Saheda

A Dominant Massachusetts White Pine And Its Carbon Sequestration Significance

By Robert T. Leverett & Jared Lockwood

Revised November 21, 2019

Introduction

New England's woodlands are not associated with exceptional trees like those on the West Coast. But it wasn't always this way. In the 1600s and 1700s, chroniclers described a landscape that featured giant eastern white pines, some claimed to be well over 200 feet in height. In fact, the white pine was the foremost symbol of the region's original virgin wilderness.

Romantic accounts exist of white pines, especially in Maine and New Hampshire, reaching astounding sizes and achieving great ages, and of course, the species was famous as a resource for ship masts. The great whites became the replacement for the exhausted European Riga Fir (actually Scotch Pine, *Pinus sylvestris*) used by the King's Navy to hold up the sails of its war ships. Trees of a certain size and shape were reserved exclusively for the Royal Navy. They were often marked by three slashes with an ax, called the broad arrow markings. But the time of those legendary pines came and went.

The intense lumbering of the region, especially in the 1700 and 1800s, depleted the region's rich old-growth forests. By the early to mid-1900s, New England's woodlands consisted of younger trees, and I expect that people's perception of what the white pine, or any species, for that matter, could achieve in size was greatly scaled down. As a consequence, today's forest historians largely relegate giant pines to the pages of history. This is evidenced by descriptions of the species in the popular 20th century field guides, which often listed the white pine as a tree capable of surpassing 100 feet in height, but commonly 75 to 100 feet. More descriptive authors like Donald Culross Peattie reminded us of the historic heights, but most of these authors made it clear that they did not believe any giants were alive today. In fact, the stature of the species had been so diminished that one hiking guide to trails in New Hampshire boasted of a pine that was purportedly 125 feet tall. This lone tree was considered the rare exception at the time the guide was written. Of course, this was the take of only one author, but other examples could be cited to strengthen the point.

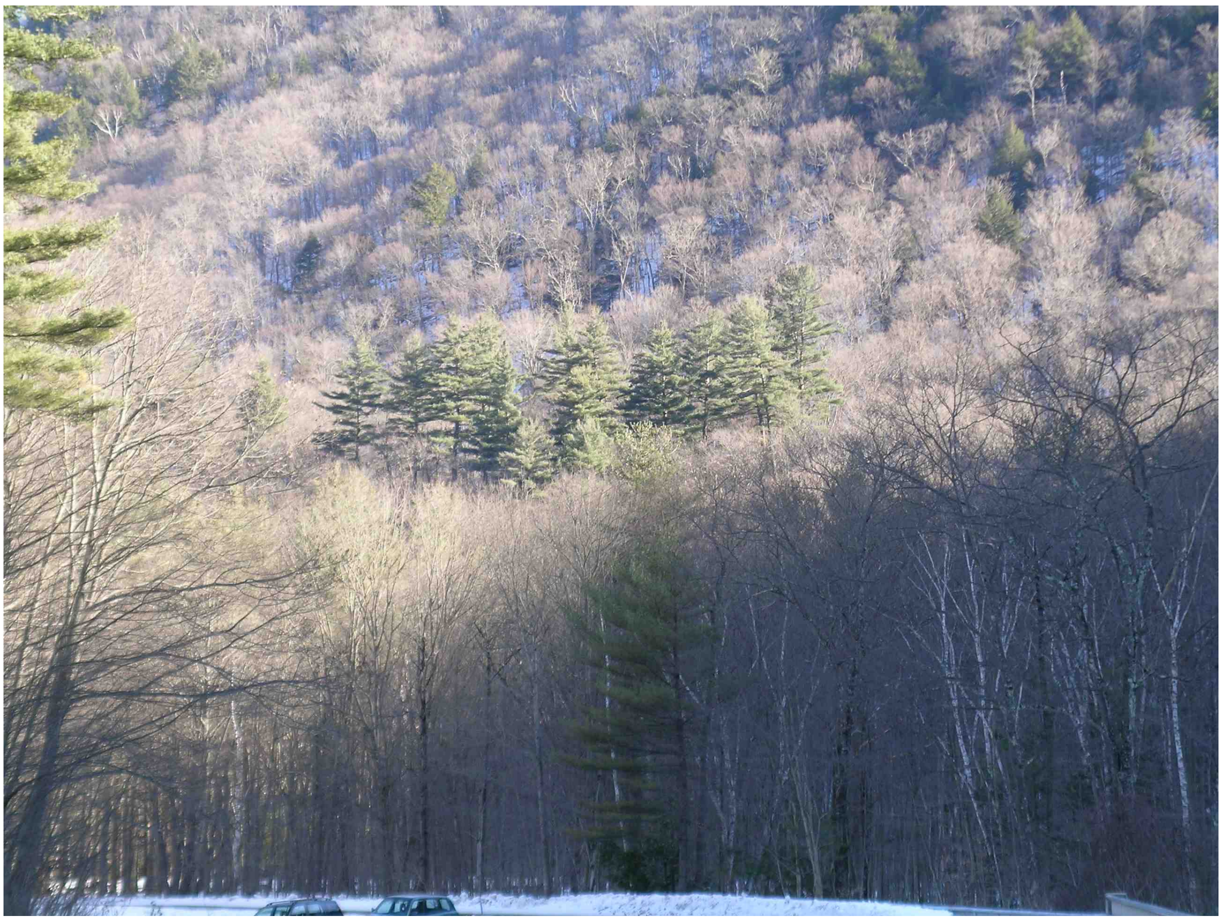
To further diminish the stature of the species in our eyes, today's forest management paradigm aims at keeping woodlands artificially young, claiming to be healthier than when trees become "over-mature". Yet despite this paradigm, the eastern white pine is re-emerging to reclaim some of its former glory as our tallest eastern species.

Today, do we have any examples of the return of the giants such as once grew in Massachusetts? In conservation areas, parks, state forests, and even on private lands, white pines are starting to reach impressive stature, and one of the best places to see them is Mohawk Trail State Forest (MTSF), located in the townships of Charlemont, Savoy, and Florida.

The Elders Grove

From the Zoar Gap bridge, looking downstream, a cluster of white pines is visible on the side of Todd Mountain. The pines are seen in the photograph below against the backdrop of the Todd-Clark Ridge. These trees are the destination - the Elders Grove.

On April 18, 2018, Ray Asselin, Jared Lockwood, and I visited the Elders. We reached the pines after a 10 to 15-minute walk on the marked Elder Grove Trail that parallels the scenic Deerfield River. The forest at the beginning consists of rather stately hardwoods, but they are only a hint of what is to come.



On the 18th, this path was slippery with recently fallen wet snow. The compromised footing presented me with challenges for my new knee. Yet, I was anxious to get as much measuring done as possible before the hardwoods leafed out. The veil of dense green of the maples, birches, and oaks 80 to 110 feet above the head makes re-measuring the heights of the over-story pines that thrust through the hardwood canopy very difficult.

Saheda

On reaching the Elders, our first task was to re-measure a particular pine, which is named the Saheda Pine. The name is in honor of a Mohawk ambassador who was murdered in the late 1600s when he was on a mission of peace to the Pocumtucks at what is now Old Deerfield. I thought the historic Saheda deserved a tree name for him in the Elders Grove, and in my Native Tree Society (NTS) capacity, chose arguably the handsomest pine in the grove. Saheda is located above the trail, near two others: Sacajawea and Ouray. The Saheda Pine is a very special tree as will what follows will amply communicate.

On this visit, I wanted to measure Saheda's great height before the onset of the growing season. I closely monitor the pine's growth and have for years. It is currently the second tallest tree that we know of in New England, and as such deserves special attention. This paper is in part an explanation of the attention we given to Saheda.

I've watched Saheda and other pines in the grove reach upward since the late 1970s, but it was in the mid-1990s when we began measuring Saheda with serious intent. Recognition of the exceptional status of this pine dates back to the mid-1990s. Jack Sobon, an architect and timber framer, and the author measured Saheda with a surveyor's transit. The height obtained was an eye-popping 160 feet, which was the highest we knew of in Massachusetts. However, the cross-triangulation method used to identify the spot on the ground directly beneath the highest point of the crown was probably off, although not known to us then. Nonetheless, my intent was to re-measure Saheda from time to time, and the opportunity came in 1998.

In November of 1998, Will Blozan, President of NTS and an arborist extraordinaire, climbed and tape-drop- measured Saheda. At that time, we confirmed Saheda's height at 158.3 feet. Based on what we believed white pines to be able to achieve growth-wise in the modern era, though less than our 160, this was nonetheless, exceptional. Only one other tree we knew of in Massachusetts topped Saheda - another white pine also in MTSF named for a Mohawk chief by the name of Jake Swamp. We had originally measured it with transit in Novemeber 1992 to a height of 155.0 feet. However, Will also climbed and tape-drop-measured Jake to a height a couple days before his climb of Saheda. The tape drop confirmed a height of 158.6 feet. The two trees were neck and neck, and as far as we knew, the two tallest in not only Massachusetts, but all New England. That remains true today.

I was reminded by the descriptions of forest historians and government resource managers who continued to maintain that the species was still in its youthful stage throughout New England, save for older pines growing on very unproductive sites – small trees. However, we had some exceptions in MTSF, along with outstanding hardwoods. These trees led to me promoting MTSF as the forest icon of Massachusetts, which had a popular ring to it with the public.

Since the late 1990s, we've watched both pines, Jake Swamp and Saheda, exceed 160 feet in height, and more recently 170. Despite being hit with a needle drop fungus, neither shows signs of stopping their upward growth. However, as the years passed, it became apparent that Jake was growing faster than Saheda. That seemed to fit with the differences in their ages. Jake is about 160 years old and Saheda, around 185 or 190. Jake's height is currently 176.2 feet, which is #1 in New England, and maybe the Northeast with the loss of the Longfellow Pine in Cook Forest, PA. It was 184.5 feet tall, but lost to a microburst own May 4, 2017.

To put a finer point on the above numbers for Jake and Saheda, the latter's growth rate has averaged 8.46 inches per year since Will's climb in 1998 while Jake has maintained an average of 9.6 inches since 1992. According to discussions I've had with a number, forestry professionals expect pines in the age range of these trees to be growing at maybe 5 inches in height per year or less.

Re-measuring Saheda – the challenges

Height measurements of Saheda are regularly made with a high-performance laser-based hypsometer using a technique that we call the sine method as follows:

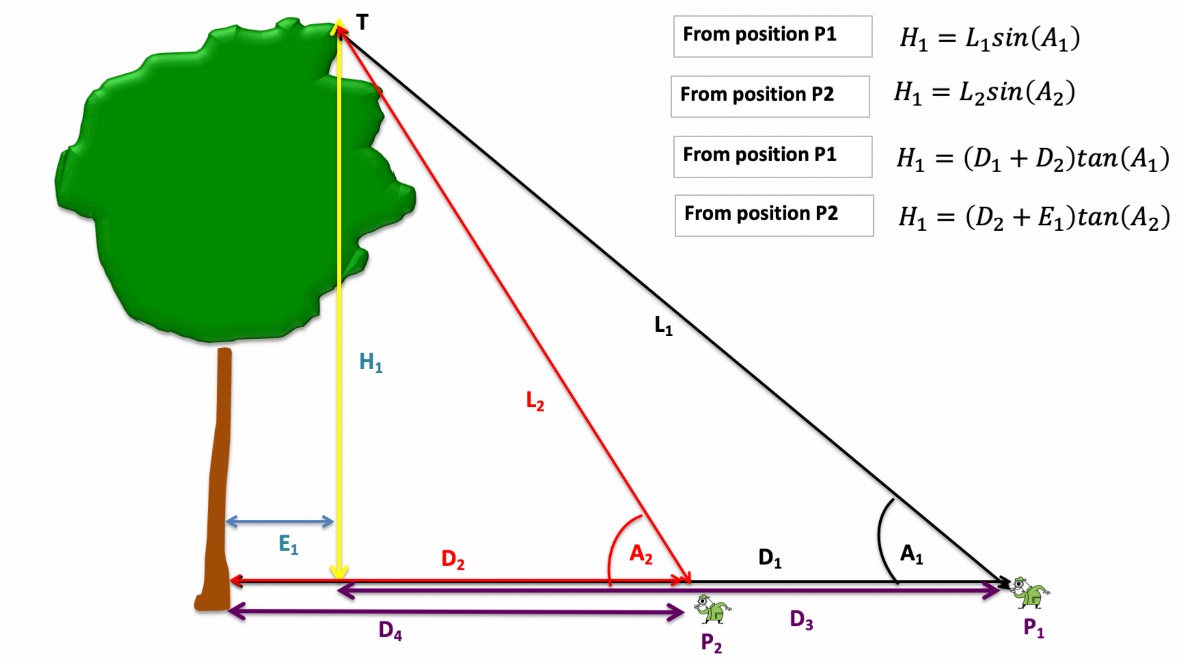
$$h = L_1 sin(A_1) - L_2 sin(A_2)$$

where L_1 = straight line distance from eye to top of tree
A_1 = angle to top
L_2 = straight line distance from eye to base of tree
A_2 = angles to base (angles below eye level are negative)

The sine method is employed to eliminate the problem when the top of the tree is not vertically positioned over the base. The traditional height measuring method (the tangent method) calls for a level baseline from eye to trunk with angle measurements taken of the top and base. Two right triangles make use of the common baseline to the trunk to get the height of the parts of the tree above and below eye level. The two components are added to get a final height. This all sounds straightforward, but what happens if the top is not vertically located above the end of the baseline? The following diagram shows two scenarios for measuring a tree where its top is not over its base.

Note in the diagram that from position P_1, the distance $D_1 + D_2 – E_1$ is the correct baseline for the tangent method. From position P_2, it is $D_2 – E_1$. However, the traditional baseline is $D_1 + D_2$ from P_1 and D_2 from P_2 when the baseline is taken all the way to the trunk. This leads to an over-estimation of the height. It can go the other way of the high point is on the other side of the trunk from the measurer.

While adjustments can be made to minimize this source of error, they require experience. The sine method eliminates this error source completely.



Notes: (Same tree, same top, same measurer, diiferent results)
Tree is on level ground. Top T is 115 feet above measurer's eye level
Measurer's height is 6.33 feet
Measurer sights the top T from position P_1, 162.18 feet from trunk and records angle A_1
Measurer sights the top T from position P_2, 94.17 feet from trunk and records angle A_2
Hgt above eye level at P_1 is measured at 134.56 feet (error = 134.55 - 115 = 19.56 feet)
Hgt above eye level at P_2 is measured at 155.33 feet (error = 155.37 - 115 = 40.37 feet)
Measurer reports at P_1 full hgt as 140.85, and at P_2 as 161.66

Error is greatest when top, end of baseline, and eye are all in same vertical plane.

Measurements of Saheda taken in July 2017 set its height at 171.4 feet. However, that number was obtained without use of a tripod, which made hitting the highest point of the top a challenge. When the measurer presses the "fire" button on a laser rangefinder or hypsometer, he/she can pull the instrument down slightly. On any given measurement, that may or may not be a factor, but movement of the instrument at the point of firing the button is a source of error. I had gotten results as low as 171.0 feet and as high as 171.8 feet with one measurement at exactly 171.4, which matched the average. The 171.4-foot height seemed an acceptable number to settle on, so it was announced as Saheda's height as of the end of the 2017 growing season.

On April 18th, 2019, I carried my tripod so that I could control handshake and button-press sources of error. While I re-measured Saheda's height, Jared Lockwood took diameter measurements up the trunk using the combination of his TruPulse 200X and Vortex Solo RT 8/36.

The hypsometer and monocular allowed him to take diameter measurements at points up the trunk from a remote location on the ground. Looking through the eye piece, the monocular's reticle covers the trunk, allowing a reading to be taken. The distance and angle to the center of the trunk is measured with the TruPulse. The formula needed to calculate trunk width is:

$$W = \frac{MD}{F - \frac{0.5M}{\cos(A)}}$$

where M = reticle reading, D = distance to middle of trunk, F = manufacturer's reticle factor, and A = angle above or below eye level of width line being measured.

How good is the measurement? The combination of the monocular and a high-performance laser-based hypsometer allows us to usually get within under a half inch of actual target width. On clear targets under 200 feet away, we can get to within +/- 0.25 inches of caliper-based measurements on well over half of the trials. This level of accuracy was unexpected when we began conducting trials.

On the April visit, our objective was to determine Saheda's height prior to the onset of seasonal growth and to model the trunk for volume, which would require width measurements at points up the trunk, as previously mentioned. The widths and vertical distances between would then be used with equations for the volumes of frustums of neiloids, cones, and paraboloids as shown below.

$$V_c = \frac{1}{3}\pi H[r_1^2 + r_1 r_2 + r_2^2] \quad \text{for the cone}$$

$$V_p = \frac{1}{2}\pi H[r_1^2 + r_2^2] \quad \text{for the paraboloid}$$

$$V_n = \frac{1}{4}\pi H\left[r_1^2 + r_1^{\frac{2}{3}} r_2^{\frac{4}{3}} + r_1^{\frac{4}{3}} r_2^{\frac{2}{3}} + r_2^2\right] \quad \text{for the neiloid}$$

In the above equations, r_1 and r_2 are successive radii, and H is the vertical distance between. Substituting the values into the above equations gives the volume of that section of trunk treated as a frustum of the chosen regular geometric solid, i.e. cone, paraboloid, or neiloid. There is precedent for treating the first 5 to 10 feet as neiloid, the section up to the crown as paraboloid, and the remainder as conical. These three forms are used by forest biometricians to describe the predominant forest-grown shape of the trunk, especially a conifer.

However, the above equations assume a circular cross-sectional area. If an additional set of trunk width measurements can be obtained 90 from degrees around the trunk at the same points as the first, we can model cross-sectional areas frustum as elliptical using:

$$V_c = \frac{H\pi}{3(a-c)}[a^2 b - dc^2]$$

Where a,b and c,d are the semi-major axes of the base and top of the frustum respectively. Getting reliable remeasurements for these four is labor intensive.

Tackling Saheda's Height

Finding a good location to see the uphill side of Saheda's crown, I set up the tripod. Below is a view of the pine's base and the location used to choose an exact spot on the ground. An argument can be made for setting the base point lower to match the mid-point of the slope of the land. I chose to be conservative on the location. That would have added about 3 inches to the height.

The instruments used to measure Saheda's height include a TruPulse 200X accurate to +/- 4.0 centimeters on distinct targets according to the manufacturer's specification. However, each instrument can vary a little. The instruments Jared and I use have been repeatedly tested and are accurate to +/- 2.5 cm on clear targets. However, this level of accuracy to clear targets can be mis-leasing. The TruPulse sends out pulses in an elliptical pattern. At 100 feet, the ellipse's major axis is 3 inches and its minor axis is 2.8. The elliptical spread is linear. At 200 feet, the ellipse would measure 6 x 5.6 inches. Targets within the perimeter of the ellipse return bounces. The returns are in the form of either strong or weak signals. What is reported on the display is a strong signal. It can take time to get a strong return from the highest target if nearby targets and/or atmospherics interfere. One gets better with experience, but it is not so simple as pointing to a target and pressing a button. For important trees, we often return repeatedly, shooting the target in different light and atmospheric conditions before settling on the most probable number.

Locations of 200 feet away or more are necessary to see both top and base of a tall tree like Saheda, and must be taken from above the base, if possible. Shifting a couple of feet one direction or another can result in the top twig becoming obscured. At the time, the highest twig will not be known or recognized as such. This can come as a surprise to new measurers who often rely from their vantage point on what looks to be the highest point in the crown to be the top. The taller the tree, the broader the crown, the greater the challenge becomes. But even from 200 feet and uphill, the highest crown points of Saheda are often a challenge to distinguish. This becomes clearer from greater distances where the pine's complex double-trunk crown stands out.

Part of the challenge of identifying the highest top becomes clearer when one realizes that candidates for the top can lie within a horizontal area of as much as 100 ft^2 on larger, older pines, and sometimes more. At their widest, mature white pine crowns are typically between 40 and 55 feet, although the points of maximum width are below the top. Still, the area that includes the highest twigs often presents many choices to a laser. On older pines, there is not often a twig that is clearly the tallest from one's vantage point. Even less often is the highest point in the crown vertically centered over the base of the trunk. Crown breakage and re-sprouting is the norm for older trees. The highest point can be horizontally offset from the base by 5 to 15 feet, and occasionally more.

Below is a view of Saheda's top taken from the Zoar Gap bridge and under high magnification. A yellow arrow points to the highest point. But, seeing that sprig from much closer requires work.

Switching from greatest height to over-all impressiveness, when I took my friend Tim Zelazo (now retired from DCR) to see the Saheda, he looked aloft, and was an immediate fan. Tim was no stranger to the Berkshire's forests, but the Elders Grove had escaped him. Gazing upward, this is what he saw.

Measurement Results – April 2018

From my vantage point, I was able to shoot to four identifiable tops of Saheda's double crown, all on the uphill side of the crown. One conspicuous top gave me a reading of 128.25 feet above the centroid of the TruPulse. Turning the TruPulse on the axis of the tripod and shooting to Saheda's metal tag, the height below the centroid read 40.5 feet on the display. The height of the tag above the point I use as Saheda's base, was 3.0 feet. The three numbers add up to 171.7 feet!

Saheda hadn't grown since the July 2017 measurement. The difference between the 171.4 of the preceding year, and 171.7 from April 2017 probably lies in the use of my tripod, which gave me a sturdier platform to shoot from in July, as previously explained. In addition, this time my vantage point was different. Regardless, there isn't a dramatic difference between 171.4 and 171.7.

Subsequent measurements of Saheda that include growth in 2018 now justify a total height of 172.4 feet for the tree. This represents an annual height increase of 0.7 feet for 2018. The 172.4 measurement was achieved by both the author and New York tree-measurer Joshua Harkness on separate, independent trips. Our circumference measurements also agree at 12.2 feet at 4.5 feet above mean mid-slope. So, we have Saheda's two primary measurements, height and circumference.

Big Tree Points

In addition to height and circumference, a third measurement, important to champion tree contests, is average crown spread. This is the most problematic of the three measurements that go into the champion tree programs. Traditionally, it has been the average of the absolute longest horizontal width of the crown with the longest width at right angles to the first. However, with an instrument like the LTI TruPulse 360 that can measure the horizontal distance between two targets in 3-dimensional space, we can get a better average by shooting many limb extensions. Linear, vertical, and horizontal separations are also returned by what is called the missing line routine. The horizontal result is the one we use for crown spread.

The height of 172.4 feet, circumference of 12.2 feet, and average crown spread of 52 feet gives Saheda 332 points on the following champion tree formula:

Points = circumference in inches + height in feet + 1/4th the average crown spread in feet.

How does this stack up with other contenders competing for the title of champion? The undisputed white pine champion in Massachusetts earns 338 points. It is in a cemetery in Conway, MA, and has a partially open-grown form. Two pines in Monroe State Forest earn 334 and 333 points respectively. A pine in Stockbridge. MA earns 332. So, Saheda is currently tied for 4th place, among <u>single-trunk</u> white pines in Massachusetts. I emphasize the single-trunk form, because when the species is grown in the open, it can reach greater girths and spreads, but is shorter, often by a lot. The two shapes compete, but the forest-growth is what is being measured. In addition, many open-grown pines are also weevil damaged, resulting in multiple leaders and a crooked shape.

How Much Wood Is in Saheda?

Using updated height and DBH figures, we:

1) converted volume into total woody biomass,
2) derived the carbon portion of that mass,
3) calculated the amount of CO_2 pulled from the atmosphere to build the trunk, and
4) profiled Saheda' growth over time.

Modeling Saheda using reticle-based measurements and frustums of the geometric solids of neiloid, cone, and paraboloid was inconclusive because of recurrent trunk visibility issues. One determination yielded 852 ft^3 of trunk volume, but required judgments in reading the reticle at points up the trunk where limbs interfered with identifying the outline of the trunk. As a consequence, we have not concluded the modeling by this method. We will eventually perform a thorough reticle measurement, but for the purpose of this analysis, we have chosen to use an FIA regression-based model that utilizes the work of Jenkins and Raile. The model, implemented through an Excel workbook, is included as part of a sweet of Carbon On-line Estimation (COLE) tools. To employ the model, we define the following variables.

Variables:

V_s = volume of stem (wood only, no bark) from a 1-foot stump to a 4-inch top measured to outside Bark. This is defined in the FIA database as VOLCFGRS, which stands for gross cubic foot volume of the stem
b = regression-based value for white pine = 0.001949
V_b = volume of bole. Volume of stem + volume of bark (bark is 0.16 x Vs)
V_{st} = volume of stump, outside bark (this is bark and wood)
V_t = volume of trunk to a 4-inch top (trunk = bole + stump)
M_{st} = mass of stump
D = diameter at 4.5 feet above mean base level in inches (3.8833 ft x 12 = 46.6 inches)
H = full height = 172.4 feet for Saheda

Equations:

The Excel spreadsheet does the calculations automatically, but implements the following process. In the equations below, the constants are regression-based derivations incorporating thousands of tree measurements.

1. $V_s = b(D^2H) = 0.001949D^2H$
2. $V_b = 1.16V_s$
3. $V_{st} = 0.005454153D^2\ [1+(5.62462)(0.08091)]+8.50038\ (0.08091^2)]]$
4. $V_t = V_b + V_{st}$

Calculations for Saheda:

$V_s = 0.001949[46.60057^2(172.4)] = 729.7\ ft^3$

$V_b = 1.16V_s = (1.16)(729.7) = 846.5\ ft^3$

$V_{st} = 0.005454153(46.60057)^2\ [1+(5.62462)(0.08091)+8.50038\ (0.08091^2)] = 17.89\ ft^3$

$V_t = 846.5 + 17.89 = 864.39\ ft^3$

By this method, the calculated trunk volume of Saheda is **864.4** ft^3. We need to include limb volume. , which adds on approximately 15.4% of the trunk's volume, giving a trunk and limb total of **997.5** ft^3.

The 15.4% is derived result from the Jenkins and Raile models using biomass as a surrogate for volume. The model computes biomass total and individually for stem, stem bark, foliage, root, stump, and top. The top includes the limbs (includes branches, and twigs), but not foliage. This is what we want. Other white pines modeled show comparable percentages to Saheda. The range is generally between 15% and 16.5%. The FIA-Jenkins-Raile model's actual limb determination is explained next:

Calculation for foliage biomass is through the following process:

Total_AG_biomass_Jenkins (lbs) = Exp(Jenkins_Total_B1 + Jenkins_Total_B2 * ln(DBH × 2.54)) × 2.2046

Foliage Ratio = EXP(-2.9584+(4.4766/(2.54DBH))) where DBH is in inches

Jenkins Foliage biomass = Jenkins Foliage Ratio x Total_AG_biomass_Jenkins

Top (limbs) = total above ground biomass – bole biomass – foliage biomass – stump biomass

The model gives 22,377.2 lbs. Approximately 50% of the total mass is elemental carbon, giving 11,188.6 lbs or 5.59 tons. The amount of CO_2 needed to deposit the calculated amount of carbon in the trunk and limbs is 5.59 x 3.664 = 20.48 tons.

These calculations give us a concrete picture of what this large pine has achieved in growth and carbon storage over a period of 180 years or slightly more. The annual volume gain for Saheda has averaged 5.54 ft^3. The operative question is how the volume gains and the associated carbon sequestration has proceeded over time. Was most of the growth achieved relatively early on, say within the first 50 or 60 years? How has Saheda gains proceeded in the last, say 20 years?

Saheda's Rate of Growth and Carbon Sequestration:

A question of importance to forest managers, forest ecologists, and climate scientists is: how effective is a tree like Saheda at its current age in sequestering carbon compared to younger pines? Forest managers stress the importance of young trees in sequestering carbon and often minimize the role of older trees under the belief that they have slowed growth so much as to no longer be an important source of sequestration.

We begin by projecting Saheda's growth at ages of 20, 40, 60, 80, and 100 years, and compare it to the last 20 years. Using assumptions about radial and height growth and overall trunk shape, we employ a stand development model that we have been working on. Since Saheda has reached great size, we assume it grew rapidly from an early age. The FIA model is used to compute volume using DBH and full height for consistency.

Saheda's Age - yrs	Radius - ft	Height -ft	Trunk Vol -ft^3 (FIA)	Limb Fac (FIA)	Trunk & Limb Vol – ft^3	20-year gain – ft^3
20	0.33	30	4.77	1.185	5.65	5.65
40	0.84	84	80.53	1.159	93.33	87.68
60	1.18	109	202.52	1.156	234.11	140.78
80	1.47	125	362.01	1.155	418.12	184.01
100	1.68	139	521.17	1.154	601.4	183.31

Note that a radius of 0.33 ft at 20 years represents an average annual radial growth of 0.198 inches. Radial growth starts fairly slowly and then increases rapildly.

As a comparison for total trunk volume (no limbs) between the FIA model and our stand-based model, we recall that at its current dimensions, the FIA model gives 864.4 ft^3. Below is what our model gives from 20 to 180 years with a comparison to FIA.

Class #6 Size Tree Development				Saheda			Maximum Girth														
Period	Age-yrs	Annual radial growth within the period - inches	Annual radial growth YTD - inches	Radius at age- inches	Diameter - inches	Radius - feet	Circumference - feet	Area- feet^2	Annual height growth - feet	Total height- feet	Trunk Form Factor	Volume - feet^3	Period volume increase- feet^3	Percentage volume increase during period of total	Cumulative volume percentage increase	Cumulative age percentage	Annual volume increase within period- feet^3	Average ring width over 200 yrs -inches	years/inch during period	FIA Volume - feet^3	Pct Diff FIA/NTS
0	0	0	0	0	0	0	0	0	0	0	0.00000	0	0	0	0	0	0	0	0		0
0-20	20	0.2	0.200	4	8	0.33	2.09	0.35	1.5	30	0.40000	4.19	4.19	0.46%	0.46%	10.00%	0.21	0.2000	5.000	4.87	-16.26%
21-40	40	0.305	0.253	10.1	20.2	0.84	5.29	2.23	2.7	84	0.41000	76.65	76.65	8.49%	8.49%	20.00%	3.83	0.2525	3.279	80.85	-5.48%
41-60	60	0.2	0.235	14.1	28.2	1.18	7.38	4.34	1.25	109	0.41000	193.84	117.19	12.99%	21.48%	30.00%	5.86	0.2350	5.000	202.52	-4.48%
61-80	80	0.175	0.220	17.6	35.2	1.47	9.22	6.76	0.8	125	0.41000	346.34	152.51	16.90%	38.38%	40.00%	7.63	0.2200	5.714	360.37	-4.05%
81-100	100	0.12	0.200	20	40	1.67	10.47	8.73	0.7	139	0.41000	497.33	150.99	16.73%	55.11%	50.00%	7.55	0.2000	8.333	515.99	-3.75%
101-120	120	0.07	0.178	21.4	42.8	1.78	11.21	9.99	0.7	153	0.41500	634.39	137.06	15.19%	70.29%	60.00%	6.85	0.1783	14.286	648.17	-2.17%
121-140	140	0.05	0.160	22.4	44.8	1.87	11.73	10.95	0.4	161	0.41500	731.40	97.02	10.75%	81.04%	70.00%	4.85	0.1600	20.000	747.09	-2.14%
141-160	160	0.025	0.143	22.9	45.8	1.91	11.99	11.44	0.4	169	0.42500	821.74	90.34	10.01%	91.05%	80.00%	4.52	0.1431	40.000	818.75	0.36%
161-180	180	0.02	0.129	23.3	46.6	1.94	12.20	11.84	0.17	172.4	0.42750	872.92	51.18	5.67%	96.72%	90.00%	2.56	0.1294	50.000	864.30	0.99%
181-200	200	0.01	0.118	23.5	47	1.96	12.30	12.05	0.09	174.2	0.43000	902.48	29.57	3.28%	100.00%	100.00%	1.48	0.1175	100.000	886.19	1.81%

As can be seen, the two models are fairly close throughout.

At 40 years, the diameter of our hypothetical pine is 20.2 inches. Average annual radial growth is now 0.252 inches. This means that average annual radial growth between 20 and 40 years is:

$$r_a = \frac{0.252(40) - 0.198(20)}{20} = 0.306\ inches$$

This is rapid growth. Were the tree to sustain such growth throughout 180 years, its diameter would be 9.18 feet, well over twice is actual diameter of 3.88 feet.

From the above table, we see that from 40 to 60 years is the period of most rapid volume gain with 140.78 ft^3 versus 87.68 between 20 and 40. What would the radial performance be during the 20 years from 40 to 60.

$$r_a = \frac{0.236(60) - 0.252(40)}{20} = 0.204\ inches$$

Not unexpectedly, both annual radial and height growth have slowed while volume continues to climb. This is a result than seems antithetical to the radial and height performances, but they are not in dispute. Smaller radial growth on a larger trunk will match larger growth on a smaller trunk in terms of added cross-sectional area.

We don't project the next two cycles of 60 years to reach 180, but we know that there are 997.5 - 234.11 = 763.4 ft^3 to go and 120 years to do it in. The gain won't be evenly distributed, but as an average, we have 381.7 ft^3 to gain in each of the remaining two 60-year periods. It is abundantly clear that volume growth accelerates after the first 60 years – contrary to the belief of those forest managers who rely on annual radial growth as an indicator of what the tree is doing. But can we determine the most recent growth trends? Saheda has to slow down its volume growth at some point. Has it done it in the last 20 years?

We can compute how much Saheda grew between 1998 and 2019 for a 21-year period – close enough. We have the circumference and height of Saheda from the Blozan climb in 1998, i.e. circumference = 11.3 feet and height = 158.3 feet. We can run these dimensions through the FIA-based model similar to above:

V_t = 682.1 ft^3

Adding 15.4% for the crown, we get an estimated **787.1** ft^3 of trunk and limb volume by the end of 1998. This compares to **997.5** ft^3 21 year later. Therefore, Saheda added **210.4** ft^3 in 21 years as compared to **140.78** ft^3 between 40 and 60. If this seems to be remarkable growth, it is, but shouldn't surprise us that much, given Saheda's current size. Growth in the next 60 years, if Saheda lives that long will be probably be slower, judging by what we see elsewhere. For example, we have pines in places like Cook Forest, PA, Hartwick Pines in Michigan, and multiple sites in New York's Adirondacks to project maximum size. As a for instance, the tallest tree we have measured in the Northeast is the Longfellow Pine in Cook Forest (now broken). It was 184.5 feet in height before a May 4, 2017 storm broke it at around 70 feet. We have a few stand-grown pines that have achieved trunk circumference of between 14 and 15 feet, but these are not our tallest. If we project a maximum circumference for Saheda of 13 feet and a maximum height of 175, what do we get for volume? We again return to the FIA model.

V_t = 995.9 ft^3

This volume increased by 15.4% for the top yields **1,149.3** ft^3. The gain in the 60-year period from 180 to 240 years is 151.8 ft^3. While this is below the 210.4 ft^3 added in the last 21 years, it equals the entire first 48-year gain of the cluster based on the following linear interpolation.

$$\frac{234.11 - 93.33}{20} = 7.039 \; rate\ of\ cluster\ increase\ between\ 20\ and\ 40\ years$$

$$7.039x = 151.8 - 93.33$$

X = 8 years. Therefore, the total cluster volume of 151.8 ft^3 is estimated to be reached at 40 + 8 = 48 years.

Even if Saheda doesn't reach 1,149 ft^3, there is a good chance it would still equal its first 40 years of cluster volume growth. This gives us an example of accelerated growth associated with tree size.

From One Pine Versus a Cluster

Forest managers will recognize that Saheda is exceptional in terms of the seamount of carbon held in its trunk, but they are likely to point out that a sufficient number of young trees should be able to outperform the one. This is often a prelude to the argument that a stand of white pines will perform better when young than when mature. The argument is that there is strength in numbers and point to the rapid growth rates of the trees when young. Today's "working forests" are very unlikely to have trees the size of Saheda, but how can we analyze the belief about the effectiveness of young trees versus mature ones using our measurements of Saheda?

We begin by computing the space controlled by Saheda's crown and comparing the growth performance of young pines occupying an equal area of ground.

Saheda has an average crown radius of 26 feet. This represents a ground area projection of 2,124 ft^2 ($\pi 26^{2)}$. Let's populate that area with 20-year old pines. From the above table, a 20-year old pine of Saheda's quality will have a trunk and limb volume of 5.65 ft^3. Therefore, it would take 176.4 (996.8/5.65) young pines growing for 20 years to equal Saheda's current volume. How many 20-year old pines can we fit into 2,124 ft^2? A 20-year old pine will have a crown radius of 5 to 6 feet. Let's assume 5 feet in order to squeeze in as many pines as possible. The crown area of the young pine is 113.1 ft^2. Therefore, we can fit 27.1 (2,124/78.5) young pines into the space that Saheda controls.

Obviously, the combined volume of the young pines gat age 20 doesn't match Saheda's total volume, but what about Saheda's last 21 years of growth. Will the combined growth of the young pines in 20 years match (or exceed) Saheda's last 21-years of growth? Saheda gained 210.4 ft^3. According to our table, a young pine 5.65 in 20 year. It would require 37.1 young pines growing for 20 years to match what Saheda did in the last 21, but we can fit in only 27.1. Therefore, stand density at the 20-year point won't make up the difference. What about 20 to 40?

Based on the above table, at 40 years a young pine will have above ground live trunk and limb volume of 93.33 ft^3 with limbs. This represents a 20-year gain of 93.33 – 5.65 = 87.68 ft^3. If we assume that the crown radius has grown to 9 feet, each young pine will control 254.5 ft^2 of ground space. At this size, 10.67 pines that are 40 years old will fit under Saheda's crown. These pines will have a combine volume of 93.33 x 10.67 = 995.83 ft^3 versus the 996.8 ft^3 that is there now. If we allow for more pines than the 10.67, they will be smaller trees.

The total volume of the young pines has caught up, but what about the rate of growth? The young pines each gains 87.68 ft^3 in volume from 20 to 40 years. That means that collectively they will add 935.6 ft^3 compared to 209.7 ft^3 for Saheda. Between 20 and 40 years, the rapid growth of the young pines exceeds what Saheda has done it its last 21, but there is a problem with this analysis.

The **995.83 ft^3** total assumes that all of the pines are on a growth trajectory that will allow them to eventually reach Saheda's size. This is entirely unrealistic. A more probable scenario is that some pines will be suppressed, others average, and only one will be the future Saheda. The following numbers are based on a stand development model that we are currently testing. It includes one extremely dominant pine like Saheda. We take the projected stand volume of an acre at 20 year increments and take the part of the acre represented by 2124 ft^2. The results for a cluster of pines using our stand model returns the following. The numbers reflect live standing pines only.

Stand Age	Trunk Volume-ft^3 (acre)	Avg Limb Factor	Trunk & Limb Volume-ft^3 (acre)	Ground Area for cluster – ft^2	Volume for this ground area – ft^3	Volume change in 20 years – ft^3	Actual Volume change in last 21 yrs Saheda – ft^3	Stand performance relative to Saheda in 20-year intervals. – ft^3
20	487.1	1.15	560.2	2124	27.3	27.3	210.4	-183.1
40	5258.3	1.15	6047.0	2124	294.4	267.1	210.4	56.7
60	11573.1	1.15	13309.1	2124	648.0	353.6	210.4	143.2
80	14288.2	1.15	16431.4	2124	801.2	153.2	210.4	-57.2
100	17667.2	1.15	20317.3	2124	990.7	189.5	210.4	-20.9

What happens at year 80 and beyond? The number of live stems is decreasing.

In this comparison of a cluster of pines growing in the ground space equal to the projected crown area of Saheda, we see that the first 20 years is not enough. The cluster will probably catch up to Saheda's annual growth in around 35 years. These projections do not allow for growth of other species beneath Saheda's crown. There will likely be some growth, and perhaps enough to push the point that the cluster catches up to 40 years.

Based on our stand model, at 80 years, the cluster of pines will hold 801.2 ft^3 of trunk and limb volume. At 100 years, the cluster total will be 992 ft^3. This is still below the volume of the one pine, Saheda. At 120 years, the cluster total is 1,122 ft^3.

There is another comparison worth making. From the table showing Saheda's trunk growth (or a Saheda-like pine) in 20-year increments to the age of 60 years, Saheda gains 5.65 ft^3 from year 0 to 20. From year 20 to 40, the gain is 87.68 ft^3. From year 40 to 60, the gain is 140.79 ft^3. The 40 to 60-year period is consider to be the period of greatest gain, but the last 21 years has seen a gain in Saheda's trunk and limb volume of 997.5 – 787.1 = 210.4 ft^3. This speaks to the accelerated growth rates in the big trees as they age - up to a point, of course.

Conclusions

1. These conclusions are applicable only to this analysis of Saheda.
2. Total carbon sequestered by the cluster of pines occupying an equal ground space to that under Saheda's crown at 60 years is:

   Total = 648.0 ft^3. This falls well short of Saheda's volume of 997.4 ft^3 at 180 years.

3. Carbon sequestered by the cluster of pines occupying an equal ground space to that under Saheda's crown during the period from 20 and 40 years exceeds that Saheda sequesters from 159 to 180 years. This supports the concept of fast stand growth between 20 and 40 years. However, it takes the combined growth of 12.2 trees to accomplish this.

4. The above analysis suggests that a white pine in Saheda's size class can perform extremely well in terms of carbon sequestration for beyond 200 years. It takes over 40 years for the cluster of pines, as hypothesized above, to catch up with Saheda's performance between 159 and 180 years.

5. This analysis does not consider trees that will be growing beneath Saheda's crown during the 180 years.

6. As large as Saheda is, there are still bigger pines in Massachusetts. The Grandfather pine in Monroe State Forest holds 1,097 ft^3 in its trunk via reticle modeling. Adding 10% for limbs brings its total to 1,206.7 ft^3. The equivalent FIA model yields 1,132 ft^3. The difference between Grandfather and Saheda is 1,206.7 – 997.4 = 209.3 ft^3. And An image of the Grandfather Pine follows.

We will conclude with a final picture of this splendid pine and my late friend and colleague Gary Beluzo who was an environmental studies professor at Holyoke Community College.

Summary

The normal growth pattern for a stand of pines produces dominant, average, and suppressed trees. Whatever helps the dominant pines to grow faster enhances carbon sequestration, and the benefits can continue for 200 years or beyond. This is an important conclusion and has particular relevance within the next several decades due to progressing global warming.