FOREST MONITORING SYSTEMS

advancing forest monitoring through
IOT dedicated SENSOR development
and applications

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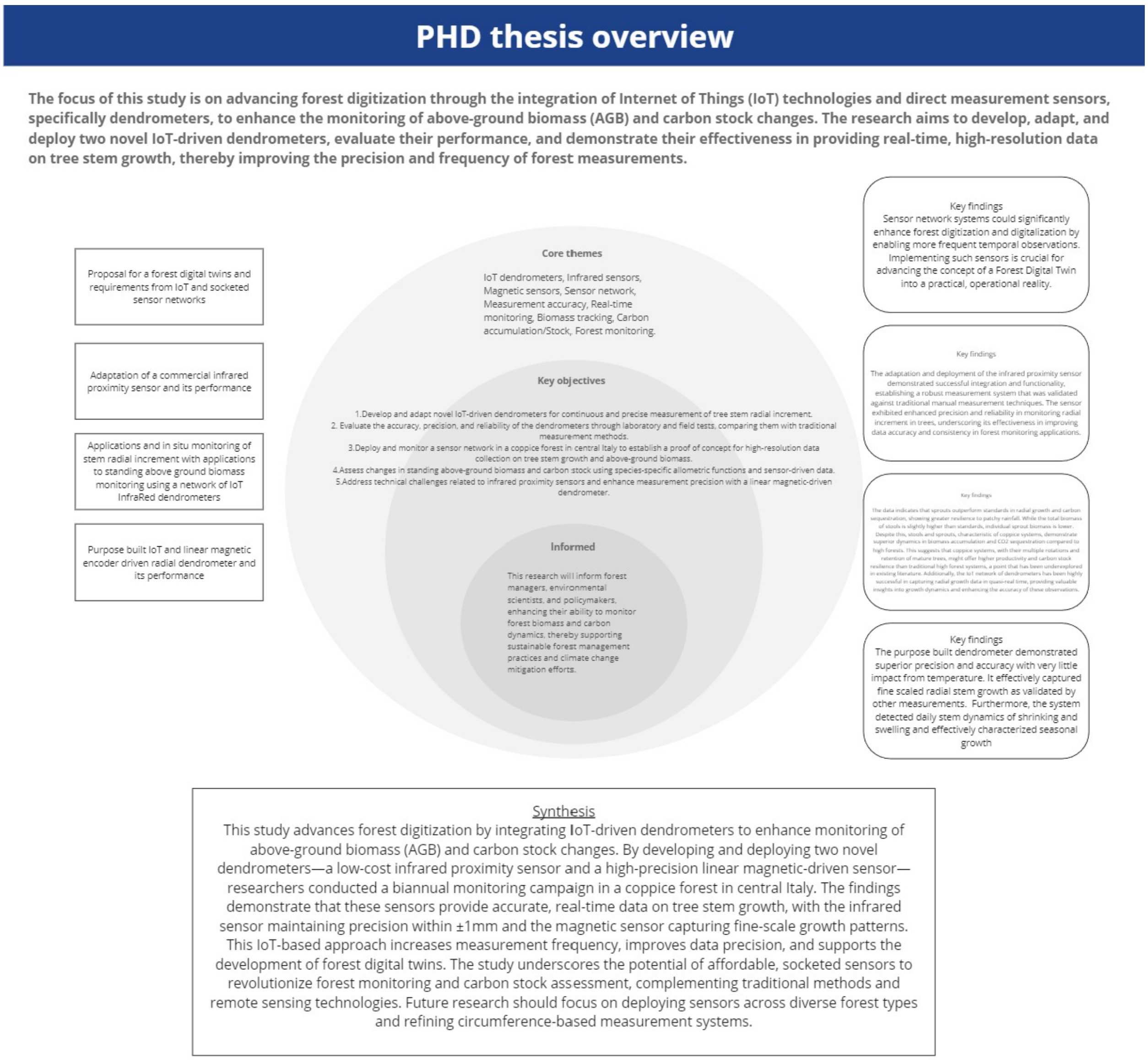
Thesis Overview

Key words

IoT dendrometers, Infrared sensors, Magnetic sensors, Sensor network, Measurement accuracy, Real-time monitoring, Biomass tracking, Carbon accumulation/Stock, Forest monitoring.



Executive summary

This research dissertation is separated into sections which represent a series of scientific reports.

The first report, Section 1 presents a concept of a forest digital twin and is indeed the introduction to the research premise of socketed smart technologies such as IoT and sensors which in part drive a digital twin.

The second report Section 2 consists of two reports (A) and (B). (A) focuses on an application of an 'off the shelf Infrared Sensor' and characterises its function by as a radial dendrometer. It explores the strengths and weakness of the sensor, provides vigorous calibration and sensitivity analyses, finally providing a concrete physical comparison between commercial high precision D6 and static automatic D1 dendrometers manufactured by UMS.

(B) further develops the application of the IR sensor and demonstrates a functional IoT driven dendrometer network to monitor woody biomass for 2 consecutive years in a Coppice With Standards (CWS) managed forest in central Italy. It explores the success of the network; it's precision and accuracy and demonstrates how such networks can effectively be used to monitor changes in woody biomass and subsequent carbon stocks at highly granular scales. In addition, data captured challenge conventional methodologies regarding conversion of coppice forest to high forest.

The third report, section 3, aims to improve the concepts of IoT networked sensors and address the issues discovered from infrared sensor, with an 'overhaul' of the system and a new approach to the dendrometer itself. It presents a bottom, from the ground up, design and application of a linear magnetic driven encoder successfully demonstrating its functionality and furthermore showing an ability to effectively detect stem diel patterns with great effect.

This research dissertation follows the bellow Hypothesis, objectives and approaches with key findings presented.

Hypothesis: Integrating direct measurement sensors, such as dendrometers, with Internet of Things (IoT) technologies is essential for advancing forest research and management. This approach will complement traditional manual measurements and possibly enhance carbon monitoring methods, providing a more comprehensive and continuous dataset on tree stem increment changes with a caveat for monitoring carbon sequestration in quai real time.

Objective: This study aims to address the growing trend toward digital technologies and the role of advances in this field in forest monitoring, particularly for monitoring above-ground biomass (AGB) and associated carbon stock changes. The research combines the development, adaptation, and deployment of two novel IoT-driven dendrometers and evaluates their performance.

Additionally, the study includes a biannual monitoring campaign on a coppice forest in central Italy to present a proof of concept for a socketed network for AGB monitoring, thus establishing a system for real-time carbon monitoring.

Approach: This dissertation investigates advances in sensor and communication technologies to deliver comprehensive, data-driven insights into tree stem growth across space and time with high resolution. The research successfully demonstrates the use of a low-power, low-cost infrared proximity sensor adapted to measure changes in radial and diameter at breast heigh (*dbh*) increment as part of an IoT network. Furthermore, it validates the capability of using such sensors to assess standing above-ground biomass changes by applying species-specific allometric functions and sensor-driven data in a novel assessment of the carbon stock in a Coppice With Standards forest type in central Italy.

Additionally, to address the challenges presented by the infrared sensor, a linear magnetic-driven dendrometer was designed and deployed, exhibiting high precision and superior capability in measuring small changes in radial increment with greater accuracy. Seasonal dynamics in radial growth and fine scaled daily stem oscillation dynamics are also presented.

Key findings

Forest Digital Twin and IoT Integration:

The development of a forest digital twin heavily relies on the integration of socketed sensors and continuous data retrieval. Consequently, new approaches to dendrometers utilizing Internet of Things (IoT) technology are intrinsically linked to this concept.

Sensor Accuracy and Precision:

The adaptation of a low-cost, commercially available infrared proximity sensor accurately captured trends and variations in stem radial increment, maintaining precision within ±1mm compared to traditional diameter at breast height (DBH) measurements.

The development of a superior dendrometer utilizing state-of-the-art technology integrates principles of linear-driven movement and the Hall effect, which is renowned for its precision in detecting magnetic field variations. This innovative approach enhances measurement accuracy, enabling more reliable monitoring of tree growth dynamics and environmental responses.

Carbon Stock Dynamics:

Data obtained from dendrometers indicated dynamic changes in carbon stock within the above-ground biomass of an actively managed coppice with standards (CWS) forest, challenging conventional perspectives on converting coppice systems to high forest systems.

Development and Deployment of New Dendrometers:

The development of a ground-up dendrometer driven by a linear magnetic encoder was successfully deployed to capture high-resolution patterns in radial growth, with absolute changes in stem radial increment aligning closely with conventional measurement methods such as static D1 dendrometer bands.

The new dendrometer successfully detected daily stem oscillation dynamics and demonstrated a capacity to capture seasonal dynamics in stem growth patterns.

Real-Time Data Capture:

Using state-of-the-art wireless technology adapted for environmental monitoring has advanced forest monitoring. By leveraging Internet of Things (IoT) technology and the LoRa protocol, researchers can detect ecophysiological features at highly granular time scales, providing new insights into plant behavior.

Both types of dendrometers demonstrated effectiveness in capturing quasi-real-time data on stem growth patterns of various tree species, potentially impacting the accuracy of established methods for estimating above-ground biomass and subsequent changes in this section of a forest resource.

Digitization and Measurement Frequency:

Evidence suggests that the digitization of forest resources necessitates the use of affordable and socketed direct measurement sensors, such as dendrometers, which increase measurement frequency and provide quasi-real-time data on these resources.

Contributions:

1. Demonstration of the adaptation, development and successful development of a functional direct measurement dendrometers embedded as part of an *in situ* IoT network
2. Validation of new technologies for measuring stem radial increments via the internet of things technologies to derive high quality time series data at scale for stem increment dynamics.
3. Provides a nuanced understanding of forest digitization and the role of IoT and socketed network sensor systems in the context of forest digital twins.

Implications:

The findings of this study contribute to the understanding of internet of things (IoT) applications toward continuous measurement of tree radial increment and could revolutionize how forests are monitored and sampled. Simple cost effective IoT driven sensor networks could be placed in permanent forest inventory plots.

Conclusion:

This research underscores the role of IoT and sensors in the growing trend toward forest digitization specifically within the context forest monitoring and above ground biomass estimations. It demonstrates that cost effective dendrometers in networks can increase the measurement frequency and thus the precision of data throughout the vegetative season of individual trees. This finding could have implications for how above ground measurements are assessed both spatially and temporally including integration into already existing technological platforms such as those using in remote sensing.

Limitations and future research

This research highlights the promise of IoT-driven dendrometers for forest monitoring but acknowledges several limitations, including the study's focus on a specific Coppice with Standards forest, which may limit the generalizability of findings to other ecosystems. Additionally, the two-year monitoring period may not capture long-term variability in tree growth and carbon dynamics. Future research should expand sensor deployment across diverse forest types to validate findings, establish long-term monitoring initiatives, and enhance sensor design for improved accuracy. Integrating IoT technologies with remote sensing data and conducting cross-validation studies with traditional measurement methods will further refine above-ground biomass assessments. Ultimately, addressing these limitations and pursuing these research directions will deepen our understanding of forest dynamics and improve carbon monitoring practices.

Thesis Introduction

Advancing forest science through technological innovation.

Forest science has experienced significant advancements over the past three decades. Driven by innovation, integration of digital technologies has transformed the way researchers' study and manage forest resources. Indeed, trends in forest research emphasize a progressive tendency toward technological adoption and subsequent sophistication in research applications (Nitoslawski et al., 2021). Digital technologies represents a significant shift in forest science and is characterized by the systematic collection, analysis and application of vast amounts of data which may prove to be the most important development in forest research over the past three decades (Zhao et al., 2005). The systematic collection, integration, synthesis and application of digital information sourced from a variety of different technologies broadly includes, sensors, computing, communication, networking, storage and processing, software, programming, database, machine learning and artificial intelligence . In forest science digital technologies aim to observe and capture data on dynamic processes within the forest ecosystem at different temporal and spatial scales, digitizing them as format for post processing applications.

Remote sensing and earth observation

A considerably significant development in forest digital technologies over the past 2 decades is that of remote sensing and earth observation. The development and adoption of active and passive sensing capabilities deployed from ground to space level observations have led to sophisticated applications in forest ecology and management (Bergseng et al., 2015; Camarretta et al., 2020; Corte et al., 2020; Guo et al., 2022; Huang et al., 2011; Pu, 2021a; Quegan et al., 2019). Passive sensors specifically refer to optical sensors such as multispectral and hyperspectral sensors detecting light according to surface or object reflectance/absorbance. Active sensors, on the other hand, include LiDAR (Light Detection and Ranging, SAR (Synthetic Aperture Radar) and RADAR (Radio Detection and Ranging) to detect land surface characteristics by infrared and microwave single to multiple frequency point density clouds (Lechner et al., 2020). Scaling from wide resolutions in the order of klm^2 to narrow, down to $1cm^2$, these include observational tracking of forest carbon fluxes at global levels (Harris et al., 2021), the construction of a global reference system for forest biomass (Schepaschenko et al., 2019), measuring large scale above ground biomass from space based platforms (Quegan et al., 2019) and single tree species identification within forests at reasonably high precision (Pu, 2021).

To underscore the impact of remote sensing technology focused research in forest ecology and management, Scopus search retrieval demonstrates a prolific adoption of this technology in forest science research. According to the combinations "Remote Sensing" and "Forest Ecology" the engine yielded 42 entries with 5 review articles which equates to approximately 14 articles each year. If one changes the search query to "Forest Management" instead of "Forest Ecology, however, this significantly increases article yield to approximately 685 entries with 44 reviews totalling 729 articles which in turn equates to 243 annually from 2020 to 2023. The breadth of research addressing this technology in forest science alone is staggering, unequivocally supporting the analysis by (Nitoslawski et al., 2021). Although firmly established as a powerful technology, critical features includes resolution width, fly over or time of flight, signal or laser penetration under atmospheric disturbance, cost of services including expertise and considerably important, a specifically lack of adequate ground truthing integration (Chave et al., 2019). In addition, rarely do these technologies support real time of even semi real time capabilities. Furthermore, the sheer size in storage, processing and dissemination of information requires high computational volume and computational power for statistical analysis. Lastly, the impacts on precision and accuracy can sometimes be counterintuitive relative to the scales for which the sensors are designed and the studies they are intended to support, particularly in monitoring applications. Nevertheless, remote sensing technologies are significant and most certainly analogous with forest monitoring and forest research in general.

Terrestrial laser scanning (TLS) is another digital technology with significant recent input in forest science. Terrestrial laser scanning involves mounting a laser scanner on a tripod or another stable platform on the ground. The scanner emits rapid pulses of laser light that bounce off surfaces and return to the scanner. By measuring the time it takes for the laser pulses to return, along with the angle at which they were emitted, the scanner calculates precise distances to objects and surfaces in its line of sight (Calders et al., 2020). This process generates a dense point cloud—a collection of millions of points in 3D space—that accurately represents the scanned area's geometry. The geometry in forest science refers to the tree including all above ground components. It has been successfully used to assess seasonal variability in radial growth for boreal tree species (Yrttimaa et al., 2023), increase the precision and accuracy of stem taper functions (McTague & Weiskittel, 2021), to assess stem volume at individual tree scale (Saarinen et al., 2017) and used to assess local changes in above ground biomass and subsequent carbon sequestration (Demol et al., 2022). Criticism of TLS applications in forest science include the cost of the systems, their efficiency, lack of standardization for data post processing and significant expertise to both operate the system and perform post processing computations.

Direct measurement sensors

Direct measurement sensors are integral to advancing understanding of forest ecosystems through real-time data collection on key environmental parameters and biological processes. Dendrometers play a critical role by measuring tree diameter changes over time, offering insights into tree growth dynamics and responses to environmental conditions (Steppe et al., 2015). Sap flow sensors measure the rate of sap movement within a plant, typically within the xylem of a tree. Sap flow is an important physiological process as it transports water, nutrients, and hormones from the roots to the leaves. Understanding sap flow rates is crucial for studying plant water use, stress responses, and overall health (Asgharinia et al., 2022; Steppe et al., 2006). Soil moisture sensors monitor soil water content, essential for assessing water availability and hydrological processes critical for plant growth. TDR or time reflectance domain sensors (Mittelbach et al., 2012) and more recently cost effective capacitance sensors are most prolific (Kulmány et al., 2022). Temperature and humidity sensors contribute to studying microclimatic conditions and their effects on plant physiology (Matasov et al., 2020). Light sensors measure Photosynthetically Active Radiation (PAR), aiding in assessing light availability for photosynthesis in forest and canopies (Gitelson et al., 2021). Gas analyzers, including CO2 and O2 sensors, track gas concentrations to study carbon dynamics and ecosystem carbon sequestration (Baldocchi, 2020; Santonico et al., 2020). Acoustic sensors detect wildlife presence and assess biodiversity based on sound levels in forest environments (Sugai et al., 2019). Water quality sensors monitor parameters like pH and dissolved oxygen in water bodies, vital for evaluating aquatic ecosystem health. Radiation sensors measure solar and UV radiation, aiding in understanding energy dynamics and radiation impacts on forest ecosystems. Wind sensors provide data on wind speed and direction, essential for assessing microclimate conditions and their effects on tree growth and forest structure. Collectively, these sensors enable comprehensive monitoring of forest ecosystems. A fundamental innovation, the "internet of things" is enhancing how these sensors are collecting and sending data.

The Internet of Things (IoT) refers to a network of physical objects, "things", embedded with sensors, software, and other technologies that enable them to connect and exchange data with other devices and systems over the internet. These objects can range from everyday household items to sophisticated industrial tools and complex environmental monitoring systems (Ng & Wakenshaw, 2017; Ud Din et al., 2019). The integration of Internet of Things (IoT) technologies represents a transformative innovation in forest science. By embedding sensors and communication devices into forest ecosystems, IoT enables real-time monitoring of environmental parameters, tree health, and forest dynamics (Zeuss et al., 2024). This innovation not only enhances the efficiency and accuracy of data collection but also opens new avenues for understanding complex ecological processes and improving forest management practices. Indeed, the concept of Nature 4.0 is intrinsically linked to IoT. Nature 4.0 signifies an evolution in systems processes and functions characterized by the integration of digital technologies, automation, data exchange and smart technologies applied to our natural environment (Valentini et al., 2019). Recent research demonstrates a sophistication in natural science observation driven by direct measurement sensors connected to an Internet of things network (IoT). A successful demonstration of this concept is presented by (Zeuss et al., 2024), where a Nature 4.0 system integrating a variety of technologies is used to monitor a forest biological system including both flora and fauna. Sensing capabilities are supported by IoT and Cloud based infrastructure capturing large amounts of digital information on species patterns and behaviour at different temporal and spatial scales. This represents a true frontier in natural sciences and observation.

Collectively, the digital technologies as described above are shaping how data is collected and digitized resulting in a novel age of forest digitalization. Note that the above synthesis does not explore forest operations technologies, nor forest management driven applications.

Considering the recent innovations and application of the internet of things, a comprehensive literature search was conducted using the Scopus search engine to better appraise trends in forest digitalization and the application of internet if things. The initial search, employing the broad keyword combination "Internet of Things" and "Forest Management," yielded a surprisingly low quantity of peer-reviewed articles, with a total of 8 articles and 1 review article published between 2020 and 2023.

Anticipating the low yield from such a broad search definition, further refinements were applied using more specific keywords:

- a) "Forestry 4.0"
- b) "Digital Forestry"
- c) "Digital Forest Ecology"
- d) "Nature 4.0"

The results from these refined searches were as follows:

- "Forestry 4.0" generated 11 articles (2020-2023).
- "Digital Forestry" yielded 14 articles (2020-2023).
- "Digital Forest Ecology" resulted in 0 articles (2020-2023).
- "Nature 4.0" produced 1 article (2020-2023).

Narrowing the focus, additional key word search included "forest monitoring" resulting in the following:

- 4 articles based specifically on forest fire early detection
- 2 articles focusing on detecting illegal logging
- 1 article focusing on urban tree monitoring

The data suggest a growing interest in the intersection of forestry and advanced digital technologies, although the adoption and exploration of these concepts in scientific research remain in the nascent stages. These findings indicate a relatively limited but emerging body of literature in the domain of digital applications in forest science. Furthermore, it highlights specific areas where further research and publication efforts are necessary. For example, forest monitoring.

Data acquisition for forest monitoring traditionally involved field surveys before digital technologies emerged to compliment them. Physical measurement of plant traits and features focused on tree geometry, spatial distribution, structural characterization combined with statistics and probability. Forest monitoring, that is the process of regularly observing and assessing the status and health of forest ecosystems over time for ecological, conservation and management activities implies this explicitly. Efforts in forest monitoring before the turn of the 20th century were primarily economic centric, that is the collection of data on these resources considered resource optimization for economic gain and thus silvicultural interventions aimed at sustained yield or regular forest models prevailed (Nocentini et al., 2021). Recognizing that these systems neither as infinite simple systems, forest research addressing sustainability began to emerge as did theories of ecology and systems theory. As such collection of data on different components of the forest system rather than just the trees helped develop new methods for explaining population phenomena including forest succession and landscape change (Christensen, 1989) and pursuits for ecological sustainable silviculture (Larsen, 1995). Field surveys included in National Forest Inventories (NFI's) accepted methods for monitoring forest resources, with remerging discourse on data acquisition, dissemination and storage (Breidenbach et al., 2021; Kangas et al., 2019; Mäkinen et al., 2010). As is often the case, physical measurement of trees may be the most suitable option for lower socio-economic regions and perhaps more importantly as the primary ground truthing exercise available (Luoma et al., 2017). Additionally, physical survey methods are still very practical and as such endorsed by the IPCC on this premise (Ogle et al., 2019). For instance, allometric biomass equations or scaling methods such as Biomass Expansion Factors (BEF's) for stands and forests (Brown, 2002; Brown S., 1997). Therefore, the temporal detection of change in stem increment remains an important geometrical feature of a tree. Indeed, it's measurement not only allows the inference of the volume and biomass, it also provides data for several important assumptions within both the plant physiological and forest sciences respectively, including almost all forest models (Porté & Bartelink, 2002; Sileshi, 2014). The common feature in all forest science investigation is that of data acquisition from simple geometric measurements initially and more recently the collection of data on tree physiological behaviour. The rapid development of methods to acquire data on forests by sophisticated technological integration is remarkable and transformative. The future of forest monitoring is being shaped by digital tools in coactive union with some level of iterative feedback and continuity operating at differing spatial and temporal scales. Forest monitoring as the term implies requires frequency and coverage, that is to assess trends in forest resources at seasonal and inter seasonal level requires observations on systems behaviour. This is to some extent being fulfilled by remote sensing, however, finer scaled processes such as individual tree behaviour and the underlying ecophysiological drivers and response to their environment continue to offer opportunities.

The Treetalker platform

Combining concepts established in the Nature 4.0 discourse a relatively recent innovation the "Treetalker" is a platform integrating the IoT (Internet of Things) with individual tree scale sensing technology focused on capturing tree ecophysiological parameters in quasi real time. The devices function on IoT technologies including physical LoRa (long range - low frequency - low power physical layer) and communication protocols, LoRaWan (Network protocol-Unlicensed spectrum) and NB-IOT (Licensed spectrum) allowing the semi-autonomous collection of data on predefined variables including, stem radial growth, sap flow, light transmission under the canopy, gyroscopic movement of the tree stem, temperature and humidity. Both the older versions and the recent versions measure parameters at hourly intervals with data recorded as a digital number from each sensor sequentially. The TT versions 3.0-3.4 stored data in a 3 phase configuration by default and operate on LoRa. That is data is stored onboard the device, via the gateway (TTCloud) and on a 3rd party server. LoRa was originally selected as it was the most efficient technology in this space at the time. Its sub gigahertz (868Hz) frequency makes it more resilient to changes in signal strength. It offered and still offers free unlicensed access to cellular networks optimizing its communication parameters accordingly. As such it is advantageous when the cell signal is lost or patchy. A disadvantage of the technology however is the distance limitations between the gate way and the devices which significantly impacts research location and design.

Each sensor of the Treetalker+ has been meticulously calibrated under laboratory conditions providing the calibration functions translating the digital signals from numerical information to tree ecophysiological parameters as selected prior to sensor builds and established throughout plant and tree physiological sciences for the past 5 decades. As such dedicated data processing packages have been developed to interpret retrieved digital information (Tomelleri et al., 2022; Zorzi et al., 2021). Recent applications of the Treetalker devices include the continuous monitoring of stem water and sap flux density via its onboard sap flow sensor, yielding insights into individual tree hydraulic behaviour at daily scales and behavioural dependent on temperature and accurate heat waves at seasonal scales (Asgharinia et al., 2022), the temporal detection of phenological phenomena driving seasonal leaf out and decay via data retrieved from device spectrometers across Italy (Vaglio Laurin et al., 2024), a synthesis and application of the Treetalker for IoT monitoring of urban ecosystem services in Moscow describing each of the sensor capabilities (Matasov et al., 2020) and breakthroughs in plant and tree physiological research with the detection of bi model relationships between stem growth and sap flow facilitated by the high resolution monitoring of sap flow using the Treetalker (Niccoli et al., 2023). That is, a cost effective device measuring quasi real time ecophysiological functionality at individual tree scale.

The forest digital twin and sensor networks

An emerging and exciting possibility closely associated with IoT supported digital technologies is that of digital twins. Digital twins are already used in aviation and automotive industries where they are used to simulate stress responses and performance of engines and systems. Their inception into forest science research is yet to be completely realised. An essential feature of the twin are sensors (Buonocore et al., 2022). In a forest monitoring system, the role of novel technologies to collect data and monitor individuals in forests creating a systematic feedback loop(Jones et al., 2020), is a responsive forest digital twin. These concepts are not quite reality yet, however the trajectory toward such concepts becoming genuineness is most certainly approaching. In fact, the concept of individual data collection, the trees from the forest, has regained attention as sensor technologies have become more accessible and financially feasible. Networks of radial point dendrometers as deployed in countries like Switzerland are being linked to remote sensing technologies to assess radial increment phenology (Eitel et al., 2023). Similarly, sensor based approaches to monitor stem water and carbon in quasi real-time are emerging(Zeuss et al., 2024; Zweifel et al., 2021). Underlying these studies is the ability for big data to be captured, transferred and stored via wireless and IoT technologies. This revolution in communication protocol and technologies along with sensor miniaturization is driving an era of Big Data in forest science.

Carbon monitoring and the role of digital technologies

Combining the concepts of applied digital technologies, forest carbon monitoring is becoming more granular at both finer spatial and temporal scales. This is a key requirement for both scientific and commercial interest where changes in forest succession both man and naturally induced impact carbon stocks. A key research theme for forest science involves the correct assessment of live woody biomass and subsequent carbon stored and sequestered by plants across space and time. Carbon monitoring, sequestration, and the role of woody biomass from forests are pivotal in the global effort to combat climate change. Currently techniques for assessment vary according to available technologies, as described earlier remote sensing plays a predominant role (Harris et al., 2021). Despite these efforts, ground truthing and finer scaled changes to forest resources remain difficult to monitor in real time. Forests act as significant carbon sinks, absorbing carbon dioxide from the atmosphere and storing it in biomass, soil, and forest products. Monitoring these carbon stocks is crucial for understanding the health and effectiveness of forests in mitigating climate change. Accurate carbon monitoring helps track changes in carbon storage over time. Direct measurement sensors are essential tools in carbon monitoring and sequestration efforts. These sensors provide real-time data on carbon dioxide levels, biomass density, and forest growth, enabling more precise and accurate assessments of carbon stocks and flows. They allow for the continuous tracking of carbon sequestration in forests, improving our ability to manage and protect these critical carbon sinks. Moreover, direct measurement sensors enhance the accuracy of carbon credits and other market-based mechanisms, ensuring that carbon offset projects deliver genuine climate benefits. As climate change intensifies, the importance of these sensors in supporting effective forest management and carbon sequestration strategies cannot be overstated.

Research Gap

Despite a steady trajectory toward digitization and digitalization through applied technological adoption in forest science, research into network IoT sensors and their application is an emerging application. A key question is how sensors such as dendrometers can be used as to comprehensively integrate and scale high-resolution, real-time data in the forms of *in situ* sensor networks, networked to capture important dynamic processes such as changes in above above-ground biomass (AGB) and thus monitor carbon stock changes within this specific pool. Despite advances in sensor technologies and IoT, several challenges persist:

Limited Spatial and Temporal Coverage: Traditional manual measurements and remote sensing methods often lack the ability to provide continuous and finer scaled monitoring. This results in gaps in data that can hinder accurate assessment of forest dynamics and carbon sequestration.

Sensor Precision and Accuracy: While various sensors have been developed to measure tree stem increment, many struggle with precision and accuracy, particularly for small changes in radial increment. There is a need for more reliable and precise sensors that can operate effectively over long periods and in diverse environmental conditions.

Data Integration and Interpretation: Integrating data from multiple sources (e.g., manual measurements, remote sensing, and IoT-based sensors) remains a challenge. Developing methodologies to harmonize and interpret these data sets to provide a coherent and comprehensive understanding of forest biomass dynamics is an ongoing research need.

Proof of Concept and Practical Application: Demonstrating the practical application and effectiveness of IoT-based monitoring systems in forests such as Coppice With Standards (CWS) and geographical regions is necessary to validate their utility and scalability. More case studies and field trials are required to establish proof of concept for these advanced monitoring systems.

Objective of this research thesis

Objective	Description
1. Contribute to the Field of Forest Digitization and Digitalization	Publish findings and share methodologies to advance the field of forest monitoring and digitization. Provide recommendations for future research and practical applications of IoT-driven dendrometer networks in various forest types and regions.
2. Develop and Adapt Novel IoT-Driven Dendrometers	Adapt, design, and build two innovative types of dendrometers that integrate IoT technologies for continuous and precise measurement of tree stem radial increment. Ensure these sensors are low-cost, low-power, and capable of long-term deployment in various environmental conditions.
3. Evaluate Sensor Performances	Conduct laboratory and field tests to assess the accuracy, precision, and reliability of the developed dendrometers in measuring radial stem increment. Compare the performance of these IoT-driven sensors with traditional manual measurement methods.
4. Deploy and Monitor a Sensor Network in a Coppice With Standards Forest	Implement a biannual monitoring campaign in a coppice forest in central Italy to establish a proof of concept for a socketed network of IoT sensors. Collect and analyse high-resolution data on tree stem growth and above-ground biomass over time. Create a comprehensive dataset that provides a more detailed and continuous understanding of forest dynamics and carbon sequestration.
5. Assess Above-Ground Biomass and Carbon Stock Changes for a Coppice With Standards Silvicultural Approach	Utilize species-specific allometric functions and sensor-driven data to estimate changes in standing above-ground biomass. Assess the standing carbon stock between fast-growing coppice sprouts and second phase rotation mature (standards).
6. Address Technical Challenges and Enhance Sensor Capabilities	Identify and address any challenges encountered with the infrared proximity sensor, including issues related to accuracy and environmental interference. Design and deploy a linear magnetic-driven dendrometer to overcome these challenges and improve measurement precision.

Section 1

A Proposal for a Forest Digital Twin Framework and Its Perspectives.

Here we presented a conceptual framework for the development of a Forest Digital Twin (FDT), emphasizing the integration of IoT technologies, remote sensing, and advanced computational modeling to create a dynamic and high-resolution virtual representation of forest ecosystems. The core objective of the FDT is to facilitate real-time monitoring, predictive analysis, and enhanced decision-making processes in sustainable forest management by leveraging cutting-edge digital tools.

The study outlines key components of the FDT, including multi-scale data collection mechanisms that capture biotic and abiotic variables within forests. IoT sensors, such as dendrometers, sap flow meters, and environmental monitoring stations, provide high-frequency data streams that feed into machine learning models and simulation frameworks. Remote sensing technologies, including LiDAR and satellite imagery, complement ground-based sensors by offering macro-level insights into forest structure, biomass estimation, and landscape dynamics.

A notable aspect of the FDT framework is its integration with blockchain technology and smart contracts. By ensuring transparent and immutable data transactions, these technologies enhance trust in forest data management and provide new opportunities for carbon credit verification, certification of ecosystem services, and compliance monitoring for climate policies.

Relevance to IoT-Dedicated Sensor Development and Applications in My Research

This article opens new perspectives for my PhD research on IoT-dedicated sensor development and applications, particularly in the advancement of dendrometer-based monitoring. By demonstrating the feasibility of high-frequency data acquisition within an interconnected digital environment, we reinforce the potential of IoT-driven forest monitoring systems for capturing intra-annual and real-time growth dynamics. The FDT framework's emphasis on precision forestry and digital monitoring validates the application of dendrometers for detecting subtle variations in tree stem increment.

Furthermore, the integration of blockchain within the FDT model aligns with the need for robust Monitoring, Verification, and Reporting (MVR) systems in carbon sequestration studies. As my research focuses on leveraging IoT networks to quantify carbon fixation in Coppice with Standards (CwS) systems, the methodologies proposed in this study provide a crucial foundation for refining digital sensor applications, enhancing data security, and improving real-time analytics.

By addressing current challenges in data interoperability, system scalability, and multi-sensor fusion, this research lays the groundwork for future advancements in forest IoT networks. The concept of an FDT serves as an ideal model for my thesis, where the development of enhanced dendrometers and their integration within digital monitoring frameworks will contribute to a more accurate and reliable assessment of tree growth and carbon sequestration potential.

Section 2 (A)

Performance assessment of an Infrared distance Sensor as an IoT driven non-contact electronic dendrometer

Abstract

Sensors integrated to Internet of Things (IoT) platforms are emerging as novel systems for forest monitoring, merging advances in micro processing, established principles of plant ecophysiology and enhancing spatial representation at single tree level. Focusing on measurements of trees stem growth, we demonstrate a novel application of an IR distance sensor as a non-invasive and cost effective dendrometer based on the adaptation of a commercial IR sensor by Sharp, ® integrated into the TreeTalker ® IoT device. The objective of this study is to describe the dendrometer sensor and, test its the performance for the detection of fine (sub millimetric) changes in tree stem radius. We report results from the laboratory including sensor's calibration, precision, accuracy and resolution as well as sensitivity to temperature changes and targeted surface characteristics complemented by field trials aimed at the comparison of seasonal tree stem growth by different state of the art dendrometers.

Our results indicate that the tested IR sensor is not comprehensively suited for radial increment measurement at resolution below xx millimetres and perturbed by environmental factors interfering with their optical path. However, the continuous monitoring of seasonal tree stem growth yields temporally coherent patterns and relatively accurate results. We suggest some practical solutions and a brief protocol for sensors already in circulation.

Introduction

The dimensional detection of changes in the size of woody stems is a basic yet fundamental operation in the fields of forest sciences and plant biology to assess the biomass productivity of trees. Both simplistic and complex tools have been developed for this purpose and the instruments designed to measure tree or plant stem girth, radius, diameter and/or its circumference, are collectively termed dendrometers (Clark et al., 2000; De Belder, 2015; Drew & Downes, 2009). Among the dendrometers types, we first limit our focus on the electronic ones, which are supplied with an electric current and designed to detect changes in stem increment autonomously or semi autonomously at considerably high spatial and temporal resolutions (e.g. <15 minute measurement resolution and in the order of microns) (Downes et al., 1999; Steppe et al., 2006, 2015; Zweifel et al., 2006). It is worth noting that these instruments have been in development and application since the 60's (Dobbs, 1969), (Pook et al., 1977) and as such differ in accuracy, precision, cost, operational simplicity, and sturdiness. Despite their history, two electronic systems prevail across plant and forest science respectively. Firstly, electronic point and band dendrometers, using linear potentiometers predominantly and secondly, LVDT sensor or Linear Variable Displacement Transducers. Both measure linear movement and displacement, thus suited to measure diametric changes of a tree stem cross section. Successful deployment of such devices includes the assessment of small daily fluctuations in stem diameter related to water transport (Zweifel et al., 2006), stem growth patterns from daily to seasonal and multiannual scales (Steppe et al., 2015) drought or hydraulic stress impacts on tree growth (Downes et al., 1999) timing and duration of wood formation in combination with data on xylogenesis (Cruz-García et al., 2019) and anisotropic radial growth in temperate conifers (Sellier & Ségura, 2020). The mechatronics behind the linear potentiometer dendrometers is based on a resistor with a sliding or rotating contact that forms an adjustable output voltage divider. Secondly, LVDT sensor or Linear Variable Displacement Transducers, which measure linear displacement or position by way of an induced voltage response created by the ferromagnetic characteristic of a metal core inserted between primary and secondary coils, the former feed with an AC current and the latter oppositely wound in different directions (Jefriyanto et al., 2020). Both systems boast high resolution measurement features with limitations predominantly associated with cost, sturdiness and temperature impacts over time i.e. wear and tear, component or device replacement and noisy sensor responses. Until recently these devices were unable to transmit data wirelessly, thus they required a connection to a datalogger and field visits to download the data. However, the recent integration of these instruments with wireless technology (e.g LoRaWan, GPRS) transmission capabilities has made the instrumental set up in the field and data management easier and more flexible. (Zweifel et al., 2021). Irrespective, many dendrometers maintain the previously stated technological approaches and innovation in this field has been relatively stagnant. This may be attributed to applied research specifically rather than operational or commercial applications, technical application specificity including (Henry et al., 2015) operational expertise and relatively high device cost (Clark et al., 2000) which in combination restrict mass deployment and contribute to lack of commercialization. Consequently, most large-scale single tree forest monitoring campaigns, such as those in permanent (Luoma et al., 2017) plots e.g. measured periodically for national forest inventories, continue to be limited to periodic manual measurements dendrometers, that consist in either tapes or bands with graduated scales measuring trunks circumference or callipers measuring directly the trunks diameter at 1.3 m height from the ground (breast height standard), (Luoma et al., 2017) (Wilson et al., 2007). Returning to communication protocol innovation and application, Internet of Things (IoT) technology offers promising and cost feasible solutions for practical individual tree monitoring using novel point dendrometers. Connections between devices, such as smart watches, housing appliances and machinery, processes, and infrastructure via the internet is steadily revolutionizing industry and business. These advances, accordingly, have migrated over to natural and environmental sciences (Asgharinia et al., 2022), and combined with cheaper options for PCB based micro processing platforms give rise to affordable multi sensor or socketed platforms such as the "Treetalker" ® (Valentini et al., 2019). This device is a semi-autonomous platform harnessing Internet of Things (IoT) technology to deliver meaningful information derived from individual trees by a set of nested sensors allowing real-time access to tree physiological and eco-physiological monitoring. Included in this system is an IR sensor for the applied purpose of measuring stem radial increment changes. Real-time measurement and sequential data transition is rarely supported at low cost for dendrometry sensors and as far as we are aware, this is the first time such a sensor has been used in this method to detect radial stem increment measurement.

We investigate the modification and application of an off the shelf infrared proximity integrated into (©SHARP Corporation, 2006) the TreeTalker system as a novel dendrometer sensor for the detection of trees' stem radial stem increment. The specific objectives of this study are:

a.) The characterization of a cost-effective infrared proximity sensor signal response by laboratory trials b.) The description of the sensor adaptation for field placement on tree trunks c.) The performance evaluation under field conditions and comparison of tree radial growth measurements throughout a growing season against independent measurements by commercial dendrometers d.) The development of best practices and recommendations for the improving data quality in the use of such a sensor as a dendrometer.

Materials and Method

Sharp GP2Y0A series distance sensors

The GP2Y0A sensor series by SHARP ® are low cost infrared distance measuring instruments, also used as proximity sensors. All sensors in this series are characterized by an integrated combination of an IR-LED (light emitting diode), a PSD (position sensitive detector), and a signal processing circuit. These sensors function on the principle of triangulation whereby pulses of infrared light are emitted by the LED toward a targeted object with the subsequent detection of a returning beam through the signal processing circuit that identifies the optical spot on the PSD (fig . 1). From this sensor series, the GP2Y0A51SK0F (©SHARP Corporation, 2006)was selected in particular for its distance (20-150 mm) and operating temperature ranges (-10 to +60°C) specifications (Electronics, n.d.), making it suitable for outdoor use as a dendrometer.

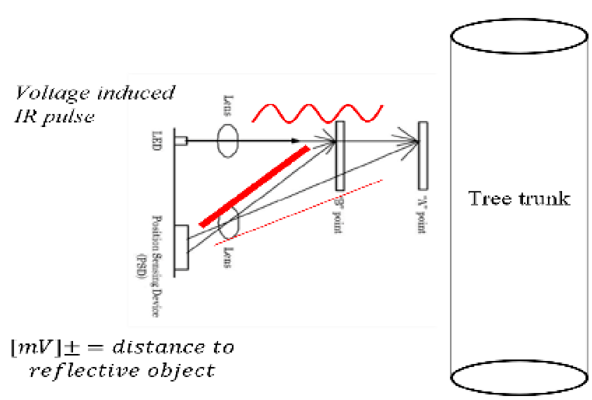


Figure 1: Basic functional principle of Infrared sensor when placed perpendicular to tree stem.

Laboratory tests: sensor characterization

The following section outlines the methodological procedures applied for assessing the performance of the Sharp sensor with particular focus on the following aspects: a) sensor calibration; b) signal precision and sensitivity, c) target surface sensitivity

Calibration

For the purpose of analysing the response curve of the sensor and its representation in analytical form by means of a calibration equation, a digital caliper with a resolution and accuracy of 0.01 mm and ±0.03 mm respectively and a measuring range of 0-150 mm was used. The Sharp sensor and a plastic flat nonluminous target surface were attached to the opposing forks of the caliper in such a way that the vertical axis of the sensor was parallel to the target surface, a controlled aspect by bringing the target surface into contact with the sensor and verifying perfect collimation while setting to zero the callipers distance reading. The initial calibration tests of the Sharp were conducted with the sensor directly connected to the analog port of an Arduino Pro Mini board (Arduino, Italy). The Arduino IDE environment was used to read the sensor output via serial transmission to a PC after the signal was converted to a 17 bit digital. The distance ranges from 0 to 5 cm between the sensor and the target, considered suitable for dendrometry applications, was covered in 1 mm step increments whereas the 5-9 cm range in 5mm steps collecting at least 20 replicates for each measured distance (fig. 2).

Additional tests were performed in the ranges of 1.5-1.6 cm distance with measurements taken at 0.05 mm step (n=30 per step) to verify the fine scale response of the sensor. The first tests on the Sharp sensor aimed at characterizing its response pattern against distance and verifying it against the technical specifications provided by the manufacturer. At a second stage the same tests were repeated with the Sharp sensor connected to a TreeTalker (Nature 4.0, Italy) device (model TT + 3.2 with TT + 5.0e embedded firmware). This second set of calibration tests were aimed at verifying the consistency of the output response provided by the Treetalker device compared with that emerged from the previous tests based on the sensor's analog output direct reading. Furthermore, being repeated with different Sharp sensors connected to the TT+ platform, this second batch of tests allowed to verify the inter-variability in the response across sensors of the same type. The acquisition of distance data from the Sharp connected to a TreeTalker took place with the device operating in test mode, having an output frequency of approximately 1 reading every 75 seconds, collecting not less than 10 measurements for each distance and it was limited to the distance range between 0 and 5 cm with 1 mm step increments. Distance values greater than 5 cm, for which the installation of the Sharp on the tree trunk is in any case impractical, were not considered since the sensitivity of the sensor decreases below acceptable levels for the intended use, as both shown by the sensor data sheet (©SHARP Corporation, 2006) and confirmed by the results of initial laboratory tests

The response function relating known distances to the sensor output was obtained by fitting the data points by means of the nonlinear estimation tool of the STATISTICA 14.0.1.25 software (TIBCO Software Inc., USA) and verifying their normal distribution of the model's residual by a Kolmogorov-Smirnov test included in the distribution fitting tool. The selected calibration model for the distance range of interest was of rational type:

$$D = y0 + a * x/b + x \qquad \text{(eq.1)}$$

where D is the distance to the target in cm, y0, a and b a model parameters and x is the Sharp sensor output, which can be either in millivolts (mV) or in digital number (DN); for TreeTalker models starting from TT3.2, these two output forms can be interconverted as follows:

$$Sharp\ OutputmV = Sharp\ Output\ DN/217 * 3300 \qquad \text{(eq.2)}$$

Sensor precision, sensitivity and resolution

Recalling that precision indicates the spread of different instrumental readings of a given distance, the Sharp sensor precision was assessed by the standard deviation of the sensor output at each targeted distance during the calibration tests.

The sensitivity of the sensor is defined as an output voltage change for a given change in the input parameter, that is the slope of the output characteristic response curve [ref]; for the Sharp sensor this was calculated as the change in the measured distance change (d) per unit of voltage output (V) change according to:

$$Sensor\ sensitivity = \Delta d/\Delta V \qquad \text{(eq.3)}$$

where Δd=1 mm an ΔV is the corresponding raw signal change during calibration tests. Resolution refers to the smallest change that a sensor can detect in the quantity it is measuring, and this was assessed as the change in the measured distance per digital number output unit.

Temperature sensitivity analysis

In order to assess the effect of temperature variations on the digital distance measurements the Sharp sensor connected to a TT+3.2 was fixed solidly to a wooden target at a given distance (3.6

cm) in a climatic cell and exposed to temperature variation between 0°C and 40°C with temperature step changes of 5°C every 20 min.

Influence of target surface features

In addition to the artificial target surfaces used in sensor calibration, a series of experiments focusing on potential variability related to different types of tree barks are considered here. Specifically, the irregular nature of different tree bark of selected species commonly found in European forests. are presented: Turkey oak (*Quercus cerris L.*), European beech (*Fagus sylvatica L.*), Scots pine (*Pinus sylvestris L.*), Aleppo pine (*Pinus halepensis Mill.*) and common ash (*Fraxinus excelsior L.*). Although there is a finite number of species from which to select bark specimens, they are far too numerous and impractical to sample all. Apart from their geographical representativeness, the chosen bark specimens attempt to categorically reflect smooth, moderately rough, and rough bark surface characteristics.

For each bark specimen, two samples cut at dimensions of approximately 40mm length and 20mm width were clipped on one of the forks of a digital caliper. These dimensions allow a large enough target surface area to sufficiently allow sensor operation. The IR sensor was activated via a tailored firmware uploaded to a TT+3.2 platform and designed specifically to increase measurement frequency, with measurements taken every 3 seconds and the average of 3 IR pulses at 3 seconds recorded. That is, the IR sensor shot at the target every 3 seconds in multiples of three pulses with mean of the triplet computed. The sensor was moved in increments of 5 mm, registering a total n=100 points at each distance across a linear distance range of 15-50mm for each bark sample.

After raw data conversion to distance mm through the calibration function, the observed versus caliper based distance readings were analysed first by linear regression to assess the linearity of the relationships and the deviation from the ideal 1:1 response and then by ANCOVA to test the difference in signal response among surface type specimens.

Sensor adaptation for field use and stem radial growth monitoring

The Sharp sensor can be used to measure the radial stem growth of woody plants by placing it at a recommended distance of 2 to 5 cm from the bark, facing perpendicular to the stem and at a customary height of 1.3 m from the ground; the sensor is kept in position by means of two round carbon fibre rods of 3mm diameter drilled into the stem, firmly embedded into the xylem, and kept in place by epoxy glue. In this way, the position of the Sharp relative to the vertical axis of the plant remains in principle unchanged, whereas the radial growth of the stem is therefore obtained from the progressive reduction of the sensor-stem distance which depends solely on the growth of the cambium tissue of the stem in its outermost portion.

A TT+3.2 connected to an IR Sharp sensor was installed at breast height (1.3m) on a spruce specimen to monitor its seasonal growth, in the forest site of Lavarone (45.956 N, 11.281 E) located in the northeastern Italian Alps in April 2022. Accompanying the Sharp sensor for intercomparison purposes, was a D1 automated mechanical dendrometer band and a D6 Strain-gage clip-sensor (UMS, Germany) (Mendis et al., 2000; Naleppa, 2010) installed at almost the same height along the trunk. It is necessary to premise that whereas the IR Sharp sensor detects the radial increase of the trunk in a point-like manner and therefore dependent on the installation position on the stem, the D1 dendrometer band and Strain-gage clip-sensor D6 sensor detect variations in circumference from which the radial increase is inferred by assuming a circular shape of the cross section of the stem itself and uniform growths in a radial direction. Therefore, the chosen tree, a white fir (*Abies alba Mill.*) with stem diameter of 60.5 cm at 1.3 m from the ground, was selected among the specimens with the most regular stem conformation. The stem diameter measured along 4 different directions spaced off by 45 degrees deviated indeed within only ± 1.6% from the mean (std.dev: 0.7 cm). Stem radial growth measurements were obtained dividing circumference growth from dendrometric belts by a 2π factor. In order to remove the numerous spikes in the distance readings (fig. 3) only the data falling within the interquartile (IQR) range calculated over a 7 days moving window were kept. The IQR upper and lower thresholds were calculated as:

$$D\_IQR\_25(i) > \; prc0.25(\, D(i-k/2), D(i-k/2+1), \ldots D(i+k/2-1))$$

$$D\_IQR\_75(i) < \; prc0.75(\, D(i-k/2), D(i-k/2+1), \ldots D(i+k/2-1))$$

Where k=24*7=168 is the moving window size, prc0.25 and prc0.75, the 25th and 75th percentile of the data in the window. The resulting filtered data will extend from the observations time series index i=k/2+1 till i=n-k/2+1.

Then a continuous time series was obtained by applying a rolling median to the filtered data series

$$DM(i) = \; median\; (\, D(i-k/2), D(i-k/2+1), \ldots D(i+k/2-1))$$

Finally the tree stem growth (TSG) was retrieved as the difference between distance measurements at a given time and the initial distance a time 0:

$$TSG(t) = DM(t) - DM(t0)$$

Nonetheless, there is almost always an obvious discrepancy between the theoretical conditions described above and the real variability of the radial growths along the circumference. This is applicable for all dendrometer instruments method in addition to measurement errors associated with repeated measurements done by hand (Binot et al., 1995; Moran & Williams, 2002; Wilson et al., 2007). Consequently, in making the comparison between the applied techniques it is necessary to keep these aspects in mind and not to ascribe any differences found exclusively to instrumental errors.

Results

Sensor response pattern and calibration

The response of the Sharp sensor with respect to the distance to the target is presented as an asymmetric bell-shaped curve with an absolute maximum value at a distance of about 1.1 cm and three distinctive features:

• distance (0-0.8 cm): although this range presents the highest sensor resolution values (fig. 2), it cannot in fact be conveniently exploited for measurements through the retrieval of a precise calibration equation given that tests on separate sensors have shown the presence of a local maximum located at about 0.5 cm, in addition to a variable intercept value (null target distance = 0). Secondly the short distance range of only 8 mm does not allow the exploitability of the space between a tree trunk and the sensor for long monitoring periods (e.g. multi-annual stem radial growth).

• distance (0.8-1.5 cm): this interval includes the maximum value of the response curve and is therefore characterized by the lowest resolution values (down to about 1 mm / mV, fig. 4).

• distance> 1.5 cm: this region of the curve appears as a decreasing monotone and, considering the application purposes of the sensor, has the most suitable characteristics for parameterizing a high-precision calibration equation.

Overall, the results indicate a generic agreement regarding the shape of the curve reported in the technical specifications of the instrument (fig. 2), and also a good correspondence regarding the positioning of the peak, however the experimental data for distances greater than 1.5 cm differ significantly from the data reported in the Sharp GP2Y0A51SK0F technical specifications for the purpose of using the latter to obtain a calibration function, confirming the need to produce a customized calibration by laboratory tests.

The parameterization of the calibration equations was performed considering the distance data range between 1.5 and 5 cm, both for the progressive decrease of the resolution response sensitivity of the sensor at increasing distances and because it corresponds to the most suitable solution for installing the sensor on the tree trunk of trees given the length of the support rods. Indeed, note that an available range of 3.5 cm is also sufficient to measure the multi-year stem radial growth of even the most productive tree species (Loccosselli et al. 2020).

The repetition of distance measurements with the same sensor (TT3.2 test 1, test 2, fig. 2) showed the high level of reproducibility of the results, moreover, linked to the sensor precision further presented. The comparison of the response curve in the 1.5-5 cm interval between different devices of the same TT3.2 series has however shown average differences ($\Delta = 2.13$ mm), which make the curves not superimposable (fig. 2). In this regard, it is interesting to note that the experimental points obtained with Arduino MiniPro, originally used to derive a sensor calibration equation, are very close to one of the two series of tests with the TT3.2 (Δ = 0.81 mm).

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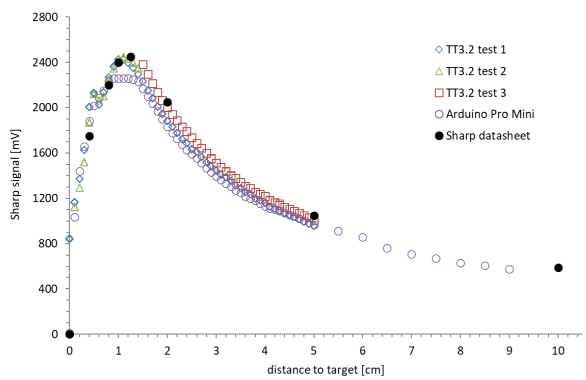

Figure 2: Sharp sensor output response curve to varying target distance. Intercomparison of tests performed on a sensor connected to a TT+3.2 device (1-3) and using an Arduino Pro Mini board. Response extracted from the instrument datasheet provided as reference.

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In light of the fact that the distance response curves obtained using both recent and previous test data maintain a common pattern denoted by the similarity in the tangents to the curves; despite being slightly shifted, we opted to retrieve a calibration function based on the 3 pooled sets of experimental data, so as to have greater general validity (fig. 3). When considering the single tests' datasets, the deviation in the slopes of the linear relation between observed and modelled distances using this general calibration equation was within 2.7% (fig. 2), that is the percentage error in estimating the distance variation. The calibration equation was of rational type and were parameterized both in the case in which the output data of the Sharp sensor are dimensionally expressed in millivolts [table 1], and in the case they correspond to the dimensionless values given by the ADC (Analog Digital Converter), as well as directly obtained from the data strings transmitted by the TreeTalker [table 1S]. These parameterizations can be used in an absolutely equivalent way, as explained below, only for TreeTalker models starting from TT+3.2.

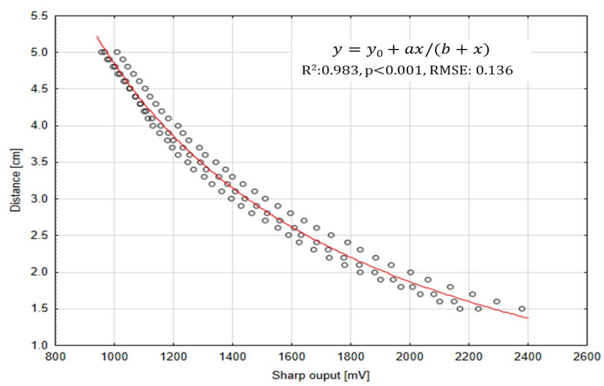


Figure 3: calibration function fitted (red line) to the sensor response data (black circles) in the distance range between 1.5 and 5 cm.

*Table 1: calibration function parameters statistics. Regression model: y=y0+(a*x)/(b+x). Fitted by Levenberg Marquardt estimation method and least squares (LS) minimization. (n=108, R2= 0.98273131, R =0.99132806).*

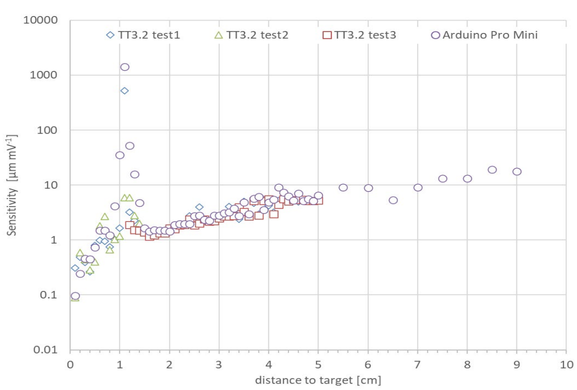
Parameter	**Mean**	**Standard error**	**t-value** (df=105)	**p-value**
y0	24.8272	6.3163	3.93065	0.0001
a	-26.9287	5.9396	-4.53372	0
b	342.8803	130.7297	2.62282	0.01

Sharp output sensitivity, precision, and resolution

The Sharp output sensitivity was between 1.2 and 6.1 µm mV-1 in the 1.5-5 cm distance range (fig. 4). When the raw output in digital number [DN] is used, the resulting sensitivity becomes finer by a factor 39.7 according to eq.2 (0.03-0.15 µm DN-1) and corresponds basically to the theoretical resolution of the sensor.

Nevertheless, when the Sharp output was checked against distance variations applying small step increments (0.05 mm) it featured a discrete stair like response pattern, making possible to gain insight on the real resolution of the sensor, which was about 200 microns a distance of 15mm from the target.

The Sharp output standard deviation was on average equal to only 0.25 mV corresponding to a precision of 0.25-1.3 µm and in any case never greater than 1.5mV in the whole range of distances between 0.6 and 5 cm (fig. 5). The results of the tests carried out with the Sharp sensor connected to a TT3.2 have fully confirmed what has already been observed for the Sharp reader connected to an Arduino MiniPro platform. For distances up to 0.5 cm, the voltage output variability of the readings occasionally resulted in significantly higher values, but still lower than 4mV, with both data acquisition platforms, still corresponding to a high precision of 0.4-3.2µm once accounting for the signal resolution in that distance range. Overall the Sharp output was characterized by a high degree of precision considering that the signal variability was on average 0.02% and always contained within the 0.08% of the signal mean throughout the distance range exploited in applying the Sharp for tree radial growth measurements.



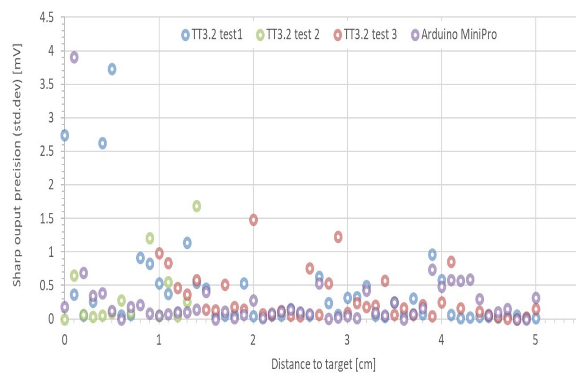


Figure 4: Sharp sensor sensitivity *Figure 5: Sensor output precision: standard deviation of measurements (n=20 Arduino Pro Mini; n=10 TT3.2).*

IR sensor temperature sensitivity

The temperature sensitivity of the Sharp sensor measurements was about 30 µm/°C as shown in agreement by both the devices used in the climatic cell experiment over the temperature range between 0 and 45°C (fig. 6)

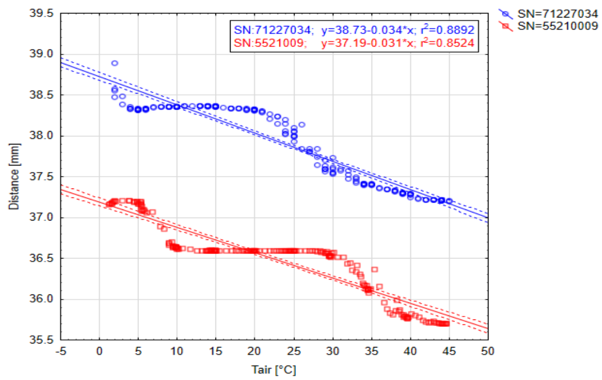


Figure 6: temperature sensitivity tests of two distinct TT3.2 devices.

Influence of target surface features

Linear regression results demonstrate a strong correlation between calibration predicted and actual distance values, (R2 >0.99, p<0.05), across all target samples. RMSE values of the different linear models varied between 0.246 and 0.893 mm equating to an averaged RMSE of 0.648mm.

The application of a ANCOVA (Table 2) controlling for physical distance, and focused primarily on the variation caused by the target (fig.7), revealed a significant difference in the variation of calibration predicted vs actual distances among target surface types (p_value <0.001). Both the Target and Physical distance to target (PhysDist(mm)) variables significantly contribute to explaining the variance sensor readings, with PhysDist(mm) having a particularly strong effect. These results highlight that target surface does not entirely explain the variance in the IR response. (§3.1).

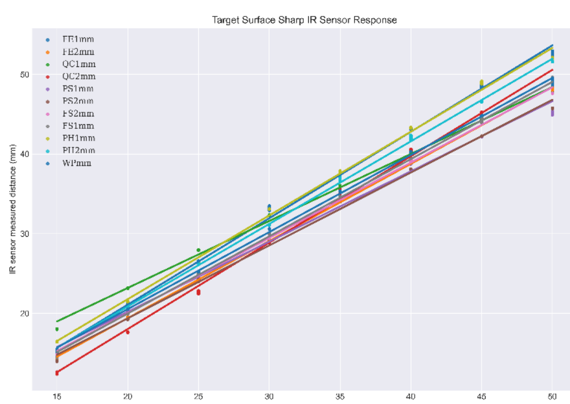


Figure 7: Comparison of distance readings by Sharp against actual distance measured by caliper with different target surface types. (FE: Fraxinus excelsior; QC: Quercus cerris; PS: Pinus sylvestris; FS: Fagus sylvatica; PH: Pinus halepensis; WP: White plastic).

Table 2: results of ANCOVA to test the "Target" effect on the relation between distance measured by Sharp sensor and independent measurements ("PhysDist")

Variable	*SS*	*Df*	*F*	*P-unc*	*np2*
0 Target	16404.1858	10	1500.198	0	0.6306
1 PhysDist(mm)	1102710.82	1	1008452.95	0	0.99136
2 Residual	9609.395	8788			

Table 3: Slope (mean, standard error) and goodness of fit (R-squared, Root mean squared error) of the linear regression model between measured and observed distances using different target surface types. (FE: Fraxinus excelsior; QC: Quercus cerris; PS: Pinus sylvestris; FS: Fagus sylvatica; PH: Pinus halepensis; WP: White plastic).

Sample	**Slope**	**R2**	**RMSE**	**SE**
FE1mm	1.0848	0.9974	0.6596	0.0044
FE2mm	0.9683	0.9995	0.2495	0.0017
QC1mm	0.8411	0.9964	0.5966	0.004
QC2mm	1.0861	0.997	0.6999	0.0047
PS1mm	0.8825	0.9925	0.9081	0.0061
PS2mm	0.9152	0.9966	0.6334	0.0043
FS1mm	0.9696	0.9989	0.3753	0.0025
FS2mm	0.9456	0.9986	0.4243	0.0029
PH1mm	1.0526	0.9964	0.7404	0.005
PH2mm	1.0369	0.9995	0.2846	0.0019
WPmm	0.9676	0.9989	0.3882	0.0026

IR sensor performance applied to tree stem growth monitoring

The Sharp tree stem radial growth pattern returned by the Sharp sensor was in good agreement with the independently observed seasonal growth phases by D1 and D6 dendrometers and it was able to capture the seasonal variations in growth intensity with a stronger increments between Doy 140 and 180 followed by late summer stem growth cessation (fig.8)

As regards the accuracy the stem radial increments measured with the Sharp sensor revealed mean daily deviations against the D6 band dendrometer of 0.09 mm (min: -0.28; fax:1.00 mm) with a more frequent tendency to overestimate (fig. 8). By reference the mean daily mismatch between the D1 and D6 dendrometers was 0.01 mm (min: -0.16; max 0.20 mm).

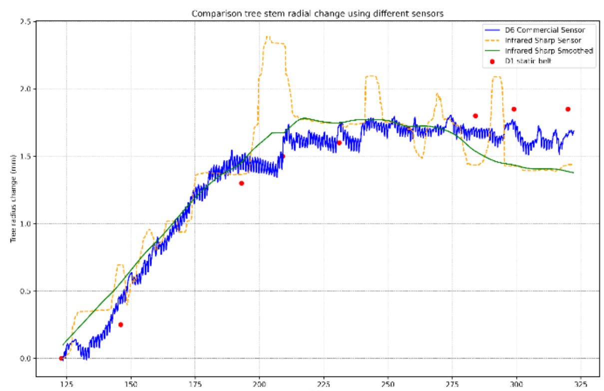


Figure 8: Tree stem radial growth (TSG) (daily means) measured continuously by D6 dendrometer band, Sharp sensor connected to TT3.2 and periodic manual readings of a D1 dendrometer band.

Discussion

Sensor response pattern and calibration

The tests confirmed the response pattern of the Sharp sensor provided by the manufacturer, although more numerous experimental points were needed to retrieve a calibration function, based on distance range 1.5-5 mm reckoned optimal for the exploitation of the sensor as a dendrometer. Differences in the measured distances emerged during the calibration trials on different devices is reflected in the calibration function having a RMSE of 1.3 mm. Nevertheless, the use of the sensor was not aimed at retrieving accurate distance measurements per se but rather distance variations over time in the application as a dendrometer. Since the response pattern across different tests was similar, the use of a calibration equation regressed from all the different datasets appeared sensible, which was confirmed by the small divergence in the predicted vs observed distance changes of less than 3% using a flat plastic target. Although it has been observed in proximity sensors prior that errors at larger distances are magnified by sensitivity (Konolige et al., 2008), we did not find a worse match of experimental points with the prediction by calibration possibly due to the narrow operational distance range.

Sharp output precision sensitivity and resolution

The sharp signal was extremely stable in lab trials and characterized by a high sensitivity and high resolution when considering its end use as a dendrometer. Results were consistent using the Sharp sensor connected to TT+ devices and an Arduino board. However, when analysing the sensor output response at finer scale, with caliper increments of 50 microns, then distance variations were not smooth but revealed a discrete step-like pattern which constitutes the real resolution limit of the sensor and that is in the order of 250 microns (at a target distance of about 15 mm).

Such feature depends on the PSD which in fact limits the performance of the sensor in measuring small distance variations and restricts its suggested use to detect tree radial growth over periods from several weeks to the whole growing season on tree species with an expected annual tree ring growth of at least 1 mm. Such a value makes the sensor suitable for monitoring the growth rate of the most common tree species in Europe (Schelhaas, 2008; Schmucker et al., 2023; Strieder & Vospernik, 2021) excluding old growth specimen or trees limited in their growth by harsh environmental conditions (alpine tree line, high latitudes, dry Mediterranean areas).

On the other extreme, the specific distance range of 3.5 cm (from 1.5 to 5 cm from the target) for which the performance of the sensor is best and the calibration equation was based on, limits its use for multi-year monitoring of diametric growth of extremely productive species in temperate climate (Criscuoli et al., 2022; Piotto et al., 2024) and most productive trees in the tropics (Groenendijk et al., 2014).

Temperature sensitivity

The Sharp sensor (model GP2Y0A51SK0F) has an operating temperature range between -10 and +60°C according to the specifications provided by the manufacturer. It is known that PSDs suffer from systematic position sensing errors particularly at high temperatures, limiting the possible application fields for usage of PSDs (Brunner et al., 2019). The observed shift in the measured distance along varying environmental temperature produced in a climatic cell was 0.03 mm/°C, a result based on the linear interpolation of a stair wise pattern, like what found in our study when investigating closely the sensor response to small distance variations and confirmed in Yoo et al. (2019). Considering that a typical intra-annual air temperature regime in temperate climates is usually of some tens of degrees centigrade, it appears that measurements of small distance changes can be subject to considerable errors when temperature differences are not considered. For example, measurements collected at about 33°C of air temperature difference would lead to 1 mm shift in distance readings, that is likely the tree ring width of an old grown tree. For this reason, the use of the sensor as a dendrometer would be most accurate when calculating radial growth as the difference of points collected under similar environmental conditions in terms of temperature such as seasonal growth based on spring and autumn data. A temperature correction is possible, yet the linear fit (fig. 6) can't interpolate very successfully the peculiar stair wise data pattern (R2:0.85-0.89, MAE:0.144-0.147 mm).

Target type response

The impact of different types of target surfaces, either artificial or natural represented by different tree bark types did not have a statistically significant effect on the relation between independent distance observations and calibrated measurements by the Sharp sensor, confirming the suitability of the calibration function for the application of the sensor as a dendrometer. Nevertheless, smaller prediction errors (RMSE) and slope deviation from the 1:1 relationship (table 3) were observed for smooth bark types (beech), being comparable to white flat plastic target, contrary to more rough and corrugated bark types (Turkey oak, pine species and ash).

Performance as a dendrometer applied to tree stem radial growth monitoring and recommendations for field use

The application of a fixed in place optical infrared sensor to measure stem incremental changes is novel. Its lack of application in the field of forest and plant science prior, is most likely associated with described sensor limitations in outdoor environments (Zielinski, 2021). We were successful in demonstrating a reasonable functioning of the sensor over a full growing season. Indeed, the stem radial growth series measured by the manual and automatic band dendrometers (D1 and D6), were coherent with the IR Sharp sensor and featured a relatively small mean error (90 µm), despite tenfold as larger local deviations. The magnitude of observed fluctuations in the Sharp sensor signal makes them not compatible with stem diametric changes associated with sap flow and wood hydration status (Drew & Downes, 2009; Steppe et al., 2015; Zweifel et al., 2006a). Nevertheless, the overall performance is appreciable, considering the small cost of the Sharp sensor (about 10 US$) is between one and two orders of magnitude smaller than commercial digital dendrometers. Moreover, there is almost always an obvious discrepancy between the theoretical conditions of a perfectly circular stem cross section with uniform radial size and the real variability of the radial growths along the circumference, hindering the comparison between dendrometer measuring circumference changes (such as the D1 and D6) and point dendrometers, in addition to measurement errors associated with repeated measurements done by hand (Binot et al., 1995; Moran & Williams, 2002; Wilson et al., 2007). Consequently, in making the comparison between the applied techniques it is necessary to keep these aspects in mind and not to ascribe any differences found exclusively to instrumental errors.

The Sharp sensor output was characterized by large spikes: not shielding the sensor in the field exposes the LED and thus the infrared beam to a variety of environmental impacts which both disrupt the infrared beam and its respective detection via the PSD array. For example, ambient illumination (sunlight), which is known to interfere with infrared light propagation and reflection (Li, 1994; Sant et al., 2012) possibly contributes to observed large peaks and troughs present across the data set at varying temporal scales. Modulation should negate this to some extent, however, despite best attempts to mitigate ambient illumination e.g., sensor installation on the northern side of the tree stem and under heavy canopy cover, it is safe to assume that interplay between sensor and light occurred daily throughout the growing season, intensifying around the late spring and summer periods. This factor alone, however, is not singular in nature and is most likely a combination of several known factors which interfere with the optics of the sensor itself. For example, moisture condensation, dust settling on the sensor and optical sensor deformation from heat daily temperature gradients (Osadcuks et al., 2014). Modification and adaptation for bicycles of an infrared distance sensor from the same manufacturer and sensor (GYPA Sharp) series reports, vibration, sunlight and pollen, as significant factors for sensor accuracy reduction (Zielinski, 2021). Indeed, the period of pollination in the Alps is harmonious with observed large sensor oscillations from April through to July as described by (Cristofori et al., 2010) over 20 years of airborne pollen counts in the region where the sensor was installed.

IR distance sensor voltage responses to target angle tilt (Nozaki & Krebs, 2022) while irregular target surface and materials (Li, 1994) and colour (Hrubý et al., 2022), although known to influence IR sensor stability, should not strictly limit the sensor for high precision detection of radial stem growth, which is generally in the order of microns to millimetres (Steppe et al., 2015; Zweifel et al., 2006a). However, placing the sensor uncovered in a forest setting and pointed toward a non-uniform surface may likely reduce the precision of the device output as reflected at higher temporal resolutions from the field trial. The position of such a sensor is ideally placed perpendicular to a flat non illustrious target which directly impacts both the angle of incidence and as such absorbance and reflectance of the LED beam changing the sensor precision accordingly.

Considering the above, possible improvements for this sensor in field applications, could be placing a small non illustrious target on the stem, acting as a target to focalize the LED IR beam and providing a target for which the beam is reflected at a perpendicular angle to the PSD. In addition, removing or limiting ambient illumination and dust/pollen via a modified shield could also prove helpful in stabilizing the sensor output signal.

Conclusion

The design and construction of new low-cost sensors for environmental monitoring has been greatly expanding in recent years fuelled by the new opportunities created by the Internet of Things technology, the sharing of open access research products and a thriving community of inventors representing the “maker” subculture. The sector of environmental research in the field of forestry however has been so far touched limitedly by this change despite the potential advantages the use of IoT low-cost sensors could bring in enhancing the forest monitoring capacity and extending its range.

We demonstrated the application of a low-cost commercial infrared optical sensor and its modification into a dendrometer for tree stem radial growth measurements with a resolution (<0.25 mm) compatible with the monitoring of seasonal growth of most tree species. After laboratory calibration, the sensor featured an error in distance change measurements within 3% and good precision but when deployed outdoor in forest environment, the output signal stability was impacted by the interference of environmental factors on the optical path, despite overall matching of tree stem growth pattern against established commercial dendrometers and a mean bias of 0.09 mm after data despiking. Although the dendrometer resolution is constrained by the technical features of the sensor, precluding its use for observations of small diametric changes of trees over short time periods, an enclosed design of the IR led optical path would allow continuous and noise unaffected data series for monitoring tree growth patterns from few weeks to multi-annual scales.

Section 1 (B)

Precision Monitoring in Coppice Forests: A Proof of Concept for IoT-Driven Dendrometry and Carbon Accumulation Assessment

Abstract
Coppicing forest management systems represent the oldest systematic silvicultural practice across the European continent. Although the extension of coppice forests is estimated at approximately 20 million hectares across Europe, they are often poorly utilized, undermanaged or altogether abandoned. Inadequate management, which often promotes over stocking on one hand and unregulated coppice sprout management inducing stool exhaustion on the other, threaten this historical management approach. A simplistic yet sustainable system, Coppice with Standards (CWS) is a well-defined silvicultural application which in general is designed to provide continuous cover forest with a commercial woody crop within a relatively short rotational period (Bessaad et al., 2021; Ferraz Filho et al., 2014). The relatively quick turnover of biomass in these systems through short rotation periods and retained mature stems across age classes present a dynamic above ground carbon pool. Consequently, novel monitoring efforts for these forest types and systems merits attention both in the context of silvicultural preservation and carbon accumulation in the above ground carbon biomass pool. As such, approaches to monitoring efforts using digital systems offers potentially new insight into stem growth and by proxy above ground biomass at higher temporal resolution. This study aims to present a sensor networked approach to monitor changes in individual above ground biomass (AGB) in quasi real time for a 2 year period. Data retrieved applies allometric functions to assess changes in standing carbon stocks between sprouts and standards. Additionally, we aim to demonstrate the performance of the sensor network

through the provision of a functional proof of concept consisting of 30 IoT driven dendrometers installed across two plots in a historically managed *Quercus Cerris L.* forest in central Italy. Results of a two year monitoring campaign suggest that the networked infrared sensor system effectively captured stem radial growth for 20 of the 30 installed devices with defective sensors excluded from analysis. Average stem radial growth varied both across sites, between years and among selected individuals. Sprouts on stools outperformed standards on average, with carbon stocks subsequently higher on the stools compared to standards for consecutive years. Validation of the sensor performance was demonstrated through comparison of between manual measurements using a dbh tape where a stinger correlation was observed in 2021 compared with 2022. The application of cost effective IoT based dendrometers offers new opportunities for forest monitoring and may be effective instruments for permanent plot monitoring within National Forest Inventories (NFI's) or MRV frameworks. Selection of sensors, rigorous calibration and device coverage warrants further investigation.

Introduction

Coppice forest management, rooted in social and historical contexts, dates to the neolithic age. Originating as a simple method, vegetative regeneration of stems on root stools offered an efficient and sustainable method for obtaining tools, fodder, building materials and perhaps more prolifically fuel in the form of charcoal (Slach et al., 2021). While once widespread as a practice across Europe, the systematic retention of coppice systems has faced challenges. The industrial revolution and transition from charcoal to fossil fuels (Müllerová et al., 2015), lower economic returns compared with high forest management practices (Bessaad et al., 2021) and a tendency toward conversion of coppice to high forest in general (Manetti et al., 2020) represent some of the challenges faced. As such these systems and indeed the silvicultural practice has seen a rapid decline since the 1600's. Recent research underscores a renewed focus on the traditional coppice forest management system. This silvicultural approach, celebrated for its multifunctional benefits, has gained attention for its ability to provide a diverse array of ecosystem services. The resurgence of interest in coppice management is exemplified by the 2018 COST Action EuroCoppice initiative, which highlights its potential for sustainable forest management and ecosystem service provision. The silviculture of coppice can be separated broadly into the following categories simple coppice (SC), pollarding, selective and coppice with standards (CWS). The latter is of particular focus in this study. The CWS is a silvicultural system in which 'standards' stems are retained at each harvest cycle of the spouts, thus promoting an uneven aged mosaic of even aged underwood and an uneven aged over story (Harmer & Howe, 2003). As (Buckley, 2020) notes, having numerous age classes at different vegetative stages provides multiple services, including wood production, soil protection and diverse structural mosaics key for flora and fauna. In addition to their biodiversity value, they provide protection for rock fall given in steep mountainous areas (Radtke et al., 2014) and in the coppice with standards systems, a form of continuous cover forestry. In working coppice forests, those in areas of higher site quality and productivity, coppice forests maintain their intrinsic economic value from firewood, structural products and more recently biofuels (Bacenetti et al., 2016). A less valued yet important service intrinsic to all forest resources is their carbon sequestration, fixation and accumulation. Coppice forest systems with regards to carbon fixation and accumulation efficiency is relevant as their rapid vegetative regeneration could provide an efficient yet simple opportunity for increasing atmospheric CO2 assimilation. A study by (Bruckman et al., 2011) explored that differences in above ground carbon stocks between high forests and coppice with standards forests highlighting an increased net primary productivity (NPP) in the latter. This is supported by observations from (Sferlazza et al., 2018) who demonstrated a similar phenomenon. They note an increase in the above ground carbon pool with age and larger volumed stems yet do not address the number of stems per hectare. The nature of fast growing sprouts and retained mature trees (standards) under short rotation coppice management systems tend to accumulate and fix carbon at a faster rate due to their higher growth rates and more frequent harvesting cycles (Bruckman et al., 2011). Caution is warranted, as research suggests that rotation and harvesting cycles are critically important in the context of forest carbon pools. Properly managing these cycles is essential to maintaining and enhancing the carbon sequestration potential of forests, highlighting the need for careful planning and execution in forest management practices (Lee et al., 2018). Furthermore, stand density, related to management and succession is also another important factor (Istrefi & Toromani, 2019). Another important factor relates to the computation of carbon pools which broadly apply allometric or biomass functions to derive biomass. Indeed, allometric functions are firmly established across the literature as a principle technique to estimate tree scale biomass since the late 1990's (Brown, 2002). Works by (Chave et al., 2014; Chojnacky et al., 2014; Muukkonen, 2007) explored these scaling mathematical relationships between components of tree variables such as diameter and height to estimate generalized functions for species across the European, United States and tropical forests respectively. Despite generalization, application of functions should be used with caution. As (Sileshi, 2014) debates, estimations using generic functions can cause estimation error and variance as tree growth is a function of climate, site and stand characteristics. Nevertheless, allometric functions are stated in the IPCC guidelines as a concrete method approach to country level monitoring and reporting and verification. In almost all studies, including recent remote sensing research and LiDAR applications, parametrization of models included, data is retrieved on the common variables of diameter at breast height and tree height. Validation often uses historical data from inventory plots and above ground carbon is assessed by way of applied allometric functions or biomass expansion factors (BEFs). In many studies, inventory plot data, measured periodically with manual instruments such as tapes and clinometers and statistical analysis to determine growth phenomena according to age, structure and site index prevail where precision is fundamental (Luoma et al., 2017).

In situ sensor networks monitoring finer scaled measurements is relatively novel. These emerging networks could reshape how data is captured and thus better inform growth modeling and analysis in combination with established measurement practices and analysis. It is not the purpose of this study to assess future growth and yield of stands under investigation. However, as coppice forests are declining and traditionally have lower economic significance than commercial high forests, emerging carbon markets could be significant for future management decisions. Therefore, sensor networks for monitoring trees to capture changes in ecophysiological parameters such as radial and diametric increment could be advantageous. Sensor networks are steadily gaining traction as efficient forest monitoring tools enabled by technological innovation in Nature 4.0 (Valentini et al., 2019). Nature 4.0 denotes the application of internet of things technologies (IoT) and connectivity between platforms, devices and systems offering big data solutions specifically in the context of nature and the environment (Zeuss et al., 2024). Central to this technology is a theme of socketed sensors gathering and transmitting information about our physical environment intrinsically connected through IoT with high frequency measurement capabilities (Buonocore et al., 2022). This is particularly appealing for monitoring activities in important yet less economically viable forest resources such as coppice forests. Access to interconnected sensors retrieving data on natural phenomena in several locations at once is but one example. Applications of such technologies are steadily growing in number with platforms such as the Treetalker highlighting the potential for these technologies. The Treetalker is a platform born from the concepts of Nature 4.0 (Valentini et al., 2019). The system includes six sensors in total combining several independent sensing technologies commonly used separately for forest monitoring in one platform. Calibration functions translate digital signals from numerical information to tree ecophysiological parameters as selected prior to sensor builds and established throughout plant and tree physiological sciences for the past 5 decades. Consequently, dedicated data processing packages have been developed to interpret retrieved digital information (Tomelleri et al., 2022; Zorzi et al., 2021). Recent applications of the Treetalker devices include the continuous monitoring of stem water and sap flux density via its onboard sap flow sensor, yielding insights into individual tree hydraulic behaviour at daily scales and behavioural dependent on temperature and accurate heat waves at seasonal scales (Asgharinia et al., 2022), the temporal detection of phenological phenomena driving seasonal leaf out and decay via data retrieved from device spectrometers across Italy (Vaglio Laurin et al., 2024), a synthesis and application of the Treetalker for IoT monitoring of urban ecosystem services in Moscow describing each of the sensor capabilities(Matasov et al., 2020) and breakthroughs in plant and tree physiological research with the detection of bi model relationships between stem growth and sap flow facilitated by the high resolution monitoring of sap flow using the Treetalker (Niccoli, Kabala, et al., 2023)

One of the sensors onboard the Treetalker platform is an infrared proximity sensor, deployed to measure changes in radial increment using infrared light. To date, this sensor has received limited attention in monitoring activities, with the exception of the work by (Yates et al., 2022) which briefly demonstrated its functionality. However, its application to practical research questions, such as monitoring changes in radial or diameter increment in the context of biomass accumulation through allometric scaling functions and subsequent CO2 accumulation, has not been thoroughly explored.

To address this gap, this study will focus on above ground biomass pools and the equivalent carbon stock as a function of incremental changes in biomass driven by variations in stem radii scaled to diameter. Rather than concentrating on carbon sequestration or fixation, we will examine carbon accumulation increment. Higher frequency temporal changes in stem growth reflect an increase in total biomass when accumulated, thus providing a better description of how carbon is accumulated over time.

The scope of this study is to provide a functional proof of concept for biomass and carbon monitoring using IoT-driven dendrometers in the context of a managed coppice forest in central Italy. The specific aims of the study are:

a) To characterize and describe the IoT-driven dendrometer sensor network.

b) To assess the measurement accuracy of the system compared to manual field measurements.

c) To demonstrate how a network of dendrometers can collect quasi-real-time information on increment changes, scaled to biomass and carbon accumulation across individual stems.

By integrating new technologies for forest carbon monitoring, this study aims to offer a new perspective on an old approach and to open a discussion about the potential application of such systems in lower-value forests or as support systems for permanent plot sampling.

Materials and methods

Study Area Roccarespampani

Roccarespampani, located in Latium central Italy is an excellent representation of Silvo pastural management dating to the 14th century (Ref). Pastures cultivated land for grain production and extensive woodlands form a complex system where the practice of silvicultural management is central to the estates' ongoing provision of forest and non-forest products e.g. grain and livestock. The woodlands themselves are estimated at approximately 1400 ha's of the entire estate with most of the stands managed under a coppice with standards (CWS) or simple coppice (SC) silvicultural system. In this investigation, the two sites are managed und CWS Predominant age classes across the estate vary between 0-30 years with a final cut rotation for the coppice of 20 years after two commercial thinning interventions and a selection for retention and removal of standard trees at the second thinning phase. The retention of standards or selected trees differs by location and according to site classes (REF). Standards are selected and retained to provide continuous cover without compromising the light resources for the sprout regeneration.

This study focuses on two forest compartments or 'Partecella' located approximately 160m above sea level and enumerated as cpt24 and cpt20 according to the most recent management plan (Ref). Each of the compartments are located to the immediate NNW (42°, 23', 21" N, 11° 55' 24" E) of the Borgo Rio Secco establishment along the principle provincial road between the town Viterbo and Tuscania in Lazio Central Italy. Site specific climatic times series are not available given the absence of a local meteorological station. Here we assume climatic conditions prevail across both sites given their close vicinity with each other and the general planar geomorphological feature of this area. According to the closest weather stations in Viterbo, the area is characterized by temperate dry and hot summers with a mean temperature of 13.9C° degrees and an annual average rainfall of approximately 850mm. Soils are classified as Chromic and Haplic Luvisol (Cutanic, Vitric); Vitrice Umbric Andosol; Dystric Andic Cambisol according to these soils are primarily defined by their horizon differentiation, presence of organic matter and volcanic materials.

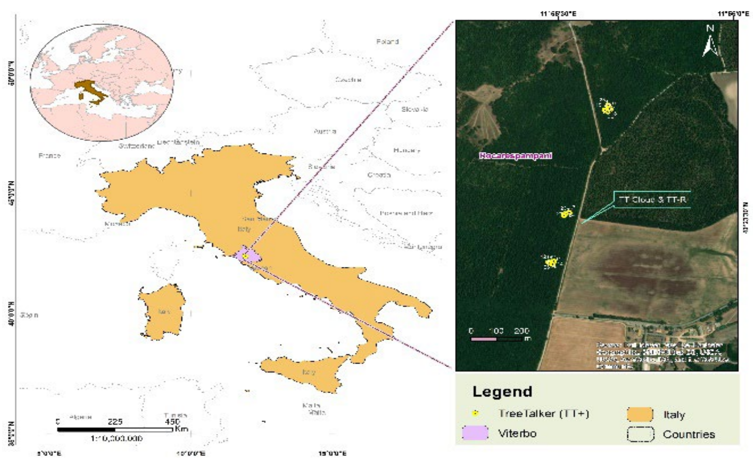


Figure 1: Site location map Roccarespamani, Central Italy, Lazio Region.

Field sampling and experimental design

The two compartments were selected based on their respective sizes, geographical location and time since recent silvicultural intervention. That is the time since the last commercial thin of the sprouts on the coppice stool, where cpt 20 was harvested in 2008/09 and cpt 24 in 2011/2012 respectively. Both compartments are separated by a single internal road and separated by approximately 600m. Site 1 was split into two groups of TT+ for access reasons.

15 Treetalkers version 3.2 were installed across each plot with stem selection for device installation informed by a plot sweep to appraise the stem size class for the sprouts in the stool, the standards and the average number of sprouts on the stool. For plot 1 site I, the average diameter at breast height for the sprouts on the stools was 13.27cm *dbh*. For plot 2, site II the average diameter at

breast height for sprouts on the stools was 14.70 *dbh.* For the standards, the average *dbh* for plot 1 was 28.81cm and for plot 2 29.95cm *dbh.* Mean dominant height for both plots in 2021 were 16.2m, plot 1 and 14.68m plot 2. Heights were taken periodically taken using a Vertex with a standard diameter tape used to measure diameter at breast height.

Stool and stem selection aimed to capture the heterogeneity of the number of sprouts per stool and a coverage of selected standards within the plot. The inventory sweep revealed relatively heterogeneous characteristics of both plots concerning the number of spouts for each stool and as such a total of 4 stools and 4 standards for plot 1 were selected for Treetalker installation with 5 stools selected in site 2 and 3 standards. The average number of spouts on each stool was 5. Given the limitation of number of Treetalkers, sprout selection followed the installation of devices on the dominant spouts generally greater than 8cm *dbh* and covered an average of 2.5 devices for every selected stool.

Treetalkers, TTCloud and a TTR were installed in April 2021 and orientated to face the TTCloud. All on board sensor IR dendrometers were installed at approximately 1.4m (dbh) at 90 degrees to the stem. Fig (x).

Figure 2: Installation photo of Treetalker+ 3.2 installed on a coppice stool with sprouts and a mature standard tree in Roccarespamani.

Laboratory and numerical analysis

Figure 3 describes the data treatment protocol for the Infrared (IR) Sensor Data Protocol. The raw data consists of data retrieved from a 3rd party server AltaVista where the TTCloud sends data from the Treetalker devices installed across the plots. Step 1: Each data series retrieved from the devices is pre-processed by firstly converting digital signals to numerical values by way of calibration functions including the application of the specific calibration function for the IR sensor itself. In addition, we employed a Turkey's method to remove outliers and used linear interpolation to handle missing values in the time series due to sensor failure generally caused by battery or device single loss. Finally, selection of date/time and respective IR sensor values based on seasonal windows were extracted in this step. May to September respectively. Step 2: Involves a processing logic to extract data values from an applied rolling median approach with a 2 week window and the computation of the cumulative delta of said values for all available IR Sensors accordingly. The final difference between sensor initial and sensor final were then extracted to give the annual increment in millimetres. Step 4. Application of regression analysis to assess accuracy between manual field measurements and retrieved IR Sensor increments for the selected period is then performed whereby conversion of cumulative delta IR sensor radial increment to diameter assuming symmetrical stem growth was computed. Step 5: Application of selected allometric functions to derive cumulative biomass increment and seasonal carbon accumulation using biomass as a proxy was then conducted.

To process the Infrared signals from the individual trees captured by active monitoring in 2021 and 2022. The empirical and numerical steps were completed using a tailored Python script following the logical data process (fig. 3). The full script can be found in the appendices and major commutation methods are detailed in the following section.

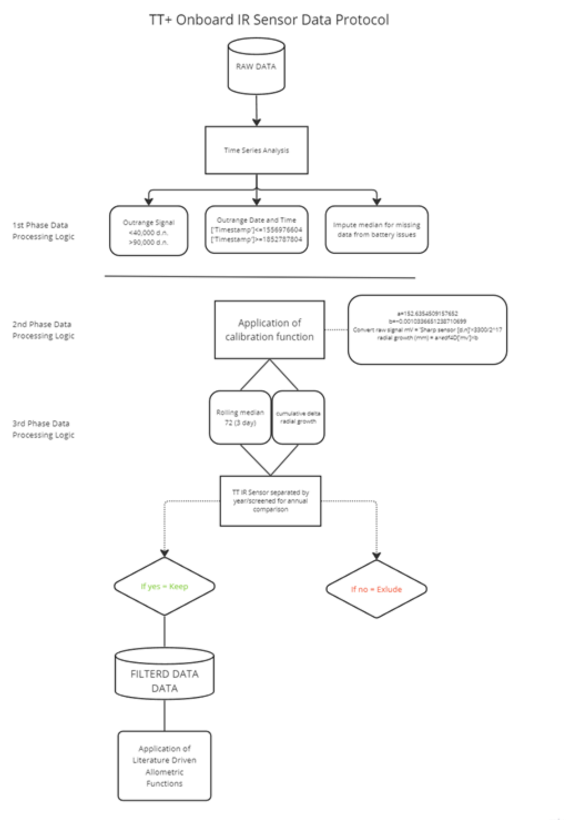


Figure 3: Data treatment protocol for the Infrared SHARP dendrometers to select or discard sensors based on sensor performance.

Data treatment

A rolling median with a bi-weekly window was employed to smooth the curves with a linear interpolation employed to compute missing values from battery failures.

$$Mt = median\left(xt - \left\lfloor\frac{W}{2}\right\rfloor, xt - \left\lfloor\frac{W}{2}\right\rfloor + 1, \dots, xt, \dots, xt + \left\lfloor\frac{W}{2}\right\rfloor - 1, xt + \left\lfloor\frac{W}{2}\right\rfloor\right)$$

Where:

- xt is the value of the data set at timestamp t and Mt is the rolling median at timestamp t calculated using a time window W = 336

The rolling median Mt at timestamp t is defined as:

- $Mt = median(xt - 168, xt - 167, \dots, xt, \dots, xt + 168)$
- Median denotes the median function applied to the values within the symmetric window of 336 data points.
- The window is cantered at the current data point t, covering the 168 data points to the left and 168 data points to the right of xt.
- This definition represents the rolling median as the median value within a 168-point window cantered at each timestamp point t in the time series.

Using a cumulative delta approach, radial growth observations derived from the rolling median values from the previous section was applied. This process aims to capture changes in data captured from the IR dendrometer sensor for selecting the selected range within the growing season and to identify trends in radial growth accordingly. Such approaches are excellent for times series based growth monitoring.

$$\Delta X_{i,j} = \sum_{k=1}^{i} \Delta x_{k,j}$$

where:

- i represents the index or position in the data set which is equal to 336 or (2 weeks) of observations as determined from the rolling median application.
- j represents the device index
- $\Delta X_{i,j}$ represents the cumulative delta radial growth for the $j-th$ device up to the $i-th$ position.
- $\Delta x_{k,j}$ represents the individual delta radial growth for the $j-th$ device at the $k-th$ position.

The absolute difference in cumulative delta radial growth ($\Delta Xdiff_j$) was computed by subtracting the cumulative delta radial growth at the initial position ($i_{initial}$) from that at the final position (i_{final})

$$\Delta Xdiff_{,j\ (mm)} = \Delta Xi_{final,j} - \Delta Xi_{initial,j}$$

To determine the accuracy between measurement methods, network functionality, physical measurements using a DBH Tape with a 1 millimetre accuracy were taken at both the beginning and the end of the selected period of analysis and compared to the delta cumulative radial growth of the IR sensor. Selection of sensors was based on an upper limit of deviation between measurement method results, < = 2mm differences, and comparison of each method was assessed using regression analysis.

Allometric functions and Carbon accumulation

To initialize the cumulative delta measurement based on the bi-weekly rolling median and track time series changes in diameter rather than radial growth, an initial or starting diameter is required. As such physical measurements of diameter were sampled at the beginning and end of each measurement period for 2021 and 2022 using a standard DBH tap with a precision of 1 millimetre. Data from the conversion of radial increment to diameter increment using the rolling median method described in the data treatment section were used for the analysis of time series observation for biomass and carbon accumulation respectively.

Where:

$$Dbh = dbh\,i,j + (\Delta Xi,j * 2)$$

The allometric function for Quercus Cerris L. was selected from the national forest inventory CRA 2011, '*Stima del volume e della fitomassa delle principali specie forestali italiane*' (Tabacchi G. et al., 2011). Functions in the literature were surprisingly scarce. Diameter driven functions for Turkey and Albania are available, however the sample trees from which they are initialized demonstrate different diameter and height features compared to the trees in this study (Istrefi et al., 2018; Saglam et al., 2020).

Table 1: Chosen allometric function by segment from the CRA 2011 sampling campaign.

Q. Cerris allometric functions	**Parameters**		**Source**
	a	*b*	
Dw1= b1+b2DBH^{2}h (Stem and large branches)	-1.3658	0.025533	CRA 2011
Dw2= b1+b2DBH^{2}h (Small branches)	1.7649	0.0045457	
Dw3= b1+b2DBH^{2}h (Stump)	0.11733	0.00067201	

Results

Network and sensor performance

The network in its simplest expression is characterised by numerous sensors operating *in situ* capturing information on a phenomena at a high temporal frequency and with a level of reliability known for the phenomena. That is connectivity on the one hand and measurement accuracy or precision on the other. Considering connectivity, active sensors capturing data from the network in 2021and 2022 were at quasi full capacity for both monitoring periods which is an acceptable result. However, a reduction in network connectivity was evident for 2022 which had 15% less sensor stability compared to 2021 (figure 5). Furthermore, a reduction in reliable sensor readings compared with 2021 was also noted. Sensor failure either due to physical damage, loss of Treetalker connectivity and electrical faults resulted in their exclusion from further analysis.

Figure 4 shows the networks total raw data measurements of cumulative radial stem growth for both 2021 and 2022. A noticeable feature for both years is the noise generated from the sensors when continuously monitoring at 1 hourly intervals which causes significant changes in daily growth dynamics and magnitude. Irrespective, a clear mean stem radial growth trend is discernible for both years and differences in growth dynamics across the network are significant (figure 4).

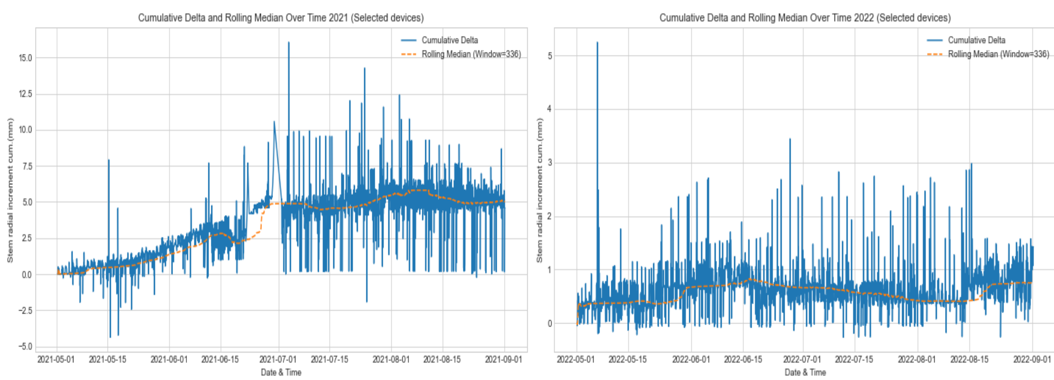


Figure 4: Combined sensor network raw cumulative radial growth for 2021 and 2022

Separating the network into individual sensors and stems, a key feature of the network, was achieved by applying the data treatment protocol described in the methods. This method emphasized the networks' ability to detect individual growth patterns across installed sensors. For both 2021 and 2022, a surprising level of detail regarding growth synchronisation is shown (figure 5.) Moreover, individual growth rates differ in magnitude while maintaining similar trajectories and the seasonal asymptote of growth is clearly detectable. In addition, while stem growth activates more or less within the same seasonal period, a markedly lower growth rate is observed in 2022 compared to 2021 with a distinct stem shrinking phenomenon observable in 2022.

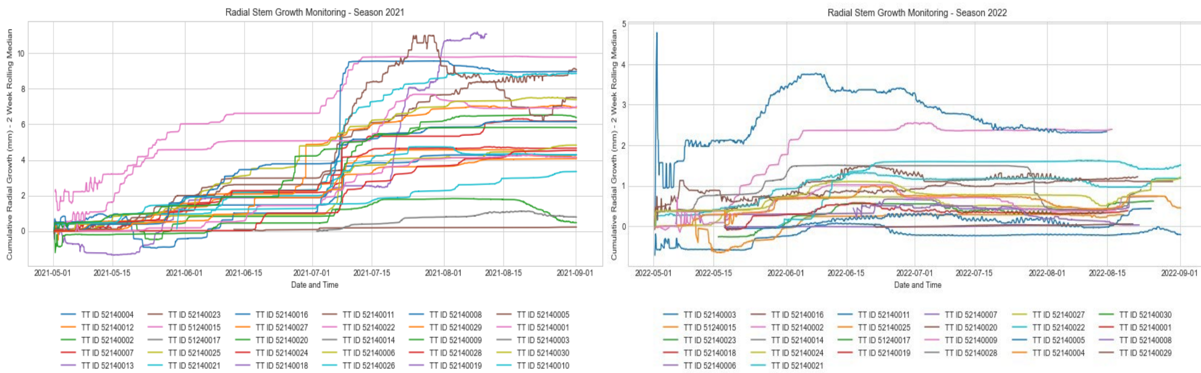


Figure 5: Individual cumulative radial growth responses for 2021 and 2022 after data treatment.

Sensor accuracy assessment

Both the total number of connected devices and the separation into individual stems demonstrating similar results support a functional network. To better address the phenomena, however, a secondary approach regarding sensor accuracy was required.

Given the failure of some sensors and the inability to assess the accuracy of the retrieved network data, the most reliable sensors from the network were chosen to assess sensor accuracy for further interpretation. Absolute measurements for seasonal tree stem radial growth were taken using dbh tapes and compared with the absolute measurements recorded from the sensors accordingly. Mean measurements compared to networked sensor measurements for 2021 and 2022 are as follows:

- PLT1: Manual measurements = 5.431mm, Infrared sensor = 6.716mm
- PLT2: Manual measurements = 3.373mm, Infrared sensor = 3.533mm
- PLT1: Manual measurements = 3.312mm, Infrared sensor = 2.601mm
- PLT2: Manual measurements = 2.083mm, Infrared sensor = 1.189mm
-

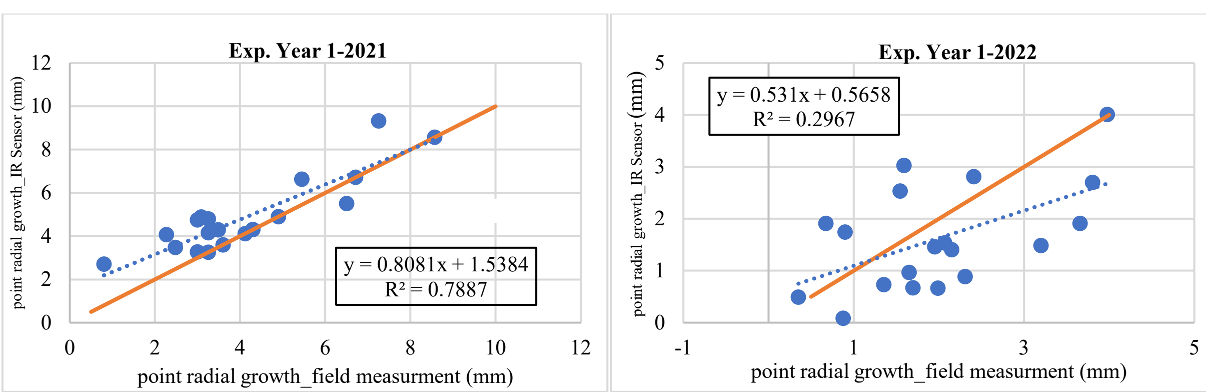


Figure 6: Comparison between absolute growth increment for selected stems for Infrared sensor and manual measurements for 2021 and 2022.

Figure 6 compares the observations between measurement methods for 2021 and 2022. 2021 shows a strong positive correlation between the IR sensors and manual measurements, p value <0.005 and an R2 of 0.78. In 2022, however, reduction in the R2 = 0.29 and a higher p value of 0.014 were observed in 2022. While best attempt to measure the same point on the stems consecutively were made, manual measurements taken with DBH tapes can be notoriously imprecise due to human error (Luoma et al., 2017). Furthermore, the relatively low growth for the 2022 season may have not been correctly captured by field measurements using a DBH tape with a 1(mm) resolution and accuracy. 65% or 19/29 of the deployed sensors were selected based on their accuracy result between manual and IR sensor measured absolute differences measured at the beginning and of the monitoring period. Despite lower regression strength in 2022, actual differences between observed sensor values and measurements were never above 100μm and compatible to the error of manual measurements in any case.

Monitoring changes in biomass and above ground CO2 stock

The results derived from the radial growth and consistency with manual measurements were scaled to above ground biomass and Carbon in kilograms respectively.

To assess the changes in biomass and carbon stock as a function of cumulative biomass, radial measurements were converted to diameter using a factor of 2π as shown in figures 7 and 8. This was driven by the accuracy results between manual and IR sensor measurements and the clarity of the radial growth curves for both seasons after data treatment. The conversion of radial measurements to biomass was first computed using allometric functions provide for Quercus Cerris from the Italian NFI. As was observed in the radial increment plots, individual responses in biomass and carbon accumulation using biomass as a proxy was captured at individual scale and separated by category e.g. sprouts and standards Table 2. The differences in biomass and subsequent carbon accumulated in biomass stocks were generally greater for standard trees compared to individual sprouts on stools for both 2021 and 2022 and a noticeable difference between years is clear as expected.

Table 2: Year 1 (2021) and Year 2 (2022)-Changes in biomass across selected monitored individuals, stools and standards by TT+ ID and subsequent changes in carbon stock calculated as derived from CRA 2011, allometric functions.

Year 1 experiment-2021						***Year 2 experiment-2022***					
TT ID	**Category**	**biomass -Tot (kg)**	**biomass + 1-Tot (kg)**	**Biomass diff (kg)**	**Carbon Accumulated (kg)**	***TT ID***	**Category**	**biomass-Tot (kg)**	**biomass + 1-Tot (kg)**	**Biomass diff (kg)**	**Carbon Accumulated (kg)**
52140011	Stool_1A	26.812	31.305	4.494	2.247	*52140014*	Stool_1B	26.322	27.240	0.918	0.4591

52140014	Stool_1B	24.106	27.445	3.338	1.669
52140016	Stool_1C	24.106	29.885	5.779	2.890
52140028	Standard_2	527.320	546.177	18.857	9.429
52140012	Stool_2A	20.255	24.356	4.101	2.050
52140002	Stool_2B	19.535	22.877	3.343	1.671
52140018	Stool_2C	18.697	21.133	2.436	1.218
52140007	Stool_3A	25.619	30.772	5.153	2.576
51240017	Stool_3B	38.218	47.011	8.793	4.396
51240015	Standard_3	341.662	363.138	21.476	10.738
52140021	Stool_4A	49.575	63.844	14.269	7.134
52140023	Stool_4B	34.486	45.470	10.985	5.492
52140024	Stool_4C	23.612	30.683	7.071	3.535
52140022	Standard_4	395.648	418.027	22.379	11.189
52140019	Stool_5B	36.996	41.457	4.461	2.231
52140030	Stool_6A	65.529	70.163	4.634	2.317
52140004	Standard_6	465.791	488.008	22.217	11.108
52140025	Stool_9A	43.643	49.346	5.703	2.851
52140029	Stool_9B	46.326	51.206	4.880	2.440

52140016	Stool_1C	30.250	32.038	1.788	0.8938
52140012	Stool_2A	23.634	27.770	4.136	2.0678
52140018	Stool_2C	21.143	21.202	0.059	0.0295
51240015	Standard_3	364.912	373.594	8.681	4.3406
52140021	Stool_4A	64.697	68.871	4.174	2.0869
52140023	Stool_4B	45.677	46.687	1.010	0.5051
52140024	Stool_4C	31.402	34.919	3.518	1.7588
52140022	Standard_4	419.549	427.001	7.451	3.7255
52140009	Stool_5A	35.062	36.111	1.050	0.5249
52140030	Stool_6A	71.415	73.672	2.256	1.1282
52140003	Stool_6B	38.112	38.821	0.709	0.3544
52140006	Stool_7A	44.124	44.896	0.772	0.3862
52140005	Stool_7C	28.527	28.980	0.453	0.2264
52140008	Stool_8A	98.456	99.327	0.871	0.4356
52140028	Stool_8B	70.148	72.310	2.162	1.0812
52140004	Standard_6	491.890	496.996	5.106	2.5530
52140025	Stool_9A	47.561	47.945	0.384	0.1920
52140029	Stool_9B	48.987	49.085	0.098	0.0491

In Year 1 (2022), the standards trees had an average biomass of 432.605 kg, accumulating 42.464 kg of carbon, and sequestering an average of 10.616 kg Carbon per year, with an average Carbon per hectare of 1061.608 kg. In contrast, stools had a lower average biomass of 33.168 kg but accumulated more carbon at 44.719 kg and sequestered 2.380 kg Carbon per year, with a higher average Carbon per hectare of 4464.428 kg.

By Year 2, the standards category saw a decrease in average biomass to 425.451 kg and a significant drop in carbon accumulation to 10.619 kg, with reduced Carbon sequestration metrics. Stools, however, increased their average biomass to 45.345 kg and maintained a positive carbon accumulation of 12.179 kg, with a slight increase in Carbon sequestration per hectare. Overall, standards showed a decline in growth and carbon sequestration, while stools demonstrated enhanced growth and improved carbon capture efficiency over the two years.

Table 3: Comparison of changes in biomass and carbon stock respectively between average growth increment for sprouts on stools and standards. Hypothetical assumption of full stocked stands carbon pool changes.

Year 1 average biomass and above ground carbon pool results by category-2021							
Category	**AVG_biomass - Tot (kg)**	**AVG_biomass + 1- Tot (kg)**	**Sum_Biomas diff (kg)**	**Carbon Accumulated (kg)**	**Avg_C/yr**	**Fully stocked C (kg)per stem**	**Avg_C(Kg)/ha**
Standards	432.605	453.838	84.929	42.464	10.616	1.062	1061.608
Stools	33.168	39.130	89.439	44.719	2.380	**4.464**	4464.428
Year 2 average biomass and above ground carbon pool results by category-2022							
Category	**AVG_biomass - Tot (kg)**	**AVG_biomass + 1- Tot (kg)**	**Sum_Biomas diff (kg)**	**Carbon Accumulated (kg)**	**Avg_C/yr**	**Fully stocked C (kg) per stem**	**Avg_C(Kg)/ha**
Standards	425.451	432.530	21.238	10.619	2.7527	0.2753	275.271
Stools	45.345	46.867	24.358	12.179	0.7612	1.4280	1427.997

Table 4: Focused comparison between selected stool and standard changes in biomass and carbon assimilated in biomass pool from individuals in graphs display din figure 7

	YEAR 1 EXPERIMENT-2021		**YEAR 2 EXPERIMENT-2022**	
CATEGORY	**Biomass diff (kg)**	**Carbon Accumulated (kg)**	**Biomass diff (kg)**	**Carbon Accumulated (kg)**
STANDARD (SELECT)	21.476	10.738	1.050	0.5249
Stool_4	33.282	16.641	8.702	4.351

The observed measurements from two distinct years of experiments, focusing on biomass differences and carbon accumulation in biomass stocks across different categories. For the Standards category, the biomass difference is notably higher in Year 1 (21.476 kg) compared to Year 2 (1.050 kg), with carbon accumulation reflecting a similar pattern—10.738 kg in Year 1 and 0.5249 kg in Year 2. This significant drop suggests a marked reduction in both biomass growth and carbon sequestration in the second year for the standard category. Conversely, the selected stool shows a different trend. In Year 1, biomass difference is 33.282 kg with carbon accumulation at 16.641 kg, while in Year 2, biomass difference increases to 8.702 kg, accompanied by a substantial rise in carbon accumulation to 4.351 kg. This indicates that, unlike the standard tree, the Stool experiment experienced a decline in biomass but a relative increase in carbon accumulation in Year 2. Overall, while the standard tree shows a decline in both parameters, the Stool exhibits a different pattern with an increase in carbon accumulation despite a decrease in biomass.

Discussion

This study introduces an internet of things (IoT) driven dendrometer sensor network designed to monitor stem incremental changes for sprouts and retained stems in a managed coppice with standards (CWS) silvicultural system in central Italy. Rather than using common electronic dendrometers such as potentiometers or linear variable transducer (De Belder, 2015), we opted for a modified off the shelf infrared proximity sensor, previously never used for such applications and briefly described by (Yates et al., 2022). The results obtained from the sensors not only track incremental changes in quasi real time for Quercus Cerris L. but allow scaling from stem increment to biomass and carbon accumulated for two consecutive years respectively.

Assessing socketed IoT driven sensor network performance.

To assess the networks success we can focus on the operational performance of the Treetalkers infrared sensor over the two year monitoring period. The dendrometer sensors themselves are 'off the shelf' infrared proximity sensors and are commonly used in closed environment settings rather than open air scenarios where temperature, humidity and automation are controlled (Karim & Andersson, 2013). While highly accurate in controlled environments, subsequent outdoor installation exhibit some peculiarities. We placed the sensor perpendicular to the stems, uncovered and under forest canopy. Thus, subject to sunlight, wind, rain, and evidently pollen. (Zielinski, 2021), reports that the same sensor underperformed when exposed to pollen and direct sunlight. In addition, we observed several sensor failures attributed to wear and tear, branch fall and incoherent data outside of sensor calibration function equations, dramatic oscillations and zero readings. Consequently we were unable to achieve 100% success rate for the network for either year in this study. However, of the total number of sensors installed, initially 30 in 2021, 65% did retrieve operational data and demonstrated reasonable point radial dendrometric functionality. While the number of functional sensors was lower than expected, the data retrieved was surprisingly consistent with manual measurements. This was more pronounced in 2021 than 2022 where cumulative incremental growth for almost all installed devices demonstrate radial growth curves coherent to secondary growth seasonality as demonstrated also by (Zweifel et al., 2006a) and where seasonal correlation between measurements were 80%. In 2022 the number of functional sensors remained consistent, however the accuracy between measurement methods reduced. The observations in 2022 for almost all devices were between 0.5-1.5mm and as such comparison between field measurement and the sensor are inconclusive. The methods for which data was manually collected, a DBH tape with a measurement accuracy of 1mm is possibly incapable of detecting such small growth increments precisely. Indeed, (Luoma et al., 2017) highlights limitations in measurement precision using DBH tapes citing human error as a significant factor. Interestingly, for both 2021 and 2022, sensor data across both observation periods demonstrate consistent secondary growth patterns irrespective of the reduced accuracy and correlation between measurements in 2022. The consistency in observed radial growth curve responses for both years points to a coherent seasonal radial stem response among individual stems irrespective of the poor correlation.

Major observations – growth decline and phenology

For almost all stems selected, cumulative incremental radial growth was significantly less in 2022 compared to 2021 with an approximate mean growth reduction of 50% across plots. This observation was rather surprising given the differences in rainfall between years was approximately 24 millimetres. However, observed rainfall patterns for both years point to very distinct seasonal rain event differences. In 2021, several good rainfall events occurred just before the onset of bud burst likely contributing to soil water availability, where in 2022 little to no rain was reported between the months of June until August. This is somewhat reflected in the mean growth responses for both years as well as individual observations. For example the cumulative diametric growth, a function of radial growth for the stool selected in this study clearly demonstrates the reduction in growth between years. In addition the combined mean growth response for all stems points to an initial radial growth approximately aligned with 2021 yet less and then a subsequent second growth phase toward the end of the season. This observation requires further clarification, however a recent study by (Niccoli, Kabala, et al., 2023) demonstrated bi-model growth as a function of bi model sap flow linked to water availability.

Observations on biomass and Carbon accumulation

Observations on stem radial increment are directly related to woody biomass accumulation for both growing periods and consequently carbon stock between standards and sprouts. Observations suggest that the sprouts outperformed the standards in cumulative radial growth across both years and showed resilience to patchy rainfall in 2022. Furthermore, while the sum of the biomass remained on average slightly higher for stools compared to standards across both years, individual sprout biomass was always lower than the standards. This observation indicates that a fully stocked high forest should theoretically have a higher carbon stock in comparison to a coppice forest (Vlachou & Zagas, 2023). Indeed conventional wisdom and forestry practices over the past 60 years have promoted the conversion of coppice to high forest on this premise (Manetti et al., 2020). On the contrary, stools and sprouts show greater resilience and growth dynamics in biomass accumulation and carbon sequestration. In this study they consistently exhibit higher carbon accumulation and Carbon sequestration per hectare than standards over both years. This suggests that stools and sprouts, which are characteristic of coppice systems (Bruckman et al., 2011; Harmer

& Howe, 2003), may function as a more dynamic carbon sink compared to the traditional high forest or short rotation coppice systems typically found across the European continent (Unrau et al., 2018). Therefore, CWS, demonstrate both a higher productivity and resilience in carbon stock in above ground pools given there are two rotations of fast growing Spouts, a final harvest and a retention of mature trees. This aspect has not been given much attention in the literature thus far.

Conclusion

This study aimed to demonstrate a functional IoT socketed dendrometer network using a low cost modified Infrared Sensor to capture temporal dynamics in woody biomass of a coppice with standards *Quercus Cerris L.* forest in central Italy. The network ran for 2 years. 100% sensor performance was not obtainable due to technical failures predominantly, although reasonably accurate stem radial changes and biomass dynamics were observed, confirmed by manual measurements in the field and supported by previous studies into these systems. Given the single species and relatively homogeneous nature of the system, carbon accumulation through high resolution data gives both insight into seasonal dynamics of the forest system and furthermore revealed carbon stock dynamics between stools/sprouts and standard trees. Observations suggest that fast growing sprouts on stools are more efficient than selected standards thus challenging the conventional approach for converting coppice forest too high forest. However, this notion is nuanced as we confirm the Coppice With Standards (CWS) specifically in this case rather than short rotation to clear fall harvest coppice systems. This study demonstrates that coppice with standards is a relevant and important silvicultural system that intrinsically has more than one benefit including continuous cover forestry and carbon stock resilience. Furthermore, we demonstrated that socketed IoT driven networks of dendrometers are a viable option for continuous monitoring of carbon stock offering a new method to monitor forest resources at highly granular levels. Data from this form of monitoring could potentially enhance both forest management practices and provide better insight into forest ecological processes.

Section 3

Building a Smart Dendrometer: Calibration and Field Deployment of a linear magnetic driven IoT Sensor for Real-Time Radial Growth Assessment

Abstract

Technological advancements in forest monitoring have led to a new era of forest digitization, revolutionizing the collection and analysis of digital information from various sensors and platforms. Concurrently, direct measurement sensors on tree stems, coupled with IoT technology like LoRa, enable real-time monitoring at individual tree scales. Direct measurement sensors are designed to target specific ecophysiological processes related to tree function and growth. They include sap flow sensors, PAR sensors, Spectrometers and Dendrometers. Here we present a dendrometer to monitor radial stem increment using the physics of the hall effect through a linear magnetic encoder based system and operated on the multi sensor IoT platform the Treetalker.

This study utilizes a commercially available linear magnetic encoder chip from AMS OSRAM GmbH, operating on the Hall effect principle without physical contact. It offers a high resolution, low power input method ideal for long-term monitoring. Design features of the dendrometer include a linear arm, sensor housing, rail and chip braces and magnetic tape. Calibration followed a linear step movement of 0.1mm using a stepper motor to control movement. At each 0.1mm increment movement, n=100 data points were taken and repeated four times. Results from regression analysis demonstrated a strong correlation between the system and physical distance, R2 0.99 and RMSE 0.05 respectively. In addition, a performed a temperature sensitivity analysis under a controlled temperature increment regime from 0-40+ C°. Observations suggest minor impact from temperature on the sensor itself across the selected temperature change regime. Finally we present one growing season of monitoring for 4 devices installed on Picea Abies and Abias Alba. Seasonal radial increment curve responses were coherent with radial growth patterns of both species including a good consistency with observed static UMS D1 diameter belt measurements. This research demonstrates a high resolution low power input IoT driven dendrometer capable of capturing annual trends in radial increment growth and by caveat the detection of stem diel oscillation shrinking and swelling phenomena. Future versions of the device should focus on increasing the measurement precision through more stable design features and direct access to the power width modulation component of the AS3511 chip.

Introduction

Technological innovation in forest monitoring is ushering in a new age of forest digitalization. The systematic collection, synthesis, analysis and application of digital information from synergistic use of sensors and digital platforms is perhaps the most important development in forest sciences over the past 3 decades (Zhao et al., 2005). As (Nitoslawski et al., 2021) highlight, trends in research related to digital applications in forest science increased significantly over the past 10 years. Of these digital applications, the most prominent relate to remote sensing instruments and systems. Operating across spatial scales from square kilometres to square centimetres and temporal scales ranging from ground-based observations taken over hours to satellite imagery spanning years, the volume of data being collected on Earth's forest ecosystems is extraordinary (Lechner et al., 2020). Underpinning the “Big Data” and forest digitalization phenomena are advances in sensor and communication technologies. Indeed, the observed trends in remote sensing research is fundamentally derived from innovation in sensors, specifically active and passive optical sensors. For example light detection and ranging (LiDAR) and Synthetic Aperture Radar (SAR) measuring backscatter to characterize land surface features including trees are widely applied to deduce features of forest resources (Beland et al., 2019; Dassot et al., 2011; Mehendale & Neoge, 2020). Whereas hyperspectral and multispectral sensors, perhaps the most commonly used sensors in remote sensing, are driving insights into both localized (Eitel et al., 2023) and global forest system behaviours (Camarretta et al., 2020; Harris et al., 2021). As these systems are integrated with advances in machine learning, including image analysis technologies, vast amounts of data stored historically may prove to be pivotal especially when assessing long term impacts of changing climate on forest resources. While remote sensing capabilities are being thoroughly explored limitations with the technology exist. The vast amount of data collected by these systems require adequate storage, processing and analysis of which expertise and computational power is essential. Limitations in spatial and temporal coverage including sensor performance under different weather conditions can be problematic especially where forest species mixtures and complex structures prevail (Eitel et al., 2023) . Remote sensing places emphasis on big data and wide aperture coverage in many instances. Rarely does it support real time or quasi real time scenarios and questions remain how well it can be applied to capture individual tree and plant processes including cost effectiveness and dissemination outside of research. Nonetheless it is a highly sophisticated and advancing field. Another field where digital information is steadily acquired on forest resources is that of direct measurement sensors placed on tree stems to monitor tree ecophysiological response and behaviour. These sensors typically include dendrometers, sap flow sensors, PAR sensors and spectrometers in historically standalone compositions. However, the emergence of IoT and subsequent accessible communication technology such as LoRa has made bundling of these sensors possible. When (Zhao et al., 2005) underlined the importance of wireless technologies to provide faster data transfer between PC’s and devices in a forestry context he was correct and the emergence of LoRa or long rang, low power wireless technology has emphasized this. LoRa communication and IoT based systems are ushering in a new era of Nature 4.0 that has allowed the connection of sensors and devices to monitor the environment in a networked matrix (Valentini et al., 2019). This technology is promising as it allows the monitoring of processes at the individual scale which in turn aims to inform ecosystem observations obtained via remote sensing (Zeuss et al., 2024). As such, it is precisely this socketed nature of sensors that leads to philosophy and thought on forest digital twins (Buonocore et al., 2022) and forest digitization (Nitoslawski et al., 2021). Therefore, the data obtained is as only as good as the sensor and system detecting it and given the trend in forest science is toward the integration of more sophisticated technologies for data acquisition, research into novel sensor instrumentation is relevant. The objective of this study was to design, build and deploy an IoT dendrometer driven by linear magnetic encoder with device calibration following relatively simple yet robust methods including temperature sensitivity. Radial growth is a significant and fundamental feature of any forest survey (De Belder, 2015) as changes in this geometric feature support a wide range of applications including describing stem water related mechanisms (Steppe et al., 2006; Zweifel et al., 2006b), research attempting to bridge the gap between net ecosystem processes and individual tree function (Zweifel et al., 2010) and new monitoring platforms such as TreeWatch (Steppe et al., 2016) and TreeNet (TreeNet.Info, 2023). Apart from linear variable displacement transducers and linear potentiometers, advances in radial dendrometer technology, apart from (Clonch et al., 2021), have been few. Therefore, this study focuses on the development of a radial dendrometer used to measure stem radial increment changes in quasi real time. Driving the system is a commercially available linear magnetic encoder and an IoT platform the TreeTalker®. The aim of this study was to design, build, and deploy a dendrometer, and to assess its overall functionality from calibration to field deployment. This included evaluating its ability to detect fine-scale and absolute changes in radial stem increment using commonly deployed D1 static diameter belts as a measurement reference.

Materials and Methods

Selected chip and functional description

The linear magnetic encoder and chip board used in this study is produced and commercially available from AMS OSRAM Gmbh. It is a contactless high resolution sensor operating on the principle of the hall effect to accurately detect position along a linear or rotary scale (AMS OSRAM Group, n.d.). The chip does not require a physical contact between the sensor and its magnetic component. The contactless feature is appealing given wear and tear issues often reported among other dendrometer contact systems such as linear variable distance transducers (LVDT) and linear potentiometers (De Belder, 2015). Additionally, the remarkable resolution of the sensor, 0.488µm, makes it a good candidate for multiple year monitoring campaigns. Ideally, the instrument should detect daily patterns of stem shrinking and swelling.

The chip itself detects changes in magnetic amplitude dependent on both the strength and position of the magnetic object. We use a magnetic tape with alternating regions of magnetic poles or markers as the magnetic object. The tape selected is provided by BOGAN Gmhb electronics, is a linear magnetic scaled tape encoded in increments across a 2mm dipole with a 1mm pole pitch. It has an accuracy class of +/-40µm/m and a magnetic flux density 20mT +10/-7 mT, good thermal expansion performance and an excellent operating temperature.

Acquiring linear position using the tape and the chip is relatively easy, making it another excellent feature of the system. It involves accessing the AS3511 PMW or pulse width modulation pin provided with the AS5311 board. The Pulse Width Modulation has a 100% duty cycle over the full incremental 2mm dipole and as such a 1µs pulse width for every 0.488um of linear movement thus allowing the detection of fine scaled shifts in linear movement. The phasing of 2mm increments equates to a digital output between 0-134000 in a digital number when given 5V and as such requires a post processing approach to incrementally count shifts if cumulative linear measurement is required. Thus a tailored python package was created to deal with the jumps in di poles. Another important feature is the orientation of the North/South poles on the magnetic tape. Orientation dictates digital signal to distance with an increase in digital number when the tape is placed from South to North over the AS3511 and *vice versa* if it is placed South to North. This is a nuanced and important factor.

Dendrometer sensor design and features

Radial dendrometer – piston system

Radial dendrometers typically apply a mechanical system based on a piston configuration as seen is LVDT and potentiometers (De Belder, 2015). That is an arm positioned perpendicular and in contact with the stem. I employed the same logic in the design called the linear arm. Each system is numbered from 1 to 4 and designated as a piston system.

To capture changes in stem radial increment the following device features were explored (fig x).

1.) A 65mm grooved linear arm with a subset holder to house a 35mm piece of magnetic tape and 20mm vertical plate to be mounted on the tree stem surface
2.) A MGN9C rail block mounted to a brace which acts as the slider for the grooved linear arm
3.) A holder for the AS3511 chip
4.) Two 3mm diameter carbon fibre rods to embed the system into the tree
5.) A System cover to protect the system from rain and dust

Pins used for data acquisition include the PWM, 5V and Ground pins on the As3511 board. The interface with the chip is conducted via TreeTalker + 3.1 and 3.2 versions.

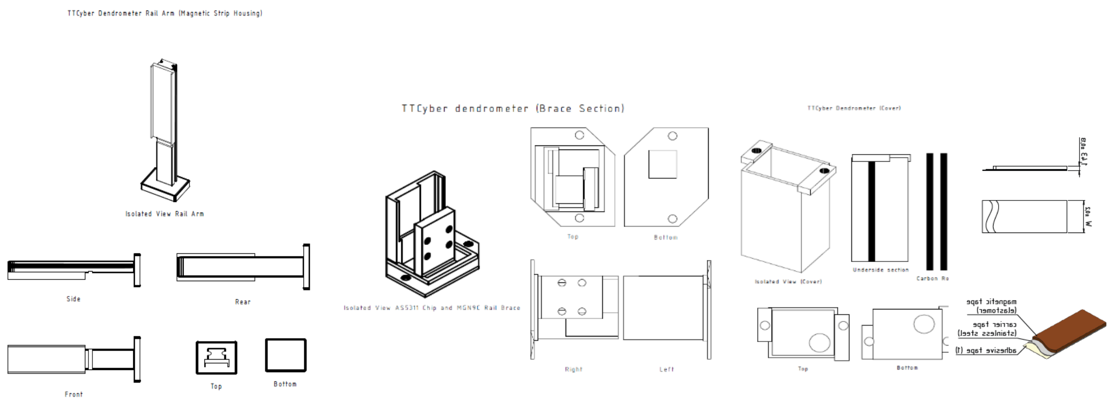


Figure 1: Design schematics for the linear magnetic driven dendrometer using FreeCAD for 3D printing.

The Treetalker

The Treetalker is an integrated platform driven by IoT and LoRa/GPRSM communication technology (Asgharinia et al., 2022). Sensors integrated into the system are selected to monitor changes in the following tree ecophysiological variables. A spectrometer with 12 bands ranging between wavelengths of 610+, 680+, 730+, 760+, 810+, 860+ nm, 450*, 500*, 550*, 570*, 600*, 650* (* ±20 nm + ±10 nm) to detect light transmitted under the canopy. An accelerometer to detect changes in stem pitch, yaw and roll primarily for observations in stem oscillation for example when under stresses such as high winds. A heater probe applying the principle of thermal dissipation (TDP) for detecting changes in sap flow and a capacitive sensor to detect fluctuations in stem moisture content. The device originally supported an infrared proximity sensor for detecting changes in radial growth. However, the original IR sensor was unstable producing significant signal noise when placed in the open environment. Here, we have utilized the ports of the IR sensor in the Treetalker for the new dendrometer system described above. The Treetalker measures and logs all variables in sequential order hourly, storing the data in an internal memory and sending each hourly data package including all sensor data to a Cloud via LoRa protocol which in turn stores the data and sends the data to a third party sever. The data is stored as UTF-8 .txt format with data stored under specific strings in digital number. Digital numbers are converted to real values by way of calibration functions performed under laboratory conditions. The device has been successfully deployed to detect effects in growth post fire event (Niccoli, Pacheco-Solana, et al., 2023), to detect seasonality regarding phenological response of forests across Italy with satellite derived multispectral sensor (Vaglio Laurin et al., 2024) and to continuously monitor stem water content and sap flux density (Asgharinia et al., 2022)

Linear Calibration of AS5311 and TT series Dendrometer.

To calibrate the dendrometer, a purpose built calibration procedure was designed with the system connected to a Treetalker+ version 3.2. Using the open source FreeCAD platform, a calibration brace with a sliding rail housing for the magnetic tape, an MGN9C rail block to guide the rail and brace to hold the AS5311 chip and board were custom designed. The distance between the AS5311 chip/board and magnetic tape set into the calibration arm was set to 0.3mm according to the recommended distance described in the datasheet of the AS5311 encoder. The calibration brace housing the encoder and the sliding rail were attached to a stepper motor with an incremental movement resolution of 0.1mm. The goal of the calibration was to establish a reliable relationship for linear movement and AS5311 chip sensor output with an aim to reproduce a function that could detect minor changes in radial stem growth. The orientation of the magnetic tape was from North (High) to South (Low) and as such we acquired a digital number from 134000 relative to 0 mm and a digital number of 0 relative to 2mm. The calibration process was meticulously executed in increments of 0.1mm across 2mm and repeated twice. Data capture or logging was performed with the Treetalker platform with a sampling rate of 100 points for every incremental step of 0.1mm. Subsequently, a comprehensive regression analysis was conducted to determine the relationship between linear movement and AS5311 signal output. The AS5311 signal output are in digital number derived from the sensors PWM (Pulse width modulation) option and all measurements were taken with a precision of 10µm. The repetition of the experiment across 2 dipoles aimed to capture the lowest and highest AS5311 digital number associated with the linear movement of 0-2mm to correctly characterize and enhance the reliability of the response curve between sensor digital output and linear movement.

Temperature sensitivity analysis

The AS5311 technical datasheets state that the chip sates an operational temperature ranging from -40 to 125 C°. However, the introduction of materials and mechanical components such as the metal MGN9C rail block, the magnetic tape and the material of the moulds themselves (PLA+) it was hypothesized that each component could have their own specific responses to temperature. Therefore, an unsophisticated temperature sensitivity experiment using a SANYO incubation chamber was conducted. The objective of this test was to determine the impact of temperature on the consistency and stability of the dendrometer when placed in the chamber under a temperature increment change of 0-40+ ˚C. The test itself involved placing the system in the chamber with an incremental cycling of 5 C◦ over 10 minute intervals between 0-40+ ˚C which allowed the temperature to stabilize at each incremental step. Following a similar concept to the calibration process, data was logged via the Treetalker in TEST_MODE which took no less than 1 measurement every minute across the full temperature increment. Regression analysis was performed to determine the relationship between temperature and the system signal output stability.

Field Test: Dendrometer performance

The objective of field trials was to assess the performance of the dendrometers to detect stem radial increment changes, four dendrometers were installed in an alpine environment in Trentino

Northern Italy. Species selected, common to the area, are Picea Abias and Abias Alba. All devices we placed at diameter at breast height and connected to Treetalkers which in turn logged data from each device hourly, subsequently sending the data via a hub (TTCloud) via LoRa and to a server via GPRSM. Accuracy of the devices are assessed using D1 automated diameter belts with a measurement resolution of 0.01µm/cm and measured periodically. The D1 belts by UMS are static belts using tension springs that expand according to stem circumference changes.

Figure 2: Installation of Treetalker with LME dendrometer installed on a P. Abias with several other measuring systems.

Results

The results from the dendrometer calibration are displayed in Figure 2. For all repetitions of linear movement of 0.1mm for 4 passes of 2mm dipole increment, the absolute maximum of 2mm was achieved only once. The lowest digital number achieved was 154 which corresponds to approximately 2mm. Note that in this calibration the signal orientation between the linear movement in mm and the digital number registered by the sensor is inverse, this is explained by the orientation of the magnetic tape used in the device to stimulate the signal between the AS5311 sensor and the tape respectively. As such distance measurements will be inverse or parallelled depending on the orientation of the magnetic tape. Noticeably, the signal response curve for the full incremental dipole across all repetitions is sigmoidal and as such to achieve the conversion of digital number to millimetres a 3rd polynomial regression provided the best fit. Higher order polynomial regression did not improve the RMSE or precision between linear movement (mm) and digital number. RMSE under the 3rd degree approach yielded an R2 of 0.99 with an RMSE = 0.05 for both the calibration and the actual versus predicted analysis.

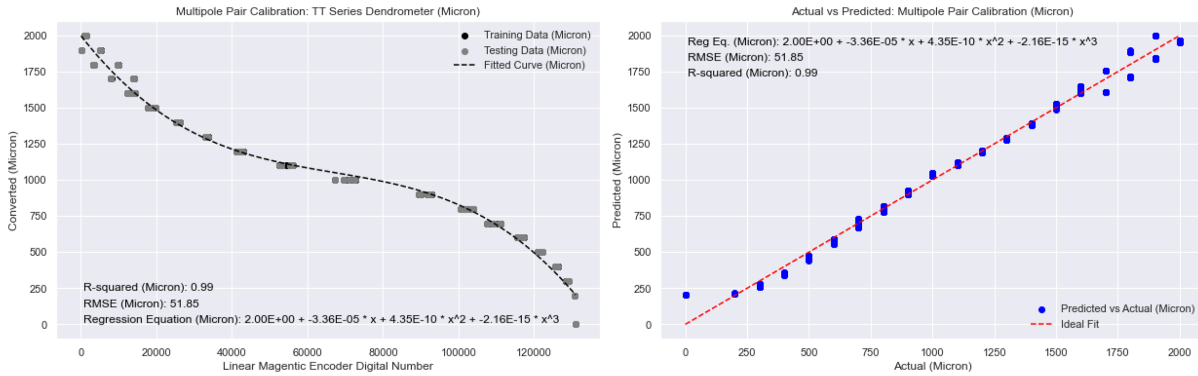


Figure 3: Calibration response curve between physical distance and linear magnetic encoder digital output from calibration trials. Regression analysis between demonstrating model performance for actual and predicted measurements.

Temperature sensitivity analysis using PLA material

Temperature sensitivity for a dendrometer utilizing PLA+ material was evaluated under a temperature regime of 0-40+ °C, as depicted in Figure 4 and 5, respectively. Two trials were conducted, and the combined response curves from the regression analysis reveal a positive correlation between digital numbers and increasing temperature, while actual millimeter measurements exhibited an inverse relationship (Figure 4) as defined by the calibration function. The slope of the response curve for digital numbers was determined to be 4.326, with an RMSE of 38.68 and an R^2 value of 0.90. When applying the calibration function to digital numbers, the slope equated to 0.00013 mm per 1-degree change in temperature, resulting in an RMSE of 1.12 µm and an R^2 of 0.90.These results indicate that the dendrometer's output is highly sensitive to temperature changes, with submillimeter impacts on actual measurements. This suggests careful consideration of temperature effects in applications utilizing this sensor.

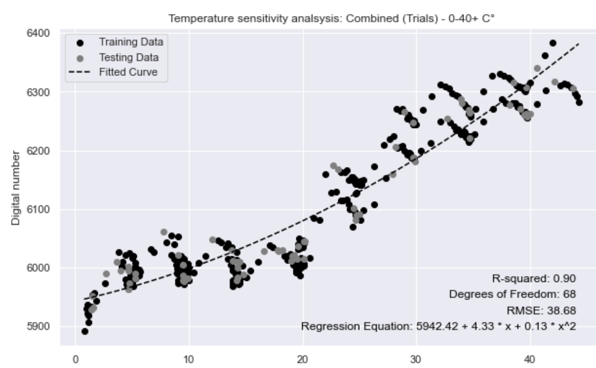


Figure 4: Temperature impact on the linear magnetic encoder fixed in place for two trials. The response of the sensor is associated with a positive relationship between increasing temperature and digital number.

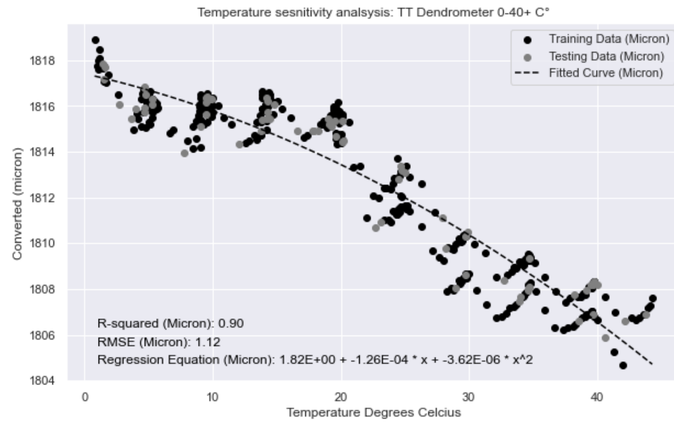


Figure 5: Impact of changing temperature on converted digital numbers to millimetres. Given low RMSE temperature impact is considered as negligible.

Field monitoring results – sensor performance

The seasonal response curves for the dendrometers monitoring radial growth on selected individuals in Trento, Northern Italy are displayed in figure 5. In absolute terms the dendrometers performed reasonability well. Similarity between devices ranged between -0.927 and 1.2 percent. The radial growth curves demonstrate similar yet distinct growth characteristics for the monitoring period. This is most clearly demonstrated in the 1st and 4th piston systems. Piston system 4 performed remarkably well.

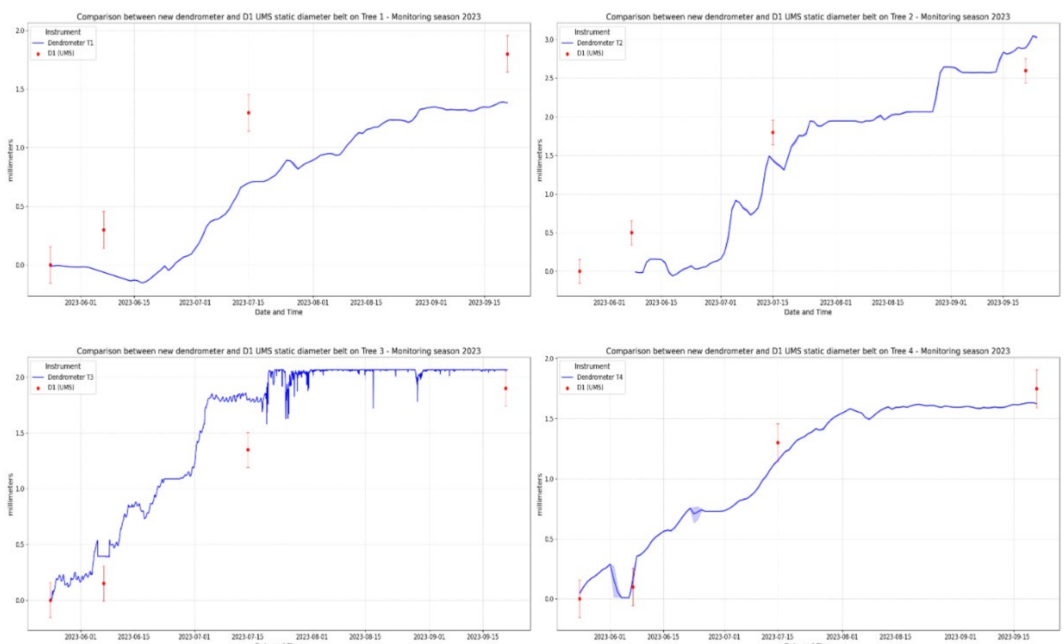


Figure 5: Graphs (top left-bottom right) display stem growth monitoring for P. Abias (Tree 1 and 4) and (A. Alba), Trees 2 and 3 for a monitoring period between late spring and early fall in 2023. D1 dendrometer bands sampled periodically are shown by the red points with respective error bars.

Detecting diel stem oscillations

In addition to the promising results for the dendrometer, considering the temporal patterns at seasonal scale, a closer investigation of stem daily shrinking and swelling dynamics appeared reasonable. The results of this query are displayed in the figure 7.

Figure 7 [A, B] displays temperature and recorded stem oscillations for two of the trees monitored with the dendrometer for a selected time window of approximately 7 days

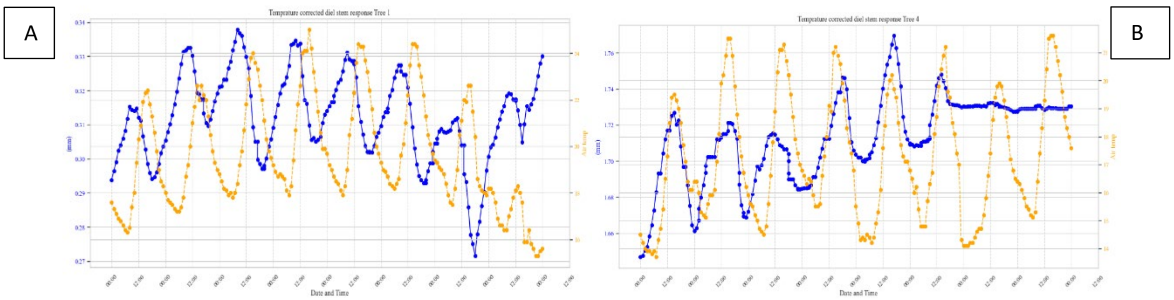


Figure 6: Selected period fine scale monitoring to detect stem shrinking and swelling dynamics for 2 trees (Left Abias Alba) and (Right Picea Abias) Temperature corrected. Two distinct orientations of LME tape inside TT_S Dendrometer Graph A Graph B Linear Magnetic Tape orientated inverse to air temperature and B parallel to temperature.

Tree A, Albias Alba, demonstrates an increase in the magnitude of the distance reading by the sensor according to a decrease in the magnitude of air temperature with maximum distance achieved later than the minimum air temperature. In this case, the magnetic tape is orientated such as the calibration function is orientated in an inverse direction to distance as described in the calibration procedure in the method section. The increase in distance equates to the swelling of the stem specifically under such conditions. Conversely, graph B, orientated as temperature shows a surprising level of syncopation where distance increases according to temperature and captures the shrinking phenomenon accurately. As temperature rises the distance from the stem to the chip increases accordingly.

Figure 8 displays extraction of the daily differences, daily Δ, for both the dendrometers and the temperature form the TT+ devices. There is a consistent phenomenon of shrinking and swelling occurring according to temperature in both cases further verifying the phenomena.

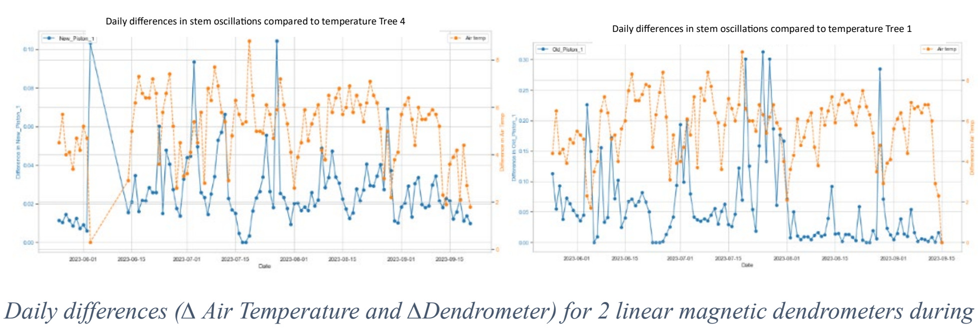


Figure 7: Daily differences (Δ Air Temperature and ΔDendrometer) for 2 linear magnetic dendrometers during late spring, summer and early fall. Species P. Abias and A. Alba. ATX is air temperature.

Although temperature sensitivity is considered minimal from experiments performed in the climatic cell, a correlation analysis and regression between air temperature and sensor response was performed nonetheless to further explore the observed phenomena. The aim was to rule out air temperature as the principal driver of observations seen at daily scales.

Correlation Analysis Between Stem oscillation and air temperature

- Tree 1 and Air temp: Pearson correlation coefficient of -0.0241, also indicating a very weak and nearly negligible relationship.
- Tree 2 and Air temp: Pearson correlation coefficient of -0.0328 indicates a very weak and nearly negligible linear relationship.
- Tree 3 and Air temp: Pearson correlation coefficient of 0.1991 suggests a weak positive correlation.
- Tree 4 and Air temp: Pearson correlation coefficient of -0.0566 suggests a very weak negative correlation.

Regression analysis between stem oscillation and air temperature

- Tree 1: The R-squared value is 0.001, and the p-value for the air temperature coefficient is 0.808, indicating a very weak effect of air temperature.
- Tree 2: The R-squared value is 0.001, which indicates that air temperature explains only 0.1% of the variance in Old_Piston_1. The p-value for the air temperature coefficient is 0.722, meaning the effect is not statistically significant.
- Tree 3: The R-squared value is 0.040, indicating that air temperature explains 4% of the variance. The p-value is 0.0292, which is statistically significant, but the overall impact is still modest.
- Tree 4: The R-squared value is 0.003, and the p-value for the air temperature coefficient is 0.559, indicating a very weak effect.

For most sensors installed (Tree 1, Tree 3, and Tree 4), air temperature has a negligible impact. The R-squared values are very low, and the p-values suggest that any observed effects are not statistically significant. For Tree 2, there is a weak positive effect of air temperature. The R-squared value is slightly higher (0.040), and the p-value indicates that this relationship is statistically significant, though the practical significance is minimal. However, these results are preliminary and require further repetition to be confirmed.

Detecting fine scaled changes in radial growth across the season at individual tree scale

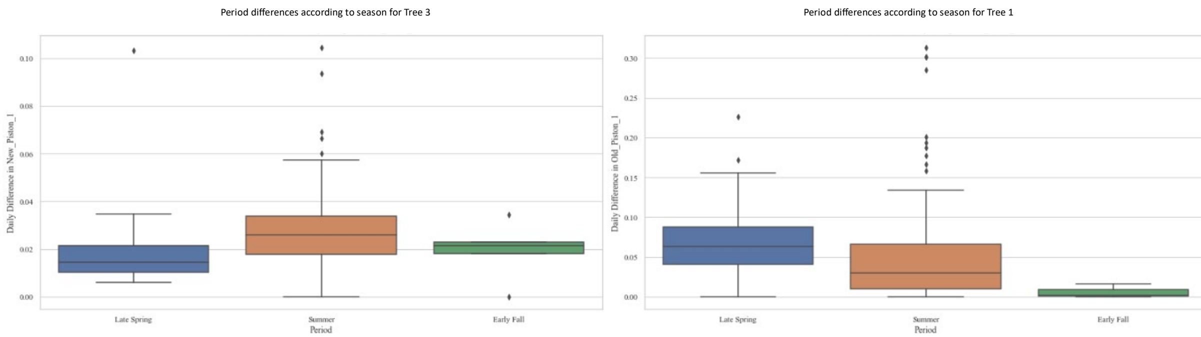


Figure 8: Seasonal growth dynamics captured by the dendrometers. Graph a (Left) species: A. alba and Graph b (Right) species Picea abies.

Table 1: Table of mean radial growth rates for each dendrometer during most active growth phases.

Comparison Of Mean Radial Increment Stem Oscillation (Shrinking And Swelling) For Piston Driven Dendrometers (millimetres)

SEASON	Tree 1	Tree 2	Tree 3	Tree 4
SPRING	0.0475	0.0736	0.0970	0.0208
SUMMER	0.0327	0.0539	0.0631	0.0283

Table 2: Summary of radial increment statistics for each individual tree over the monitoring period of 2023.

Variable	Period	Mean	Standard Deviation	Trend
Tree 1	Early Fall	0.0055	0.0068	Low values, minimal growth
	Late Spring	0.0736	0.0516	Peak growth, significant increase
	Summer	0.0568	0.0742	Slight decrease from Late Spring, still high
Tree 2	Early Fall	0.0164	0.0103	Low values, minimal growth
	Late Spring	0.0475	0.0486	Peak growth, significant increase
	Summer	0.0337	0.0261	Slight decrease from Late Spring
Tree 3	Early Fall	0.0194	0.0125	Moderate values, gradual growth
	Late Spring	0.0208	0.0226	Continued growth, slight increase
	Summer	0.0289	0.0181	Highest value, steady growth
Tree 4	Early Fall	0.0548	0.1069	Low values with high variability
	Late Spring	0.0970	0.1977	Peak growth, significant increase
	Summer	0.0637	0.0812	Decrease from Late Spring

Discussion

Calibration precision, accuracy and resolution.

The calibration function serve as the physical computation of the digital numbers into a physical unit in this case millimetres. The datasheet of the AS5311 describes a sensor resolution in the order of 0.488 microns. We did not have the instruments to test this resolution in our laboratory. However the calibration efforts and resultant root mean square error of 50 microns sufficiently address the scale of measurements for seasonal radial growth monitoring. Using a different calibration bench with a finally tuned calibration bench and an optical laser could be used to improve the calibration. Although the RMSE was higher than expected, the actual impact on the accuracy of the device was minimal. This is most clear when compared to the Infrared sensor from sections 1 and 2 of this thesis. The signal stability of the sensor is far superior in this aspect. This can be attributed to the closed natured of the actual sensor system itself and furthermore the contactless sensing mechanism between the sensor magnetic tape and the AS3511 chip. Indeed a similar chip and system were used to measure small stem displacement and radial growth of fruit trees (Clonch et al., 2021). Although results suggest a higher mean daily stem oscillation pattern dependant on season, we can confirm that the sensor performs extremely well under diverse temperature regimes. This was further confirmed by the low not negligible impact of temperature on the sensor inside the climate chamber. The dendrometers were sufficiently accurate considering the shape and response curve for seasonal radial growth monitoring being closely aligned to the D1 dendrometer belt and demonstrating small deviations of -1% and + 1% absolute diameter growth when a factor of 2π was used to scale radius to diameter. Indeed this result was sufficient given that one of the focuses of this study was to build a proof of concept.

Stem shrinking and swelling

The analysis conducted on the relationship between stem oscillation and air temperature, as measured by the dendrometers However the findings suggest that while there is some interaction between temperature and stem behaviour, temperature is not the primary driver of stem shrinking and swelling for the trees studied, nor is it specifically impacting the sensor itself. The observed timing of stem shrinking (during midday) and swelling (during nighttime) aligns with typical diurnal water transport patterns in trees (Steppe et al., 2006, 2015; Vospernik et al., 2020; Zweifel et al., 2000). However, the weak correlation with air temperature suggests that factors other than temperature are driving the oscillations. Possible alternative factors include Vapor Pressure Deficit (VPD), High VPD during the day can cause rapid water loss, contributing to midday shrinkage (Salomon et al., 2024). Soil moisture availability as well, which affects the tree's ability to replace lost water during cooler, nighttime periods could possibly explain the phenomena better. These processes typically lead to the shrinkage of tree stems during the heat of the day when transpiration exceeds water uptake and swelling at night when water uptake resumes. Based on both the statistical analysis and the visual inspection of the graphs, it is clear that air temperature is not the dominant factor controlling stem oscillation or causing the dendrometers materials to obscure the phenomena. While the data show some patterns related to temperature changes, particularly in

Tree 3 the low R-squared values and lack of significant p-values for most sensors imply that air temperature explains very little of the variance in stem oscillations. Thus, it is likely that the observed shrinking and swelling is indeed a true daily stem oscillation phenomena which was not a specific objective of this study. Future investigations should focus on more robust analysis including data on VPD, Sap Flow, Solar Radiation and Soil Water Moisture (Steppe et al., 2006, 2015) preferably at the same temporal resolution at the dendrometer designed in this study.

Seasonal growth dynamics

Considering the seasonal trends and dynamics of radial growth for monitored trees, the growth curves and timing of growth are similar to previous studies for P. Abias and A. Alba, in addition to with the monitored trees growing within observed annual increments (Cavlovic et al., 2014; Van Der Maaten-Theunissen et al., 2013). Results also indicate that individual trees behave differently in the same plot with seasonal growth dynamics differing according to seasonality. For example the two trees monitored by the piston system 1 and piston system 4, *P. Abias*, showed mean peak growth during spring and a depreciation in summer to late fall. While the other two systems installed on *A. alba* demonstrated a more constant growth increment throughout the season. This result was similarly captured in a study by which also used high precision dendrometers (Leštianska et al., 2024).

Conclusion

This study represents a significant step forward in the development and application of IoT-driven dendrometers for monitoring tree growth, particularly in the context of seasonal and diel stem dynamics. The calibration of the dendrometers demonstrated a high degree of precision, with the third-degree polynomial regression providing a strong fit between digital output and physical distance. Despite some challenges, such as the inverse relationship between movement and digital output due to sensor orientation, the calibration process achieved an RMSE of 0.05 mm, indicating that the sensors are well-suited for monitoring radial growth with a high level of accuracy.

The investigation into the temperature sensitivity of the dendrometers revealed minimal impact on sensor performance, with submillimeter variations in response to temperature changes. This finding is crucial for long-term monitoring, as it confirms that the sensors can reliably track stem growth without significant interference from environmental temperature fluctuations. The field monitoring results further validated the dendrometers' performance, showing that they closely matched the expected growth patterns of Picea abies and Abies alba. The observed radial growth dynamics, including diel oscillations, align with established physiological responses to environmental conditions, reinforcing the reliability of these sensors in capturing fine-scale growth changes.

Overall, this research provides a robust proof of concept for the use of linear magnetic-driven dendrometers in forest monitoring. The sensors demonstrated strong performance in both controlled and field conditions, offering accurate and continuous measurements of tree growth. The ability to detect diel stem oscillations and seasonal growth variations opens new avenues for understanding tree physiology and forest dynamics at a granular level. The results of this study contribute valuable insights to the field of forest monitoring, offering a viable tool for researchers and forest managers seeking to enhance their understanding of tree growth and carbon sequestration processes. Future work could focus on refining sensor calibration and exploring broader applications across different forest types and environmental conditions, further solidifying the role of IoT-driven dendrometers in forest digitization.

Thesis Conclusion

This thesis explored key concepts of digital technologies and their role in advancing forest science to introduce the growing trend toward applications of such technologies in forest science. The reason for pursuing such research was driven by the work completed on forest digital twins and the intrinsic need for smart technologies such as socketed reliable direct measurement devices. The objectives of the research was the following and will be addressed separately and do not follow the same sequence as the objectives stated at the beginning of this research.

- Develop and Adapt Novel IoT-Driven Dendrometers
- Adapt, design, and build two innovative types of dendrometers that integrate IoT technologies.
- Ensure continuous and precise measurement of tree stem radial increment.
- Make sensors low-cost, low-power, and capable of long-term deployment.
- Test and adapt sensors for various environmental conditions.

I demonstrated the functional adaptation of an off the shelf low cost low power input dendrometer which accurately captured radial growth, scaled to DBH for 2 growing seasons, characterising its behaviour under several rigorous sensitivity tests under laboratory conditions. It demonstrated quasi real time measurement capabilities driven by internet of things technology capturing stem radial increment changes consistently. Long term deployment is not a feature of such a sensor given it perishes easily, however enclosing the sensor improved both sensor stability and signal. Future use of such a sensor would require modification primarily focused on stabilising the laser beam from the infrared sensor.

- Evaluate Sensor Performances
- Conduct laboratory tests to assess the accuracy of developed dendrometers.
- Perform field tests to evaluate precision and reliability.
- Compare IoT-driven sensor performance with traditional manual measurement methods.

All sensors developed and deployed in this thesis underwent rigorous sensitivity analysis and comparison with available measurement instruments and methods. Robust laboratory tests were used to calibrate the dendrometers and establish stable connectivity. The infrared sensor performed much better under controlled environments, while the linear magnetic driven dendrometer maintained its stability from laboratory conditions to the field. In both cases the sensors demonstrated sensible results when compared to other measurement methods and as such support the use of low cost dendrometer sensor networks which may be placed in permanent pots for example, collecting highly granular data and *in situ.*

- Deploy and Monitor a Sensor Network in a Coppice With Standards Forest
- Implement a biannual monitoring campaign in a coppice forest in central Italy.
- Establish a proof of concept for a socketed network of IoT sensors.
- Collect and analyse high-resolution data on tree stem growth.
- Monitor woody biomass over time
- Create a dataset for understanding forest dynamics and carbon sequestration.

The biannual monitoring of the CWS in central Italy was successful, however a loss in total sensor network functionality occurred where several sensors failed or perished over the monitoring period. Irrespective a proof of concept for an IoT driven network was strongly supported. In addition the network captured highly granular time series on stem growth dynamics for both spouts and standards which has had little to no attention in the literature. The information derived from this monitoring campaign gives valuable insight into the growth dynamics of such silvicultural systems although it is highly site specific. Carbon dynamics between sprouts, stools and standards revealed a contrary hypothesis where the continued use of a coppice with standards (CWS) silvicultural method is more dynamic and resilient with respect to carbon stored and sequestered in live woody biomass. This contradicts conventional wisdom in the subject, however, requires a longer time series to confirm such notions.

- Address Technical Challenges and Enhance Sensor Capabilities
- Identify and address challenges related to the infrared proximity sensor.
- Overcome accuracy and environmental interference issues.
- Design and deploy a linear magnetic-driven dendrometer for improved precision.

The development of a new linear magnetic driven dendrometer significantly addressees the issues demonstrated from the Infrared Sensor. Spikes and dips in noisy data was significantly reduced. Furthermore, the measurement resolution and precision of the new dendrometer was greater than the infrared sensor where shrinking and swelling was identified and was not intended in the study specifically. Furthermore, seasonal dynamics of radial growth were also revealed.

The objectives outlined in this project represent a strategic and innovative effort to enhance forest monitoring through the integration of IoT-driven dendrometers. The development and adaptation of novel dendrometers tailored for continuous and precise measurement of tree stem radial increment are at the forefront of this initiative. By ensuring that these sensors are low-cost, low-power, and capable of withstanding diverse environmental conditions, the project addresses critical challenges in long-term forest monitoring. This endeavour not only advances sensor technology but also sets the stage for more accurate and reliable data collection, which is essential for understanding forest dynamics.

A key component of this project is the evaluation of sensor performance through a combination of laboratory and field tests. By rigorously comparing the accuracy, precision, and reliability of these IoT-driven sensors with traditional manual measurement methods, this thesis aimed to ensure that the new technology meets the high standards required for effective forest management. The deployment of a sensor network in a coppice with standards forest in central Italy further exemplifies the practical application of this technology. The biannual monitoring campaign provided a proof of concept for the use of IoT sensors in real-world conditions, generating a high-resolution dataset that offers unprecedented insights into tree growth, biomass accumulation, and carbon sequestration.

Beyond technical development and field application, the project also sought to address the broader implications of IoT sensor integration in forestry. By overcoming technical challenges, such as environmental interference and measurement precision, this research paves the way for the creation of forest digital twins—virtual models that can provide real-time, actionable insights for forest management. The exploration of these digital twins' potential applications, particularly in monitoring forest health, growth, and carbon stock changes, positions this project at the cutting edge of forest digitization. The dissemination of findings and methodologies will contribute to the ongoing evolution of forest monitoring technologies, offering valuable recommendations for future research and practical applications across diverse forest ecosystems.

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