlled experiments (Marvin and Greene, 1951; Sauter et al., 1973; Tyree, 1983; Cirelli, 2005). These field and laboratory experiments have shown that sap flow: 1) rates decrease over the long term with several days without $\leq 32^{\circ}\text{F}$ ($\leq 0^{\circ}\text{C}$) temperatures; 2) is weather dependent, and therefore is often intermittent (i.e., 2–12 sap-runs-per-year); 3) is caused by stem pressure produced during alternating diurnal cycles of $\leq 32^{\circ}\text{F}$ ($\leq 0^{\circ}\text{C}$) and $\geq 32^{\circ}\text{F}$ ($\geq 0^{\circ}\text{C}$); and 4) will not form in the absence of both freezing and thawing. Further, sap sweetness is highly influenced by seasonal temperatures and previous year precipitation patterns (Taylor, 1945). In general, the effects of springtime warming have been hypothesized by many

sugar-makers and extension programs (MacIver et al., 2006), but no long-term studies have shown empirically how fluctuations in spring temperatures affect interannual yields.

Several studies have used raw maple syrup production as their variable of interest. Maple syrup production is not only sensitive to climate but to economic, social, and political policies (Skinner et al., 2008) as well. Thus, to remove variation in production caused by non-climatological factors such as the reduction in the workforce of maple farmers during World War I and II, and to provide a meaningful index of production for the modeling, I will use the industry standard of yield-per-tap for analyses. Yield-per-tap is the yearly production of syrup in gallons divided by the number of taps used to collect the sap and is unaffected by non-climatological trends.

[1.10] Tree-rings

Tree rings of most temperate-latitude species have well-defined increments of xylem tissue that encircle the entire trunk corresponding to annual growth cycles. The frequency of species with tree rings is directly related to the seasonality of the climate. However, not all woody plants produce ring-width sequences that are datable and usable for climatic inference or ecological studies (Fritts, 1971). In the tropics where seasonality is limited by the absence of cold winters, many trees do not produce visible annual rings.

Light intensity and duration, temperature, water, nutrient supply, wind, mechanical damage to the crown, roots and stem, and pollution of air and soil can affect tree growth (Schweingruber, 1996). These abiotic factors can influence the rate of radial growth of the trunk over any temporal period (e.g., months, current year or a previous

year (lag)). The information contained in annual tree rings based on width variations is a valuable resource for studying environmental change. However, identifying the effects of a single growth factor may be difficult or impossible (Fritts, 1976; Biondi and Waikul, 2004). Often there is irrelevant noise present, and the desired signal must be extracted. Because of the presence of this noise in the series, a tree-ring series is thought of as a linear aggregation of several signals that can be interpreted as signal or noise depending on the hypothesis. Tree-ring growth (R_t) in any one year can be defined by the Principle of Aggregate Tree Growth (Fritts, 1976)

$$R_t = A_t + C_t + \delta D1_t + \delta D2_t + E_t$$

Where,

A = the age related growth trend due to normal physiological aging processes

C = the climate that occurred during that year

$D1$ = the occurrence of disturbance factors within the forest stand

$D2$ = the occurrence of disturbance factors from outside the forest stand

E = random (error) processes not accounted for by these other processes

δ = indicates either a "0" for absence or "1" for presence of the disturbance signal

Dendrochronology is the science of assigning statistically accurate yearly calendar dates to the xylem growth layers (i.e., tree rings) found in the stems and roots of woody plants (Fritts, 1971). The strength of this method relies on the ability to accurately date the year of each growth ring using crossdating. This technique is reliable

if the cambial growth in trees responds to environmental conditions that vary yearly. In certain species, the ring boundaries are difficult to define and occasionally a second ring (e.g., false ring, double rings, multiple rings, or intra-annual bands) is formed within the same calendar year. This process is predominantly found in conifers, and their appearance in dicotyledons is rare, although false rings have been observed in English oak (*Quercus robur*) (Schweingruber, 1996). Conversely, trees that grow under intense competition, on marginal sites, have been severely defoliated or damaged by air pollution, or are of great age may not produce a growth ring along the entire cambial surface every growing season. In this case, the ring is considered missing or, more accurately, locally absent. Rings will often appear somewhere along the circumference of the tree and therefore, tree slabs (i.e., cookies) are preferred for tree-ring analysis. Unlike false rings, locally absent rings are common in both conifers and dicotyledonous trees. The potential for both false and missing rings increases with the age of the tree, the position of the tree in the canopy (i.e., dominant or subdominant), and the degree of seasonal stresses.

Many tree species growing in the temperate to Arctic zones produce a distinct layer of xylem that can be correlated with the growing season. Generally, it is assumed that each ring represents the product of x year's growing conditions. However, the development of a single complete growth ring each year is not a given process (Kramer and Kozlowski, 1979). Xylem anatomy varies considerably among species and in different parts of the tree. Angiosperms are classified as ring porous (e.g., oaks, ashes, and elms) or diffuse porous (e.g., poplars, maples, Figs. 1.25–1.26; and birches). In ring-

porous trees, the diameter of the xylem vessels formed early in the growing season are much larger than those formed later. In diffuse porous rings, all the vessels are relatively small diameter, and therefore no visible boundary exists between the early and latewood.

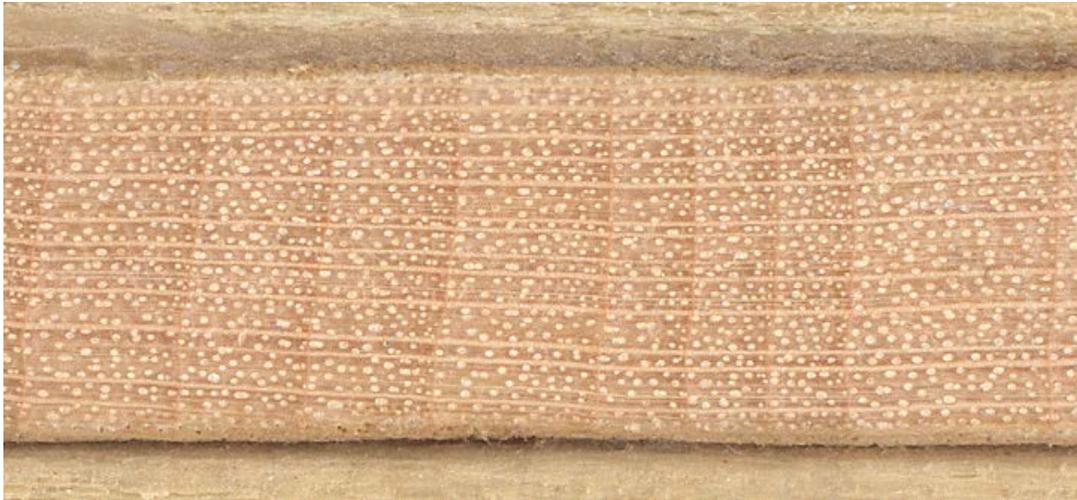


Figure 1.23. A macroscopic transverse view of sugar maple wood. Note the numerous, homogenous pores and the slim latewood boundary (Photo by author).

Counting back 100 rings from the cambium along a single radius of the stem does not ensure that the 100th ring was produced 100 years ago. To aid in crossdating, the list method is often used whereby years that are narrow are listed for each tree and then are compared. Typically, within a large sample, a pattern will develop and be used to check the dating accuracy of the cores. After this, the rings will be measured and the dating is statistically checked using a computer program called COFECHA (Holmes, 1986; see methods). If the dating is incorrect and not fixed, the signal strength of past conditions can be reduced and shifted away from the years in which the actual events such as droughts or ice storms occurred.

In synopsis, dendrochronology is a practical tool when the following conditions can be met (Telewski and Lynch, 1991):

- 1) a tree must have a distinct ring boundary;
- 2) the growth rings must occur on an annual basis;
- 3) the annual rings must vary either in ring width or in an alternative measurable feature from ring-to-ring; and
- 4) the patterns of the ring characteristic must crossdate within the tree and must crossdate between trees within a study site (and in some cases, between sites).

Typically, when these conditions are met, accurate calendar years are assigned to each tree ring and statistically verified. Once a series of tree rings (i.e., tree core) are obtained from several trees at a site and have been crossdated, they are combined to form a tree-ring chronology that will then be analyzed to obtain climatic or environmental data. Prior to growth/climate analysis, rings widths are typically standardized through curve fitting to remove known biological growth trends.

[1.11] Growth and Climate

Temperature is a major limiting factor of tree growth and is apparent in the zonal growth (i.e., boundary between early and late wood) differences. Within a species, tree rings are narrower in forests along northern timberlines and larger in warm, moist regions. However, extreme temperature changes and early- and late-frost can injure the tree and drastically alter its growth pattern. Both the qualitative and quantitative properties of temperature influence growth. Absolute values are important, especially

based on the season in which they occur and their amplitudes (e.g., maximums and minimums, cold air out breaks, and heat waves). There are also robust relationships between tree growth and geographical position including latitude, proximity to the ocean, distance inland, elevation, and topography (Fritts, 1976). Topographic irregularities, for example, may influence the duration of snow cover, soil temperatures, and the length of the growing period. These in effect, alter the complete physiology of the plant, which are important in the water-conducting and annual growth processes.

The water supply of a region or site has as large of an impact on the trees as temperature (Kahle, 1994). There are close relationships with geographical location and moisture availability, e.g., equator (dry), tropics (moist), altitude, and locations along ocean currents or mountains (wind/leeward). The qualitative and quantitative properties of precipitation also vary greatly, which—along with the relationship of daily and yearly cycles—determine plant growth rates. Additionally, the physical properties of the parent soil are variable, and soils with different compositions dictate the availability of water.

[1.12] Principles

In dendrochronology, the degree to which a tree reacts to environmental factors is its sensitivity. Sensitivity depends on the tree species and is visible in the tree-ring sequence. Sensitivity is reflected in the increase in particular narrower or wider tree rings throughout the series. Mean sensitivity is the measure of change and expresses the difference between two successive values in a series by means of percentages (Schweingruber, 1988). It is the average of the absolute values of the individual

sensitivities in a series and can be calculated either from raw or standardized values. The mean sensitivity for a series of rings widths is

$$\frac{1}{n-1} \sum_{i=1}^{n-1} \left| \frac{2(x_{i+1} - x_i)}{x_{i+1} + x_i} \right|$$

where x is either the ring width of the ring-width index for year i , and n is the total number of rings. The mean sensitivity is a relative measure of the differences and highlights variation in narrow rings more than variation in wide rings.

By calculating the sensitivity, it is possible to determine the extent to which growth of an individual species on a particular site is influenced by environmental factors, both abiotic and biotic. Additionally, periods of growth conditions can be identified and classified based on whether the ring width variation is stable or variable. Tree-ring widths that have little variation are referred to as “complacent,” and trees that have highly variable ring widths are said to be “sensitive.” Complacent tree rings will have little sensitivity while “sensitive” tree rings will have greater sensitivity. Mean sensitivity appears to be a strong indicator of the variability of those environmental factors that fluctuate annually.

Complacent rings indicate uniformity in the affects of climate factors upon the trees during a succession of years. If rainfall is the limiting factor, the effective rainfall must be evenly distributed throughout the series of years. Therefore, the trees are assured a constant supply of moisture and are seldom subjected to periods of drought (Glock,1939). Further, abundant rainfall evenly distributed over time is stored in the soil,

acting as a moisture reserve during drier periods. A constant and abundant supply of moisture tends to form consistently wide rings, while a constant but restricted supply of moisture tends to cause the formation of consistently thin rings.

Sensitive rings indicate significant departures from uniformity in the climatic effects upon the trees during a succession of years. Rings typically become more sensitive in regions close to the forest border and in areas where rainfall averages less than 10 centimeters per year (Glock, 1939). Differences in ring width in a sequence appear to vary in proportion to the departures of rainfall from the mean; the greater the departures, the greater the sensitivity. Sensitive rings indicate an environment in which annual moisture fluctuates distinctly from year-to-year.

Variations in year-to-year tree-ring widths can serve as natural records of climate when they represent a limiting factor(s). However, non-climatic factors including fire, erosional events, changes in water table, lightning strikes, ice- and wind-storms, insect infestations, nitrogen deposition, and changes in atmospheric CO₂ concentrations can alter tree growth rates (McIver et al., 2007)

Trees are typically selected from sites where ring-widths express significant interannual variability. Additionally, rings must be crossdated and sufficiently replicated to provide precise dating and to assure that the inferred climatic “signal” is robust and properly placed chronologically. Any random error, known as “noise,” from non-climatic variation in growth, is reduced when ring-width indices are averaged for *n* many trees.

Dendroecological techniques help evaluate the age structure and tree-growth patterns to document changing stand conditions either related to disturbance, stand development, or climatic variation (Payette et al., 1990; Foster et al., 199). Dendroecological techniques can also help to assess relationships between climate, site conditions, and tree growth to evaluate factors that influence the growth of a plant community (Cook and Kairiukstis 1989).

[1.13] Dendrochronology Applications

A basic means of predicting changes in an ecosystem is to create simulation models of the interactive processes between the ecosystem and its abiotic and biotic factors. Given the shortage of experimental data from long-term studies, the accuracy of determining many ecological characteristics is either indefinite or insufficient to make tangible practical applications (Menshutkin, 1971). To overcome the restraints of simulation modeling, we will use a dependent set of parameters (i.e., tree-growth) modeled to a set of environmental factors. These factors will then be used to characterize a parallel process (i.e., maple syrup production) that is affected by the same environmental factors.

Dendroecological studies have shown the feasibility of predicting future behaviors of ecological systems for 5–15 years (Cook and Kairiukstis, 1992). That said, there are few examples of the use of tree-ring chronologies for yield forecasting with the exception of the work done by Kairiukstis and Dubinskaite (1986) who investigated the dynamics of grain crops using a dendrochronological master series from *Pinus sylvestris* in Lithuania. The model obtained from their chronology was able to explain 72% of the

variance in crop yields, and projections of future yields were validated with the subsequent harvests. These results suggest the potential for successful forecasting of other crop yields using tree-ring data.

The application of tree-ring records to estimate previous crop yields was earlier suggested to discouraged Texas farmers dealing with a string of exceptional dry years by in 1858 (Campbell, 1949). Because of the lack of meteorological records and understanding of Texas climate on agriculture at the time, the application of tree rings to predict agriculture yields allowed farmers to put into perspective the occurrence and frequency of these exceptional dry years in Texas. More recently, agricultural reconstructions have been applied to the prehistoric Mississippian societies' food reserves in Georgia and South Carolina (Anderson et al., 1995) and for the reconstruction of historical maize yields for central Mexico (Therrel et al., 2006).

Following the comprehensive work of Fritts (1976), researchers have implemented standard dendroclimatological techniques to reconstruct a wide variety of climatic variables extending backward in time beyond the earliest instrumental records. For example, tree-ring data have been used to reconstruct drought indices, spatio-temporal patterns of precipitation and temperature, seasonal and annual atmospheric circulations, stream flow, lake levels, insect outbreaks, ice storms, and volcanic eruptions (Duvick and Blasing, 1981). Conversely, a limited number of studies have directly employed tree-ring data to examine crop variability. Tree-ring data obtained from sugar maples may provide another promising opportunity to determine crop yield, as several studies have demonstrated the feasibility of the species for dendroecological (e.g., Yin et

al., 1994) and dendroclimatological studies (e.g., Lane et al., 1993; Tardif et al., 2001). Coring practices have been used in the sugaring industry to assess tree growth rates as an indicator of competition (Heiligmann et al., 2006), but no studies have documented the application of tree-growth data for syrup yield predictions.

Therefore, understanding the effects that climate variability may have on crop and pasture yields—including those of maple syrup—has become increasingly important. Thus, this research will help to promote the effectiveness of using tree-ring data to predict agricultural yields, which will ultimately provide farmers additional information about crop yield cycles. This knowledge will in turn help to determine appropriate management methods for sugarbush operators during less-favorable climatological conditions. High-quality long-term crop yield data are scarce for many species, and the use of tree-ring data to reconstruct yield may be a viable method for extending historical records to examine annual-to-decadal harvest fluctuations.

CHAPTER II

METHODS

[2.1] Tree-Ring Data Collection and Field Methods

Data collection, sample preparation, and tree-ring chronology development follow methodology outlined in Stokes and Smiley (1968) and Fritts (1976). I collected tree-ring data from six study sites in New York State: 1) Arnot Teaching and Research Forest, Schuyler County (ASM); 2) Independence River Wild Forest, Herkimer County (IRM); 3) Keeney Swamp State Forest, Allegany County (KSM); 4) Madava Maple Syrup Farm, Dutchess County, (MDM); 5) R. Milton Hick State Forest, Otsego County (MHM); and 6) the Uihlein Sugar Maple Research & Extension Field Station, Essex County (UUM) (Figs. 2.1 and 2.2).

[2.2] Regional Forest and Site General Descriptions

2.2.1 The Hemlock–White Pine–Northern Hardwoods Region

This forest region extends from northern Minnesota and extreme southeastern Manitoba through the upper Great Lakes region and eastward across southern Canada and New England, toward the southeast, much of the Appalachian Plateau in New York and northern Pennsylvania. Outliers of the region include the southern Allegheny Mountains of Pennsylvania, Maryland, and West Virginia. The region has pronounced variations of deciduous, coniferous, and mixed forest communities.

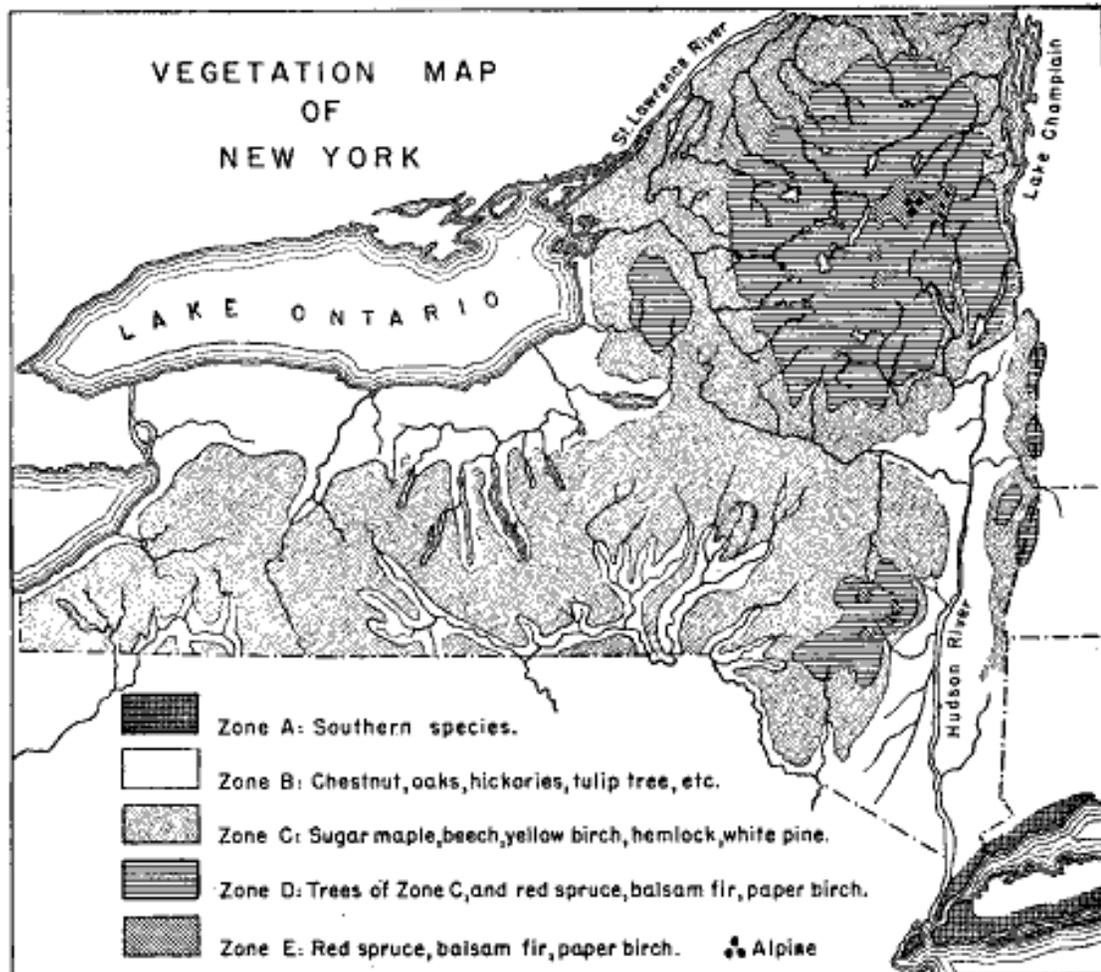


Figure 2.1. Generalized vegetation map of New York (From Braun, 1950).

Sugar maple (*A. saccharum*), beech (*Fagus grandifolia*), and basswood (*Tilia Americana*), sugar maple and beech, or sugar maple and basswood are typically the dominant primary deciduous communities while yellow birch (*Betula alleghaniensis*), white elm (*Ulmus americana*), and red maple (*A. rubra*) occur less frequently. Secondary deciduous communities are composed of aspen (*Populus* spp.), balsam poplar (*P. balsamifera*), paper birch (*Betula papyrifera*), and gray birch (*B. populifolia*). Additionally, two main coniferous communities occur; white pine (*Pinus strobus*), red or Norway pine (*P. resinosa*), and jack pine (*P. banksiana*) prevail in the sandy plains and ridges; and in moist, bog or muskeg, areas black spruce (*Picea mariana*), northern white cedar (*Thuja occidentalis*), and larch are dominant. In addition, a third conifer community of red spruce (*P. rubens*) occupies mesic flats and slopes in the northeastern section. The primary mixed communities are hemlock and northern hardwoods or red spruce and northern hardwoods, hardwood species include sugar maple, beech, basswood, and yellow birch, with an infusion of white pine.

The boundaries of The Hemlock–White Pine–Northern Hardwoods Region are poorly defined, and encroaching southern species and migrating northern species complicate this distinction. The boundaries of this region do not coincide with any soil province boundaries, but a moderate association between this region and the area of Podzols exists. The Hemlock–White Pine–Northern Hardwoods Region consists of two main divisions, the western Great Lakes–St. Lawrence Division and on the eastern side, the Northern Appalachian Highland Division. The regional division coincides roughly

with the topographic break between the physiographic regions and is retained by the biogeographical range of regional dominate forest species.

2.2.2 Northern Appalachian Highland Division

The Northern Appalachian Highland Division covers the northern Appalachian Highlands from northern Pennsylvania northeastward across New York, New England, and the maritime provinces of Canada, and northward onto the plains of Lake Ontario. The region is marked by mountainous terrain, with more relief than that of the Great Lakes–St. Lawrence Division. Most of the region experienced glacial activity except for its southern extension in Pennsylvania. Additionally a great extent of the topography is controlled by underlying bedrock movement (Braun, 1950).

The North Appalachian Highland Division has three subsections. The **Allegheny** section, which includes the entire region south of the Mohawk River and south of the lowland adjacent to Lake Ontario; the **Adirondack** section, north of the Mohawk River, including the Adirondack Mountains; and the **New England** section, including most of New England and adjacent areas in Canada (e.g., Acadian Forest region) (Braun, 1950).

2.2.3 Allegheny Section

The Allegheny Section occupies most of northern Pennsylvania and southern New York. Its southern end in Pennsylvania lies between the northern extensions of the Mixed Mesophytic region on the southwest and the northern end of the Oak–Chestnut region on the southeast. Along the area adjacent to Lakes Erie and Ontario, it is in contact with a section of Beech–Maple region. The Allegheny section includes both the

Catskills Mountains and a majority of the Allegheny Mountains of Pennsylvania. This section occupies the northern end of the unglaciated Allegheny Plateau in northern Pennsylvania and adjacent New York and all of the glaciated Allegheny Plateau excluding Ohio and eastern Pennsylvania.

Forest vegetation of the Allegheny Plateau and Allegheny Mountains portion of the section is similar throughout its boundaries. However, local and regional differences are often related to soil or moisture profiles. Additionally, forest vegetation of the upland has been so profoundly modified by lumbering and greater fire suppression activities that it bears little resemblance to the original cover.

2.2.4 Catskill Mountains

The relief and range of elevation of the Catskill Mountains result in a greater diversity of vegetation than seen in most regions of the Allegheny Plateau (*sans* the Finger Lakes district). Deciduous forest and mixed deciduous-coniferous (e.g., hemlock, white pine, red spruce, and balsam fir) exist over most of the Catskill Mountains to an elevation of ~1,068–1,128 meters while Oak of oak–hickory (formerly oak–chestnut) forest are found in the lowest elevations. In these low-elevation, white-oak dominant forests, topography often dictates the abundance of red oak, chestnut oak, black oak, scarlet oak, hickories, historically chestnut, sugar maple, white ash, basswood, butternut, and white pine.

Above ~368 meters, the hardwood forest dominants are sugar maple, beech, yellow birch, hemlock, and white pine communities. Sugar maple is prominent and intermixed with beech, yellow birch, basswood, red oak, butternut, white ash, black

cherry, and hemlock. From ~549–610 meters, red spruce and balsam fir become apparent, marking a transitional forest zone. The transition into Hemlock–White Pine–Northern Hardwood region is distinguishable by the dominance of maple, beech, yellow birch, hemlock, white pine, red spruce, and balsam fir.

2.2.5 Adirondack Mountains

The entire area of the Adirondack Mountains experienced glacial modifications. The eastern part of the Adirondacks is mountainous with two summits above 1,524 meters (5,000 feet) and fourteen other peaks above 1,220 meters. The western part of the Adirondacks is a dissected plateau of ~610 meters. The elevated regions are predominantly occupied by deciduous or mixed deciduous–coniferous forests. The lowlands of the section are occupied by extensions of the oak–chestnut forest and the hemlock–hardwood forest, both which prevail over the northern Allegheny Plateau. More characteristic of the Adirondack section are the uplands, which support what may be termed a mixed or spruce–hemlock–hardwoods, or spruce–hardwoods forest; however, this varies in composition in relation to soil and moisture regimes and altitude. The principal species are red spruce, balsam fir, yellow birch, sugar maple, and beech, with hemlocks and white pines dispersed

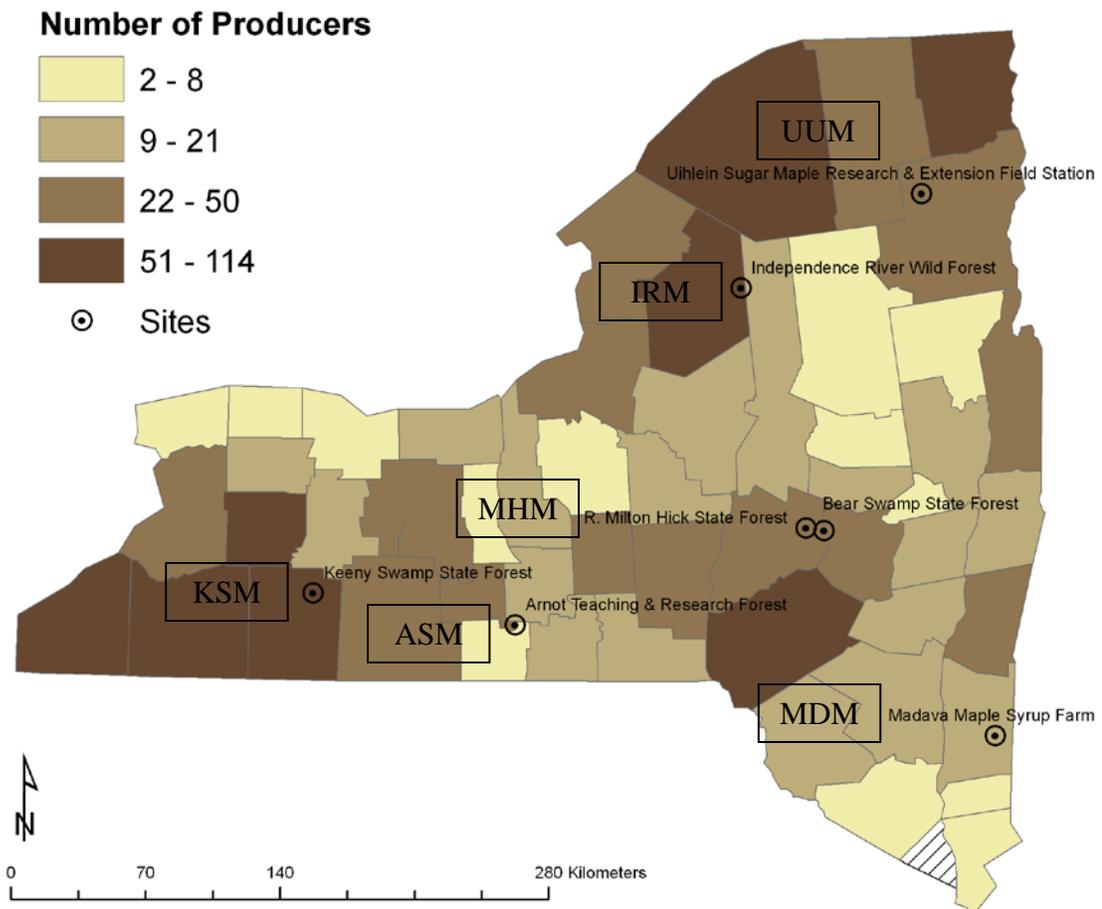


Figure 2.2. Study sites and the number of maple syrup producers classified based on the modified Jenks' natural breaks by county.

The six sites were strategically chosen to ensure a comprehensive growth analysis of sugar maples across the topographically and climatological diverse landscape of New York (Fig. 2.1 and Table 2.1). New York State is divided into two climatological regions based on the average position of the convergence of winter Arctic and Pacific Frontal Zones (Pederson et al., 2004). Accordingly, the sites were appropriately distributed across the two regions. However, to reduce the variation in tree growth attributed to an

elevational gradient; all sites are located within 1.4 standard deviations (149 meters) of the mean site elevation.

Table 2.1 Sugar maple tree-ring chronologies located throughout New York State developed by author.

Sites	Elevation (m)	Chronology interval	Series length (yrs.)	Mean length (yrs.)	Sample size (cores)	Number of trees
ASM	389	1885–2008	124	108.3	32	23
IRM	460	1796–2009	214	133.7	30	20
KSM	534	1746–2009	264	155.1	32	24
MDM	366	1876–2009	134	93.2	36	28
MHM	606	1784–2008	225	115.6	34	27
UUM	595	1906–2009	104	88.3	33	23
Median	497	-	174	112	32.5	23.5

Table 2.2. Generalized site descriptions.

Site	Forest Type	Predominant Soil Type	Slope (%)
1) ASM	Allegheny Section	Philo silt loam, Valois gravelly silt loam	3–8
2) IRM	Adirondack Mountains	NA	NA
3) KSM	Allegheny Section	Ischua channery silt loam	25–35
4) MDM	Catskill Mountains	Hollis-Chatfield-Rock outcrop complex	>30
5) MHM	Catskill Mountains	Bath channery silt loam	15–25
6) UUM	Adirondack Mountains	Adams loamy sand, Croghan fine sand	3–8

During the spring and summer of 2008, 2009 and 2010, I sampled 30 living, healthy-appearing sugar maples at each site using a 5.15 mm (0.20 in.) Swedish increment borer. Areas on the tree stem with defects, burls, signs of dieback, or potential for rot were avoided (Fig. 2.6). The forests/sampling sites were pre-surveyed for desirable trees (i.e., potential for individual trees to be at least 110–300 years old) with the assistance from the New York Department of Conservation’s regional foresters. Upon arrival to sites, the forests were visually surveyed and tree selections were made based on generalized old-growth morphological characteristics (Fig. 2.4) (Pederson, 2010) that include large size, gnarled upper limbs; few low living branches (Figs. 2.7 and 2.8). Additionally, attention was paid to topographic position of the trees so that various aspects, slopes and forest communities were represented.

Two cores were extracted at breast height (~1.3 meters) from opposing sides parallel to slope contours to avoid problems associated with reaction wood (Fig. 2.4). Therefore, each site contained 60 samples, representing two cores from all trees. Additionally, while obtaining the core samples, I recorded additional information about each tree, including basal diameter and crown characteristics.



Figure 2.3. Justin T. Maxwell holding a freshly extracted sugar maple tree core from ASM. Unlike conifers, it is often difficult to visualize the ring boundaries and therefore, estimates of tree age based on visual inspection in the field are hard (Photo by author).



Figure 2.4. Coring a shaggy-sugar maple at Independence River Wild Forest, Herkimer County, NY, May 2010. Shaggy bark is thought to be a characteristic of older (>150 years) sugar maples (Photo by Justin T. Maxwell).

I sampled crown codominant and dominant (Fig. 2.5) sugar maples to minimize forest dynamics effects and thus increase the likelihood that the variability in tree growth is principally a response to climate variables. The study sites fit several criteria designed to reduce potential confounding influences associated with anthropogenic disturbance. I selected areas historically protected by the state government or with known dates of disturbances such as logging, which allows for a more precise dating of releases or suppressions. Additionally, I avoided forest parcels with known tree-tapping activity, as tapping can affect tree growth patterns and vigor (personal observations; B. Chabot, Cornell University Sugar Maple Extension Program, pers. com., 2010).



Figure 2.5. A crown-dominant sugar maple. Note the absence of lower branches. (Photo by author).

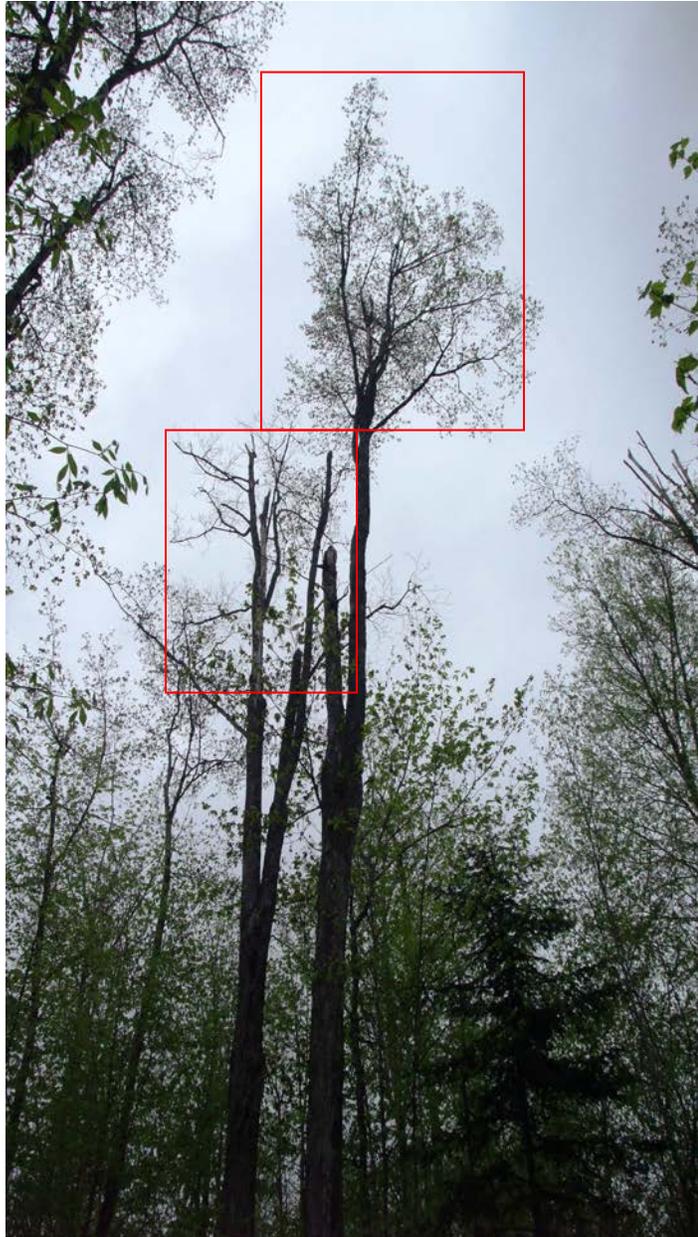


Figure 2.6. Two sugar maples exhibiting signs (i.e., broken and leafless branches) of dieback. Trees with visual signs of dieback were not sampled (Photo by author).



Figure 2.7. Coring at Keeney Swamp State Forest, Allegany County, NY (KSM). The oldest sugar maple from the six sites, 246 years old (not pictured), was sampled here (Photo by Justin T. Maxwell).

To examine potential changes in growth rates across the time span of human-caused climate changes (pre- and post-1950), I avoided sampling trees younger than 50 years. Thus, these results indicate the response of mature, wild sugar maple trees that: 1) germinated before anthropogenically caused changes, and 2) where tree growth, particularly post-1950, has occurred under rapidly increasing CO₂ concentrations that may have affected growth through atmospheric CO₂ fertilization.



Figure 2.8. This characteristic understory dominated the six research sites. Photo by Justin T. Maxwell, was taken at the Arnot Teaching and Research Forest, Cornell University, Schuyler County, NY.

Table 2.3. Sugar maple tree-ring chronologies series statistics.

Sites	Interseries correlation (Pearson's <i>r</i>)	Mean Sensitivity	Auto Correlation	Percent Missing Rings
ASM	0.691	0.314	0.654	0.606
IRM	0.553	0.294	0.731	0.249
KSM	0.563	0.358	0.776	2.478
MDM	0.611	0.316	0.732	0.388
MHM	0.680	0.376	0.625	0.432
UUM	0.712	0.217	0.635	0.034
Median	0.645	0.315	0.693	0.410

[2.3] Meteorological Data

Mean monthly temperatures and mean monthly precipitation for January–December were obtained from NY climatic divisions 1, 2, 3, 5, and 10 for the period of 1895–2009 from The National Climatic Data Center (NCDC). State-level mean monthly temperatures and precipitation, and monthly heating and cooling degree days (HDD and CDD, respectively) were also obtained from the NCDC for the same period.

[2.4] Maple Syrup Yield Data and Modeling

I used statewide yearly maple-syrup production (gallons) and number of taps obtained from the United States Department of Agriculture’s National Agricultural Statistics Service New York Field Station. Typically, production is measured in terms of the number of gallons produced. “Bumper” years are identified by years of above-average production preceded by a series of below-average years. Production, as

measured by the number of gallons produced in the state does not offer much information about the efficiency of sap flow for a given year or region. The number of gallons produced during a season can be influenced by the physical environment (e.g., meteorological) as well as other variables including the number of producers and trees tapped and season start and end dates. To adjust for these factors and to provide a measure expressing the meteorological-based variation in yield, the industry standard, *Yield-per-Tap*, is commonly used. Thus, this measure allows practical comparisons between years and regions where syrup is produced.

Previous studies have used raw maple syrup production (i.e., gallons produced) as their variable of interest (*cf* Whitney and Upmeyer, 2004). However, maple syrup production is not only sensitive to climate, but to economic, social and political policies (Chabot et al., 2008). Thus, to remove variation in production caused by non-climatological factors including a decline of maple farmers during WWI and WWII, and to provide a meaningful index of production for my modeling, I used the industry standard of yield-per-tap for analysis. Yield-per-tap is the yearly production of syrup in gallons divided by the number of taps used to collect the sap and is independent of non-climatological trends.

I used multivariate regression analysis to produce the best model and to determine which variables account for the variation in maple syrup yield. Because of the complexity of ecophysiological processes, the initial number of predictors (20–30) was relative to the complexity of the system being studied (Kairiukstis and Dubinakaite, 1986). To reduce estimation bias, I used Mallows' C_p Statistic, Predicted- R^2 , and the

Variance Inflation Factor (VIF) as regression diagnostics. The meteorological predictors were then modeled with the variable yield-per-tap obtained through the United States Department of Agriculture National Agricultural Statistics Service New York Field Office.

[2.5] Lab Methods

Increment cores were allowed to air dry and then mounted onto a wooden core mount with the cells aligned vertically so that the ring boundaries were visually apparent after sanding. The cores were sanded using progressively finer sandpaper, beginning with ANSI 120-grit (105–125 μm) and ending with ANSI 600-grit (26–29 μm). The sanding process allowed the cellular structure of the tree rings to be visible under standard 10X magnification.

I crossdated my samples using visual and statistical crossdating techniques to assign calendar years to each ring in my samples. I also used the list method by identifying and recording notable marker rings to assist in crossdating (Yamaguchi, 1991). Visual crossdating was accomplished through recognition of patterns of wide and narrow rings common to all my sites (Fritts, 2001). This procedure also accounted for locally absent and false rings.

Each set of raw tree-ring measurements was evaluated using the computer program COFECHA (Holmes, 1983) to ensure proper crossdating and assess series correlation and mean sensitivity of ring widths (Table 2.3). The COFECHA program analyzed patterns in the ring-width measurement series of each individual sample from a data site and detected (flags) possible errors in crossdating. The assignment of flags by

COFECHA to individual samples in a data set can guide a reconsideration of the crossdating of increment core samples. Cores that correlated poorly in COFECHA were removed from the population prior to chronological development in ARSTAN. Cores that were removed had Pearson's r -values of <0.450 , or in some cases, the core was stripped in length to remove low correlating 50-year segments if sample depth was needed. However, COFECHA allowed only a statistical analysis of the similarity between the individual time series at the site. Further examination of the physical samples may indicate that COFECHA, rather than the crossdating procedure, was in error (Fritts, 1991). COFECHA provides two other critical measures of the quality of a tree-ring data set. First, the program assesses the inter-series correlation of each sample at a site; a mean inter-series correlation above 0.40 is considered desirable (Holmes, 1983). Second, the program provides the mean interannual sensitivity of all samples. Higher mean sensitivity at a site may indicate a greater likelihood of a strong growth-limiting signal, often climate-related (Stahle and Cleaveland, 1992).

After crossdating the cores, individual ring widths were measured to an accuracy of 0.001 mm using a linear encoder. I used the program ARSTAN (Cook and Holmes, 1985) to develop the standardized chronology for each site. In order to preserve low-frequency signals that may contain oceanic atmospheric teleconnections, I employed conservative standardization techniques such as fitting a negative-exponential curve or a negative linear curve for the development of our chronologies (Figs. 2.9 and 2.10). Additionally, if stand dynamics were present (i.e., growth effects of canopy openings, windfalls, ice storms) a Freidman super smoother (Fig. 2.11) was used to reduce the

influence of short periods (3–5 years) of suppressed or abrupt growth at that may be caused by stand dynamics present in the tree-ring time series while simultaneously preserving long-term trends.

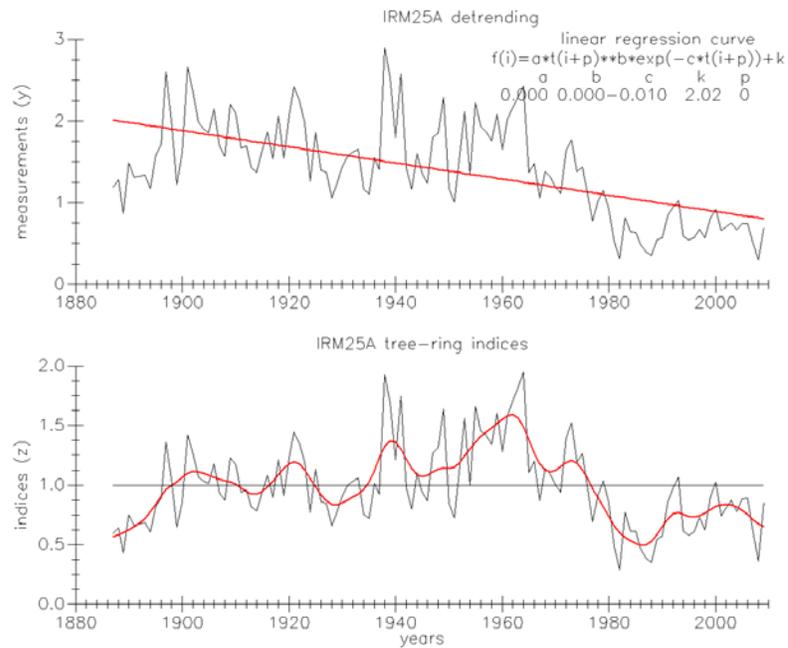


Figure 2.9. Raw ring-width measurements exhibiting a negative linear growth pattern (top). The raw series is detrending using the fitted linear model and is then standardized (bottom).

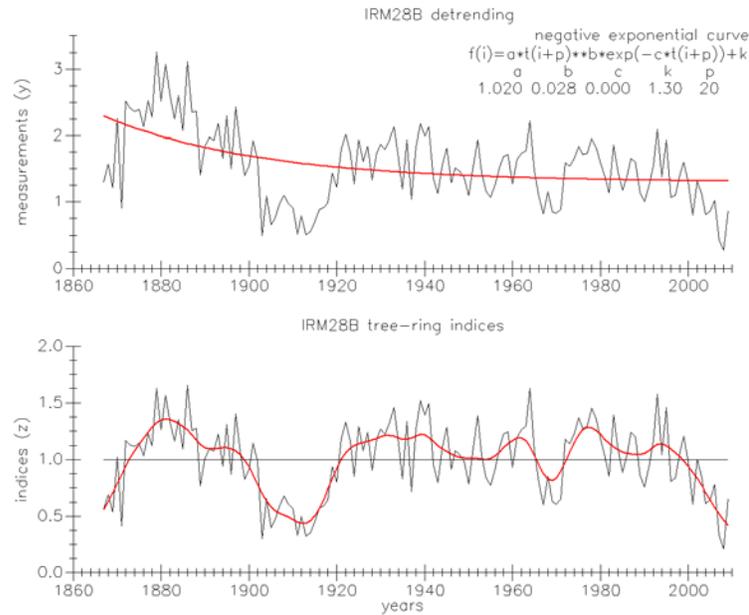


Figure 2.10. Raw ring-width measurements exhibiting negative exponential growth (top). The raw series is detrending using the fitted exponential model and is then standardized (bottom).

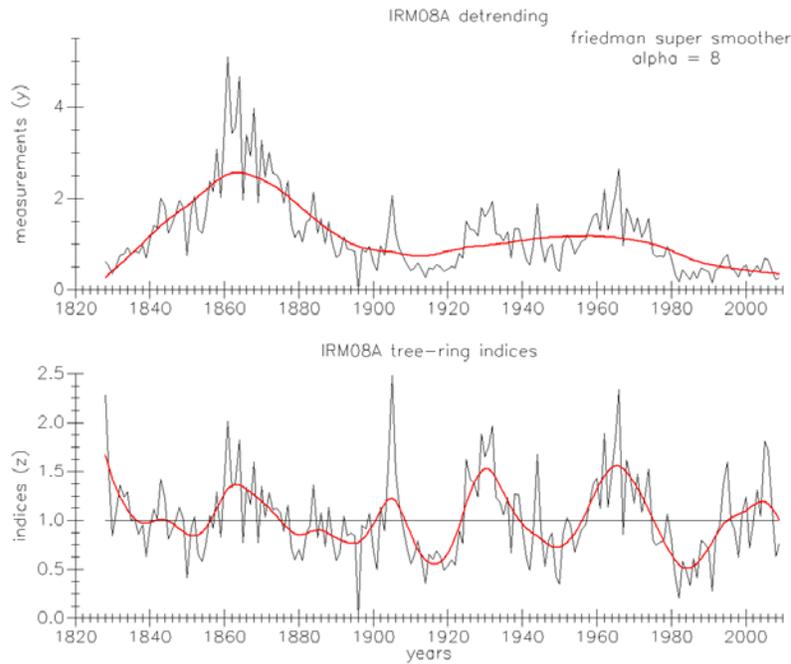


Figure 2.11. Due to forest dynamics, in some cases neither a negative linear nor negative exponential model can be used for detrending. Therefore, a Friedman super smoother curve is fitted to reduce the effects of short periods (ca. 1860) of growth releases.

After detrending, each series of tree growth are averaged using a biweight robust mean function to create the mean value function for each population of trees (Pederson et al., 2004). Using a biweight robust mean will reduce the effects of outliers for individual tree-ring series in the chronology (Cook and Holmes, 1992). To capture the climate signal, a residual chronology, which contains the least amount of disturbance-related growth and lacks autocorrelation (Cook, 1985), was evaluated for possible selection for use in the development of growth-climate models.

Chronology reliability (i.e., quality) was estimated using the metrics *rbrar* (Briffa, 1995) and expressed population signal statistics (*EPS*) (Wigley et al., 1984). *EPS* and *rbrar* are the chief diagnostics tools in testing chronology reliability for climatological studies and, to a lesser degree, in ecological studies. *Rbar* is independent of sample size and unbiased, and is the mean correlation of all growth series (i.e., cores) within a population of sampled trees (Fig. 2.12). *EPS* is a function of *rbrar* and sample size and describes how well a finite sample size estimates an infinite, hypothetical population (Fig. 2.12). Chronology lengths were then stripped to the year that corresponded with an *EPS* value ≥ 0.85 (Fig. 2.12; Cook et al., 1992)

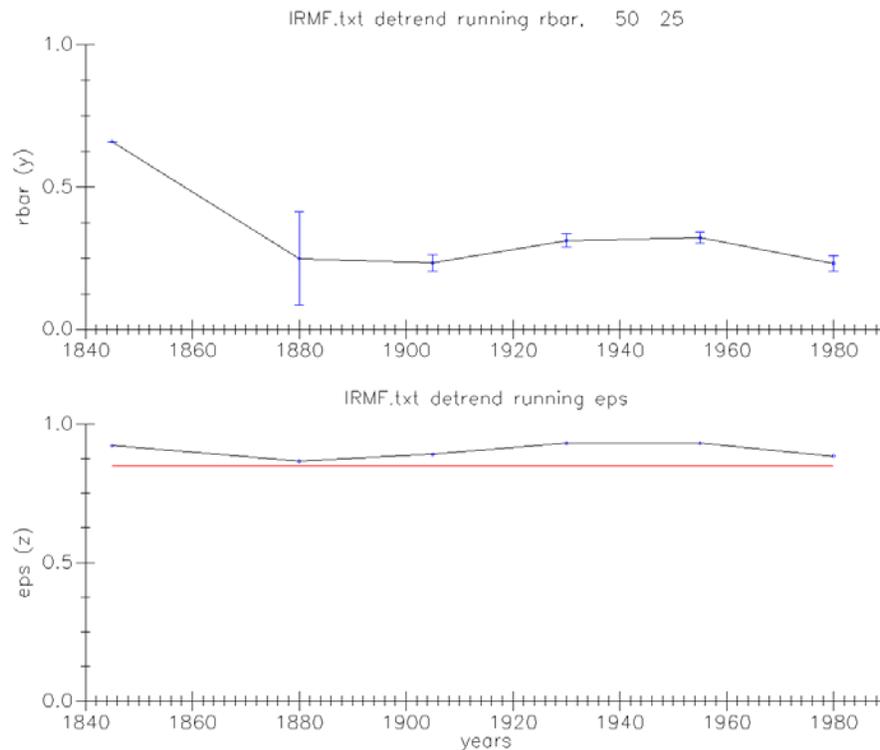


Figure 2.12. *Rbar* (top) is the mean correlation of all combinations of ring width series (i.e., tree cores) and measures the strength of the common growth signal within a chronology. *EPS* (bottom) is a function of *rbar* and sample replication; an *EPS* value of 0.85 (red line) is preferred and quantifies the degree to which a particular chronology portrays the hypothetically perfect chronology (Cook et al., 1992).

[2.6] Principal Component Analysis

A number of studies have identified homogeneous climatic zones within larger regions using some form of principal component analysis (PCA) such as Knapp et al., (2002) and Ali (2004). The most common method of identifying clusters of common climatic variability is eigenvector analysis (White et al., 1991; Malmgren and Winter 1999). Although eigenvector analysis refers collectively to empirical orthogonal functions, PCA, and common factor analysis, PCA is better suited for the interpretation of modes of variation (White et al., 1991). The regionalization exposed patterns that

allowed correlation analyses with atmospheric teleconnection features and regional climatic data.

Climatic regionalization is inherent to tree-ring reconstructions of climate. Tree-ring data from a given location often have strong correlations with climate data in a larger surrounding region (Griggs et al., 2007; Akkemik et al., 2008). Tree-ring data may have also correlated strongly with climate data in areas far removed (e.g., > 200 km) from the data-collection sites (Stahle and Cleaveland, 1992; Griggs et al., 2007). Regions with strong correlations between instrumental climate data and tree-ring data are considered homogeneous climatic regions, despite observed variability within the identified region (Stahle and Cleaveland, 1992; Griggs et al., 2007).

I compiled and analyzed radial-growth indices from each site using Eigenvector analysis. My study employed S-mode PCA, the most commonly cited approach for climatic analysis (Kolivras and Comrie 2007; Timilsena and Piechota, 2007).

The fundamental goal of PCA is to express a majority of the variance in the original data in a smaller number of variable dimensions, thereby reducing complex data sets to physically interpretable abstractions (White et al., 1991; Malmgren and Winter, 1999). In practice, a small number of PCs can often account for as much variance as the original variables by discounting noise in the data. Regardless of the procedure, the PCs are orthogonal (uncorrelated), with the first PC accounting for as much of the variance as possible. Each successive PC accounts for the maximum possible remaining variance. Principal components explaining a substantial portion of the total variance can be extracted with various applications based on the objectives of the analysis (Cattell 1966).

After an initial S-mode PCA retaining all factors, the investigator selects one to several PCs for further analysis. Retention of too few components may oversimplify spatial patterns, while the retention of too many involves the inclusion of increased noise in the data. In turn, over-retention may distort spatial patterns and lead to splintering of spatial units (Richman, 1986). A common approach for PCs retention is based on scree-plot evaluation (Cattell, 1966). The plot shows the curve of explained variance associated with each successive PC. A leveling-off of the scree plot indicates a substantial reduction in explained variance by the addition of more PCs, and provides a valuable guide for selecting a range of factors to retain. However, no method insures extraction of the correct number of PCs. The results must come from PCs that display logically interpretable patterns (Cattell, 1966).

[2.7] Growth-Climate Analysis

Step one of climate analysis was to determine climate variables significantly related to sugar maple growth at the six sites. I used two techniques, correlation analysis and response-function analysis, to test the growth response to climate. I used DENDROCLIM2002, a dendroclimatic analysis program (Biondi 1997; Biondi and Waikul 2004), for both analysis types. PRECON (Fritts, 1991) is an alternative software program that develops a bioclimatic model of tree growth and calculates the explained variance of each climate variable using response function analysis (RFA). However, DENDROCLIM2002 is preferred first because of its user friendly interface and secondly because the bootstrapped confidence intervals are calculated for both correlation and response functions. Bootstrapping was added to this technique in order to avoid bias,

limit error, and achieve more accurate results (Guiot, 1991; Biondi and Waikul, 2004). DENDROCLIM 2002 checks the statistical significance of response function coefficients with the bootstrap method and highlights coefficients exceeding the 95% significance level (Biondi, 1997; Biondi and Waikul, 2004). This ensures accurate testing for significance of variables (Biondi and Waikul, 2004) and even in the presence of autocorrelated data. DENDROCLIM2002 assumes data to be normal and therefore the correlation analyses generates Pearson product-moment correlation coefficients (r) between monthly climate variables and ring-width indices.

[2.8] Correlation Analysis

Within DENDROCLIM2002, the Pearson product-moment correlation coefficient is calculated between each year's ring-width index and monthly climate variables from June of the previous growing season to November of the current growing season. I calculated correlation coefficients from 1910 to the most recent common growth year, 2007.

[2.9] Response Function Analysis

Originally developed by Fritts (1991), response function analysis (RFA) uses principal components multiple regression to eliminate the effects of interdependence among climate variables (Fritts et al., 1971; Fritts, 1976). Like correlation functions, RFA identifies monthly climate variables significantly affecting tree growth. DENDROCLIM2002 uses bootstrapped confidence intervals to comprehensively test for significance (Biondi and Waikul, 2004).

I conducted response function analyses to complement the correlation analyses of the climate-tree growth relationship. RFA is a widely applied technique that uses principal components multiple regression to estimate indexed values of ring-width growth. The products of the regression coefficients and the principal components are calculated to obtain a new set of regression coefficients related to the original climate data (Briffa and Cook, 1990; Biondi and Waikul, 2004). An advantage of RFA over correlation analysis is that RFA removes the effects of interdependence among the climate variables (Fritts, 1976). When correlation and RFA are conducted together in DENDROCLIM2002, RFA typically identifies fewer significant relationships than correlation analysis.

[2.10] Moving Correlation Analysis

After the initial correlation and RFA, I performed moving-correlation analysis between growth and monthly precipitation, temperature, and PDSI at moving x -year intervals using DENDROCLIM2002. Biondi and Waikul (2004) suggest a window length of at least twice the number of predictor months. For precipitation and temperature the period of analysis was the common period of all chronology, 1910–2007.

The objective of this analysis was to test for temporal changes in the climate-tree growth relationship (Biondi, 1998; Biondi and Waikul, 2004), including complete shifts to which variables a tree, or stand of trees, responds and changes in response strength. A consistent response to a given climate variable indicates that a dataset may have climate reconstruction potential. The results of moving correlation analysis will be displayed individually for each variable (monthly mean temperature and precipitation) using the

standard graphical outputs from DENDROCLIM2002. Intervals during which a variable was not significantly correlated to tree growth are shaded green, while significant correlations are colored according to the strength of the correlation coefficient

Analyzing the changing relationships between tree growth and climate has a long history within dendroclimatology (Visser and Molenaar, 1987), with increasing importance since the identification of the divergence problem (Briffa et al., 1998; Esper and Frank, 2009). In the 1980s, Van Deusen (1987) and Visser and Molenaar (1987) applied the Kalman filter to dendrochronology. The Kalman filter has been used to create tree-ring chronologies from numerous ring-width series and to generate predictors of tree growth, based on climate variables that can change temporally (Van Deusen, 1987). This technique indicates if correlations levels of specific climate predictors are stable and has been used to analyze tree growth-climate relationships in the eastern U.S. The earlier work of Van Deusen (1987) and Visser and Molenaar (1987) suggested that the climate variables that affect tree growth today might not be the same variables that affected past tree growth. Significant climate response variations throughout the calibration period compromises reconstruction reliability.

[2.11] Reconstruction

I used a two-stage process of calibration and verification to develop the yield-per-tap (i.e., syrup yield) reconstruction. Simple correlation analysis between the tree-ring chronologies and yield-per-tap was used to determine the reconstruction potential. I then used calibration and verification tests of the reconstruction model for two periods: 1916–1960 and 1961–2006 and developed a yield-per-tap regression model for 1960–2006

using tree-ring chronology indices as the dependent variable and the yield-per-tap as the independent variable.

The resulting predicted values obtained from linear regression models were verified against the observed yield-per-tap for the independent period (1916–1960). I repeated this procedure using the earlier period (1916–1960) as the dependent period and latter half (1961–2006) as the independent period used for verification. I checked the two calibration models for statistical significance using several verification tests. The verification procedures assessed whether the model accurately replicated the observed data (i.e., the independent period not used to calibrate the model). The reliability of the reconstruction was assessed using the Pearson correlation coefficient; the reduction of error statistic (*RE*) (Fritz, 1976)

$$RE = 1 - \left[\frac{SSR_v}{\sum (Y_i - \bar{Y}_c)^2} \right]$$

where *SSR* equals the sum of squares residuals from the verification period and Y_i and \bar{Y}_c are the actual period and calibration mean period predictands, respectively; and the coefficient of efficiency (*CE*), an extremely stringent statistic used to estimate the verification period R^2 (Nash and Sutcliffe, 1971)

$$CE = 1 - \left[\frac{SSR_v}{\sum (Y_i - \bar{Y}_v)^2} \right]$$

where \bar{Y}_v is the mean of the actual data in the verification period. Therefore, if $\bar{Y}_v = \bar{Y}_c$, then $CE = RE$, if however, $\bar{Y}_v \neq \bar{Y}_c$, then $CE < RE$. RE and CE have a theoretical range of $-\infty$ to 1.0, and CE and RE values >0 are usually interpreted as an indication of regression model validity (Cook, 1997). Additionally, since the verification and calibration period means will almost never be identical, CE will almost always be less than RE , therefore, a positive CE is more difficult to obtain.

CHAPTER III

RESULTS

[3.1] Principal Components

Two procedures were used to ensure statistical validity of tree-ring data reduction when using principal components analysis. The Kaiser-Meyer-Olkin Measure (KMO) of Sampling Adequacy test-statistic varies between 0 and 1, and values closer to 1 indicate that patterns of correlation are sufficiently compact and factor analysis should yield distinct and reliable factors. A value of 0.500 is suggested by Kaiser (1974) as the minimum. Bartlett's Test of Sphericity tests the null hypothesis that the correlation matrix is an identity matrix, which would indicate that the factor model is inappropriate. Thus, rejecting the null hypothesis is most favorable. Together, these tests provide a minimum standard, which should be passed before a principal components analysis, should be conducted. Using the aforementioned criteria, the tree-ring data passed the initial diagnostics: KMO measure = 0.622, and therefore, > 0.500; and Bartlett's Test of Sphericity $p < 0.05$ (Table 3.1).

Table 3.1. Results of KMO Measure and Barlett's Test of Sphericity.

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.622
Bartlett's Test of Sphericity	Approx. Chi-Square	176.540
	Degrees of freedom	21
	<i>p</i> -value	0.000

Significant correlations among site chronologies using Pearson's r varied between 0.238 and 0.683 (Table 3.2) with inter-site proximity positively affecting correlations. IRM and MHM have the highest median correlations with all sites (0.294 and 0.300; respectively). The input matrix for the first-run, unrotated S-mode PCA consisted of seven variables representing the individual tree-ring chronologies and 97 observations representing annual growth index values for the common period 1910–2007. The results of the first-run, unrotated S-mode PCA retaining all factors ($n = 7$) determined that the first three PCs of tree-ring data explained 69.96% of variance (Table 3.3) among the tree-ring chronologies and eigenvalues for only PCs 1–3 were >1 (Fig. 3.1). Additionally, the scree plot indicated a leveling off (Fig. 3.1) in explained variance after the third PC. Therefore, I proceeded by retaining only the first three PCs in order to determine the number of subregions that were logically and physically interpretable. The data were then submitted to PCA with and a varimax rotation using the three retained PCs.

In general, the results of unrotated PCA do not yield physically interpretable patterns of climate behavior (Richman, 1986). The varimax rotation technique is the dominant orthogonal rotation identified in the climate literature (Malmgren and Winter, 1999; Timilsena and Piechota, 2007). After rotation, the subregions showed no signs of splintering and were spatially contiguous (i.e., stabilized) when three PCs were retained. The chronologies were grouped according to the loading scores on the three PCs, which reflected spatial patterns of variance in the selected tree-ring data across New York.

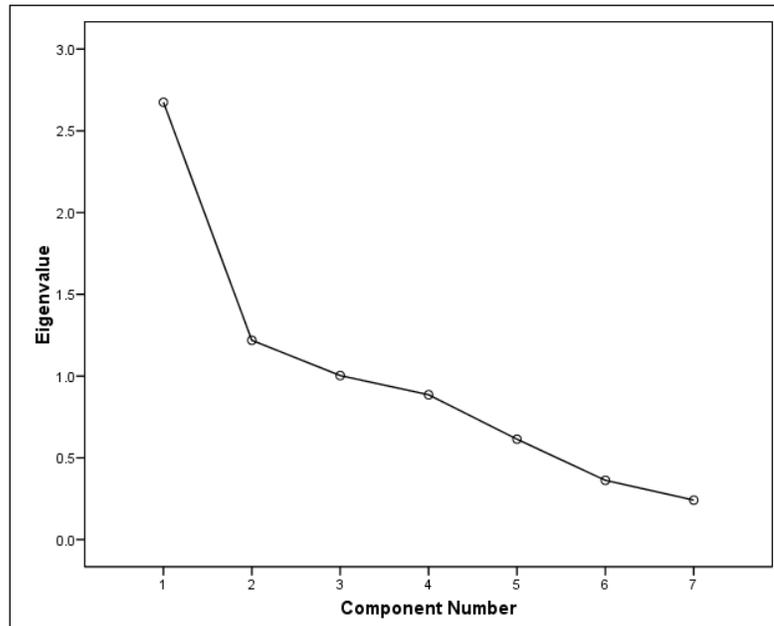


Figure 3.1. Scree plot for unrotated S-mode PCA.

Table 3.2. Correlation matrix for all tree-ring sites (significant values are bold).

	Site	MHM	MDM	KSM	IRM	UUM	ASM
<i>r</i> -value	MHM	1.000	-0.006	0.298	0.341	0.290	0.242
	MDM	-0.006	1.000	-0.091	-0.015	-0.054	0.006
	KSM	0.298	-0.091	1.000	0.323	0.228	0.683
	IRM	0.341	-0.015	0.323	1.000	0.405	0.282
	UUM	0.290	-0.054	0.228	0.405	1.000	0.311
	ASM	0.242	0.006	0.683	0.282	0.311	1.000
<i>p</i> -value	MHM	-	0.477	0.001	0.000	0.002	0.008
	MDM	0.477	-	0.186	0.440	0.297	0.476
	KSM	0.001	0.186	-	0.001	0.011	0.000
	IRM	0.000	0.440	0.001	-	0.000	0.002
	UUM	0.002	0.297	0.011	0.000	-	0.001
	ASM	0.008	0.476	0.000	0.002	0.001	-

Table 3.3. Total explained variance for the three components before and after varimax rotation.

Component	Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.675	38.210	38.210	1.953	27.897	27.897
2	1.219	17.414	55.624	1.934	27.627	55.525
3	1.003	14.332	69.955	1.010	14.431	69.955

Table 3.4. Rotated component matrix.

	Component		
	1 (Eastern)	2 (Western)	3 (Hudson Valley)
MHM	0.867	0.151	0.025
UUM	0.453	0.402	-0.101
KSM	0.088	0.879	-0.069
ASM	0.117	0.875	0.058
IRM	0.446	0.458	-0.014
MDM	-0.011	-0.022	0.995

Principle components revealed three distinct geographical subregions that were divided longitudinally: Region 1 including sites MHM and UUM located in eastern NY; Region 2 including sites ASM-KSM-IRM are located in western NY; and Region 3 comprised of site MDM, located in the Hudson Valley. Interestingly, MDM falls into its own component (3), possibly because it is the south-easternmost site and located in the Hudson River Valley; an area know to be a plant-climate transition zone. These results differ from what would be expected given the recognized statewide latitudinal-climatological boundaries.

[3.2] Modeling Maple Syrup Yield and Meteorological Data

3.2.1. Step-Wise Regression, Yield-Climate Model I

Independent variables used were January–December of previous-year mean monthly temperature, mean monthly precipitation, January–April of the current-year mean monthly temperature, and mean monthly precipitation. The total number of initial variables $n = 32$. Alpha-to-Enter of 0.10 and Alpha-to-Remove of 0.15 were used to select initial variables. The response variable is NY syrup yield for 1916–2008, $n = 91$. After the addition of the 6th variable, Mallow's Cp fell below the optimal value (Table 3.5). The most adequate model will have the lowest Mallow's Cp value that is approximately equal to the number of predictors plus one (i.e., p). Despite improvements to the R^2 (30.18% v. 32.55%), R^2 -adjusted (25.31% v. 26.99%), and R^2 -predicted (17.65% v. 19.03%), Mallow's Cp becomes $< p$ (i.e., 6.9), which indicates an over fitting of the model. The selected variables are consistent with known meteorological parameters that affect syrup yield.

Table 3.5. Order of insertion of possible yield predictors used for step-wise regression fitting for yield-climate model I. Yellow shading indicates selected model.

Step	1	2	3	4	5	6
Constant	0.287	0.337	0.344	0.167	0.143	0.220
Mar Temp	-0.003	-0.003	-0.003	-0.003	-0.003	-0.002
<i>T</i> -value	-3.310	-3.770	-3.130	-3.110	-3.370	-2.660
<i>p</i> -value	0.001	0.000	0.002	0.003	0.001	0.009
Jan Temp		-0.002	-0.002	-0.002	-0.002	-0.002
<i>T</i> -value		-2.810	-2.980	-3.130	-3.390	-3.500
<i>p</i> -value		0.006	0.004	0.002	0.001	0.001
Jun _p Prec			-0.006	-0.005	-0.005	-0.004
<i>T</i> -value			-2.160	-1.910	-1.730	-1.560
<i>p</i> -value			0.034	0.060	0.087	0.122
Jun _p Temp				0.003	0.003	0.003
<i>T</i> -value				1.740	1.790	1.820
<i>p</i> -value				0.086	0.076	0.072
Feb Temp					0.001	0.002
<i>T</i> -value					1.740	2.130
<i>p</i> -value					0.086	0.036
Apr Temp						-0.002
<i>T</i> -value						-1.930
<i>p</i> -value						0.056
<i>R</i> ²	10.74	17.94	22.02	24.61	27.14	30.18
<i>R</i> ² -adjusted	9.76	16.12	19.39	21.18	22.96	25.31
Mallow's Cp	22	15	12	10.7	9.6	7.8
<i>R</i> ² - predicted	6.24	11.98	14.98	15.37	16.2	17.65

Table 3.5. Continued.

Step	7	8	9
Constant	0.344	0.332	0.336
Mar Temp	-0.003	-0.003	-0.003
<i>T</i> -value	-2.930	-3.350	-3.250
<i>p</i> -value	0.004	0.001	0.002
Jan Temp	-0.002	-0.002	-0.002
<i>T</i> -value	-3.440	-3.380	-3.420
<i>p</i> -value	0.001	0.001	0.001
Jun _p Prec	-0.004		
<i>T</i> -value	-1.430		
<i>p</i> -value	0.158		
Jun _p Temp	0.003	0.004	0.004
<i>T</i> -value	2.060	2.290	2.380
<i>p</i> -value	0.043	0.024	0.019
Feb Temp	0.002	0.002	0.002
<i>T</i> -value	2.190	2.370	2.580
<i>p</i> -value	0.031	0.020	0.011
Apr Temp	-0.002	-0.002	-0.002
<i>T</i> -value	-1.850	-1.970	-2.010
<i>p</i> -value	0.068	0.052	0.048
Sep _p Temp	-0.003	-0.003	-0.003
<i>T</i> -value	-1.730	-1.850	-1.890
<i>p</i> -value	0.088	0.068	0.063
May _p Prec			-0.005
<i>T</i> -value			-1.780
<i>p</i> -value			0.079
R^2	32.55	30.94	33.41
R^2 -adjusted	26.99	26.12	27.93
Mallow's Cp	6.9	6.9	5.8
R^2 - predicted	19.03	18.68	19.69

3.2.2 Final Model for Step-Wise Regression yield-climate model I

The final yield-climate model I is:

$$\begin{aligned} \text{Yield} = & 0.215 - (0.00253 \cdot \text{Jantemp}) - (0.00213 \cdot \text{Martemp}) - (0.00352 \cdot \text{Jun}_p \text{precip}) \\ & + (0.00281 \cdot \text{Jun}_p \text{temp}) + (0.00186 \cdot \text{Febtemp}) - (0.00254 \cdot \text{Aprtemp}) \end{aligned}$$

and has an $R^2 = 33.70\%$, $p < 0.001$; a D-W statistic = 1.94 (95% CI, 1.38;1.66); and normally distributed residuals (Figs. 3.6 and 3.7; Table 3.6). This model indicates that NY maple syrup yield responds to mean January, March, and April temperatures inversely, where warmer mean temperatures reduce syrup production and cooler spring temperatures increase sap yields. Conversely, the positive mean February coefficient indicates increased syrup production for warmer Februaries. Additionally, previous June (i.e., 2010 syrup season = 2009 summer conditions) precipitation and temperature have a negative and positive affect of syrup yield, respectively. Mean March and previous mean June precipitation and previous mean June temperature are the strongest predictor variables, accounting for 22.00% of the 33.70% explained variance.

Table 3.6. Model Statistics and Diagnostics for yield-climate model I.

R^2	33.70%
R^2 -adjusted	28.90%
Durbin-Watson statistic	1.94
R^2 -predicted	22.01%
Cp statistic	7.80

Table 3.7. Variable coefficients and diagnostic values for yield-climate model I.

Predictor	Coefficient	SE Coefficient	<i>T</i> -statistic	<i>p</i> -value	VIF
Constant	0.2152	0.1070	2.01	0.048	
Jan Temp	-0.0025	0.0006	-4.14	0.000	1.04
Mar Temp	-0.0021	0.0009	-2.43	0.017	1.20
Jun _p Prec	-0.0035	0.0024	-1.45	0.151	1.14
Jun _p Temp	0.0028	0.0014	1.96	0.053	1.04
Feb Temp	0.0019	0.0007	2.60	0.011	1.11
Apr Temp	-0.0025	0.0012	-2.20	0.030	1.18

Table 3.8. ANOVA table. for yield-climate model I.

Source	DF	SS	MS	<i>F</i> -statistic	<i>p</i> -value
Regression	6	0.0350	0.0058	7.11	0.000
Residual Error	84	0.0689	0.0008		
Total	90	0.1038			

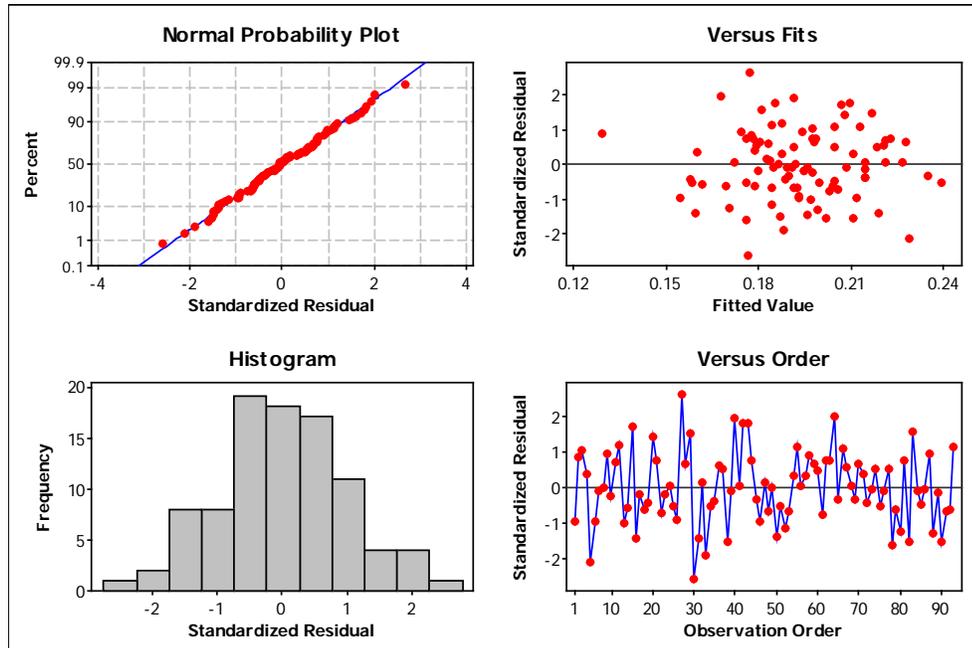


Figure 3.2. Residual plots for yield-climate model I.

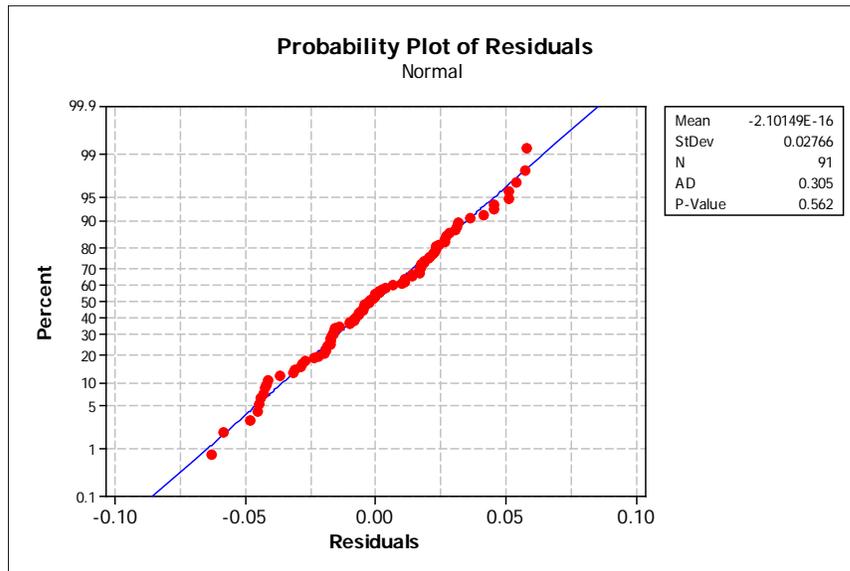


Figure 3.3. Normality plot of residuals for yield-climate model I.

3.23 Step-Wise Regression, Yield-Climate Model II

Independent variables used were identical to yield-climate model I step-wise regression with the addition of January–December of previous year Heating Degree Days (HDD) and Cooling Degree Days (CDD); and January–April of current year HDD and CDD. Again, an Alpha-to-Enter of 0.10 and Alpha-to-Remove of 0.15 was used. Response variable is NY syrup yield on 64 predictors, $n = 91$. After the addition of the 7th variable, Mallow's C_p fell below the optimal value. Despite improvements to the R^2 (41.11% v. 47.64%), R^2 -adjusted (39.40% v. 42.54%), and R^2 -predicted (33.33% v. 35.66%), Mallow's C_p becomes $< p$ (Table 3.9), which indicates model over fitting.

Table 3.9. Order of insertion of possible yield predictors used for step-wise regression fitting for yield-climate model II.

Step	1	2	3	4	5	6
Constant	0.205	0.251	0.313	0.071	0.060	0.000
Mar CDD	-0.001	-0.001	-0.002	-0.002	-0.001	-0.001
<i>T</i> -Value	-3.070	-3.500	-4.190	-4.360	-4.140	-4.340
<i>p</i> -Value	0.003	0.001	0.000	0.000	0.000	0.000
Jan Temp		-0.002	-0.002	-0.003	-0.003	-0.003
<i>T</i> -Value		-3.280	-3.820	-4.200	-4.650	-4.760
<i>p</i> -Value		0.001	0.000	0.000	0.000	0.000
Feb HDD			0.000	0.000	0.000	0.000
<i>T</i> -Value			-2.780	-2.930	-2.770	-2.460
<i>p</i> -Value			0.007	0.004	0.007	0.016
Jun _p Temp				0.004	0.004	0.004
<i>T</i> -Value				2.710	2.920	2.960
<i>p</i> -Value				0.008	0.004	0.004
Jul _p HDD					-0.032	-0.032
<i>T</i> -Value					-2.450	-2.560
<i>p</i> -Value					0.016	0.012
Aug _p CDD						0.000
<i>T</i> -Value						2.550
<i>p</i> -Value						0.013
<i>R</i> ²	9.60	19.46	26.02	31.86	36.30	40.93
<i>R</i> ² -adjusted	8.58	17.63	23.47	28.69	32.62	36.71
Mallow's Cp	47.0	34.3	26.6	20.0	15.3	10.5
<i>R</i> ² - predicted	4.77	13.85	19.29	23.15	28.04	31.47

Table 3.9. Continued. Yellow shading indicates selected model.

Step	7	8	9
Constant	0.146	0.149	0.158
Mar CDD	-0.002	-0.002	-0.002
<i>T</i> -Value	-4.700	-5.030	-4.890
<i>p</i> -Value	0.000	0.000	0.000
Jan T	-0.003	-0.003	-0.003
<i>T</i> -Value	-4.710	-4.690	-5.000
<i>p</i> -Value	0.000	0.000	0.000
Feb HDD	0.000	0.000	0.000
<i>T</i> -Value	-2.720	-3.190	-3.190
<i>p</i> -Value	0.008	0.002	0.002
Jun _p Temp	0.004	0.005	0.005
<i>T</i> -Value	3.260	3.750	3.660
<i>p</i> -Value	0.002	0.000	0.000
Jul _p HDD	-0.030	-0.025	-0.025
<i>T</i> -Value	-2.450	-2.030	-2.090
<i>p</i> -Value	0.016	0.045	0.040
Aug _p CDD	0.000	0.000	0.000
<i>T</i> -Value	2.530	3.020	3.170
<i>p</i> -Value	0.013	0.003	0.002
Sep _p Temp	-0.003	-0.003	-0.003
<i>T</i> -Value	-2.170	-2.460	-2.520
<i>p</i> -Value	0.032	0.016	0.014
Jan _p Temp		-0.001	-0.001
<i>T</i> -Value		-2.350	-2.330
<i>p</i> -Value		0.021	0.022
Dec CDD			0.002
<i>T</i> -Value			1.760
<i>p</i> -Value			0.083
<i>R</i> ²	44.11	47.64	49.57
<i>R</i> ² -adjusted	39.40	42.54	43.96
Mallow's Cp	7.8	4.6	3.7
<i>R</i> ² - predicted	33.33	35.66	37.45

3.2.4 Final Model for Step-Wise Regression II

The final model for step-wise regression II is:

$$\begin{aligned} \text{Yield} = & 0.146 - (0.0015 \cdot \text{MarCDD}) - (0.0027 \cdot \text{Jantemp}) - (0.001 \cdot \text{FebHDD}) \\ & + (0.0043 \cdot \text{Jun}_p \text{temp}) - (0.0302 \cdot \text{Jul}_p \text{HDD}) + (0.0002 \cdot \text{Aug}_p \text{CDD}) - (0.0027 \cdot \text{Sep}_p \text{Temp}) \end{aligned}$$

and has an $R^2 = 44.11\%$, $p < 0.001$; a D-W statistic = 2.10 (95% CI, 1.36;1.69); and residuals are normally distributed (Tables 3.10, 3.11, 3.12; Figs. 3.5 and 3.6). This model indicates that NY maple syrup yield responds negatively to March CDD, mean January temperatures, February HDD, previous July HDD, and previous mean September temperature. Conversely, previous June precipitation and previous August CDD have a positive affect on syrup yields. March CDD, mean January temperatures, and February HDD account for 65% of the total explained variance.

Table 3.10. Model statistics and diagnostics results for yield-climate model II.

R^2	44.11%
R^2 -adjusted	39.40%
Durbin-Watson statistic	2.10
R^2 -predicted	33.33%
Cp statistic	7.80

Table 3.11. Variable coefficients and diagnostic values for yield-climate model II.

Predictor	Coefficient	SE Coefficient	T-statistic	p-value	VIF
Constant	0.1457	0.1111	1.31	0.1930	
1) Mar CDD	-0.0015	0.0003	-4.70	0.0000	1.11
2) Jan Temp	-0.0027	0.0006	-4.71	0.0000	1.07
3) Feb HDD	-0.0001	0.0000	-2.72	0.0080	1.13
4) Jun _p Temp	0.0043	0.0013	3.26	0.0020	1.03
5) Jul _p HDD	-0.0302	0.0123	-2.45	0.0160	1.06
6) Aug _p CCD	0.0002	0.0001	2.53	0.0130	1.03
7) Sep _p Temp	-0.0027	0.0013	-2.18	0.0320	1.05

Table 3.12. ANOVA table for yield-climate model II.

Source	DF	SS	MS	<i>F</i> -statistic	<i>p</i> -value
Regression	7	0.0458	0.0065	9.36	0.000
Residual Error	83	0.0580	0.0007		
Total	90	0.1038			

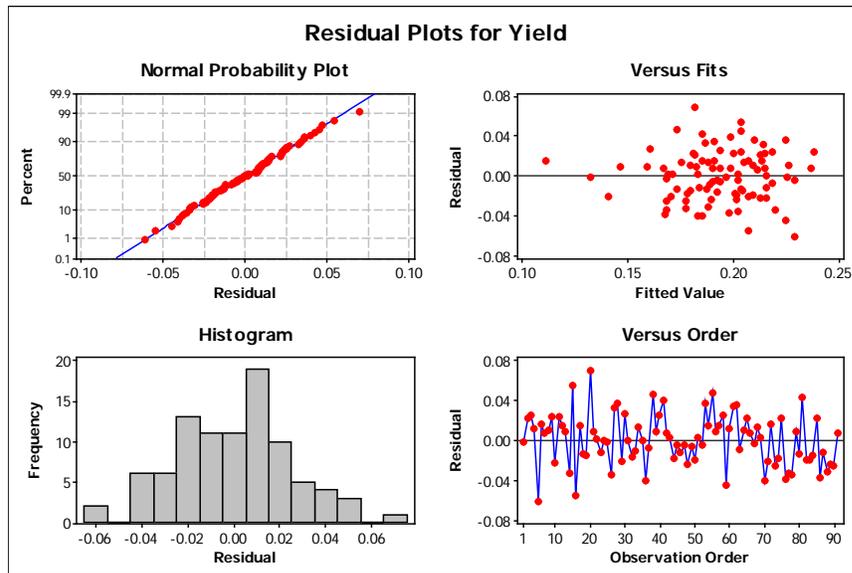


Figure 3.4. Residual plots for yield-climate model II.

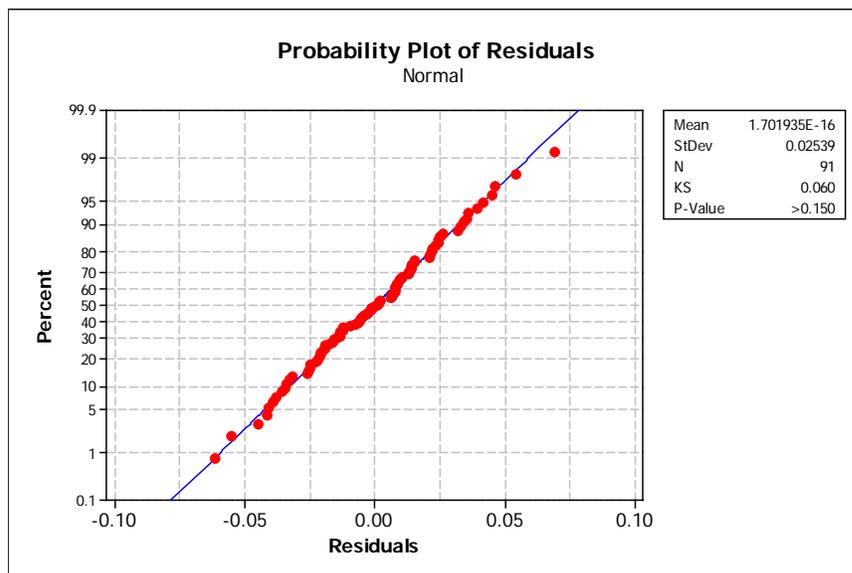


Figure 3.5. Normality plot of residuals for yield-climate model II.

[3.3] Tree-Ring Growth-Climate Results

3.3.1 ASM Growth-Climate Analysis

Correlation and response function analysis yielded comparable results for precipitation; previous mean January and June precipitation correlations were significant ($r = 0.247$ and 0.225 ($p > 0.05$); 0.308 and 0.198 ($p > 0.05$), respectively; however, no current year mean monthly precipitation showed any affect on tree growth (Table 3.13). Conversely, current-year mean monthly temperature is important at this site; mean February temperature ($r = 0.189$; $p > 0.05$) (Table 3.14), mean July temperature ($r = 0.237$; $p > 0.05$), and mean September temperature ($r = 0.311$; $p > 0.05$). Mean September temperature is temporally consistent over the complete record. There is, however, a decrease of correlation strength in the late-1970s although previous mean September temperatures become significant during the same period. Unlike previous mean June precipitation, and previous mean July precipitation exhibits a strong positive relationship exists early in the chronology, but diminishes during the last quarter century (Fig. 3.7). Around the same period, previous July precipitation becomes less important and previous January precipitation exhibits an early-1980 shift in correlation strength. Additionally, previous mean September temperature is significant ($r = 0.241$; $p > 0.05$). Mean July temperature is the only variable that is flagged significant in the correlation analysis and is not a significant variable according to the response function analysis.

Table 3.13. Correlation and response function analysis of monthly precipitation at ASM.

Month	Pearson's <i>r</i>	Month	Pearson's <i>r</i>
Jan _p P	0.247*	Jan P	0.076
Feb _p P	0.113	Feb P	-0.075
Mar _p P	-0.135	Mar P	-0.140
Apr _p P	-0.007	Apr P	-0.021
May _p P	0.094	May P	-0.087
Jun _p P	0.308*	Jun P	0.111
Jul _p P	0.129	Jul P	0.012
Aug _p P	-0.004	Aug P	0.069
Sep _p P	0.008	Sep P	0.066
Oct _p P	-0.018	Oct P	0.090
Nov _p P	-0.033		
Dec _p P	0.035		

Correlation analysis

Month	Pearson's <i>r</i>	Month	Pearson's <i>r</i>
Jan _p P	0.225*	Jan P	0.026
Feb _p P	0.041	Feb P	-0.075
Mar _p P	-0.107	Mar P	-0.092
Apr _p P	-0.074	Apr P	-0.084
May _p P	0.046	May P	-0.066
Jun _p P	0.198*	Jun P	0.106
Jul _p P	0.060	Jul P	0.007
Aug _p P	0.072	Aug P	0.108
Sep _p P	-0.033	Sep P	0.070
Oct _p P	0.000	Oct P	0.038
Nov _p P	-0.010		
Dec _p P	0.052		

Response Function

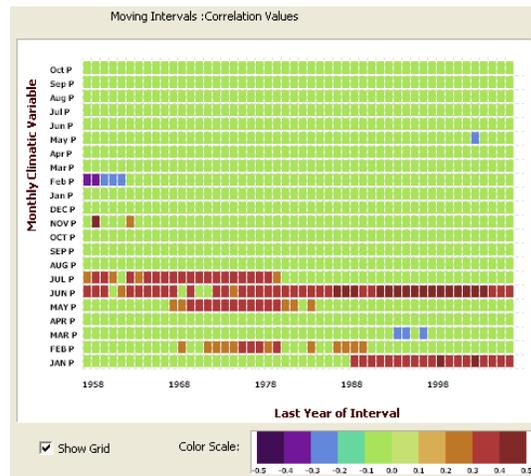


Figure 3.6. Moving correlation analysis of precipitation and growth at ASM site.

Table 3.14. Correlation and response function analysis of monthly temperature at ASM.

Month	Pearson's r	Month	Pearson's r
Jan _p T	-0.088	Jan T	-0.058
Feb _p T	-0.049	Feb T	0.189*
Mar _p T	-0.038	Mar T	0.100
Apr _p T	-0.083	Apr T	0.188
May _p T	0.039	May T	0.090
Jun _p T	-0.106	Jun T	0.103
Jul _p T	-0.115	Jul T	0.237*
Aug _p T	0.025	Aug T	0.075
Sep _p T	0.241*	Sep T	0.311*
Oct _p T	0.074	Oct T	-0.100
Nov _p T	0.025		
Dec _p T	0.033		

Correlation analysis

Month	Pearson's r	Month	Pearson's r
Jan _p T	-0.054	Jan T	-0.096
Feb _p T	-0.067	Feb T	0.171*
Mar _p T	-0.010	Mar T	0.018
Apr _p T	-0.092	Apr T	0.047
May _p T	0.095	May T	0.097
Jun _p T	-0.052	Jun T	0.057
Jul _p T	-0.020	Jul T	0.109
Aug _p T	0.018	Aug T	0.006
Sep _p T	0.197*	Sep T	0.216*
Oct _p T	0.087	Oct T	-0.088
Nov _p T	0.016		
Dec _p T	0.012		

Response Function

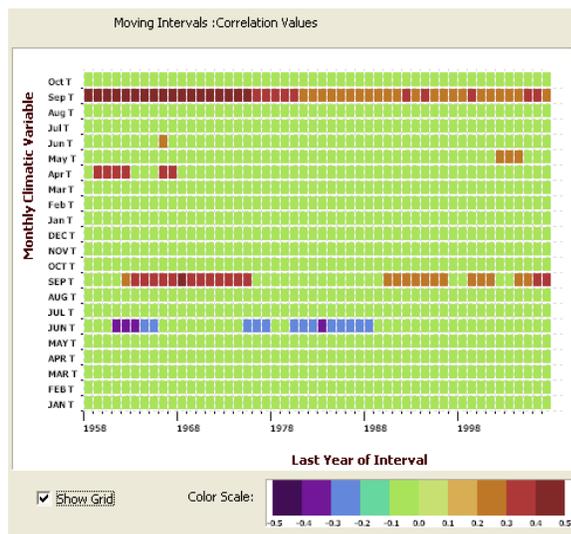


Figure 3.7. Moving correlation analysis of temperature and growth at ASM.

3.3.2 IRM Growth-Climate Analysis

Previous-year precipitation was the strongest predictor of tree growth at IRM (Table 3.15). Previous mean June and mean October precipitation were the only significant variables using correlation analysis; $r = 0.234$ ($p < 0.05$) and -0.207 ($p < 0.05$), respectively. Previous mean June precipitation exhibited a stable temporal pattern over the majority of the time series, but with a decline in correlation strength beginning in the late 1980s (Fig. 3.9). After subjecting the precipitation data to response function analysis, previous mean June precipitation no longer remains significant, $r = 0.193$ ($p > 0.05$) while previous mean October precipitation continues to be a significant variable (Fig. 3.9). IRM tree growth did not exhibit any statistically significant relationship with mean monthly temperatures with correlation and response function analysis (Table 3.10); all absolute r -values were low, ranging from 0.018–1.154. Therefore, tree growth at this site seems to be principally responding to late-summer and mid-fall precipitation of the previous year.

Table 3.15. Correlation and response function analysis of monthly precipitation at IRM.

Month	Pearson's r	Month	Pearson's r
Jan _p P	0.049	Jan P	0.018
Feb _p P	0.087	Feb P	0.049
Mar _p P	0.084	Mar P	0.016
Apr _p P	0.050	Apr P	0.093
May _p P	0.022	May P	0.001
Jun _p P	0.234*	Jun P	-0.022
Jul _p P	0.187	Jul P	0.100
Aug _p P	-0.015	Aug P	-0.055
Sep _p P	-0.040	Sep P	-0.169
Oct _p P	-0.207*	Oct P	0.039
Nov _p P	0.022		
Dec _p P	-0.041		

Correlation analysis

Month	Pearson's r	Month	Pearson's r
Jan _p P	0.029	Jan P	0.013
Feb _p P	0.090	Feb P	0.061
Mar _p P	0.074	Mar P	0.010
Apr _p P	0.040	Apr P	0.121
May _p P	-0.035	May P	-0.002
Jun _p P	0.193	Jun P	-0.082
Jul _p P	0.123	Jul P	0.089
Aug _p P	0.058	Aug P	-0.035
Sep _p P	-0.041	Sep P	-0.114
Oct _p P	-0.177*	Oct P	-0.011
Nov _p P	0.011		
Dec _p P	-0.030		

Response Function

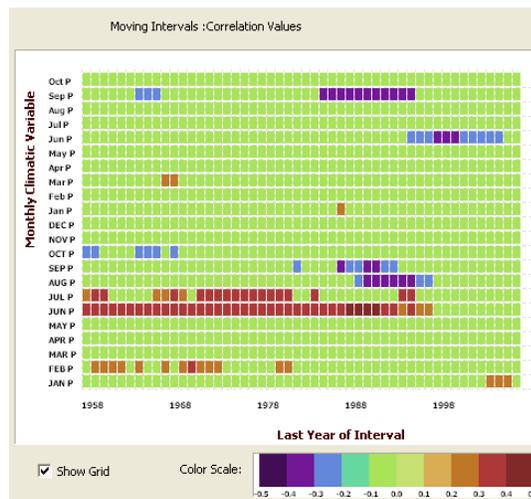


Figure 3.8. Moving correlation analysis of precipitation and growth at IRM.

Table 3.16. Correlation and Response Function analysis of monthly temperature at IRM.

Month	Pearson's r	Month	Pearson's r
Jan _p T	-0.094	Jan T	-0.018
Feb _p T	0.110	Feb T	0.057
Mar _p T	0.120	Mar T	0.148
Apr _p T	0.032	Apr T	0.091
May _p T	-0.073	May T	0.002
Jun _p T	-0.014	Jun T	0.048
Jul _p T	0.029	Jul T	0.055
Aug _p T	0.045	Aug T	0.017
Sep _p T	0.132	Sep T	0.154
Oct _p T	0.114	Oct T	-0.151
Nov _p T	0.038		
Dec _p T	0.027		

Correlation analysis

Month	Pearson's r	Month	Pearson's r
Jan _p T	-0.082	Jan T	-0.024
Feb _p T	0.077	Feb T	0.015
Mar _p T	0.135	Mar T	0.104
Apr _p T	-0.002	Apr T	0.022
May _p T	-0.091	May T	0.018
Jun _p T	-0.056	Jun T	-0.004
Jul _p T	0.072	Jul T	0.000
Aug _p T	0.026	Aug T	-0.016
Sep _p T	0.074	Sep T	0.056
Oct _p T	0.065	Oct T	-0.159
Nov _p T	0.010		
Dec _p T	0.005		

Response Function

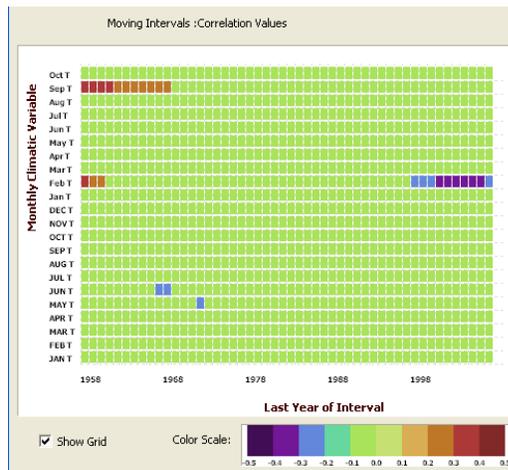


Figure 3.9. Moving correlation analysis of temperature and growth at IRM.

3.3.3 KSM Growth-Climate Analysis

Radial growth at KSM is correlated with previous mean January precipitation ($r = 0.244, p < 0.05$) and mean May precipitation ($r = -0.192, p < 0.05$); however, mean May precipitation is not significant when response function analysis is used. Mean monthly temperature also yielded low correlations with only mean October temperature being significant in both the correlation and response function analysis ($r = -0.215, p < 0.05$; $r = -0.213, p < 0.05$; respectively). All significant variables excluding previous mean January precipitation have negative correlation coefficients indicating that tree-growth is decreased with increased precipitation, although these relationships are counterintuitive and possibly spurious. Additionally, moving correlation analysis indicates that previous mean January and May precipitation have become significant in the last 30 years. A similar pattern exists for mean October temperature. The growth-climate relationships for this site are weak and temporally unstable for a majority of variables again suggesting some relationships may be spurious (Figs. 3.11 and 3.12)

Table 3.17. Correlation and Response Function analysis of monthly precipitation at KSM.

Month	Pearson's r	Month	Pearson's r
Jan _p P	0.244*	Jan P	0.116
Feb _p P	0.033	Feb P	-0.005
Mar _p P	-0.202	Mar P	0.008
Apr _p P	-0.037	Apr P	0.031
May _p P	-0.142	May P	-0.192*
Jun _p P	0.096	Jun P	-0.115
Jul _p P	0.162	Jul P	-0.064
Aug _p P	0.117	Aug P	-0.030
Sep _p P	-0.041	Sep P	0.015
Oct _p P	-0.010	Oct P	0.082
Nov _p P	-0.082		
Dec _p P	-0.026		

Correlation analysis

Month	Correlation (r)	Month	Correlation (r)
Jan _p P	0.199*	Jan P	0.057
Feb _p P	0.008	Feb P	0.030
Mar _p P	-0.164	Mar P	-0.030
Apr _p P	-0.066	Apr P	0.005
May _p P	-0.136	May P	-0.068
Jun _p P	0.114	Jun P	-0.027
Jul _p P	0.147	Jul P	-0.046
Aug _p P	0.127	Aug P	0.019
Sep _p P	-0.088	Sep P	0.035
Oct _p P	0.006	Oct P	0.041
Nov _p P	-0.011		
Dec _p P	-0.022		

Response Function

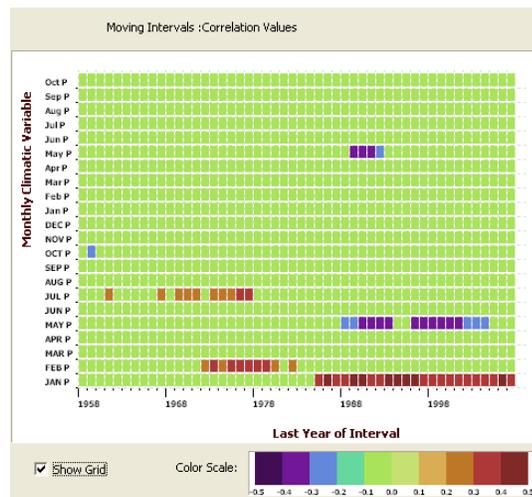


Figure 3.10. Moving correlation analysis of precipitation and growth at KSM.

Table 3.18. Correlation and Response Function analysis of monthly temperature at KSM.

Month	Pearson's r	Month	Pearson's r
Jan _p T	-0.003	Jan T	-0.109
Feb _p T	-0.063	Feb T	-0.115
Mar _p T	-0.130	Mar T	-0.023
Apr _p T	-0.060	Apr T	0.103
May _p T	0.074	May T	0.050
Jun _p T	-0.063	Jun T	0.041
Jul _p T	-0.016	Jul T	0.132
Aug _p T	-0.067	Aug T	0.058
Sep _p T	0.108	Sep T	0.153
Oct _p T	0.102	Oct T	-0.215*
Nov _p T	-0.036		
Dec _p T	0.031		

Correlation analysis

Month	Pearson's r	Month	Pearson's r
Jan _p T	-0.034	Jan T	-0.092
Feb _p T	-0.022	Feb T	-0.036
Mar _p T	-0.062	Mar T	-0.012
Apr _p T	-0.050	Apr T	0.046
May _p T	0.062	May T	0.028
Jun _p T	-0.007	Jun T	0.086
Jul _p T	0.032	Jul T	0.089
Aug _p T	-0.060	Aug T	0.062
Sep _p T	0.109	Sep T	0.102
Oct _p T	0.124	Oct T	-0.213*
Nov _p T	-0.027		
Dec _p T	0.008		

Response Function

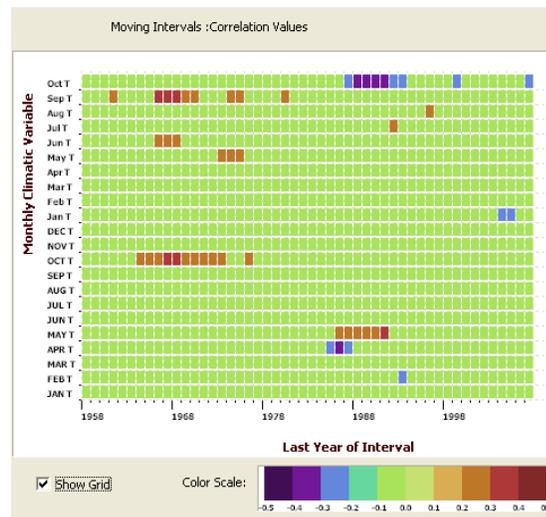


Figure 3.11. Moving correlation analysis of temperature and growth at KSM.

3.3.4 MDM Growth-Climate Analysis

MDM radial growth responds positively to previous mean May precipitation ($r = 0.265$; $p < 0.05$) and mean March precipitation ($r = 0.227$; $p < 0.05$) are the only precipitation variables significantly related to growth. However, when response function analysis is used, mean May precipitation and mean July precipitation are significant ($r = -0.173$, $p < 0.05$; $r = 0.302$, $p < 0.05$; respectively). At MDM, monthly temperatures have a minimal influence, with only previous mean November temperature significantly impacting growth ($r = 0.224$; $p < 0.05$). This relationship is not significant when response function analysis is used. Moving-interval analysis revealed that the role of previous mean May and mean March precipitation has become more important post-1970. Though summer precipitation was not correlated with growth when considering the entire chronology, the moving-correlation function yielded significant results for the early part of the series with mean July and June precipitation. The response function analysis did flag mean July precipitation as a relatively strong predictor of growth ($r = 0.302$; $p < 0.05$), which is more intuitive with growth-climate paradigms. The moving correlation analysis on monthly temperature produced no temporally consistent relationships (Fig. 3.20).

Table 3.19. Correlation and Response Function analysis of monthly precipitation at MDM.

Month	Pearson's r	Month	Pearson's r
Jan _p P	-0.001	Jan P	-0.094
Feb _p P	0.140	Feb P	-0.069
Mar _p P	-0.113	Mar P	0.227*
Apr _p P	-0.058	Apr P	0.028
May _p P	0.265*	May P	-0.159
Jun _p P	-0.040	Jun P	0.180
Jul _p P	0.109	Jul P	0.243
Aug _p P	0.104	Aug P	0.041
Sep _p P	0.143	Sep P	0.013
Oct _p P	-0.072	Oct P	0.133
Nov _p P	0.087		
Dec _p P	0.143		

Correlation analysis

Month	Pearson's r	Month	Pearson's r
Jan _p P	-0.001	Jan P	-0.045
Feb _p P	0.134	Feb P	-0.041
Mar _p P	-0.005	Mar P	0.219*
Apr _p P	-0.043	Apr P	0.040
May _p P	0.198*	May P	-0.173*
Jun _p P	-0.019	Jun P	0.153
Jul _p P	-0.017	Jul P	0.302*
Aug _p P	0.014	Aug P	0.016
Sep _p P	0.060	Sep P	0.102
Oct _p P	-0.046	Oct P	0.094
Nov _p P	0.050		
Dec _p P	0.112		

Response Function

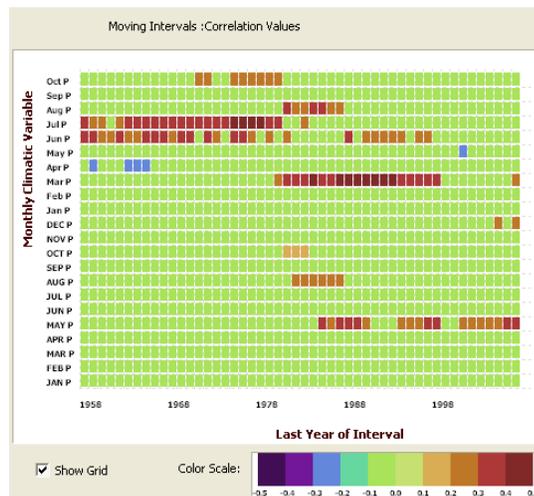


Figure 3.12. Moving correlation analysis of precipitation and growth at MDM.

Table 3.20. Correlation and Response Function analysis of monthly temperature at MDM.

Month	Pearson's r	Month	Pearson's r
Jan _p T	-0.115	Jan T	0.071
Feb _p T	-0.003	Feb T	-0.018
Mar _p T	0.068	Mar T	-0.054
Apr _p T	0.062	Apr T	-0.043
May _p T	-0.042	May T	0.016
Jun _p T	-0.026	Jun T	-0.111
Jul _p T	-0.059	Jul T	-0.074
Aug _p T	0.032	Aug T	0.116
Sep _p T	-0.042	Sep T	0.169
Oct _p T	0.152	Oct T	0.188
Nov _p T	0.224*		
Dec _p T	0.059		

Correlation analysis

Month	Pearson's r	Month	Pearson's r
Jan _p T	-0.118	Jan T	0.034
Feb _p T	-0.100	Feb T	-0.034
Mar _p T	-0.019	Mar T	-0.087
Apr _p T	0.013	Apr T	-0.028
May _p T	0.013	May T	0.012
Jun _p T	0.006	Jun T	-0.111
Jul _p T	-0.051	Jul T	-0.067
Aug _p T	0.103	Aug T	0.052
Sep _p T	-0.050	Sep T	0.143
Oct _p T	0.104	Oct T	0.135
Nov _p T	0.116		
Dec _p T	0.016		

Response Function

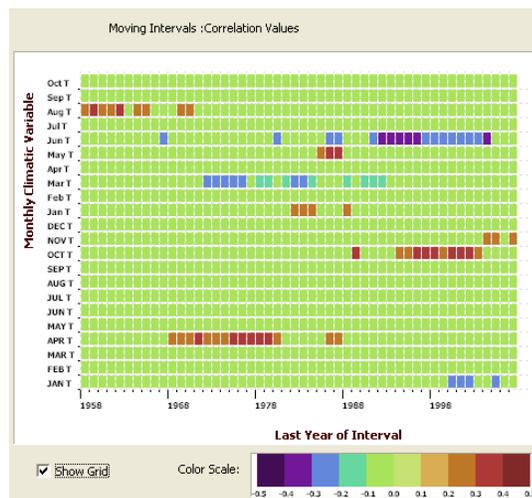


Figure 3.13. Moving correlation analysis of temperature and growth at MDM.

3.3.5 MHM Growth-Climate Analysis

Growth was weakly correlated to mean April precipitation ($r = 0.210$; $p < 0.05$); however, April precipitation was insignificant using response function analysis. Additionally, the moving correlation analysis reveals a shift in the growth-climate response (Fig. 3.11), as for roughly half of the record, previous mean July precipitation has a strong correlation with growth ($r > 0.300$; $p < 0.05$). However, mean July precipitation does not maintain significance into the later part of the 20th century. Mean April precipitation ($r = 0.210$; $p < 0.05$) becomes the dominant growth influence mid-20th century, as does previous mean March temperature. Previous mean January temperature has a consistent appearance in the time series with a positive affect on tree growth. Conversely, previous mean March temperatures have a negative correlation coefficient, in both the correlation and response- function analysis. Trees at this site exhibit the weakest climate signal among the six sites. Similar to the other sites, no current-year monthly temperatures have an influence on growth.

Table 3.21. Correlation and Response Function analysis of monthly precipitation at MHM

Month	Pearson's r	Month	Pearson's r
Jan _p P	-0.037	Jan P	0.107
Feb _p P	0.104	Feb P	0.086
Mar _p P	-0.008	Mar P	0.099
Apr _p P	-0.114	Apr P	0.210*
May _p P	-0.102	May P	0.024
Jun _p P	0.095	Jun P	0.016
Jul _p P	0.162	Jul P	0.068
Aug _p P	0.016	Aug P	0.018
Sep _p P	-0.013	Sep P	-0.054
Oct _p P	-0.132	Oct P	0.024
Nov _p P	0.002		
Dec _p P	0.092		

Correlation analysis

Month	Pearson's r	Month	Pearson's r
Jan _p P	-0.029	Jan P	0.095
Feb _p P	0.081	Feb P	0.080
Mar _p P	-0.009	Mar P	0.099
Apr _p P	-0.081	Apr P	0.162
May _p P	-0.101	May P	-0.028
Jun _p P	0.053	Jun P	-0.002
Jul _p P	0.152	Jul P	0.076
Aug _p P	-0.010	Aug P	0.020
Sep _p P	-0.019	Sep P	-0.063
Oct _p P	-0.087	Oct P	0.005
Nov _p P	-0.028		
Dec _p P	0.117		

Response Function

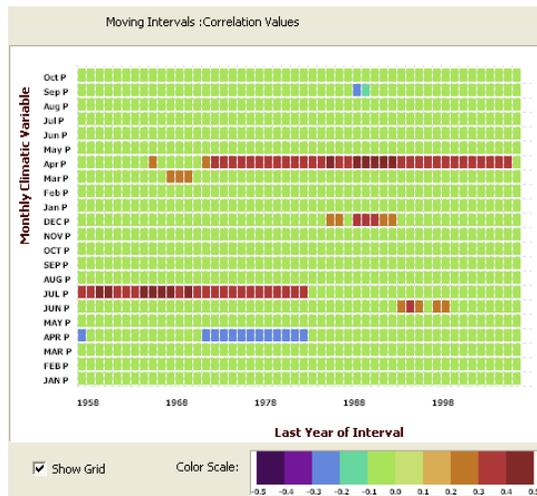


Figure 3.14. Moving correlation analysis of precipitation and growth at MHM.

Table 3.22. Correlation and Response Function analysis of monthly temperature at MHM.

Month	Pearson's r	Month	Pearson's r
Jan _p T	0.230*	Jan T	-0.085
Feb _p T	0.022	Feb T	0.163
Mar _p T	-0.267*	Mar T	0.078
Apr _p T	-0.103	Apr T	0.110
May _p T	-0.091	May T	-0.158
Jun _p T	0.039	Jun T	0.093
Jul _p T	0.017	Jul T	0.113
Aug _p T	0.030	Aug T	0.031
Sep _p T	-0.108	Sep T	0.000
Oct _p T	0.129	Oct T	-0.129
Nov _p T	0.038		
Dec _p T	0.042		

Correlation analysis

Month	Pearson's r	Month	Pearson's r
Jan _p T	0.161	Jan T	-0.134
Feb _p T	0.017	Feb T	0.116
Mar _p T	-0.169*	Mar T	-0.011
Apr _p T	-0.007	Apr T	0.035
May _p T	-0.106	May T	-0.072
Jun _p T	0.072	Jun T	0.041
Jul _p T	0.060	Jul T	0.100
Aug _p T	-0.020	Aug T	0.052
Sep _p T	-0.079	Sep T	-0.026
Oct _p T	0.086	Oct T	-0.103
Nov _p T	0.045		
Dec _p T	-0.009		

Response Function

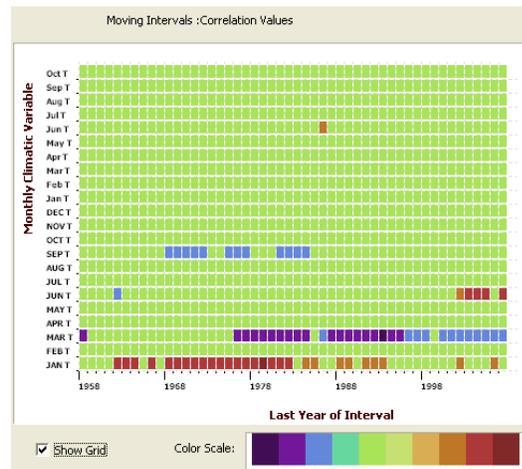


Figure 3.15. Moving correlation analysis of temperature and growth at MHM.

3.3.6 UUM Growth-Climate Analysis

Correlation analysis revealed this site (UUM) to be most sensitive to temperature. Mean January temperature was significant ($r = -0.306$; $p < 0.05$), although only in the last six 48-year moving correlation windows (Fig 3.17). However, mean January temperature does not remain significant under the more discriminating response function analysis ($r = -0.216$; $p > 0.05$). Previous mean August precipitation is negatively correlated with tree-growth ($r = -0.189$; $p < 0.05$) and is temporally steady for the majority of the time series (Fig. 3.18). Of note, are the early moderately strong positive correlations (e.g., $r > 0.400$) of mean July temperatures in the early part of the chronology (1911–1990).

Table 3.23. Correlation and Response Function analysis of monthly precipitation at UUM.

Month	Pearson's r	Month	Pearson's r
Jan _p P	-0.003	Jan P	-0.138
Feb _p P	-0.157	Feb P	-0.014
Mar _p P	-0.058	Mar P	-0.182
Apr _p P	-0.070	Apr P	0.135
May _p P	-0.034	May P	0.011
Jun _p P	0.064	Jun P	-0.031
Jul _p P	0.126	Jul P	0.123
Aug _p P	-0.189	Aug P	0.035
Sep _p P	-0.008	Sep P	0.012
Oct _p P	-0.118	Oct P	-0.028
Nov _p P	-0.058		
Dec _p P	0.012		

Correlation analysis

Month	Pearson's r	Month	Pearson's r
Jan _p P	0.006	Jan P	-0.051
Feb _p P	-0.078	Feb P	-0.021
Mar _p P	-0.059	Mar P	-0.070
Apr _p P	-0.053	Apr P	0.104
May _p P	-0.031	May P	-0.017
Jun _p P	0.035	Jun P	-0.029
Jul _p P	0.101	Jul P	0.087
Aug _p P	-0.050	Aug P	0.060
Sep _p P	-0.025	Sep P	-0.035
Oct _p P	-0.130	Oct P	-0.051
Nov _p P	-0.002		
Dec _p P	0.049		

Response Function

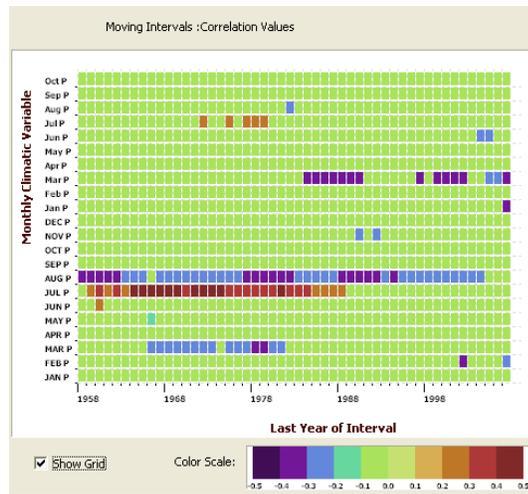


Figure 3.16. Moving correlation analysis of precipitation and growth at UUM.

Table 3.24. Correlation and Response Function analysis of monthly temperature at UUM

Month	Pearson's r	Month	Pearson's r
Jan _p T	-0.006	Jan T	-0.306
Feb _p T	-0.027	Feb T	-0.054
Mar _p T	-0.029	Mar T	0.138
Apr _p T	-0.008	Apr T	-0.031
May _p T	-0.068	May T	0.019
Jun _p T	-0.028	Jun T	-0.073
Jul _p T	0.157	Jul T	0.020
Aug _p T	0.167	Aug T	-0.117
Sep _p T	0.115	Sep T	0.106
Oct _p T	-0.015	Oct T	-0.178
Nov _p T	-0.005		
Dec _p T	-0.066		

Correlation analysis

Month	Pearson's r	Month	Pearson's r
Jan _p T	0.001	Jan T	-0.216
Feb _p T	0.021	Feb T	-0.036
Mar _p T	0.010	Mar T	0.074
Apr _p T	-0.042	Apr T	-0.071
May _p T	-0.081	May T	0.068
Jun _p T	-0.065	Jun T	-0.029
Jul _p T	0.091	Jul T	0.031
Aug _p T	0.109	Aug T	-0.076
Sep _p T	0.077	Sep T	0.064
Oct _p T	0.033	Oct T	-0.153
Nov _p T	0.028		
Dec _p T	-0.036		

Response Function

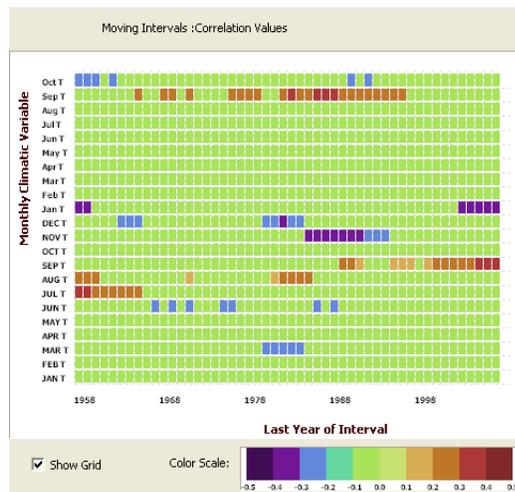


Figure 3.17. Moving correlation analysis of temperature and growth at UUM.

Table 3.25. Summary of growth-climate analysis for all sites with only significant correlations shown. Subscript “p” indicates previous year.

Site	Precipitation-correlation (<i>r</i>)	Precipitation-response (<i>r</i>)	Temperature-correlation (<i>r</i>)	Temperature-response (<i>r</i>)
ASM	Jan _p (0.247) Jun _p (0.308)	Jan _p (0.225) Jun _p (0.198)	Sep _p (0.214) Feb (0.189) Jul (0.237) Sep (0.311)	Sep _p (0.197) Feb (0.171) Sep (0.216)
IRM	Jun _p (0.234) Oct _p (-0.207)	Oct _p (-0.177)	-	-
KSM	Jan _p (0.244) May (-0.192)	Jan _p (0.199)	Oct (-0.215)	Oct (-0.213)
MDM	Mar _p (0.265) Mar (0.227)	May _p (0.198) Mar (0.219) May (-0.173) Jul (0.302)	Nov _p (0.224)	-
MHM	Apr (0.210)	-	Jan _p (0.230) Mar _p (-0.267)	Mar _p (-0.169)
UUM	Aug _p (-0.189)	-	Jan (-0.306)	-

Overall, correlations were weak (Table 3.18). Seven of the 10 (70.0%) significant precipitation variables were from the previous year, while only four of the nine (44.4%) temperature correlations were for the previous year. However, using the response function analysis, a more stringent test, fewer variables were significant, more specifically, eight precipitation and only four temperature variables. The proportion of significant variables that were from the previous year is consistent with that of the correlation analysis (62.5% and 50.0%; respectively). There are two precipitation variables, previous mean January and June that are significant at multiple sites (Table 3.18), but no significant temperature variables are found at more than one site.

[3.4] Correlation Analysis of Syrup Yield and Tree-Ring Chronologies

There were no significant correlations using both Pearson's r and Spearman's r , with the individual tree-ring chronologies, the composite chronology (i.e., all sites combined) and the maple syrup yield series, at lag 0 (Table 3.26). All correlations were weak (-0.020 – 0.131 , Pearson's r ; -0.025 – 0.150 , Spearman's r), while the non-parametric correlation analysis, on occasion, yielded higher coefficients; possibly indicating a non-linear relationship between tree growth and syrup yield. The strongest correlation, albeit not significant, was Spearman's $r = 0.150$ (p -value = 0.076) at site MHM, located in the northern Catskills.

Table 3.26. Correlations of NY maple syrup yield and NY maple chronologies; lag = 0.

Chronology (Site)	Pearson's r	Spearman's r
ASM	-0.020	-0.025
p -value	0.426	0.407
IRM	-0.014	0.005
p -value	0.448	0.481
KSM	0.062	0.040
p -value	0.277	0.351
MDM	-0.060	-0.045
p -value	0.284	0.335
MHM	0.131	0.150
p -value	0.107	0.076
UUM	-0.035	-0.017
p -value	0.371	0.437
NY All	0.028	0.007
p -value	0.394	0.473

The weakest relationship, Spearman's $r = 0.005$ (p -value = 0.481), was at site IRM, located in the western Adirondacks. Additionally, there is no evidence of increased absolute correlation strength with the geographical location of the sites. In other words, sites found in the eastern part of the state do not have stronger correlations to the yield data when compared to western, northern, and southern sites. This is also true for the direction of the correlation, as negative and positive site-yield correlations show no noticeable geographical patterns.

Conversely, tree-growth at ASM was inversely correlated to NY syrup yield Pearson's $r = -0.209$ ($p = 0.023$) at lag 1 (Table 3.26). No other chronologies exhibited significant correlations, but correlations coefficients improved compared to lag 0 (-0.209 – 1.05 , Pearson's r ; -0.198 – 0.138 , Spearman's r). The non-parametric correlation analysis again yielded higher coefficients at times indicating the possible presence of a non-linear relationship. The strongest correlation was Pearson's $r = 0.209$ (p -value = 0.023) at site ASM, located in the Finger Lake region of NY. The weakest relationship, Pearson's $r = -0.024$ (p -value = 0.410), was at MHM, located in the northern Catskills. Comparable to the results from lag 0 there is no evidence of any site subregion (e.g., eastern) exhibiting a defined pattern of correlation strength or direction. Despite the inverse relationship between ASM and syrup yield, this was the only significant variable and thus, the best candidate to test the validity of reconstructing maple syrup yields.

Table 3.27. Correlations of NY maple syrup yield and NY maple chronologies; lag = 1.

Chronology (Site)	Pearson's r	Spearman's r
ASM	-0.209*	-0.198*
p -value	0.023	0.030
IRM	-0.131	-0.104
p -value	0.108	0.163
KSM	-0.149	-0.133
p -value	0.080	0.105
MDM	0.105	0.138
p -value	0.160	0.096
MHM	-0.024	-0.031
p -value	0.410	0.385
UUM	-0.042	0.032
p -value	0.346	0.382
NY All	-0.134	-0.157
p -value	0.102	0.068

[3.5] Yield Reconstruction

3.5.1 Late period (1961–2006)

The late period calibration failed to produce a reliable and statistically valid model (p -value < 0.05 ; Table 3.26 and 3.27) and there was no relationship ($R^2 = 0.00\%$) between syrup yield and tree-ring growth. These results are surprising, as the period of 1961–2006 was thought to be the more robust data set, with better record keeping and data collection practices. Because this model was unusable, there was no need to verify the independent data (i.e., the early period). Therefore, I calibrated the early period (1916–1960) data.

Table 3.28. Analysis of Variance.

Source	DF	SS	MS	<i>F</i>	<i>p</i> -value
Regression	1	0.0002	0.0002	0.19	0.667
Residual Error	44	0.0422	0.0010		
Total	45	0.04238			

Predictor	Coefficient	SE Coefficient	<i>T</i>	<i>p</i> -value
Constant	0.2043	0.01673	12.22	0.000
Tree-ring	0.0070	0.01618	-0.43	0.667

Table 3.29. Regression statistics for late-period calibration.

R^2	0.00%
R^2 -adjusted	0.00%
Durbin-Watson statistic	1.98

3.5.2 Early period (1916–1960)

Regression analysis on the early period record yielded a more favorable outcome; albeit, an unexpected negative relationship between yield and tree-ring width. The model was significant (p -value < 0.01) and tree-ring width explained 19.30% (Table 3.28 and 3.29) of the variance in year-to-year yield. Additionally, the model lacked autocorrelation (Table 3.29). At this stage, the regression model from the early period was then used to create a new late-period dataset. This new dataset was constructed using the model:

$$Yield = 0.338 - 0.107(tree - ring)$$

derived from the regression analysis. The output of this model will produce expected late period yield values. These expected late period yield values were then compared to the original or true late period yield (i.e., the verification stage) to determine the reliability of the dependent data to reconstruct yield.

Table 3.30. Regression statistics for early period-calibration.

R^2	19.30%
R^2 -adjusted	17.50%
p -value	< 0.01
Durbin-Watson statistic	1.70

Table 3.31. Analysis of Variance of early period calibration model.

Source	DF	SS	MS	F	p -value
Regression	1	0.0192	0.0192	10.31	0.003
Residual Error	43	0.0799	0.0019		
Total	44	0.0991			

Predictor	Coefficient	SE Coefficient	T	p -value
Constant	0.3378	0.0341	9.91	0.000
Tree-ring	0.1073	0.0334	-3.21	0.003

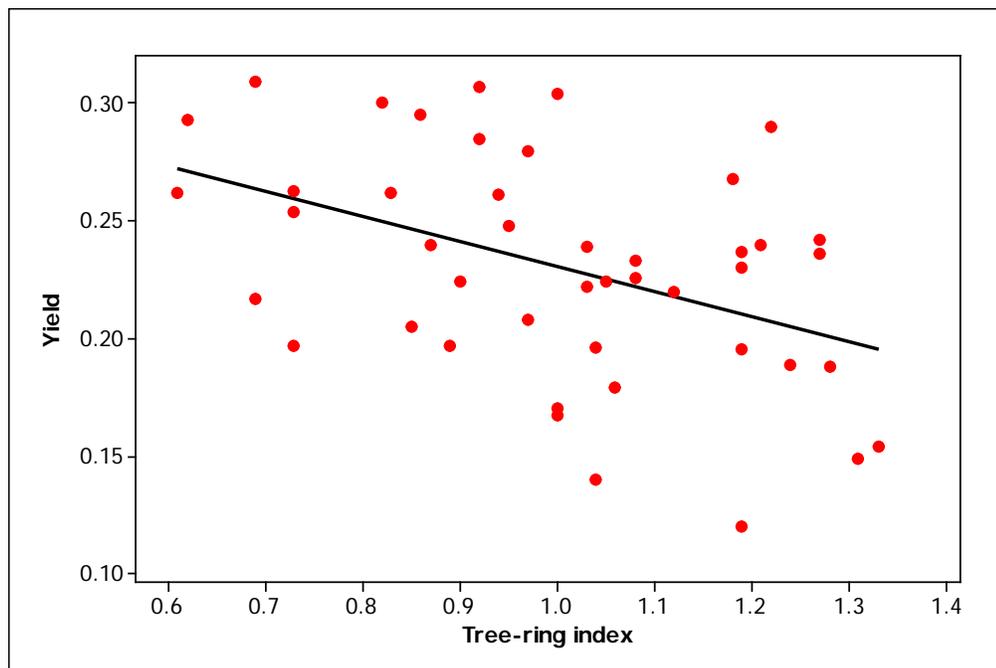


Figure 3.18. Linear model for the early record (1916–1960). Note the negative relationship between tree-ring width and syrup yield.

Table 3.32. Model calibration-verification statistics (CE and RE > 0 is significant).

Calibration, 1916–1960	
Model R^2	19.30%; $p < 0.01$
Verification, 1961–2006	
Pearson's r	0.065; $p = 0.667$
Reduction of Error (RE)	-0.418
Coefficient of efficiency (CE)	-2.060

Despite the significant model from the early period data, the model failed to significantly reproduce the independent period data, Pearson's $r = 0.065$ (Table 3.30). Additionally, both the RE and CE statistics were below the accepted threshold of > 0 (-0.418 and -2.060; respectively). Typically, RE and CE are calculated if the independent data are verified via correlation analysis (i.e., Pearson's or Spearman's r) to ensure the reconstruction reliability of a period outside the calibration-verification period. Interestingly, the failure of the model to reconstruct an independent period may indicate a changing relationship between radial growth and syrup yields. In other words, the relationship may not be stable over the entire period, indicating a shift in the physiological response of sugar maples to their environment.

I also attempted a calibration and verification on the early period data only (1916–1960) and found that the 1916–1937 segment yielded a significant regression model ($R^2 = 27.8$; $p = 0.01$) while the 1938–1960 period did not ($R^2 = 7.4$; $p = 0.220$). Using the calibration model from the early period (1916–1937), I proceeded to produce a reconstructed data set for the latter half of the truncated record (1938–1960). Like the full-period calibration and verification, only one significant calibration model was

constructed; however, it fails to verify the independent data. Because of the failure to produce a significant correlation between the actual and predicted 1938–1960 yields, calculating the RE and CE statistic was unnecessary. Therefore, this warranted additionally analysis to determine if there was a shift in the relationship between tree-ring width and syrup yield. A 15-year moving correlation analysis was chosen to evaluate the full period of 1916–2006. Lastly, I also examined if replacing syrup yield with price per gallon would reveal a better relationship with tree-ring widths. This method also generated a non-significant relationship (Pearson’s $r = 0.10$; $p > 0.10$)

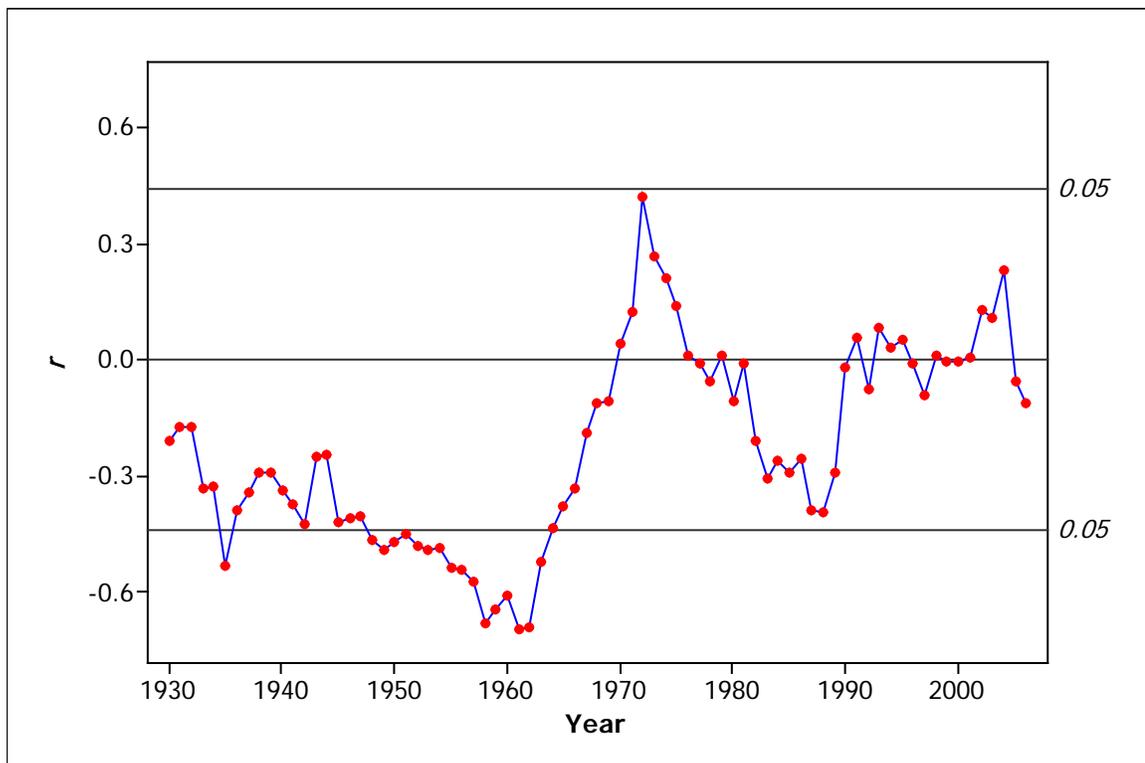


Figure 3.19. Fifteen-year moving correlation analysis between tree-ring width at ASM and syrup yield for NY State. Significant correlations are marked by the 0.05 line. Note the shift in relationship ca. 1970, albeit not significant.

The moving correlation revealed a series of unexpected results. The direction of the relationship makes a dramatic reversal in the late 1960s and early 1970s. The shift from a negative to a positive relationship may explain why the verification of the late period failed. Because the relationship is reversed, the late period model becomes invalid as the physiological ecological processes operating in the early half no longer function in the same mode. Even in the absence of this reversal, the correlation between tree-ring width and yield are weak throughout (Fig. 3.19) and rarely exceed the significant threshold.

CHAPTER IV

DISCUSSION

[4.1] Overview of Sugar Maple Physiological Ecology

The crown of a sugar maple tree can be viewed as its photosynthetic factory for the production of essential sugars used in the development of growing new tissues and maintenance of existing tissue (Noland et al., 2006). Additionally, these sugars are found in the tree's sap, which form the main constituent of maple syrup. Because syrup production is significantly correlated to winter and early spring temperatures and summer precipitation, the climatic linkage between tree-ring growth and syrup yields is an appropriate proxy for reconstruction. These variables also influence the growth rates of sugar maples and can serve as a proxy to model prior and future sugar seasons.

There was considerable concern over observed declines in the health and growth of certain northern tree species, especially in the 1980s–1990s (Payette et al., 1996) and whether this impacted syrup producers. Several theories were posited involving the role of acid deposition and air pollution in an effort to explain the observed declines of forest health, and especially the effect on sugar maple trees. The nature and extent of this decline initiated considerable debate and research about the roles of natural and anthropogenic changes to forests. This is, however; complicated by the intricate roles of natural determinants of growth including climatic variability and forest dynamics.

Previous work demonstrates that sugar maple radial growth is correlated with both spring temperatures and summer and fall drought conditions (Lane et al., 1993; Payette et al., 1995). Additionally, it is well established that maple syrup production is also significantly correlated with spring temperatures and summer precipitation (MacIver et al., 2006; Skinner et al., 2009). Thus, the factors that influence sugar maple growth rates in New York can be used as a proxy to model prior and future sugar season yields. While several studies conducted in Canada have used sugar maple tree-ring chronologies to deduce the possible causes for sugar maple mortality in northern forests (Payette et al., 1995), impacts of ice-storm damage on radial growth (Lane et al., 1993), the effects of climate (Tardif et al., 2001) and soil properties (Yin et al., 1994) on tree growth, no current literature addresses variability in tree growth and its relationship to production trends in maple syrup production.

[4.2] Tree Growth-Climate Analysis

To evaluate and interpret changes in radial growth rate, the expected tree growth rate under normal conditions must be identified. However, given the nature of deciduous forests and northern hardwood forests where sugar maple trees exist, quantification of the growth metrics is difficult. If expected growth with temporal consistency can be defined, then it becomes possible to identify the principal factors associated with short- and long-term changes in radial growth. Despite the sugar maple trees across the six sites in New York showing some degree of growth-climate response, no temporally stable and geographically consistent variable was found. Non-climatic impacts on tree growth vary at many temporal scales, serving to reduce the growth-climate correlation.

There was no uniform pattern across the sites in terms of growth trends. The lack of consistency in growth-climate response between sites is common. Across five sites in Michigan and Minnesota, Lane et al., (1993) found no definitive pattern and suggested that asynchronous insect defoliation events among sites and seed crop production may play a role in differences in ring-width indices. In Vermont, Gavin et al., (2008) suggested that several non-climatic factors may be responsible for the decoupling of growth and climate throughout a given time series. Houle's (1990, pp. 899–900) analysis of sugar maple growth in Quebec also failed to reveal any relationship to any climatic variable and states that “undoubtedly present, the climatic signal does not appear strong enough in relation to other factors, or not consistent enough through the years to be revealed by the statistical analysis performed.”

Prior-year(s) climatic conditions also influence radial growth. In Minnesota, Lane et al., (1993) found that maple tree growth was significantly correlated with at least one climatic variable from the previous year as initial spring sprout and root growth of temperate deciduous trees depend on their carbohydrate reserves (i.e., from the previous year). Interestingly, autumn temperature conditions that lengthen the previous growing season could be associated with an increase in carbohydrate reserves, and therefore, have a positive affect on growth. Conversely, tree growth appears to be enhanced by temperature conditions that allow an earlier start to the current growing season and can be unfavorable to the following year's growth (Lane et al., 1993). Gavin et al., (2008) found that July temperature was the most important control of sugar maple growth and growth was positively correlated with temperature, notably since approximately 1980.

Conversely, previous studies by Payette et al., (1996) and Tardiff et al., (2001) found that summer precipitation was a limiting factor for sugar maple growth.

Previous growth history may play a considerable factor in how the tree responds to subsequent environmental stimuli (i.e., lag effect) (Le Blanc et. al., 1987) and the lack of perfect synchronism in the growth reaction of trees between sites may indicate site-specific sensitivity. The poor growth-climate model was also noted by Ryan et al., (1994) and showed that once the effects of tree age, year, region and climate were removed from the chronology, 79% of variance was attributed to yearly variation within a tree, and 13% to tree-to-tree variation among stands within a region (Ryan et al., 1994). The trees from Ryan’s study showed a high degree of autocorrelation, as did the trees from the 6 New York sites that I analyzed (Table 4.1). In addition, Van Deusen (1989) reported this high level of autocorrelation. These non-climatological variables may also influence trends in the temporal stability in site growth-climate relationships

Table 4.1. Autocorrelation structure for the six study sites (median = 0.693)

Site	Auto Correlation	Site	Auto Correlation
ASM	0.654	MDM	0.732
IRM	0.731	MHM	0.680
KSM	0.776	UUM	0.712

Alternatively, climatic effects on tree growth may be realized through the effects of soil variables, and not just monthly climatological variables. Unlike Ryan et al., (1994), Yin and Yarp (1994) were able to explain 63% of the interannual variation in

tree-growth indices using only climatic factors. They found that precipitation during May–September and February air temperatures during the current growing season, and prior October affected radial growth. Additionally, when precipitation was replaced with soil water content (i.e., climate-soil model), and soil solution NO₃ concentrations in August and in the preceding September–March growth predictions increased significantly (R^2 from 63% to 83%). However, tree growth and soil water content for any specific period were not related to each other by simple correlation, and partial correlation between tree growth and mean soil water content revealed a parabolic dependency (Yin and Yarp, 1994). Spurr and Barnes (1980) results support Yin and Yarp (1994), and generalized that tree growth responds more to soil water deficiency than to any other perennial site factor. Because sugar maple has specific requirements for moist, fertile, well-drained soils, excessive soil moisture could lead to inadequate oxygen supply, which could lead to reduction in root surface absorption.

The poor growth-climate models from New York do bring into question whether soil moisture levels would be a better indicator of growth. The use of the Palmer Drought Severity Index (PDSI) or especially the Palmer Modified Drought Index (PMDI) with the New York tree-ring data may have revealed stronger relationship, given that these indices are a good measure of available soil moisture. However, overall the correlations with precipitation were weak (greatest absolute $r = 0.308$) with several of them negative. The use of seasonal precipitation (i.e., spring, summer) may have produced differing results, but given the low correlations with monthly precipitation, this

scenario is unlikely. Furthermore, the use of response function showed no growth relationships with precipitation at two of the six sites.

Complicating factors affecting ring-width indices at different sites that cannot be accounted for by climatic modeling are often poorly or never recorded making it difficult to explain in the models. The majority of the New York sites showed monthly climatic relationships unique to each site and the lack of common growth variables may reflect the influence of subtle differences in the timing of phenological events (Lane et al., 1993). The use of dendroclimatology analysis on sugar maple trees has not been widely attempted and results from the majority of studies implicate the obstacles of maple forest stand-dynamics and the difficulty in producing strong growth-climate models. Factors influencing tree-ring formation of sugar maple differ across its geographical range and are important to consider when extrapolating the results of a dendroclimatological study to different locations. Therefore, the lack of congruency should be taken into account when conducting regional assessment (e.g., statewide) of sugar maple tree growth.

Many of the New York sites had significant wintertime climatological predictors. For example, at site AMS, previous mean January precipitation, and mean February temperature; KSM, previous mean January precipitation; MDM, previous and current mean March temperature and MHM and UUM, mean January temperature. Initially these relationships appeared spurious, but Pederson et al., (2004) showed that winter temperatures significantly influence radial growth of the northern range margin of tree species in the Hudson Valley, New York. Winter temperatures were the strongest and most consistent temperature factors (January temperatures most strongly limit radial

growth) in the Hudson River Valley. In theory, the geographic temperature response could result from the potential negative influence of winter xylem embolisms on growth via disrupting the conductance of water within a tree's stem. Xylem embolisms have been shown to be a physiological limitation of oak and hickory trees. This damage would cause a shift in resource allocation, and energy that would have been used for growth would likely be used for winter embolism recovery.

An interaction between snow cover and fine root mortality are additional factors that could account for the stronger winter temperature response at the New York sites. Differences between northern tree species suggest that temperature sensitivity may be related to phenology and life history traits. Deep snow pack in late winter has been shown to effectively reduce radial growth rates by maintaining low soil temperatures and delaying the initiation of cambial expansion (Pederson et al., 2004). At tree line a lack of snow cover can also have a detrimental effect through increased winter desiccation and erosion of cambium and foliage from wind-blown snow and ice crystals. Thus, a reduction in snow cover may reduce growth through the increase of fine-root mortality. The potential impact of annual snow cover on a tree's roots may be a logical explanation of the geographic relation between winter temperatures and radial growth. Increased winter temperatures in areas of inconsistent annual snow pack may mean less winter damage to roots, which may mean less of a growth limitation. However, this would require a detailed analysis of snow cover differences among the New York maple sites. Regardless, this is a possible growth influence factor and Pederson et al., (2004) note that local site conditions may play an important role in temperature sensitivity.

The instability in the growth-climate relationship as depicted by the moving correlation analysis was also noted for the current growth-year's early-summer conditions and prior-year late-summer conditions in southern Quebec by Tardiff et al., (2001). Trees at this site had a negative correlation with prior July–August and current June temperatures. Additionally, prior-July temperature and current May and June precipitation correlations were observed in 62%, 46%, and 62% of the observed record, respectively. In other words, a cool July and wet August in the prior growing season had a positive impact on growth rates. The reduction in water stress therefore allows for supplementary accumulations of carbohydrate reserves. Conversely, too much water in early summer may be detrimental to growth. Payette et al., (1996) conclude that abundant precipitation during the growing season could lead to an excessive soil water content and in effect lower growth. This is also true for two of the New York sites. Both KSM and UUM had growth relationships that were negatively correlated with May and August mean precipitation. Conversely, all other sites had positive growth relationships with spring and summer precipitation. Summer temperature stress does not seem to be a limiting factor for growth at the New York sites, as only one site, ASM, showed a significantly positive relationship with July temperatures. Correlations with both spring and fall monthly temperatures were present at four of the sites. The correlations with the fall and spring time temperatures were more prominent compared to any summer monthly variable

[4.3] Syrup-Climate Models

In the New England Regional Assessment Group, Rock and Spencer (2001) report an inverse relationship between sap production and average winter temperatures for four states in the Northeast. This inverse relationship is well-known and not a new principle, but they hypothesize a decline in sugar production could result from a warming climate in this region. Interestingly, based on the analysis of 11 Canadian weather stations, two northern Vermont stations, and one New York station (MacIver et al. 2006) found using a temperature interval for sap flow (i.e., number of sap flow days) resulted in significantly increased sap flow days for three Canadian locations, and non-significant trends for all remaining Canadian, Vermont and New York stations. In other words, a portion of the northern most locations showed significant changes. These results fit with the observed trend of increases in temperature trends with increased latitude. These results may indicate that many locations in New York and New England may not be experiencing a noticeable change in wintertime climatology. Despite this not being an objective of this analysis, it does provide additional information about the climatological trends of the study area.

Previous research on the impacts of maple syrup production in the Northeastern U.S. had been mostly based on correlative associations between syrup production and average temperatures (Skinner et al., 2009). The well-established relationship of alternating freezing and thawing daily temperatures and its effects on internal stem pressure and therefore sap production is influenced by but not limited to climate. In addition, soil moisture, tree health, and snow cover are implicating factors. Few existing

studies (Rock and Spencer, 2001; Skinner et al., 2009) provide state or regional assessments based on limited, easily obtained data. However, Skinner et al., (2009) used a sap flow model to capture the spatial and temporal variations of sap flow across the Northeast, especially in New York. Duchesne et al., (2009) argue that the myriad of non-climatological factors that could affect the variation in syrup production at any given sugarbush, and would not exhibit a strong influence on the annual variability in maple syrup production for a large geographical area. Thus, these differences in production trends via local effects would be averaged or cancelled out when the data are combined into a larger geographical unit; and the variation that is present in the New York data set should display a relatively strong climatic signal. The maple syrup yield data in fact did confirm a strong relationship to state-level climatological data, and therefore, supports Duchesne et al., (2009) findings. The best regression model was able to account for 44% of the variance in year-to-year maple syrup production. Additionally, the random distribution of the residuals indicates that the model is not under or over estimating any period. For the number of complexities that contribute to maple syrup yields, a significant model, regardless of its predictive strength, is adequate and valuable.

Most of the existing studies on syrup-climate modeling have focused on the relationship between daily sap flow variations and daily climatic variables for specific sites with temperatures having the most significant influence. To my knowledge, only two studies have reported annual sap yield variation and relationships with climate based on 14-year (Pothier, 1995) and 22-year periods (Duchesne et al., 2009). Given the previously established link between maple syrup yield and climate, it is important to

develop quantitative models that could be used to evaluate the impact of a variable climate on the maple syrup industry. Duchesne et al., (2009) developed a multivariate model using four monthly climatic variables using mean January and April temperatures, and February and March maximum temperatures. They were able to explain 84% of the variance in syrup yield during 1985–2006 in Quebec and found that mean January and April temperatures were negatively related to annual yield. Conversely, maximum temperatures of February and March had a positive effect on yield. Maximum February and mean April temperature accounted for 70% of the 84% explained variance. The comparison of yields from individual Quebec sites indicated that annual variation was similar among regions and therefore, yield-climate relationships were relatively stable during the 1985–2006 study period. The yield-climate stability that Duchesne et al., (2009) propose raises an interesting principle in climate modeling, with a linkage to tree growth-climate modeling.

Canada, and specifically Quebec, may have yield records that more accurately reflect the industry's production trends and therefore provide considerably higher yield predictive power. Though the two models developed for the New York maple syrup yield were unable to explain a similar level of variance (R^2 s = 33.70% and 44.11% v. 70.00% and 84.00%), they did provide a longer record of verification (91 years v. 22 years). However, looking at the residual plots for both climate-syrup models I and II, the residuals show no sign of bias over the study period and therefore truncating the record should not improve the record. If the record was truncated, it is possible that a different suite of climatological variables would be entered into the models, reflecting and

identifying a possible shift in the syrup-climate model. Unlike Duchesne et al., (2009) who only included climatological variables from the current year (i.e., sugarseason) I included prior climatological conditions from the previous year as these are identified (see MacIver et al., 2006) as influencing syrup yields.

Uniquely, absent from other attempts at modeling syrup yields, I used heating degree days (HDD) and cooling degrees days (CDD) as possible predictors. This measure differs from the traditionally used mean monthly temperature in that it measures the amount of variation from the mean temperature for a specific month. In other words, a HDD is the number of degrees per day that the daily average temperature is below a specific temperature, usually 65° F. Therefore, years with months with larger diurnal ranges will be identified while the mean monthly temperature does not provide any information about how the temperatures behave. This is true for CDD; except that CDD measures the number of degrees per day that the daily average temperature is above 65° F. The addition of HDD and CDD significantly improved the syrup yield models, from R^2 of 33% to 44%. Even though the model with HDD and CDD contained one additional variable, the Cp statistic indicated that the addition of this variable did provide significant information to the model. Interestingly, these results suggest that the use of HDD and CDD could potentially provide better predictive models for agricultural crops that require specific temperatures for optimum yields.

Looking at the two climate-syrup models for New York I find similarities in significant variables and coefficients with that of Duchesne et al., (2009). Both models indicated that cooler January and April temperatures and warmer February temperatures

increased syrup production. The negative January correlation may be linked to affects of snow pack cover, where deep snow actually inhibits water uptake via the roots, thereby reducing sap flow. In addition, too thin of a snow pack can enhance the soil vulnerability to freezing and frost damage (Duchesne et al., 2009) and has been linked to reductions in seasonal sap flow (Robitaille et al., 1995). Conversely, the New York model had a negative coefficient for March temperature while the climate-syrup model for southern Quebec yielded a positive coefficient. One possible reason for this dichotomy could be the effect of using maximum March temperatures, but it is more plausible that the more northerly location of Quebec has colder March conditions which would reduce sap flow. Interestingly, the addition of the prior climatological year does improve the predictive power of the regression model. Additionally, both the previous mean June precipitation and temperatures are higher in predictive power over the current year (i.e., sugarseason) February and April temperatures. This could reflect the influence of tree growth via stored starch from the growing season on syrup production and the basis for a tree-ring reconstruction of syrup yields.

[4.4] Tree-Ring Reconstruction

Because syrup production is significantly correlated to winter and early spring temperatures and summer precipitation, the climatic linkage between tree-ring growth and syrup yields should be an appropriate proxy for reconstruction. These variables also influence the growth rates of sugar maples and can in theory serve as a proxy to model prior and future sugar seasons. Attempts to model New York state tree growth and syrup production were not successful, but the analysis revealed an unexpected and interesting

outcome. The early period (1916–1960) provided the only significant calibration model. The model indicated that tree-ring growth was negatively correlated to syrup production. Hence, years with poorer tree growth are associated with years with higher syrup production. While this seemed counter to the idea that increased radial growth is an indication of a more productive year, in terms of biomass accumulation, and starch storage; it may indicate an alternative mechanism. It is plausible that years with lower growth rates would have more available stored starch because it was not metabolized for production of xylem, but this does not explain the shift in correlation in tree-ring widths and syrup production over the period of record. The shift from a negative to positive correlation was dramatic and occurred over short period (5–10 years), and is unlikely that it is a response to a shift in the growth- or syrup- climate responses.

An alternative reason for the reversal could be in the method of data collection and data recording between the two temporal halves (i.e., early and late period). Data prior to the 1960s was collected by state-level bureaus that reported to the USDA compared to post-1960s when the USDA collected their own survey data. A single reporting bureau offers a more direct method of data collection, and therefore, is more likely to provide a higher level of data validity. Additionally, prior to the 1970s yield was measured in terms of yield-per-tree, rather than yield-per-tap, but the change in this metric should not have an effect on the relationship between tree growth and syrup yield as the addition of taps still provides a measure of yield-per-tree. For cases where the tree contains two taps, the addition of the second tap would not change the yield-per-tree. While the non-significant positive correlation in the latter half of the record are more in

line with the physiological response that would be expected, the model was not strong enough to use for calibration.

The method of using lagged ring-width data is based on several known physiological responses of sugar maple trees to environmental variability including climate. Several studies have shown that radial growth in sugar maples is strongly associated to at least one climatic factor from the previous year (Yin and Arp, 1994; Ryan et al., 1994; Payette et al., 1996; Tardiff et al., 2001). Additionally, Smith and Shortle (2003) demonstrated that environmental stress can alter tree growth, in some cases, for a duration of three to four years and Pisaric et al. (2008) found that tree growth (i.e., recovery) showed the greatest increase five years after ice-storm damage. Spring tree growth is positively related to temperatures and dependent on carbohydrate reserves stored from the previous fall growing season. Similarly, the amount of starch stored during early autumn in the xylem is often used as an indicator of tree vitality and photosynthetic capacity (Kramer and Kozlowski, 1979; Wong et al., 2003). Most of the organic carbon produced during the photosynthetic process is utilized during the growing season. However, following starch utilization during the growing period, starch becomes stored as the major carbohydrate reserve during the leafless period (Wong et al., 2005). During dormancy, starch becomes the main source of carbon and energy substrate for metabolic processes, development of cold tolerance, cellular maintenance and respiration and for primary growth in the spring (Wong et al., 2003). Additionally, changes in starch and soluble sugar profiles could indicate stress-induced changes in tree physiology.

By comparison, maple-syrup production and the variability in yield and flavor of this natural product are similar to that of wine. Wine production is intricate and complex with significant variability in wine crop quality and characteristics associated with the microenvironment in which the grapes are cultivated (Sommers, 2008). This specificity of grape cultivation and wine production is widely important to consumers, as wines are characterized by the regions from which they are derived. These metrics and regional specialties are given a special French term, *terroir*. *Terroir* represents the relationship between the qualities of an agricultural product (color, taste, and aroma) and its geographic origin, which might influence these characteristics.

The concept of *terroir* is frequently used to explain the hierarchy of high-quality wines, and can be defined as an interactive ecosystem specific to a given place, including the climate, soil and the vine (Seguin, 1988). To understand the way *terroir* functions, it is essential to take into account the interactions among the factors that contribute to *terroir*. Some authors also include human factors such as viticultural and enological techniques in their definition of *terrior* (Seguin 1986). Many authors have assessed the impact of a single parameter of *terroir* on grape quality include climate (Gladstones, 1992), soil (van Leeuwen and Seguin, 1994), and cultivar (Huglin and Schneider 1998). For example, the effects of vine water and nitrogen status, linked to soil type, have been shown for Cabernet Sauvignon (Choné et al., 2001) and Merlot (Tregoat et al., 2002).

Given the considerable site specificity that may be present for syrup producers, a sugarbush (i.e., site) level analysis of tree growth and syrup yields may reveal a higher degree of correlation. In other words, sugarbushes also have their own *terroir*, which

likely explains why maple syrup produced at sites only a few miles apart may have different colors, flavor, and smell, and why annual productivity can vary between sites. In turn, these site specifics may explain why reconstructing yield using tree-rings from multiple sites did not produce significant results.

A wider geographical analysis of maple syrup yield has potential, given that a stronger growth-climate model might be found. Therrell's et al. (2006) reconstruction of Mexican corn yields showed that agriculture yields could be modeled using tree-ring data. However, they used the climatic variable, drought, to reconstruct corn yields. Their tree-ring series linked narrow Douglas-fir rings (i.e., drier climatological years) with low-production years for corn. Unlike Therrell's reconstruction, I directly employed tree growth as the dependent variable, albeit corn lacks annual rings. Corn yield is strongly correlated to rainfall and therefore provides an ideal proxy. The sugar maple chronologies lacked strong climate response and responded to a myriad of climate variables, and therefore, are poor candidates to serve as a proxy.

With the economic importance and geographical heritage associated with maple syrup production, a need for reconstructing maple syrup yields still exists. Despite the success of predicting syrup production in New York using standard monthly climatological variables, a lack of radial growth and syrup production correlation deserves a more detailed analysis as it could potentially reconstruct the yield record by over a century. The poor climate signal found in sugar maples complicates this methodology and an alternative to traditional dendroclimatology correlation analysis could be useful for sugar maple modeling. It is unlikely that a strong consistency in

growth-climate response variables would be found across New York, but the increasing the number of sampling sites may help to identify regional patterns of tree growth. Subjecting the increased sampling density to principle component analysis may produce more reliable regional-scale chronologies. In turn, using these regional chronologies in concert with the coinciding regional maple syrup yields, a reconstruction could be encouraged.

CHAPTER V

CONCLUSION

The decline of the maple syrup industry in New York and New England coupled with the worldwide demand for maple products has increased the importance of understanding the response of sugar maple growth and sap production to warming spring temperatures. The modernization of sap collection and processing, including the use of plastic tubing, vacuum pumping, and updated taps, have gained in popularity over the last 20–30 years. These changes were expected to have a positive effect of maple syrup production. However, the data for New York indicate a significant production decline.

Here, I demonstrated that the use of sugar maple tree-ring data has potential, despite the lack of model verification, for forecasting and hindcasting maple syrup yields and merits additional study at a finer, regional or sugarbush scale with a more robust data set. Forecasting of maple syrup yields may provide farmers with a better preseason estimate of productivity allowing for adjustments in sugaring operations such as fuel and labor costs. Conversely, because sugar maple trees can live several centuries, samples can be easily collected from individuals with interior dates beginning in the early 19th century. Therefore, the potential exists to hindcast these data to obtain annual maple syrup yields during a period when records are limited or non-existent, which could in turn provide a greater historical context of maple syrup yield responses to climatic variability.

Despite the failure to reconstruct statewide maple syrup yield, interesting results were recognized in these analyses. First, maple syrup production appears to respond principally to microclimatic and local site variables in analogous way grapes do in wine production, with the influence of macroclimatic parameters being secondary. As such, the effects of *terroir* may be as operative for maple syrup production as it is for wine. Specifically, local site conditions may account for the largest portion of interannual variability that exists for maple syrup production. These microclimatic and micro-site conditions should provide a higher degree of explained variance for sugarbush production trends than that of coarser-scale climatic division data. Additionally, the modeling is complicated by the weak climatic signal that maples exhibit, but this may also reflect the micro-scale site effects insufficiently captured by broader-scale climate variables.

Understanding the effects climate change may have on crop and pasture yields including maple syrup has become increasingly important. Thus, these results will help promote the effectiveness of using tree-ring data to predict agricultural yields, which will ultimately provide farmers additional information about crop yield cycles. This knowledge will in turn help determine appropriate management methods for sugarbush operators during less-favorable climatological conditions. These results suggest that the basic physiological responses that affect both starch and photosynthate production, which in turn affect sap production, are multi-year and multi-variable processes. Whether this lag and/or average are consistent among sites is unknown, but the ease in which the tree-ring data can be modeled allows site-specific results to help with forecast. The industry has increased in importance over the last three decades under the influence of

technological improvements to the industry's infrastructure, and increased governmental assistance (e.g., farm bill, state and federal programs). The economic importance of the maple syrup industry provides an impetuous and the imperative need for additional studies with the possible use of dendrochronology.

Despite the large body of research on maple syrup production since the late-1800s focusing on the impact of climatic conditions from large-scale to micro-site levels, the understanding of what control sap volume, sap sugar content, and sap quality remains incomplete. In turn, this increases the difficulty for prediction of environmental impacts on the industry. The reliability of predictive models is dramatically decreased when the complications and the variability of magnitude, duration, and timing of the host of non-climatological variables that can influence sugar maple health, growth, and sugar production. That said, further research can build upon the findings from this study and find ways to possibly decrease the noise-to-signal ratio found in the data. Ultimately, regional models and forecasts will be more useful to syrup producers, especially in areas like New York where the climatology and topography are diverse.

REFERENCES

- Akkemik, U., D'Arrigo, R., Cherubini, P., Kose, N., and Jacoby, G.C. 2008. Tree-ring Reconstructions of Precipitation and Stream Flow for North-Western Turkey. *International Journal of Climatology* 28:173–183.
- Ali, A.H. 2004. Application of Neural Network Principal Components to Climate Data. *Journal of Atmospheric and Oceanic Technology* 21:149–157.
- Anderson, D. G., Stahle, D. W., and Cleaveland, M. K. 1995. Paleoclimate and the Potential Food Reserves of Mississippian Societies: A case study from the Savannah River Valley. *American Antiquity* 60:258–286.
- Anderson, W.R., 1951. Open Crown Maples are Basis for Profitable Sugar Operation. *Ohio Farm and Home Research* 36(51):62–63.
- Beckage, B., Osborne, B, Gavin, D.B., Pucko, C., Siccama, T., and Perkins, T. 2008. A Rapid Upward Shift of a Forest Ecotone During 40 Years of Warming in the Green Mountains of Vermont. *Proceedings of the National Academies of Science* 105(11):4197–4202.
- Biondi, F. 1997. Evolutionary and Moving Response Functions in Dendroclimatology. *Dendrochronologia* 15:139–150.
- Biondi, F. and K. Waikul. 2004. DENDROCLIM2002: A C++ Program for Statistical Calibration of Climate Signals in Tree-Ring Chronologies. *Computers & Geosciences* 30:303–311.
- Blair, W. F. 1958. Distributional Patterns of Vertebrates in the southern United States in Relation to Past and Present Environments. pp. 433–468, in Zoogeography (C. L. Hubbs, ed.), *American Association for the Advancement of Science* 51:1–509.
- Blum, B.M. 1973. Relation of Sap and Sugar Yields to Physical Characteristics of Sugar Maple Trees. *Forest Science* 19:3.
- Braun, E. L. 1950. *Deciduous Forests of Eastern North America*. New York: McGraw-Hill Book Company. 596 pp.

- Briffa, K.R. 1995. Interpreting High-Resolution Proxy Climate Data Example of Dendrochronology. In: von Storch, H. and Navarra, A., editors, *Analysis of Climate Variability: Applications of Statistical Techniques*, Berlin: Springer, pp.77–94.
- Briffa, K.R. and E.R. Cook. 1990. Methods of Response Function Analysis. In *Methods of Dendrochronology*. Cook, E.R. and L.A. Kairiukstis, editors. Kluwer Academic Publishers, Amsterdam.
- Briffa, K.R., F.H. Schweingruber, P.D. Jones, T.J. Osborn, I.C. Harris, S.G. Shiyatov, E.A. Vaganov, H. Grudd, and J. Cowie. 1998. Trees Tell of Past Climates: But Are They Speaking Less Clearly Today? *Philosophical Transactions: Biological Sciences* 353:65–73.
- Burns, R. M., and B. H. Honkala. 1990. Silvics of North America: 2. Hardwoods. Agriculture Handbook 654. U.S. Department of Agriculture, Forest Service, Washington, DC. vol.2, 877 pp.
- Cambell, T.N. 1949. The Pioneer Tree-Ring Work of Jacob Kuechler. *Tree Ring Bulletin* 15:16–20.
- Cattell, R.B. (1966). The Scree Test for the Number of Factors. *Multivariate Behavioral Research* 1:245–276.
- Chipello, C.J. 2000, July 27. Looking for Syrup’s Snob Appeal—Tasters Talk of ‘Floral’ Hints as Quebec Producers Try to Boost Prices, Cachet. Wall Street Journal (Eastern edition). New York, New York.
- Choné, X., C. van Leeuwen, P. Chéry, and P. Ribéreau-Gayon. 2001. Terroir Influence on Water Status and Nitrogen Status of Non-Irrigated Cabernet Sauvignon (*Vitis vinifera*): Vegetative Development, Must and Wine Composition. *South African Journal for Enology & Viticulture* 22(1):8–15.
- Cirelli, D. 2005. Anatomy and Physiology of Sugar Maple (*Acer saccharum* Marsh.) in Relation to Xylem Sap Pressure. M.A. thesis, University of Maine.
- Cook, D. 2005. Anatomy and Physiology of Sugar Maple (*Acer saccharum* Marsh.) in Relation to Xylem Sap Pressure. M.A. thesis, University of Maine.
- Cook, E.R. and R.L. Holmes. 1985. Program ARSTAN and User’s Manual. Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona, 28 pp.

- Cook, E.R., Bird, T., Peterson, M., Barbetti, M., Buckley, B., D'Arrigo, R. and Francey, R. 1992. Climate Change Over the Last Millennium in Tasmania Reconstructed from Tree-Rings. *The Holocene* 2:205–17.
- Cook, E.R. and L. Kairiukstis. 1992. *Methods of Dendrochronology: Applications in the Environmental Sciences*. Kluwer Academic Publisher, Boston, MA.
- Cortes, P.M. and T.R. Sinclair. 1985. The Role of Osmotic Potential in the Spring Sap Flow of Mature Sugar Maple Trees (*Acer saccharum* Marsh). *Journal of Experimental Botany* 36(162):12–24.
- Currier and Ives, 1856. *American Forest Scene: Maple Sugaring*. Library of Congress, Washington, DC.
- Currier and Ives, 1872. *17 Maple Sugaring: Early Spring in the Northern Woods*. Library of Congress, Washington, DC.
- Dent, T.C., R.P., Adams. 1983. Relationships of Two Isolated Groups of Sugar Maples (*Acer saccharum* Marshall ssp. *saccharum*) in West Central Oklahoma to Eastern and Western Species. *Rhodora* 85:439–456.
- Duchesne, L., D. Houle, M.A., Côte. 2009. Modelling the effect of Climate on Maple Syrup Production in Quebec, Canada. *Forest Ecology and Management* 258(12):2683–2689.
- Duvick, D.N. and Blasing, T.J. (1981). A Dendroclimatic Reconstruction of Annual Precipitation Amounts in Iowa Since 1680. *Water Resources Research* 17:1183–1189.
- Easterling, D.R. 2002. Recent Changes in Frost Days and the Frost-Free Season in the United States. *Bulletin of the American Meteorological Society* 83:1327–1332.
- Foster, D. R. and E. R. Boose. 1992. Patterns of Forest Damage Resulting from Catastrophic Wind in Central New England, USA. *Journal of Ecology* 80:79–98.
- Frank, D., Büntgen U., and Esper J. 2009. Response to Late 20th Century Growth Acceleration in Greek Firs (*Abies cephalonica*) from Cephalonica Island, Greece: A CO₂ Fertilization Effect? *Dendrochronologia* 27:223–227.
- Fritts, H. C. 1971. Dendroclimatology and Dendroecology. *Quaternary Research* 1(4):419–49.
- Fritts, H.C. 1976. *Tree Rings and Climate*. London: Academic Press, 567 pp.

- Fritts, H. C. 1991. *Reconstructing Large-Scale Climatic Patterns from Tree-Ring Data: A Diagnostic Analysis*. University of Arizona Press, Tucson, Arizona. 286 pp.
- Fritts, H.C., Blasing T.J., Hayden B.P., Kutzbach J.E. 1971. Multivariate Techniques for Specifying Tree-Growth and Climate Relationships and for Reconstructing Anomalies in Paleoclimate. *Journal of Applied Meteorology*, 10:845–864.
- Fritts, H.C., E.A. Vaganov, I.V. Sviderskaya, and A.V. Shashkin. 1991. Climatic Variation and Tree-Ring Structure in Conifers: Empirical and Mechanistic Models of Tree-Ring Width, Number of Cells, Cell Size, Cell-Wall Thickness and Wood Density. *Climate Research* 1:97–116.
- Gabriel, W. J. 1972. Phenotypic Selection in Sugar Maple for Superior Sap Sugar Production. Res. Pap.NE-221. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 12 pp.
- Garrett, P.W., and K.R. Dudzik. 1989. Ray Tissue as an Indirect Measure of Relative Sap-Sugar Concentration in Sugar Maple. U.S. Department of Agriculture, Forest Service. Research Paper NE-626. 7 pp.
- Gladstones, J. 1992. *Viticulture and Environment*. Winetitles, Adelaide, 310 pp.
- Gavin, D.G., B. Beckage, and B. Osborne. 2008. Forest Dynamics and the Growth Decline of Red Spruce and Sugar Maple on Bolton Mountain, Vermont: A Comparison of Modeling Methods. *Canadian Journal of Forest Research* 38:2635–2649.
- Glock, W. 1939. The Response of Plants to Climate. Proceedings VI. Pacific Science Congress. Vol. 3:617–619.
- Godman, R.M., H.W., Yawney, and C. H., Tubbs. 1990. Sugar Maple. *Silvics of North America: 2. Hardwoods*. Agriculture Handbook 654, U.S. Dept. of Agriculture, Forest Service, Washington, D.C. vol. 2, 877 pp.
- Gregory, H. A. 1981. A Rapid Method of Estimating the Relative Amount of Vascular Ray Tissue. *International Association of Wood Anatomists Bulletin* 2 (2–3): 77–78.
- Griggs, C., DeGaetano, A., Kuniholm, P., and Newton, M. 2007. A Regional High Frequency Reconstruction of May–June Precipitation in the North Aegean from Oak Tree Rings, A.D. 1089–1989. *International Journal of Climatology* 27:1075–1089.

- Guiot, J. 1991. The Bootstrapped Response Function. *Tree-Ring Bulletin* 51:39–41.
- Henshaw, H.W. 1890. Indian Origin of Maple Sugar. *American Anthropologist* 3(4):341–352.
- Heinrich, B. 1992. Maple Sugaring by Red Squirrels. *Journal of Mammalogy* 73:51–54.
- Holmes, R.L. 1983. Computer-Assisted Quality Control in Tree-Ring Dating and Measurement. *Tree-Ring Bulletin* 43:69–78.
- Horsley, S.B. and R.P. Long. 1999. Sugar Maple Ecology and Health: Proceedings of an International Symposium. Gen. Tech. Rep. NE-261. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station, 120 pp.
- Horsley, S.B., R.P. Long, S.W. Bailey, R.A. Hallet, and P.M. Margo. 2002. Health of Eastern North America Sugar Maple Forest and Factors Affecting Decline. *Northern Journal of Applied Forestry* 19(2):34–44.1
- Houle, G. 1990. Growth Patterns of Sugar Maple Seedlings and Mature Trees in Healthy and Declining Hardwood Stands. *Canadian Journal of Forest Research* 20: 894–901.
- Huglin, P., and C. Schneider. 1998. Biologie et écologie de la vigne. Lavoisier Tec & Doc, Paris. 370 pp.
- Huntington T.G., G.A. Hodgkins, B.D. Keim, R.W. Dudley. 2004. Changes in the Proportion of Precipitation Occurring as Snow in New England (1949–2000). *Journal of Climate* 17:2626–2636.
- Iverson, L.R. and A.M. Prasad. 1998. Predicting Abundance of 80 Tree Species Following Climate Change in the Eastern United States. *Ecological Monographs* 68(4):465–485.
- Jones, C.H., A.W. Edson, and W.J. Morse. 1903. The Maple Sap Flow. Vermont Agricultural Experimental Station Bulletin 103, 144 pp.
- Jones, G.V., M.A. White, O.R. Cooper, and K. Storchmann. 2005. Climate Change and Global Wine Quality. *Climatic Change* 73: 319–343.
- Kahle, H.P. 1994. Modeling Growth-Climate Relationships of Norway Spruce in High Elevations of the Black Forest. PhD thesis, University of Freiburg, Germany.

- Kairiukstis, L. and J. Dubinakaite, 1986. Application of Rhythmical Fluctuations of Radial Increment of Trees for Prognosis of Climate Conditions. In: L. Kairiukstis, Dendrochronology and Dendroclimatology. Nauka Publishing House, USSR.
- Kallio, E., C. H., Tubbs. 1980. Sugar maple (*Acer saccharum* Marsh.), American wood. United States. Forest Service Department of Agriculture, Forest Service Series.
- Keough, G.R. 2008. Maple Syrup. New England Agricultural Statistics, NASS, USDA.
- Keim, B. and B. Rock. 2001. The New England Region's Changing Climate, pp. 8–17. In: Preparing for Changing Climate: The Potential Consequences of Climate Variability and Change. New England Regional Overview, U.S. Global Change Research Program, 96 pp., University of New Hampshire.
- Keough, G.R. 2008. Maple Syrup. New England Agricultural Statistics, NASS, USDA.
- Koelling, M.R. 1968. Sap Yields From Fall and Spring Tapping of Sugar Maple. Research Paper NE-115. Upper Darby, PA: U. S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 8 pp.
- Koelling, M.R., R.B., Heiligmann, T.D., Perkins. 2006. North American Maple Syrup Producers Manual. Second edition. Bulletin 856. Produced by Ohio State University Extension in cooperation with the North American Maple Syrup Council.
- Kolivras, K.N., and Comrie, A.C. 2007. Regionalization and Variability of Precipitation in Hawaii. *Physical Geography* 28:76–96.
- Knapp, P.A., Grissino-Mayer, H.D., and Soulé, P.T. 2002. Climatic Regionalization and the Spatio-Temporal Occurrence of Extreme Single-Year Drought Events (1500–1998) in the Interior Pacific Northwest, USA. *Quaternary Research* 58:226–233.
- Knapp, P. A., and P.T. Soulé. 2008. Use of Atmospheric CO₂-Sensitive Trees May Influence Dendroclimatic Reconstructions. *Geophysical Research Letters* 35: L24703 doi:10.1029/2008GL035664.
- Kramer, P.J., and T.T. Kozlowski. 1979. *Physiology of Woody Plants*. Academic Press, New York.
- Laing, F.L., and D.B., Howard. 1990. Sap Sweetness Consistency vs. Growth Rates in Young Sugar Maples. *Northern Journal of Applied Forestry* 7:5–9.

- Lane, C.J., D.D. Reed, G.D. Mroz, and H.O. Liechty. 1993. Width of Sugar Maple (*Acer saccharum*) Tree Rings Affected by Climate. *Canadian Journal of Forest Research* 23:2370–2375.
- Lauten, G., B. Rock, S. Spencer, T. Perkins, and L. Irland. 2001. Climate Impacts on Regional Forest. pp. 32–48. In: *Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change*. New England Regional Overview, U.S. Global Change Research Program, 96 pp., University of New Hampshire.
- Larochelle, F., Forget, É., Rainville, A. and Bousquet, J. 1998. Sources of Temporal Variation in Sap Sugar Content in a Mature Sugar Maple (*Acer saccharum*) Plantation. *Forest Ecology and Management* 106:307–313.
- Le Blanc, D.C, Raynal, D.J. and White, E. H. 1987. Dendroecological Analysis of Acidic Deposition Effects on Forest Productivity. In *Effects of Atmospheric Pollutants on Forests, Wetlands and Agricultural Ecosystems*. T. C. Hutchinson and K. M. Meema (eds). NATO ASI series, Volume 16. Springer-Verlag, Berlin, 291-306.
- Lobell, D.B. and G. P. Asner. 2003. Climate and Management Contributions to Recent Trends in U.S. Agricultural Yields. *Science* 299:1032.
- Lovett, G. M. and M. J. Mitchell. 2004. Sugar Maple and Nitrogen Cycling in the Forests of Eastern North America. *Frontiers in Ecology and the Environment* 2:81–88.
- MacIver, D.C., M. Karsh, N. Comer, J. Klaassen, H. Auld, and A. Fenech. 2006. Atmospheric Influences on the Sugar Maple Industry in North America. Environment Canada Adaption Impacts and Research Division. Occasional Paper No. 7, 21 pp.
- Malmgren, B.A. and Winter, A. 1999. Climate Zonation in Puerto Rico Based on Principal Components Analysis and an Artificial Neural Network. *Journal of Climate* 12:977–985.
- Marvin, J.W. 1957. Investigation of the Sugar Content and Flow Mechanism of Maple Sap. University of Vermont Extension Publication MR 62, 7 pp.
- Marvin, J.W. 1958. Physiology of Maple Sap Flow. University of Vermont Extension Publication MR 64, 29 pp. 2
- Marvin, J.W., M.F. Morselli, and F.M. Laing. 1967. A Correlation Between Sugar Concentration and Sap Volume Yields in Sugar Maple: An 18-Year Study. *Forest Science* 13:346–351.

- Marvin, J.W. and M.T. Greene. 1951. Temperature-Induced Sap Flow in Excised Stems of *Acer*. *Plant Physiology* 26:565–580.
- Marvin, J.W. and R.O. Erickson. 1956. A Statistical Evaluation of Some of the Factors Responsible for the Flow of Sap from the Sugar Maple. *Plant Physiology* 31:57–61.
- McGlashen, A. 2009. What Can Climate Models Tell Cherry Growers? *Scientific American*, May 6th.
- Menshutlin, V.V. 1971. Simulative Modeling of Water Organisms, Populations, and Communities. Nauka Publishing House. Moscow.
- Moore, H.R., W.R. Anderson, and R.H. Baker. 1951. Ohio Maple Syrup—Some Factors Influencing Production. Ohio Agricultural Experimental Station Research Bulletin 718, 58 pp.
- Morselli, M.F., J.W. Marvin, and F.M. Lang. 1978. Image-Analyzing Computer in Plant Science. More and Larger Vascular Rays in Sugar Maples of High Sap and Sugar Yield. *Canadian Journal of Botany*. 56:983–986.
- Morrow, R.R. 1952. Consistency in Sweetness and Flow in Maple Sap. *Journal of Forestry* 50:130–131.
- Morrow, R.R. 1953. Big Tree Crowns Mean Cheaper Syrup. Cornell University Farm Research, January, Ithaca, NY.
- Morrow, R.R. 1955. Influence of Tree Crowns on Maple Sap Production. Cornell University Agricultural Experimental Station Bulletin 916.
- Morrow, R.R. 1973. Unpredictability of Maple Sap Flow. N.Y. Food and Life Sciences. Bulletin No. 14. Agricultural Experiment Station. Cornell University. 17 pp.
- Nash, J.E. and Sutcliffe, J.V. 1971. Riverflow Forecasting Through Conceptual Models. 1, A Discussion of Principles. *Journal of Hydrology* 10: 282–290.
- Nearing, H. and Nearing, S. 2000. *The Maple Sugar Book: Together With Remarks on Pioneering As a Way of Living in the Twentieth Century*. Chelsea Green. 305 pp.
- Noland, T.L., G. McVey, and D. Chapeskie. 2006. Ice Storm and Fertilization Effects on Root Starch, Sap Productivity and Sweetness, diameter Growth, and Tap Hole Closure in Sugar Maple Stands of Eastern Ontario. Ontario Forest Research Institute, Forest Research Note, No. 68. 6 pp.

- Payette, S., M. Fortin, and C. Morneau. 1996. The Recent Sugar Maple Decline in Southern Quebec: Probably Causes Deduced from Tree Rings. *Canadian Journal of Forest Research* 26: 1069–1078.
- Pederson, N. 2010. External Characteristics of Old Trees in the Eastern Deciduous Forest. *Natural Areas Journal* 4:396–407.
- Pederson, N., E.R. Cook, G.C. Jacoby, D.M. Peteet, and K.L. Griffin. 2004. The Influence of Winter Temperatures on the Annual Radial Growth of Six Northern-Range Margin Tree Species. *Dendrochronologia* 22: 7–29.
- Peng, S.B., Huang J.L., Sheehy J.E., Laza R, C., Visperas R.M., Zhong X.H., Centeno G.S., Khush G.S., Cassman KG. 2004. Rice Yields Decline with Higher Night Temperature from Global Warming. *Proceedings of the National Academies of Science* 101:9971–9975.
- Perkins, T., T. Wilmot, and M. Zando. 2004. Fertilization of Sugarbushes—Part I. Physiological Effects. *Maple Syrup Digest* 16A(3):23–27.
- Perkins, T., T. Wilmot, and M. Zando. 2004. Fertilization of Sugarbushes—Part II. Physiological Effects. *Maple Syrup Digest* 16A(4):23–27.
- Perkins, T. 2007. Congressional Testimony to the House Select Committee on Energy Independence and Global Warming Global Warming Mountaintop ‘Summit’: Economic Impacts on New England.
- Phipps, R.L. 1985. Collecting, Preparing, Crossdating, and Measuring Tree Increment Cores. U.S. Geological Survey Water Resources Investigations Report 85-4148:1–48.
- Pisaric, M.F.J., D.J. King, A.J.M. MacIntosh, and R. Bemrose. 2008. Impact of the 1998 Ice Storm on the Health and Growth of Sugar Maples (*Acer saccharum* Marsh) Dominated Forests in Gatineau Park, Quebec. *Journal of the Torrey Botanical Society* 135, 530–539.
- Pothier, 1995 D. Pothier, Effets des coupes d’éclaircie et des variations climatiques interannuelles sur la production et la teneur en sucre de la sève d’une érablière, *Canadian Journal of Forest Research* 25:1815–1820.
- Prasad, A. M., L. R. Iverson., S. Matthews., M. Peters. 2007–ongoing. A Climate Change Atlas for 134 Forest Tree Species of the Eastern United States [database]. <http://www.nrs.fs.fed.us/atlas/tree>, Northern Research Station, USDA Forest Service, Delaware, Ohio.

- Richman, M.B. 1986. The Retrieval of Meteorological Patterns via Rotated Principal Components. *Bulletin of the American Meteorological Society* 62:879–879.
- Robitaille, G., R. Boutin, and D. Lachance. 1995. Effects of Soil Freezing Stress on Sap Flow and Sugar Content of Mature Sugar Maples (*Acer saccharum*). *Canadian Journal of Forest Research* 25:577–587.
- Rock, B. and S. Spencer. 2001. CASE STUDY 2, The Maple Sugar Industry, pp. 39–42. In: Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change. New England Regional Overview, U.S. Global Change Research Program, 96 pp., University of New Hampshire.
- Ruth, R.H., J.C. Underwood, C.E. Smith, and H.Y. Yang. 1972. Maple Syrup Production From Big-Leaf Maple. Research not PNW-181, Portland, OR: USDA Forest Service, Northwest Forest and Range Experiment Station.
- Ryan, D.A.J., O.B. Allen, D.L. McLaughlin, A.M. Gordon, A.M. 1994. Interpretation of Sugar Maple (*Acer saccharum*) Tree-Ring Chronologies from Central and Southern Ontario Using a Mixed Linear Model. *Canadian journal of forest research* 24(3):568–575
- Sauter, J.J., W. Iten, and M.H. Zimmerman. 1973. Studies on the Release of Sugar into the Vessels of Sugar Maple (*Acer saccharum*). *Canadian Journal of Botany* 51(1):1–8.
- Schweingruber, F.H. 1988. *Tree Rings. Basics and Applications of Dendrochronology*. Kluwer, Academic press, Dordrecht, Boston, London
- Schweingruber, F.H. 1996. *Tree Rings and Environment*. Swiss Federal Institute for Forest, Snow and Landscape Research, CH-8903 Birmensdorf.
- Seguin, G. 1988. Ecosystems of the Great Red Wines Produced in the Maritime Climate of Bordeaux. In Proceedings of the Symposium on Maritime Climate Winegrowing. L. Fuller-Perrine (Ed.), pp. 36–53. Department of Horticultural Sciences, Cornell University, Geneva, NY.
- Skinner, C.B., A. DeGaetano and B. Chabot. 2009 Implications of 21st Century Climate Change on Northeastern United States Maple Syrup Production: Impacts and Adaptations. *Climatic Change* 10.1007/s10584-009-9685-0.
- Smith, K., and W.C. Shortle. 2003. Radial Growth of Hardwoods Following the 1998 Ice Storm in New Hampshire and Maine. *Canadian Journal of Forest Research* 33:325–329.

- Sommers, B. 2008. *The Geography of Wine: How Landscapes, Cultures, Terroir, and the Weather Make a Good Drop*. Penguin Group, New York, New York, 304 pp.
- Spurr, S.H., and B.V. Barnes. 1980. *Forest Ecology*. John Wiley & Sons, New York.
- Staats, L.J. 1994. Propagation and Cultural Improvements of Sugar Maple for High Sap Sugar Concentrations. *National Maple Digest* 64(4):17–19.
- Stahle, D.W., and Cleaveland, M.K. 1992. Reconstruction and Analysis of Spring Rainfall over the Southeastern U.S. for the Past 1000 Years. *Bulletin of the American Meteorological Society* 73:1947–1961.
- Stokes, M.A. and T.L. Smiley. 1968. *An Introduction to Tree-Ring Dating*. University of Chicago Press, Chicago, IL, 73 pp.
- Tardiff, J., J. Brisson, and Y. Bergeron. 2001. Dendroclimatic Analysis of *Acer saccharum*, *Fagus grandifolia*, and *Tsuga canadensis* from an Old-Growth Forest, Southwestern Quebec. *Canadian Journal of Forest Research* 31: 1491–1501.
- Taylor, F.H. 1945. Factors Influencing the Growth and Yield of Hard Maple Trees. Report of the College of Agriculture, University of Vermont. 1, 21 pp.
- Taylor, F.H. 1956. Variation in Sugar Content of Maple Sap. University of Vermont Extensions Publication MR 56. 20 pp.
- Telewski, F.W. and Lynch, A.M. 1991. Measuring Growth and Development of Stems. In: *Techniques and Approaches in Forest Tree Ecophysiology*, edited by J.P. Lassoie and T.M. Hinkle, pp. 503–555.
- Therrell, M.D., D.W. Stahle, M.K. Cleaveland, J. Villanueva-Diaz, E. Cornejo Oviedo, 2006. Tree-Ring Reconstructed Maize Yield in Central Mexico: 1474–2001. *Climatic Change* 74:493–504.
- Timilsena, J. and T. Piechota. 2008. Regionalization and Reconstruction of Snow Water Equivalent in the Upper Colorado River Basin. *Journal of Hydrology* 352:94–106.
- Trégoat, O., J.P. Gaudillère, X. Choné, and C. van Leeuwen. 2002. The Assessment of Vine Water and Nitrogen Uptake by Means of Physiological Indicators. Influence on Vine Development and Berry potential. (*Vitis vinifera* L. cv. Merlot, 2000, Bordeaux). *Journal International des Sciences de la Vigne et du Vin* 36(3):133–142.

- Tyree, M.T. 1983. Maple Sap Uptake, Exudation, and Pressure Changes Correlated with Freezing Exotherms and Thawing Endotherms. *Plant Physiology* 73:277–285.
- Tyree, M.T. and M.H. Zimmermann. 2003. Xylem Structure and the Ascent of Sap. Second edition. New York: Springer.
- United States Department of Agriculture's National Agricultural Statistics Service, New York Field Office. http://www.nass.usda.gov/Statistics_by_State/New_York/
- Van Duesen, P. 1989. A Model-Based Approach to Tree Ring Analysis. *Biometrics* 45(3):763-779.
- van Leeuwen, C., and G. Seguin. 1994. Incidences de l'alimentation en eau de la vigne, appréciée par l'état hydrique du feuillage, sur le développement de l'appareil végétatif et la maturation du raisin (*Vitis vinifera* variété Cabernet franc, Saint-Emilion, 1990). *International des Sciences de la Vigne et du Vin* 28(2):81–110.
- Visbeck, M.H., J.W. Hurrell, L. Polvani, and H.M. Cullen. 2001. The North Atlantic Oscillation: Past, Present, and Future. *Proceedings of the National Academies of Science* 98:12876–12877.
- Visser, H. and J. Molenaar. 1988. Kalman Filter Analysis in Dendroclimatology. *Biometrics* 44:929–940.
- Wake, C.P. 2005. Indicators of Climate Change in the Northeast. Clean Air-Cool Planet and the Climate Change Research Center, University of New Hampshire, Durham, NH.
- Wallner, W. E, and Gregory, R. A. 1980. Relationship of Sap Sugar Concentrations Sugar Maple to Ray Tissue and Parenchyma Flecks caused by *Phytobia setosa*. *Canadian Journal of Forest Research*. 10:312–315.
- Walters, R. S. 1978. Coniferous Understory Influences Sugar Maple (*Acer saccharum* Marsh.) Sap Production Research Paper NE-398. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 5 pp.
- Watterston, K.G., L.L. Leaf, and J.H. Engelken. 1963. Effect of N, P, and K Fertilization on Yield and Sugar Content of Sap of Sugar Maple Trees. *Soil Science Society of America Journal* 27:236–238.
- White, D., Richman, M., and Yarnal, B. 1991. Climate Regionalization and Rotation of Principal Components. *International Journal of Climatology* 11:1–25.

- Whitney, G.G. and M.M. Upmeyer. 2004. Sweet Trees, Sour Circumstances: the Long Search for Sustainability in the North American Maple Products Industry. *Forest Ecology and Management* 200(1):313–333.
- Wigley, T.M.L., K.R. Briffa, and P.D. Jones. 1984. On the Average Value of Correlated Time Series, with Applications in Dendroclimatology and Hydrometeorology. *Journal of Climate and Applied Meteorology* 23:201–213.
- Wong, B.L., K.L. Baggett, A.H. Rye. 2003. Seasonal Patterns of Reserve and Soluble Carbohydrates in Mature Sugar Maple (*Acer saccharum*). *Canadian Journal of Botany* 81:780–788.
- Wong, B.L., Staats, L.J., Burfeind, A.S., Baggett, K.L., and Rye, A.H. 2005. Carbohydrate Reserves in *Acer saccharum* Trees Damaged During the January 1998 Ice Storm in Northern New York. *Canadian Journal of Botany* 83:668–677.
- Yin, X. and P.A. Arp. 1994. Tree-Ring Based Growth Analysis for a Sugar Maple Stand: Relations to Local Climate and Transient Soil Properties. *Canadian Journal of Forest Research* 24:1567–1574.