Appalachian Mountain Club Final Report to the Forest Ecosystem Monitoring Collaborative Project: Comparing performance of low-cost dendrometers to traditional dendrometers in tracking tree growth in a changing climate

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Preferred Citation: Tourville, J. C., Lineman, B., Murray, G. (January 2025). Comparing performance of low-cost dendrometers to traditional dendrometers in tracking tree growth in a changing climate. https://doi.org/10.18125/o821u0

Abstract

The northeastern United States is experiencing some of the greatest shifts in climate in the US, with warming winters, increased frequency of extreme precipitation events, and severe droughts. For instance, annual mean temperatures across the Northeast have risen ~1.7 °F since the 1930s. Currently, we lack adequate information to connect potential montane tree growth and productivity trends across the broader context of the Northern Appalachian region, which is critical to understand adaptation under future climate scenarios. Automated broad-scale study of tree growth is limited in feasibility due to the cost-restrictive dendrometer instruments (devices that measure the radial, or outward growth of tree stems) required to reliably measure these characteristics. In this project, we captured variation in tree radial growth as measured by two different dendrometer models across climate and edaphic gradients linked to elevation, and between different age classes of trees and tree species within Tuckerman's Ravine (White Mountain National Forest, WMNF) in New Hampshire. Our project provided valuable comparative data for the performance of traditional point dendrometers, priced at approximately $400 (Ecomatik, Germany), to the performance of low-cost point dendrometers, priced at approximately $100 (TOMST, Czechia), to determine the accuracy of low-cost dendrometers for the study of tree growth dynamics. Overall, we find that, in addition to better ease-of-access, simpler installation and maintenance, and better durability, the low-cost dendrometers have comparable measurement accuracy to more expensive traditional point dendrometers. This study has expanded our understanding of the viability of using low-cost dendrometers to measure tree response to climate warming in environments across the northeastern US. Additionally, our work provides a foundation to establish a robust monitoring network to aid in gathering data to understand the effects of a warming climate as well as make inferences about the future character and health of tree species in the northeastern region.

Introduction

Global changes in our environment, such as climate change, have the potential to greatly influence the spatial distribution of plant species [1]. This is particularly true in the mountains of the northeastern US, which are expected to experience continued increases in air temperature and fluctuating precipitation regimes over the next several decades [2, 3]. Tree productivity, defined here as the annual accumulation of tree biomass, may be impacted by global change factors, such as warming, changes in precipitation, drought, wildfires, and pathogens. However, the spatial heterogeneity and complex dynamics of montane forests, both between and within mountain ranges, suggest that tree distribution and species demography are sensitive to many different controlling factors, both climatic and non-climatic [4, 5, 6]. Climate effects on montane tree growth and survival can also be modified by topography. Trees growing on slopes with northerly aspects (in the northern hemisphere) will likely experience colder temperatures but also lower risk of photoinhibition due to less direct exposure to solar radiation [7]. Trees more exposed to high winds will likely suffer increased cold- related tissue damage and icing, while less-exposed trees may be more protected from increased snow cover. Coupled with a lack of suitable substrate (deep, developed soils), complex species distributions can arise from the confluence of multiple climatological and topographical mechanisms acting to increase adult and seedling mortality, and limiting growth [8, 9].

Mountain ecosystems are often understudied due to the paucity of data collection in complex landscapes, especially in terms of long-term sustainable monitoring, yet their importance in terms of diverse habitat, connectivity, and role as refugia in a changing climate are coming more into focus [10]. Tree radial growth rate is a critical measurement for an improved understanding of the patterns and drivers of montane ecosystems and forest dynamics. Taking these measurements, with an eye on changing abiotic conditions, particularly in montane ecosystems, can help improve projections of tree and forest productivity throughout the region. The barriers to this kind of effective monitoring are the costs, technology, integration and methodology utilized to measure productivity metrics.

Tree growth has historically been measured via a variety of approaches, each touching upon a discrete scale. Repeated tree diameter measurements taken by individual technicians on a small number of trees is easy to perform but prone to survey error and more difficult to scale to a stand/regional level. Remote sensing approaches, particularly the use of lidar, to measure biomass and tree architecture, are promising and effective at stand scales, but is expensive and requires field validation to make sense of the data. Dendrometers are devices that autonomously measure small changes in tree diameter through time without much human intervention. A dendrometer works by attaching a small sensor to the trunk of a tree, which measures minute changes in the tree's diameter, allowing researchers to monitor tree growth and detect subtle variations in the tree's physiological state due to factors like water availability, weather, or stress, by recording these changes over time; essentially, it acts like a tiny piston that measures how much the tree's girth expands or contracts [11, 12, 13]. A band dendrometer consists of a stainless-steel band that is tightly wrapped around the circumference of a tree's trunk. The band is connected to a tightly wound spring where the expansion and contraction of the spring is detected as a voltage and measured as plant growth. A point dendrometer measures changes in a tree's diameter by using a small, pointed sensor (linear potentiometer) that is pressed lightly against the bark, allowing it to detect sub-micron fluctuations in the tree's girth, recording these changes over time through a data logger; these data can be used to study a tree's water stress and growth patterns based on how its diameter changes throughout the day or season. Dendrometers represent a viable middle-ground between potentially inaccurate field-based repeated manual diameter measurements and expensive and cumbersome remotely sensed scanned approaches. However, the use of dendrometers in large-scale monitoring efforts could be limited by high costs [11, 12, 13].

Overall, we noted that a large obstacle for consistent measurement of tree growth rates at meaningful scale is the need to use cost-restrictive dendrometers. Low-cost alternative instruments exist, but there is currently not adequate information on the reliability of these devices to support their use in gathering scientific-grade data. In this study we ask two main questions: (**Q1**) Can we adequately capture and compare intra- annual tree growth patterns with both traditional and low-cost dendrometers?, and (**Q2**) can we feasibly implement a low-cost dendrometer network to measure tree radial growth rates across climate/edaphic gradients and between different age classes of trees and tree species both during summer growing periods and colder seasons? Using both traditional and low-cost dendrometers, we proposed to measure tree radial growth rates across climate/edaphic gradients and between different age classes of trees and tree species within the White Mountains of New Hampshire, both during summer growing periods and colder seasons, which can be extreme in the White Mountain region. This allowed for intra- annual growth patterns to be captured with both traditional and low-cost dendrometers – enabling comparison and sufficient analysis of the feasibility of low-cost dendrometers in larger projects.

Methods

Study Area

This project was conducted in northern hardwood, montane spruce-fir, and subalpine fir krummholz forests in Tuckerman's Ravine adjacent to the AMC's Pinkham Notch Visitor Center, east of Mt. Washington (Presidential Range, New Hampshire). The area is within the Adirondack-New England highlands, characterized by highly variable terrain (generally ranging from 150 to 1,220 meters above sea level), cold rocky spodosol soils, continental forest climate with warm summers and cold and snowy winters (mean annual temperatures between 3 and 11˚C; mean length of the frost-free period ~100 days; mean annual snowfall > 2,550 mm), and evenly distributed precipitation (annual mean precipitation of 890 mm) [9]. The mean annual temperature has increased by ~1˚C since the 1930s in the White Mountains [3]. Upland northern hardwood forests in the region are heavily dominated by sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), American beech (*Fagus grandifolia*), and yellow birch (*Betula alleghaniensis*). Montane spruce-fir forests are comprised primarily of balsam fir (*Abies balsamea*) and red spruce (*Picea rubens*).

Study Design

We selected one elevation transect (Tuckerman's Ravine) on the Presidential Range in the White Mountains of New Hampshire to test dendrometer performance. Four sites spaced 200 meters in elevation (600 meters asl – 1200 meters asl) on our transect were identified (Figure 1). At each site, eight trees differing in size class were selected on which to place dendrometers. One low elevation site (550 m), and one high elevation subalpine site (1500 m) were subsequently included in our study (6 sites, total n = 52 trees). The small size class included four trees at each site with a diameter at breast height (dbh) between 5-15 cm, and the large size class included four trees with a dbh between 25-35 cm. This was not done at the subalpine krummholz site where all trees were too short in stature for a dbh measurement to be taken. The three lower elevation sites used sugar maple (*Acer saccharum*) as the focal tree species and the three higher elevation sites used balsam fir (*Abies balsamea*). On each tree, we attached one expensive traditional point dendrometer device (Ecomatik, Munich, Germany) and one low-cost point dendrometer device (TOMST, Czechia) 50 centimeters apart (Figure 2; model specifications in Table 1). The identity of the dendrometer type that was placed higher on the tree was randomized. Dendrometers record the displacement of attached metal springs as trees grow (radial growth rates); the dendrometers that were used in this study generally have a resolution of ~0.2-0.3 microns. DBH for all trees were measured using a standard forestry DBH tape at the point where each dendrometer was attached to establish the baseline size of the individual tree. Dendrometers were installed in late September 2023 by AMC staff and left in place to record. Final measurements for this project were manually downloaded in October 2024 (with the possibility of extension per agreement by FEMC staff to decommission at a later date) (see Table 2 for site characteristics).

Data management and analysis

Raw .csv files of dendrometer time series were collected and downloaded using the software HOBOware (Ecomatik) and lolly (TOMST). The package "myClim" [14] was used in R [15] to read-in and organize all .csv files, collate all data using time and date of measurements, and aggregate measurements to daily mean values. Temperature values recorded from the TOMST dendrometer at each individual tree were also aggregated to daily means. Raw dendrometer measurements are read as a voltage and converted to micrometers (µm) using a conversion factor unique to each set of instruments (see Table 1). Once the data are displayed in units of distance, we calculated a baseline, which represents the daily mean value read by the device one day after installation (to allow for any settling of the instrument on the outer tree bark). Deviation from baseline represents the change between each subsequent mean value for each day and is the metric used to directly compare the performance of each dendrometer to each other (radial growth). All outliers were double-checked to ensure quality control.

All data were partitioned by dendrometer type, site elevation, tree size class (large vs. small vs. krummholz), and species (*Acer* vs. *Abies*), and observations for each tree and day were assigned a mean temperature from the TOMST sensor. We used two-tailed t-tests to evaluate statistically significant differences between Ecomatik and TOMST dendrometer readings of deviation from baseline across time, after checking our data for the assumptions of a t-test (normality, etc.). The described approach was used for all aggregated data and for data partitioned between our factors of interest. Further, we constructed generalized linear mixed effects models (GLMM) in "lme4" using deviation from baseline as a response and allowed random intercepts and slopes for individual trees and species. Model comparison was facilitated by AIC on a series of reduced models derived from a global model including sensor type, temperature, elevation, and size class as fixed effects, and tree identity and species as random effects.

The correspondence of Ecomatik and TOMST readings were visualized with scatterplots showing 1:1 lines using "ggplot2" in R. This was also done for data partitioned by all factors of interest. An interclass correlation coefficient (ICC) was calculated for the comparison of Ecomatik and TOMST daily sensor readings. Relationships between temperature and sensor deviation from baseline readings for both dendrometer types were also visualized using scatterplots. All data, metadata and R code used in this study are located within this project's FEMC data repository (see Appendix). All results from this work are summarized below.

Results

Addressing **Q1** above, in general, we find that TOMST dendrometers systematically underestimate tree radial growth rates relative to Ecomatik dendrometers across a wide array of environmental conditions. The mean deviation from baseline measurement was 909 µm (0.91 mm) for Ecomatik compared to 650 µm (0.65 mm) for TOMST dendrometers (relative percent difference, RPD = 33.2%), with a t-test indicating this to be a significant difference ($t = -26.59$, $p<0.001$; Figure 3). However, 95% of TOMST and Ecomatik growth measurements fell within ± 1.4 mm (1400 µm); 50% within ± 0.2 mm (200 µm), meaning that while TOMST units consistently underestimate tree growth relative to Ecomatik units, the magnitude is quite small (see Figure 4). An ICC of 0.75 between the dendrometer models indicates good agreement between the two (Figure 5) [16].

Our best-fit global GLMM supported the previous finding that TOMST dendrometers consistently underestimated growth measurements relative to Ecomatik dendrometers (estimate = -162.8 µm (±8.9 µm), $t = -18.27$, $p<0.001$, Table 3). Model comparison via AIC revealed that our global model outperformed all our reduced models (Table 4). Our GLMM also indicated that temperature had a strong positive significant effect, and elevation (Figure 6) had a weak negative significant effect on growth measurements (Table 3). There were no significant differences in growth between the two dendrometer types for tree size classes with the exception of krummholz trees (Table 3, Figure 7). Plots of growth across variation in recorded temperature revealed a threshold response to the initiation of growth, presumably during the spring months for both Ecomatik (LOESS fit, Figure 8) and TOMST (LOESS fit, Figure 9) units. Interestingly, krummholz initiation of growth generally occurred at lower temperatures than conspecific trees growing at lower elevations, potentially indicating some phenotypic plasticity in that trait/phenology. Further, a time series of tree radial growth also shows the spring initiation of tree growth as a threshold response to mean daily temperature (which is likely correlated with accumulated temperatures) which may serve as a good phenological indicator in future dendrometer studies (Figure 10).

Discussion

Overall, addressing **Q1**, we find that the more expensive Ecomatik dendrometers tended to significantly overestimate tree radial growth relative to the cheaper TOMST units, but the magnitude of these differences was small (<33.3% of the mean of associated measurements), and there was generally good agreement between the two. The same overall trends as above were also attributed to different tree species, size classes and sites. As expected, trends in radial growth were closely tied to temperature, with threshold responses of the onset of seasonal growth detected with both devices. Elevation, however, was only weakly tied to trends in seasonal radial growth. Krummholz trees displayed reduced growth compared to all other trees monitored, but experienced growth onset at lower temperatures. There were no detectable differences in growth trends between large and small diameter trees.

The finding that half the differences between the two dendrometers fell within ±0.2 mm highlights both the extreme sensitivity and fine resolution of these dendrometer devices and the promise of wide-scale installation of relatively cheap units for future monitoring networks. This suggests that small changes in tree biomass over the course of a single growing season can be well captured via this approach. The systematic difference between the two dendrometer types is also encouraging as it illustrates that such differences can be accounted for and potentially corrected, assuming the cause can be identified. Anecdotal evidence suggests that both how the dendrometer is anchored and how the outer bark of the tree is treated prior to device installation are both critical for measurement accuracy (Tim Rademacher, personal communication). For instance, our Ecomatik dendrometers attach to trees with two points of contact in a horizontal arrangement while TOMST dendrometers attach with one in a vertical arrangement, and only after removing some of the outer bark. To complicate matters, band dendrometers would likely record radial growth differently than our point dendrometers [17]. Such nuances need to be considered when planning any monitoring scheme.

When considering relationships between tree growth and both abiotic and biotic factors, we find a strong positive relationship between growth and temperature. Temperature-dependent growth is well documented in the relevant literature and was not surprising here [18, 19]. The weak relationship with elevation, on the other hand, was a bit surprising as temperature is known to strongly co-vary with elevation [20, 21]. These weak ties may suggest that microclimates at a site level are more relevant to tree growth than absolute elevation, and that measuring temperature directly is more critical than understanding landscape position in this context [22, 23]. Further, the timing of seasonal growth was highly temperature dependent and easy to track with our data. This points to the utility of dendrometers in other areas of inquiry, particularly in tracking tree phenology [24] and carbon cycling. The lack of evidence to support differing trends of growth between larger mature trees and smaller juvenile trees was also somewhat surprising, as higher metabolic costs should in theory slow growth rates in older trees relative to younger ones, depending on the tree species [25]. However, it may be the case that these trends play out and become obvious over multiple growing seasons and may not have been detected in our one-year study. Krummholz trees potentially growing at their physiological limit began accumulating biomass at lower temperatures (although at later times of the year given their position at high elevations) than their lower-elevation conspecifics, and points to the utility of dendrometers in studies of environmental adaptation and acclimation within tree species [19].

Overall, we anticipate that this initial work will spur further interest to explore and design methods to establish a dendrometer network across the FEMC monitoring region. We also suggest that future research examine growth trends across more seasons and include other relevant climate variables, such as accumulated growing degree days (AGDD) and chilling degree days (CDD), and test the feasibility of other dendrometer models, particularly those with remote data signaling capability (Note: AMC will continue to monitor dendrometer plots and maintain devices to continue to collect and analyze growth data). Following up on **Q2** above, we highlight recommendations for the future establishment of such a dendrometer monitoring network:

Recommendations

1. Establish dendrometer network

Given the cost effectiveness of the TOMST (model D1) dendrometer and its systematic agreement with more expensive and well-established brand models of dendrometer (Ecomatik), we advocate for the installation of these units across a wide range of FEMC forest monitoring plots. TOMST dendrometers have proven to be both easy to use and hardy in extreme weather (cold). They also experience increased longevity compared to corded devices which are often vulnerable to animals and downed woody debris. As unit performance is consistent across tree taxa and tree size, we find that these units could be appropriate in any forest community type and location currently monitored by the FEMC. The degree of replication at a given site is contingent upon the specific goals of FEMC, but we recommend at least 10 trees of any target should be fixed with dendrometers at a given site across a subset of all FEMC sites. Species selection should focus on a small number of dominant species as determined by measured relative basal area or relative frequency. Installation of TOMST units are straightforward (see link to TOMST and Ecomatik product handbooks in Appendix) and require few people and equipment. Data acquisition requires manual download with the proprietary “lolly” software but is easy to use and acquisition need only be done 1-2 times per season, coinciding with any scheduled site maintenance. Based on expert feedback, the best approach for effective monitoring of plot/site-level tree productivity could include affixing 90% of all target trees with TOMST units and 10% with both TOMST and Ecomatik units; to ensure continued data agreement. These ground-based approaches can be supplemented with aerial lidar surveys of the site/plot. Many methods now exist to measure tree biomass and productivity metrics based on lidar, and growth data acquired via dendrometers could serve as an ideal ground validation tool [26, 27, 28].

2. Explore different uses for data

Dendrometers provide an excellent avenue for determining tree biomass production, and once scaled up, provide a lens for examining productivity of an entire forest. However, as our data illustrate, dendrometer sensor data can provide insights into other less explored areas of inquiry. This is especially true when considering the additional functionality of TOMST units which have built-in temperature sensors. For example, in our study we uncovered some interesting results related to the onset of seasonal tree growth. We were able to calculate precise estimates of the time of year where trees begin accumulating biomass, and the abiotic drivers (temperature, elevation) for which this occurred. Further, while landscape position was not an important driver of radial growth within the forest interior, we found stark differences in the timing and temperature constraints on seasonal growth for the high-elevation sites (e.g., krummholz trees initiated growth at lower mean temperatures than lower elevation conspecifics). Such data could be extremely valuable in monitoring tree phenology, which pairs nicely with field-based observations conducted by the AMC (data not shown, [24]). These data could also be used to explore other potential drivers of tree productivity related to temperature, such as accumulated growing degree days (AGDD), and winter chilling/vernalization requirements (CDD) [29].

3. Examine other methods of data acquisition

All dendrometers used in this study require manual data downloads to acquire their data. Recently, discussion around the idea of remote data signaling has increased in the relevant literature [30]. The advantages of such a platform are numerous: real-time data visualization, a dramatic decrease in the labor associated with operating the sensor network, and instant diagnosis of any faulty sensors. In this proposed network, dendrometers communicate with a remote base station via a cellular, wi-fi, or Bluetooth connection, potentially with the assistance of a network relay station if the devices are in a distant and remote location. Further, as no such devices are currently being commercially sold, homemade units using components that are relatively cheap are themselves inexpensive compared to the devices used in this study. While we do not discuss this above, four remote band dendrometer dataloggers were assembled by an NSF INSPIRES project based out of the University of Maine (https://crsf.umaine.edu/inspires/) and tested on adult sugar maple trees adjacent to the AMC's Pinkham Notch Visitor Center. These devices communicated with a nearby base station via a wi-fi network. While these devices successfully transmitted growth data to the base station, one notable issue was that the communication range was limited by dense vegetation, so that the station needed almost clear line-of-sight with the dendrometers to function. In the future, this issue could be overcome by the placement of relays at high points above the dendrometers, which could increase the range of communication to between 1-3 km. In sum, such an approach would be a useful method to further explore by the FEMC.

Conclusions

Currently, few data on northeast upland tree growth rates exist. This project aligned with FEMC priorities, as (i) all data collection took place in forested areas within the White Mountain National Forest and our work (ii) improves our understanding of technology that has the potential to substantially increase our capacity to collect field data to address emerging needs. By establishing foundational comparative data and methodology for the use of low-cost dendrometers to measure tree growth, we strive to provide scientists engaging in research on ecosystem trends in relation to climate change valuable knowledge for the feasibility of using such methods in the Northeast region and beyond. Ultimately, this will make tree growth research more accessible and less cost prohibitive, enabling more studies to be completed and spatial variability to be better characterized, thereby increasing our collective understanding of the impact of climate change on northeast upland tree growth rates.

Acknowledgements

We would like to thank the Forest Ecosystem Monitoring Collaborative (FEMC) for the generous funding and logistical support that made this project possible. We would also like to thank the White Mountain National Forest (WMNF) for permitting and providing access to our field sites. We thank Leo Edmiston-Cyr at the University of Maine, and the NSF INSPIRES project for heling to pilot our remote dendrometer units.

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Tables

Table 1: Detailed 2024 specifications for the specific point dendrometer models used in this study.

Specification	Ecomatik	TOMST
Model Name	DR3W	D1
2024 Cost Per Unit[1]	$414	$110
Plant Diameter Requirements	>3cm	>3cm
Sensor Range	11mm	9mm
Sensor Resolution	0.20µm	0.27µm
Accuracy	±0.1%	±1.0%
Ideal Temperature Range	-25°C to 70°C	Untested
Sensor Weight	13g	15g
Battery Life	Infinite/Replaceable	~14 years
Datalogger	HOBO Datalogger (DL18)	Internal
Software	HOBOware	lolly

Material	Steel/Aluminum	Steel/Aluminum
Cable Length	5m	N/A
Voltage to µm Conversion[2]	V*11,000	(V-1,279)*0.2717

[1]Cost is in US dollars but units are sold in Euros (€). 2024 costs based on conversion rate of $1.04 per €1.00.

[2]V in equations represents raw voltage readings.

Table 2: Site characteristics for all locations where dendrometers were placed in this study. Mean growing season temperature based on TOMST sensor readings.

Site (Elevation (m))	**Genus**	**Forest Community**	**Mean (±SE) Growing Season Temperature (°C)**	**Number of Trees**	**Diameter Range (cm)**	**Date Installed**
Programs (550)	*Acer*	Hardwood	7.97 (±0.32)	4	18.4-27.6	11/1/2023
Low (600)	*Acer*	Hardwood	7.74 (±0.16)	8	11.0-42.6	10/3/2023
Ecotone Low (800)	*Acer*	Mixed Hardwood	7.72 (±0.16)	8	10.3-41.0	10/3/2023
Ecotone High (1000)	*Abies*	Spruce-fir	6.82 (±0.16)	8	8.7-31.0	10/3/2023
High (1200)	*Abies*	Spruce-fir	4.94 (±0.17)	8	11.5-22.1	10/3/2023
Krummholz (1500)	*Abies* (krummholz)	Fir Krummholz	3.98 (±0.23)	16	2.2-7.6	7/1/2023

Table 3: Results of global generalized linear mixed model (GLMM) including sensor (dendrometer type), temperature, elevation, and size class (large diameter vs. small vs. krummholz) as fixed effects, and tree identity and species as random effects. Bold and starred p-values indicate significant effects (α = 0.05). *** (p<0.001), ** (p<0.01), * (p<0.05).

Response	**Factor**	**Estimate**	**SE**	**t-value**	**Prob**
Growth	**Intercept**	622.3	288.2	3.15	**<0.001*** **
	Sensor				
	TOMST	-162.8	8.91	-18.27	**<0.001*** **
	Temperature	41.14	0.43	95.74	**<0.001*** **
	Elevation	-16.92	6.93	-2.18	**0.04***
	Size Class				
	Large	27.81	188.2	0.15	0.99
	Small	81.65	188.3	0.43	0.98

Table 4: Model comparison with AICc.

Model selection based on AICc:					
Model	K	AICc	Delta AICc	AICc Weight	Residual LL
Diff ~ sensor_type + temperature + elevation + size_class + (1 | tree) + (1 | species)	9	336073	0.00	0.97	-168027.3
Diff ~ sensor_type + temperature + size_class + (1 | tree) + (1 | species)	8	336080	7.08	0.03	-168031.8
Diff ~ sensor_type + temperature + (1 | tree) + (1 | species)	6	336099	26.20	0	-168043.4
Diff ~ sensor_type + (1 | tree) + (1 | species)	5	385996	49923	0	-192993.0
Diff ~ 1 + (1 | tree) + (1 | species)	4	386228	50156	0	-193110.0

Figures

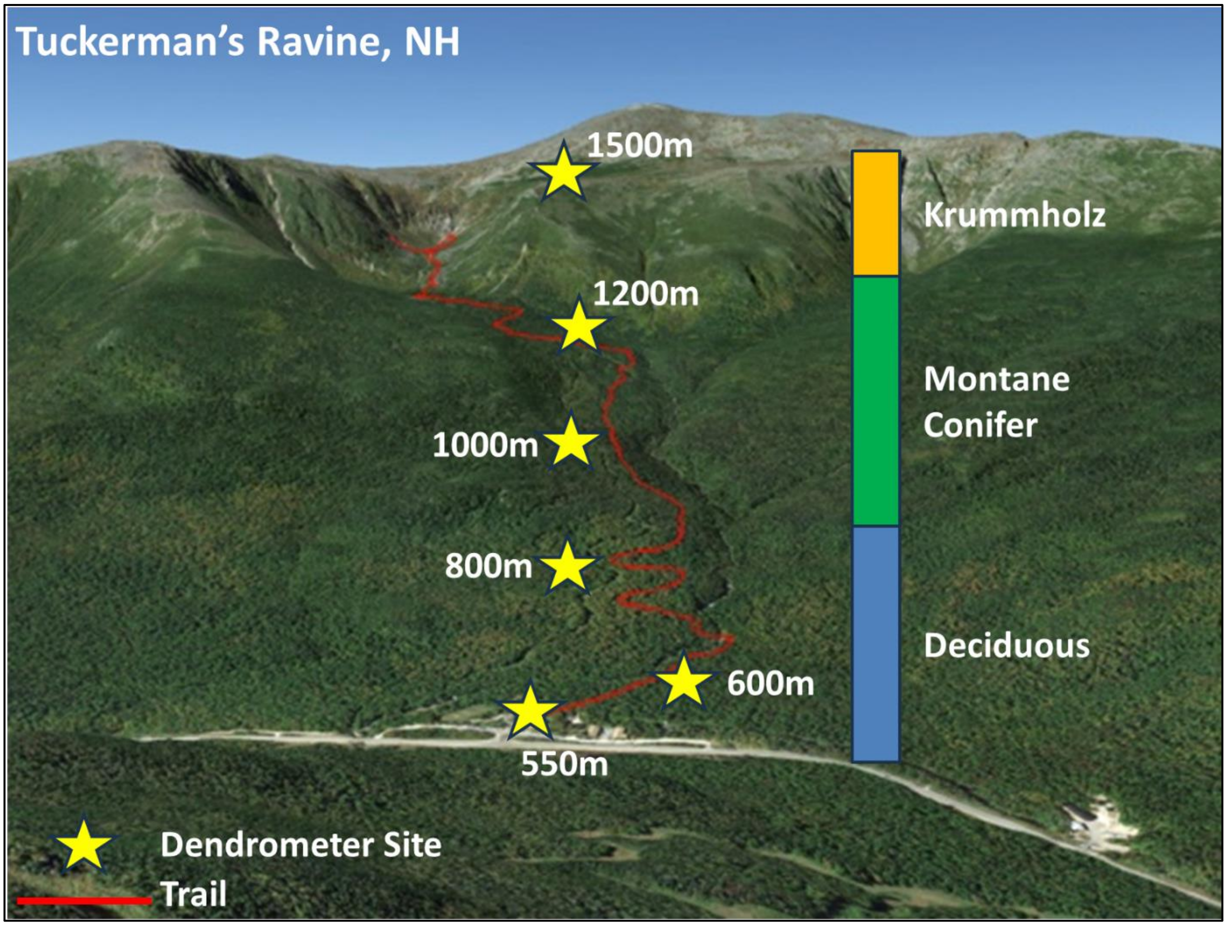

Figure 1: Dendrometer site placement along the Tuckman Ravine elevation transect on the eastern flank of Mt. Washington, NH. The red line denotes the Tuckerman's Ravine Trail. The colored bar indicates the forest community type dominant at a given elevation.

Figure 2: Images of the two dendrometer models used in this study. Left: Ecomatik point dendrometer with a cost of approximately $400. Right: TOMST point dendrometer with built in temperature sensor with an approximate cost of $100.

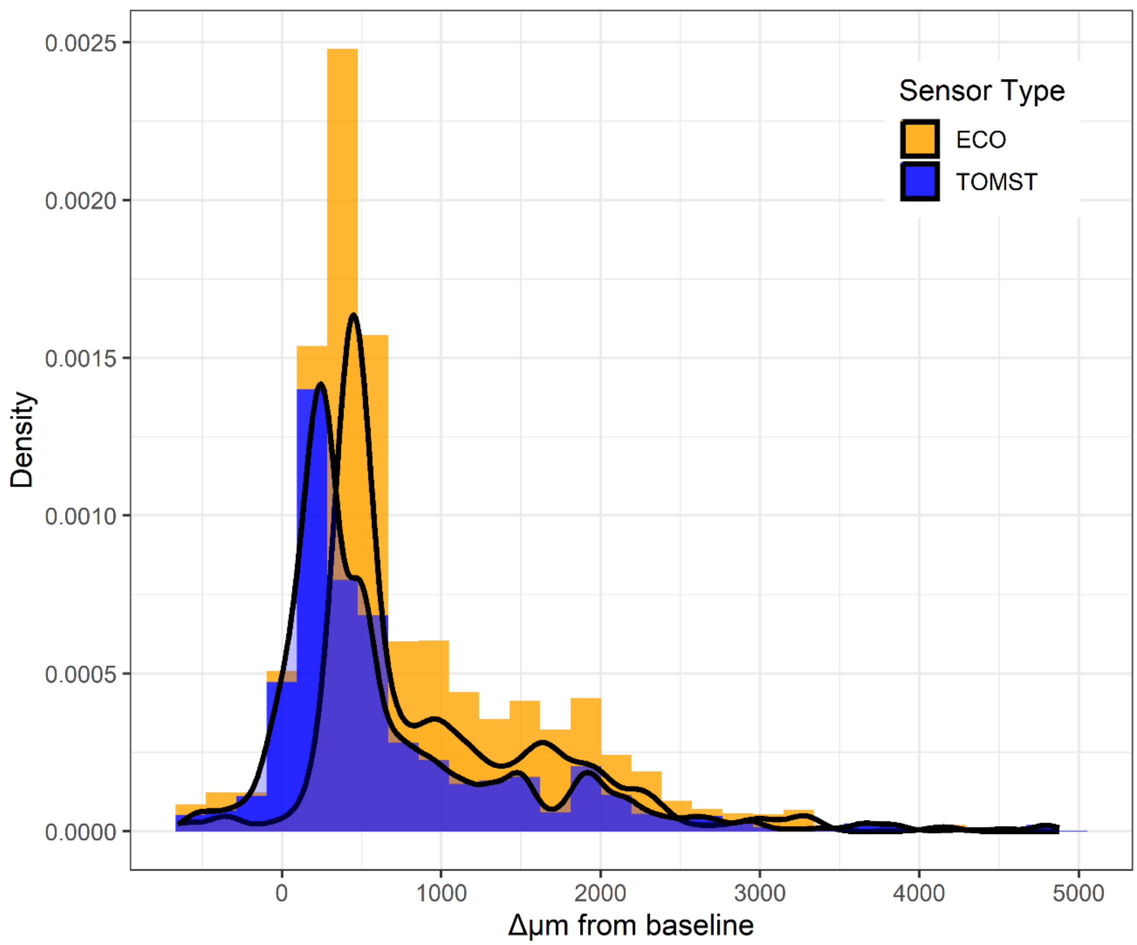

Figure 3: Growth measurement histogram for the two dendrometer types. Line indicates measurement density distributions.

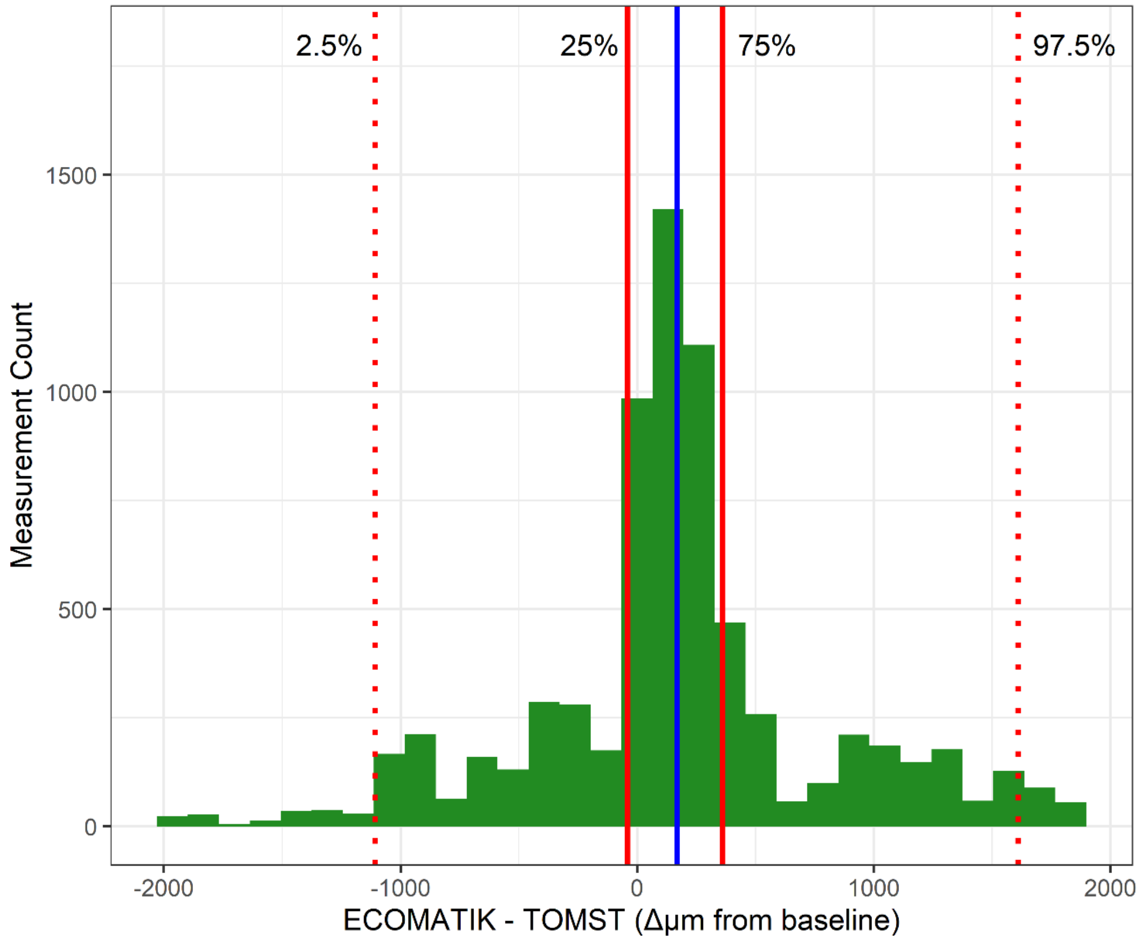

Figure 4: Distribution of daily sensor differences between Ecomatik and TOMST units (with 50% and 95% quantiles). Summary statistics include the following: N: 7102; minimum difference: -1947 µm (-1.9 mm); Q2.5: -1107 µm (-1.1 mm); Q25: -40 µm (-0.04 mm); mean difference (±sd): 168 (±64) µm (0.17 mm); Q75: 361 µm (0.36 mm); Q97.5: 1610 µm (1.6 mm); maximum difference: 1846 µm (1.8 mm); range 95%: 2717 µm (2.7 mm).

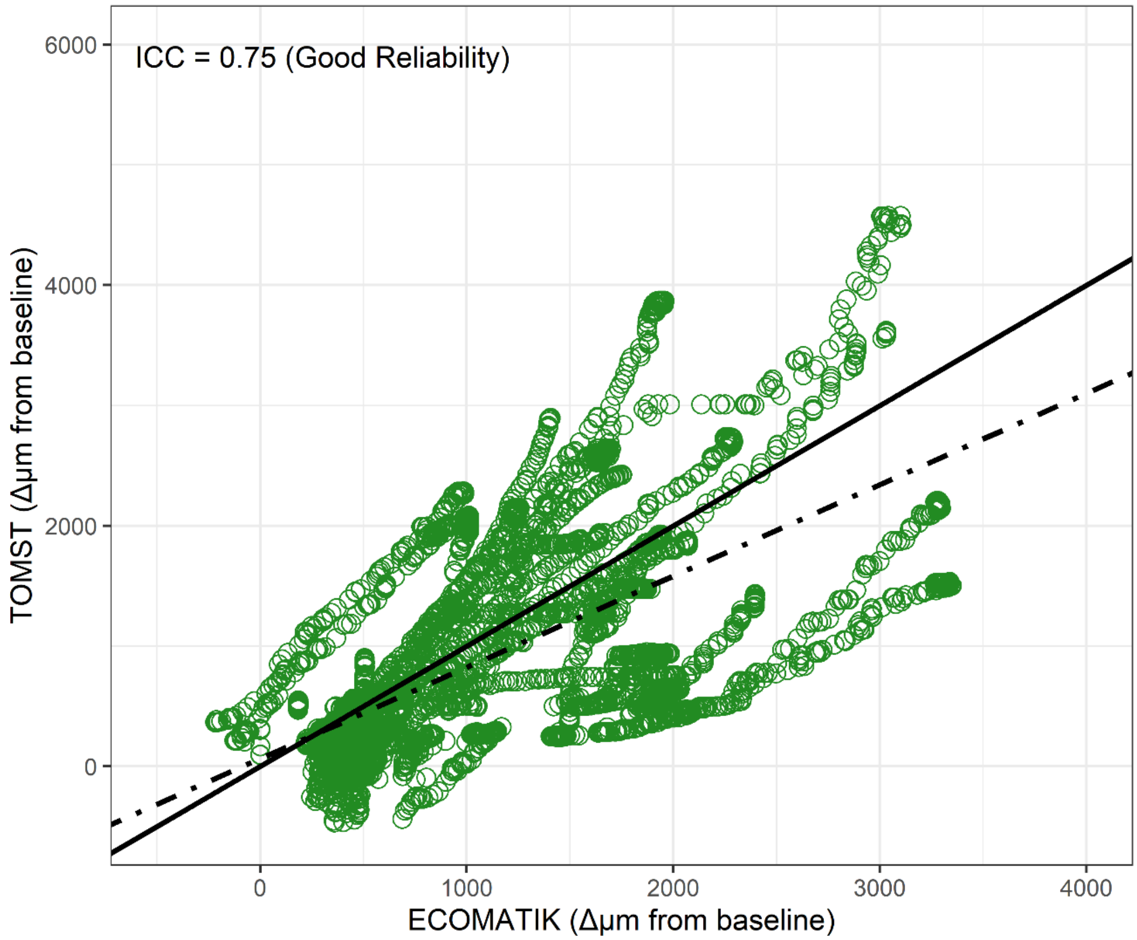

Figure 5: Direct sensor measurement comparison between Ecomatik (x-axis) and TOMST (y-axis) dendrometers. Interclass Correlation Coefficient (ICC) of 0.75 indicates good agreement between the two sensors. The solid line indicates the 1:1 line and dotted line indicates best linear fit.

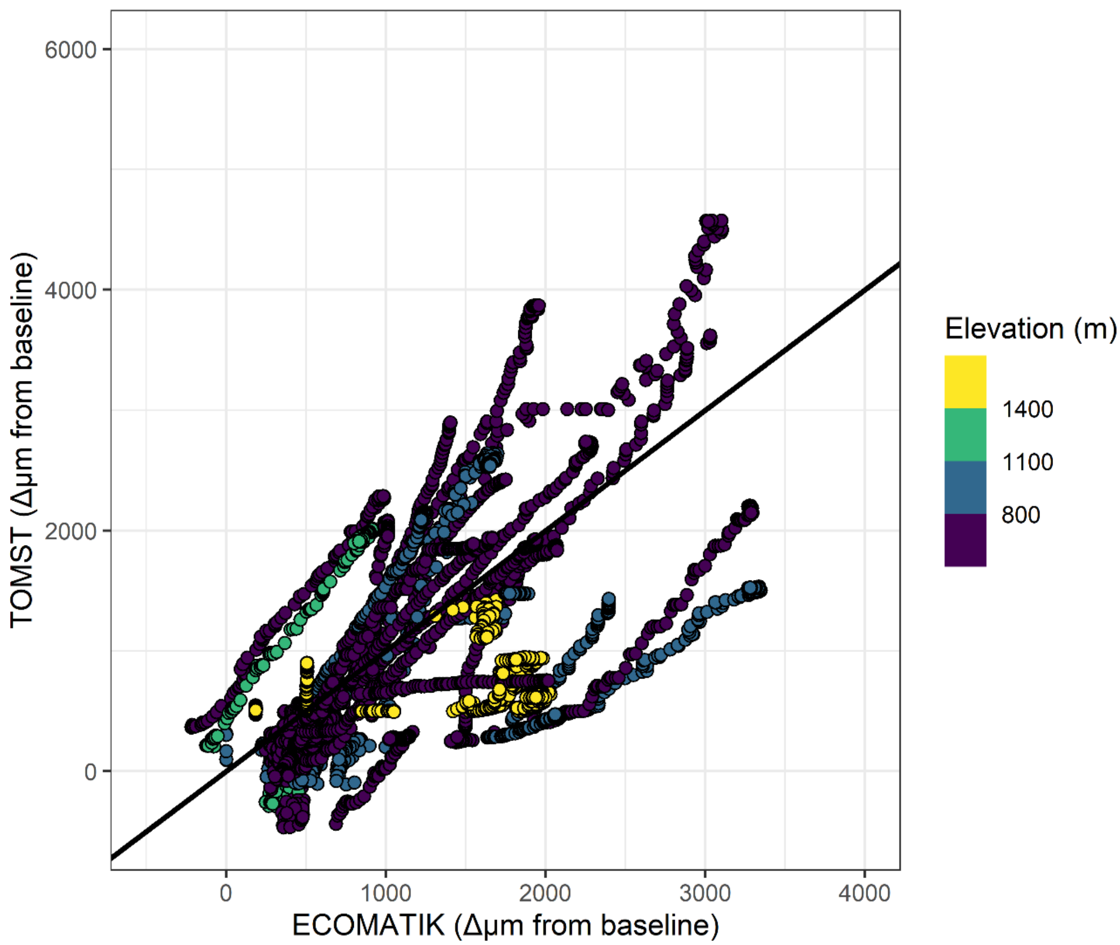

Figure 6: Comparison of TOMST and Ecomatik growth measurements partitioned by site elevation. Solid line indicates 1:1 line.

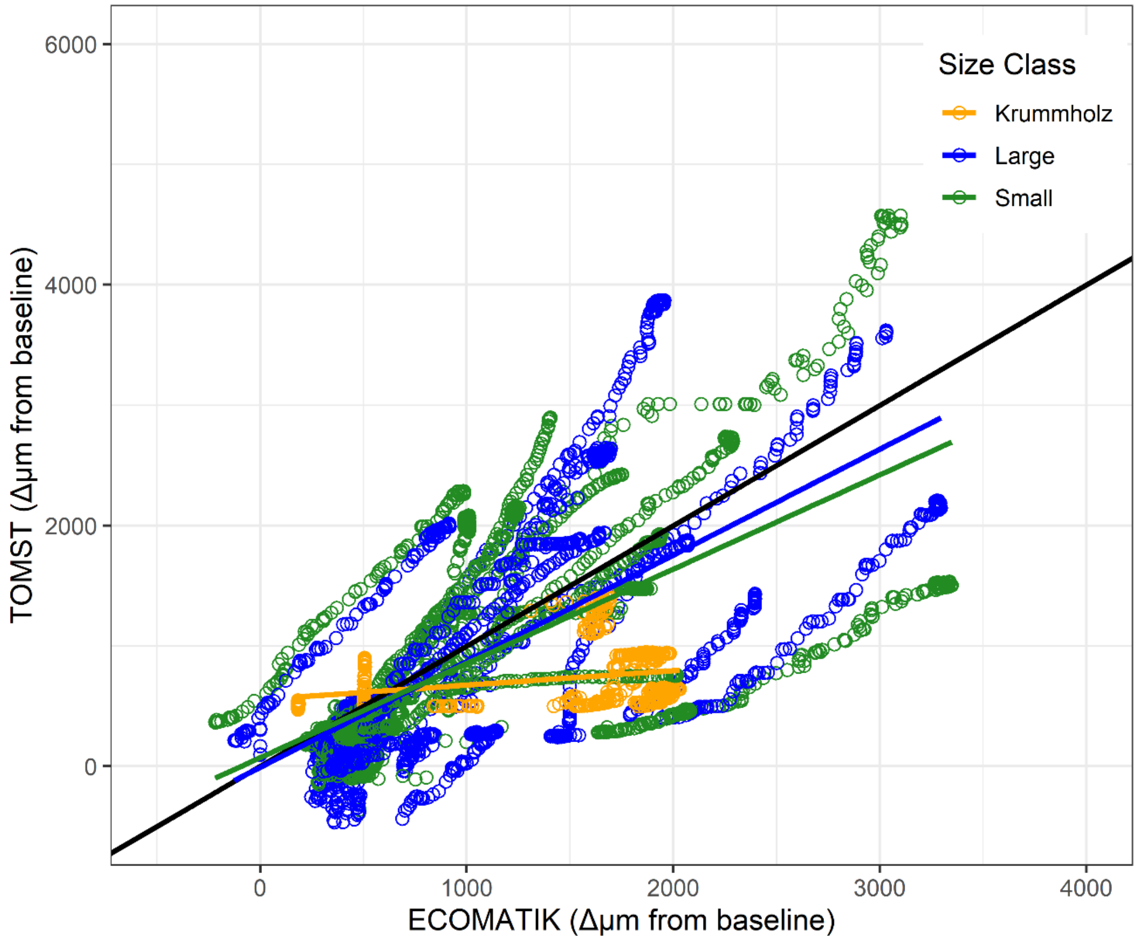

Figure 7: Comparison of TOMST and Ecomatik growth measurements partitioned by tree size class. Solid line indicates 1:1 line. Colored solid lines indicate best linear fits by tree size class.

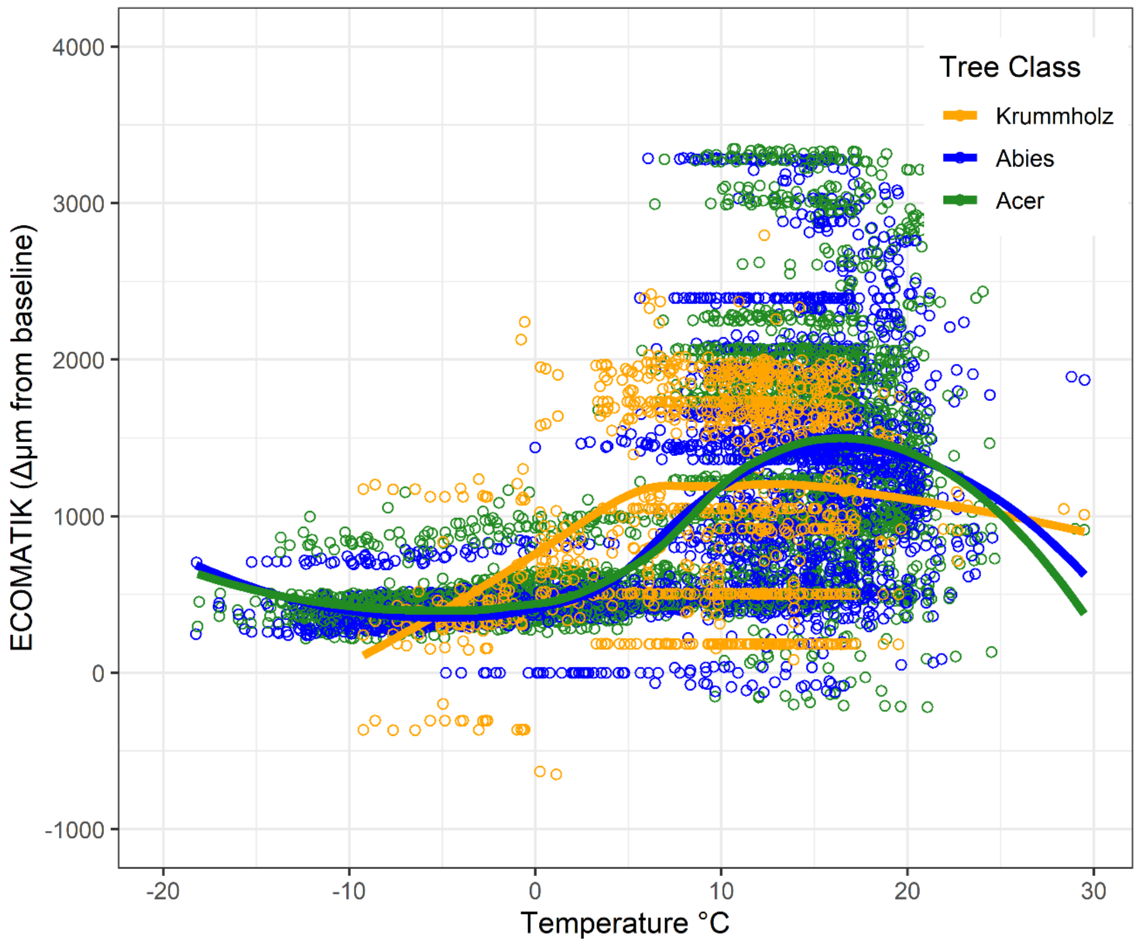

Figure 3: Ecomatik tree growth measurements across a range of temperatures partitioned by tree type (krummholz indicates stunted *Abies* at treeline). Colored solid lines indicate LOESS fits.

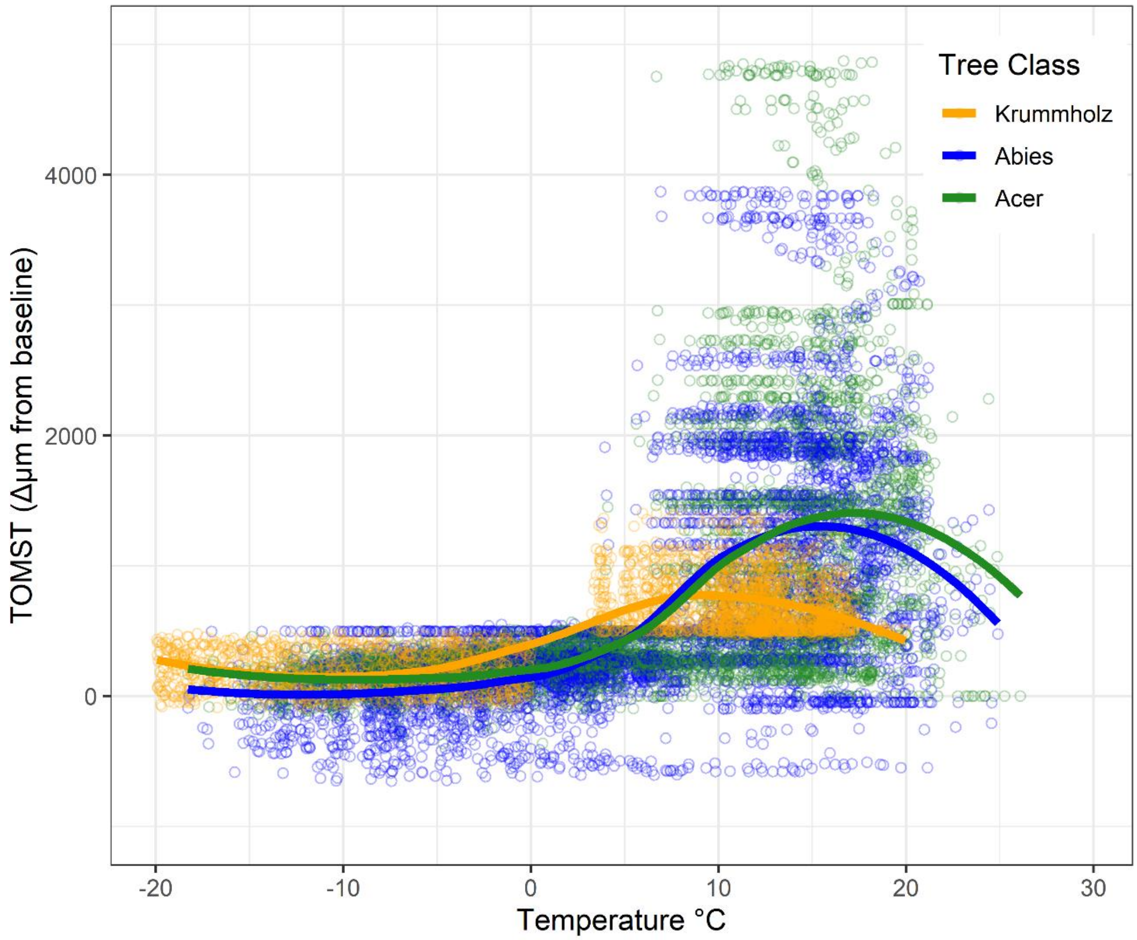

Figure 4: TOMST tree growth measurements across a range of temperatures partitioned by tree type (krummholz indicates stunted *Abies* at treeline). Colored solid lines indicate LOESS fits.

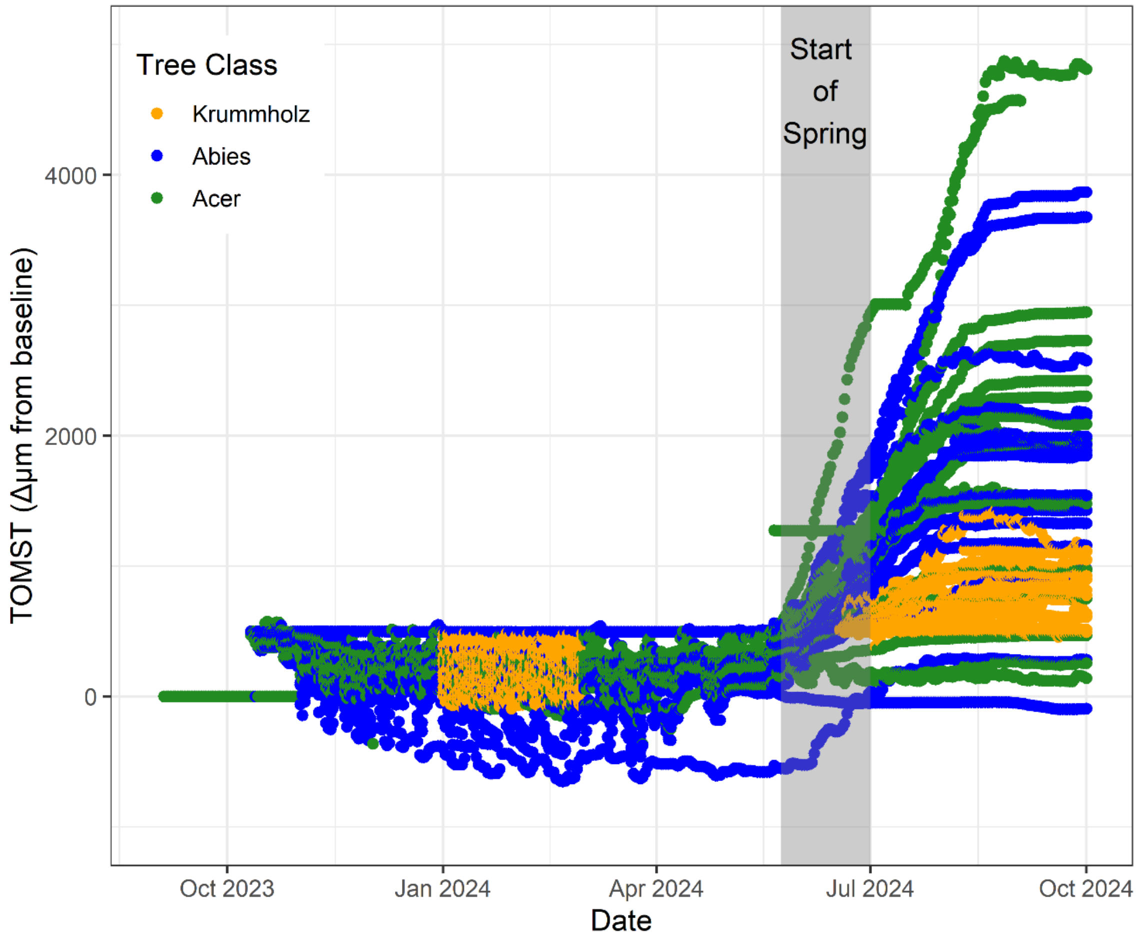

Figure 5: Time series (between October 2023 and October 2024) of TOMST tree growth trends partitioned by tree type (krummholz indicates stunted *Abies* at treeline). Shaded area displays initiation of seasonal tree growth (5/21 – 6/30).

Appendix

Relevant Links:

TOMST lolly software:

https://tomst.com/web/en/systems/tms/software/

TOMST D1 dendrometer user's handbook:

https://tomst.com/web/wp-content/uploads/2019/08/D1_users_manual_3.pdf

Onset HOBOware software:

https://www.onsetcomp.com/products/software/hoboware?gad_source=1&gclid=Cj0KCQiAsaS7BhDPARIsAAX5cSALqjHZV2LOwBSZWK04Jkg48lsnszljd0t-SmhFrnv3XxTJAc9qqpkaAqJVEALw_wcB

Ecomatik DR3W dendrometer user's handbook:

https://ecomatik.de/site/assets/files/14060/usermanual_dr3w.pdf

FEMC Project Data Repository:

Dendrometer metadata: Basic information for the specific dendrometers used in this study. Note: plot coordinates are not included.

Raw dendrometer data: Dendrometer readings and temperature data from each unit on each tree at each site.

Project R code: Annotated R code used to read, manage, analyze, and visualize data in this study.