Drivers of Sap Flow in Maple

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Introduction

Sap flow in maple trees has been described many times. Milburn and O'Malley (1984) provided the first well-accepted modern description, which was later modified and improved by Tyree (1984), then further by Cirelli et al. (2008). Stem pressure and flow in maple were then mathematically modelled in detail by Graf et al. (2015) with additional refinements and comparison with field-derived measurements by Zarrinderakhta et al. (2024). While these articles provide extensive detail into the anatomy and physiology of the science of the sap flow mechanism, they are somewhat unavailable to most people. A good general description of the sap flow mechanism is described in more modest detail in the Third Edition of North American Maple Syrup Producers Manual (Perkins et al. 2022), so won't be discussed at length here. Rather, this article is aimed at describing pressure gradients and the sources and magnitude of those pressures as they related to sap exudation from maple tapholes.

Gradients in Pressure Cause Sap Flow

Sap flow within maple stems and from tapholes occurs in response to various gradients of pressure within the tree xylem. At the simplest, a gradient is a difference in pressure from one area to another. An example can be useful to help explain gradients and liquid flow. In the case of a stream, water flowsdownhill in response to an elevational gradient (gravity). If the hill is steep, water will flow quickly. If less steep the water flows slowly. If the stream is large, more water will flow. A small stream will only contribute a small amount of liquid. We can change the direction of water movement if we use a pump to create a pressure gradient that pushes the water uphill against the downward (gravitational) force. Whichever way you manage to do it, water will flow in the direction of the pressure gradient, from areas of high pressure to areas of low pressure. The amount that moves depends on the size of the pressure gradient and the carrying capacity of the system (big stream, small stream). In a sealed system where you can't increase the size of the stream, liquid under the same pressure gradient will move faster through a small pipe than it will in a large pipe.

In the case of maple sap exudation 1 , a gradient is the pressure difference from a particular area in the tree to the area of the taphole. The gradient is important since it establishes both the direction and rate of flow of a substance, in this case sap. In this paper we will describe the primary factors important in establishing gradients, how they form, and how they change within a maple stem under different conditions.

1. For this sake of simplicity and length, we restrict this discussion to the sap exudation (thaw) phase of maple sap flow only. The uptake (freeze) phase has some similarities, but also some crucial differences, and is not discussed here.

A Confusing Variety of Pressure Measurements

There are several phenomena which give rise to the pressure gradients in maple stems. Unfortunately, maple producers tend to use a variety of units to describe pressure. For pressure within the stem, PSI (pounds per square inch) is generally used. For osmotic pressures, producers might use PSI when they're conversing about RO systems, but °Brix or % sugar might also be used when talking about sap sugar content. For producers using vacuum, inches of mercury (Hg) are common, but the negative sign is generally ignored, but implied. Barometric (air) pressure is typically expressed in millibars. Temperature can also create pressure differences in a closed system (like within the gases found inside of tree fibers), so °F or °C are used. Lastly, another complication is that some of those scales use a fixed value as the starting point in the case of absolute units, or can use a point relative to some starting value as in the case of tree stem pressure or vacuum level. This is referred to as gauge pressure and uses air pressure as the starting value. However, air pressure itself is not fixed, so the reference point is constantly shifting a little. When vacuum is used it can become confusing. Vacuum is generally thought of as negative pressure in terms of our scale relative to air pressure, but it is really just a lower point along a continuous pressure system. All these things together make talking about sap flow a bit more complicated.

To simplify things, Figure 1 shows the major contributors to stem pressure in maple trees. These include: tree height, vacuum, temperature rise, weather, and osmotic variables. More importantly, these are all expressed in this chart in common units of inches of water. We can all picture quite simply what an inch of water in a column looks like. Expressed in this way we can more easily explain and understand what contributes to gradients, the direction that sap is moving (from higher values towards lower values), how those factors might change over the course of a sap run, and how fast sap might move in response to the gradient (the magnitude of the pressure difference across the distance involved and the resistance encountered in moving).

Factors Giving Rise to Gradients that Contribute to Sap Flow

Tree height is important because it cre ates a gravitational (or elevational) gradient in the tree. Unless restrained or acted upon by other forces, sap will flow down within the wood during the dormant season during a thaw. The magnitude of the gradient is dependent upon the tree height. If a tree is 85 feet tall, the gradient would be close to 80 feet of water if the taphole were placed at 5 feet above the ground (Figure 1). Most of that flow occurs within the tree vessels and is primarily downward since vessel elements within maple xylem are oriented vertically. While these vessels are quite small, they are considerably larger than the surrounding fibers and are mostly open on the top and bottom (or have pits/sieve plate openings between vessel ends) and have lots of interconnections between them. Therefore, the vast majority of sap moving through xylem takes place in the vessels. As the tree comes out of the frozen state, the weight of the sap will push downward. If there is a hole in the wood, sap will flow downward and out through that hole in response to this pressure. The pressure is higher within the stem than air pressure is in the taphole and outside the stem. Because there is some resistance to flow through wood (even in vessels), and only a reasonably small number of vessels is severed by a taphole, the sap doesn't spray out, but drips out of the severed vessels. One key factor of gravitational flow is that it is not constant. Sap flow will be fastest immediately after the tree thaws because the pressure is initially high. As the vessels drain, the pressure in the stem and the rate of flow of sap will fall. It may take a few days for sap to fully drain from the top of the branches all the way down the stem and out of the taphole, but eventually the pressure due to the gravitational gradient will fall to close to zero and sap flow will cease unless some other factor is involved.

As gravitation flow occurs, most of the sap movement will be downward. However, because of the interconnectedness of vessel elements, there will also be some bulk flow of sap sideways. Since vessels are oriented vertically, sap movement sideways occurs primarily within and along the cell walls of fibers. The resistance to sap flow sideways is about ten times that of downward flow, so not all the sap above the taphole in a tree with gravity sap collection will flow out, but the majority will if the thaw continues long enough.

If **vacuum** is used to assist in sap collection, another pressure gradient comes into play. This gradient artificially lowers the pressure outside the tree. Therefore, the pressure at the start of a sap flow period will be the pressure due to the height of the sap column in tree plus the pressure of the vacuum below air pressure. For a vacuum level of 25 inches Hg, this equates to about 28 ft of water. Therefore, when the tree first thaws, the total gradient would equivalent to 108 feet of water (80 ft due to tree height + 28 ft due to vacuum). Given the higher pressure gradient pushing down towards the taphole without any change in the number or diameter of the wood vessels, the sap flow rate out of the taphole will be higher for collection with vacuum than under purely gravity flow conditions. Sap will more strongly be pulled through the stem due to the higher gradient towards the taphole.

Measurements of stem pressure of trees connected to vacuum lines clearly show that stem pressures are affected across the entire circumference of even large trees during extended thaws, indicating that flow of sap occurs across the stem. How much this happens depends on the magnitude of the gradient, previous wounds/compartmentalized areas in the stem, heartwood/sapwood distribution, and the extent of thawing during a flow period. Eventually, when the gravitational pressure component, downward, and across-stem flow of sap is close to being exhausted, the vacuum pressure component continues (as long as the pump stays on) and sap flow will continue. At this point, bulk flow of sap will transition to moving upward in the stem from below the taphole. If vacuum is good enough, sap flow can continue indefinitely as long as there is adequate soil moisture. In essence, water will be pulled directly out of the soil into the roots, up the stem, and out of the taphole. During this phase of sap flow, sap sugar content will steadily drop and some producers may decide to stop sap collection.

Besides the strong gradients created by tree height and vacuum, there are a few other pressures that can come into play at various times. These all tend to be small, but are large enough to be noticeable at times.

Temperature rises that occur during and continue after the transition from freezing to thawing cause expansion of gas bubbles in wood fibers and vessels as well as thermal expansion of sap. For example, a change in temperature from 32°F to 52°F during a sap flow event would result in the pressure equivalent of about 1.7 feet of water. Although small relative to the pressure gradients related to tree height (gravity) or vacuum, this change is enough to produce "weeping flows" when the temperature rises above the previous day's temperature. The higher temperatures cause gases in the wood to expand creating (slightly) higher stem pressure. As long as temperatures continue to increase in succeeding days, these types of slow flows can continue. If temperatures stop reaching new highs, the weeping flow of sap will greatly diminish or stop.

Similarly, changes in **weather**, more particularly barometric air pressure, can result in an increase in pressure and small increases in sap flow under certain conditions. This effect is quite small, only on the order of about 0.7 feet of water of pressure, but can again produce noticeable increases in sap flow similar to that created by temperature rise if the change in barometric air pressure is high.

Lastly, **osmotic** forces can alter the pressure gradient and result in movement of sap. In general, sugar loading (which produces osmotic pressure) tends to be fairly minor and diffuse in maple stems, and thus does not result in any particular directionality to the gradient. In terms of magnitude of osmotic effects, it could produce a pressure up to about

1.5 feet of water, but that would only be in extreme cases. This phenomenon would mostly be found high in the branches of the trees. Sugars are produced by the leaves in the crown, with the result that more sugar is stored in wood higher up in the tree than lower in the stem. The overall effect would be simply to increase pressure high up in the crown where it adds to the gravity effect. Regardless, while osmotic effects are less well understood than other forces, sucrose does seem to be very important in generating stem pressure overall in maple trees, but less so as a driver of sap flow towards tapholes.

Summary

An understanding of how pressure gradients form in maple, the factors that generate these gradients, and the magnitudes and directions of these forces helps maple producers to understand how sap flows under various conditions during the spring season. This knowledge, in turn, helps in the formulation of tapping guidelines, in the development of better sap collection methods and devices, and influences other management decisions in maple operations. The goal is that scientists, equipment designers and manufacturers, and producers can use the developments in our understanding of the driving forces in sap flow to generate good sap yields.

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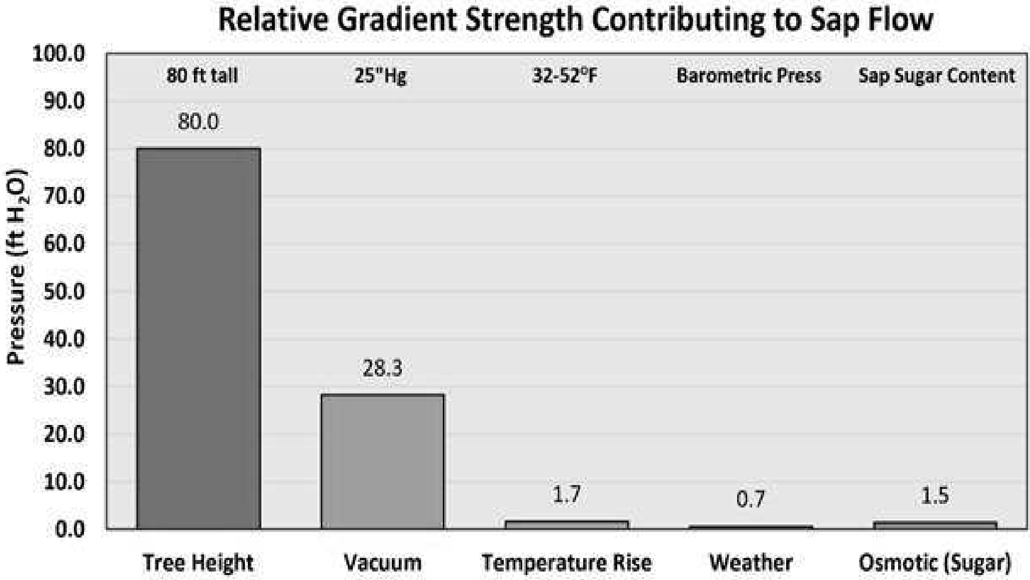

Figure 1. Sources of pressure gradients that can contribute to sap flow from tapholes in maple stems during the leaf-less spring sap flow period. All pressures have been converted to a common unit, ft of H2O to allow a better comparison of the magnitude of the pressure. Note that although Tree Height is the largest contributor to the pressure gradient at the start of a sap run, this pressure drops off as flow happens, eventually reaching close to zero during an extended sap run. Vacuum pressure is shown at 25 inches Hg within the tubing system near the taphole. Temperature rise is from 32-52°F.