TECHNISCHE UNIVERSITÄT WIEN

MASTER THESIS

Assessing forest parameters through the evaluation of smartphone-based measurement techniques

for the attainment of the academic degree

Diplom-Ingenieur/in

within the study program

Geodesy and Geoinformation

submitted by

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carried out at Department of Geodesy and Geoinformation
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Wien, 03.02.2025

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Declaration instead of an oath

I, Christoph Neumayr,

born on 16 September 1997 in Sankt Pölten, declare,

- that I have written my Master's thesis independently, have not used any sources and aids other than those specified,
- that I have made use of translation and style adaptation software as a tool to enhance my writing style,
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Christoph Neumayr BSc
Vienna, on February 3, 2025

Abstract

The growing need for accessible and cost-effective methods in forest inventories has driven interest in utilizing smartphone-based technologies. This thesis examines the potential of six smartphone applications in assessing key forest parameters, namely tree height and diameter at breast height (DBH), and compares their performance against established methods such as terrestrial laser scanning (TLS) and manual measurements. The thesis is motivated by the demand for scalable, affordable, and user-friendly tools capable of supporting both professional forest management and citizen science initiatives.

Field data were collected in a diverse forested area, where the selected applications were tested under real-world conditions to evaluate their measurement accuracy, usability, and efficiency. TLS and in-situ measurements using a measuring tape served as the reference for data validation, ensuring a robust benchmark for comparison. Particular attention was paid to identifying the strengths and limitations of the applications, including error sources related to environmental conditions and user experience. Furthermore, the thesis explored whether these smartphone-based solutions could achieve comparable or faster measurement times than traditional TLS methods while maintaining acceptable accuracy levels. Additionally, a simulation of errors was conducted to evaluate their detectability using real measurement data, offering recommendations for workflow adjustments to minimize errors.

The results indicate that smartphone applications offer a promising alternative for forest inventories, particularly in scenarios where affordability and portability are critical. The average root mean square error (RMSE) across all tested applications was 2.3 cm for DBH and 1.75 m for tree height, demonstrating a competitive level of accuracy. Notably, the maximal reduction of measurement errors for DBH for Geo-Quest was achieved when the tree occupied approximately 2/3 of the smartphone screen during measurement. The analysis also highlighted opportunities for optimization in application design, including the integration of advanced error correction algorithms and more intuitive user interfaces.

This research contributes to the growing body of knowledge on leveraging mobile technologies in forestry and provides practical recommendations for enhancing the reliability and efficiency of smartphone-based measurement tools. By bridging the gap between professional-grade equipment and accessible technologies, this thesis underscores the potential of smartphones to democratize forest data collection and foster greater public engagement in environmental monitoring.

Kurzfassung

Der wachsende Bedarf an zugänglichen und kostengünstigen Methoden für Forstinventuren hat das Interesse an der Nutzung smartphonebasierter Technologien geweckt. Diese Masterarbeit untersucht das Potenzial von sechs Smartphone-Anwendungen zur Erfassung zentraler Forstparameter, insbesondere der Baumhöhe und des Brusthöhendurchmessers (DBH), und vergleicht deren Leistungsfähigkeit mit etablierten Verfahren wie terrestrischem Laserscanning (TLS) und manuellen Maßbandmessungen. Der Forschungsansatz wird durch die Nachfrage nach skalierbaren, kostengünstigen und benutzerfreundlichen Werkzeugen motiviert, die sowohl die professionelle Forstwirtschaft als auch Citizen-Science-Initiativen unterstützen können.

Die Felddaten wurden in einem heterogenen Waldgebiet erhoben, in dem die ausgewählten Anwendungen unter realen Bedingungen auf ihre Messgenauigkeit, Benutzerfreundlichkeit und Effizienz getestet wurden. TLS und Vor-Ort-Messungen mit einem Maßband dienten als Referenz für die Datenvalidierung. Besonderes Augenmerk lag auf der Identifizierung der Stärken und Schwächen der Anwendungen, einschließlich der Fehlerquellen im Zusammenhang mit Umweltbedingungen und der Benutzererfahrung. Darüber hinaus wurde untersucht, ob diese smartphonebasierten Lösungen mit herkömmlichen TLS-Methoden vergleichbare oder schnellere Messzeiten bei akzeptabler Genauigkeit erreichen können. Zusätzlich wurde eine Simulation von Messfehlern durchgeführt, um deren Erkennbarkeit anhand realer Messdaten zu bewerten und Empfehlungen für Workflow-Anpassungen zur Minimierung von Fehlern abzuleiten.

Die Ergebnisse zeigen, dass Smartphone-Anwendungen eine vielversprechende Alternative für herkömmliche Aufnahmeverfahren bei Forsteinventuren darstellen, insbesondere in Szenarien, in denen Kosteneffizienz und Tragbarkeit entscheidend sind. Der durchschnittliche Root-Mean-Square-Error (RMSE) über alle getesteten Anwendungen betrug 2.3 cm für den DBH und 1.75 m für die Baumhöhe, was ein wettbewerbsfähiges Genauigkeitsniveau darstellt. Bemerkenswert war, dass die maximale Reduktion von Messfehlern beim DBH erreicht wurde, wenn der Baum etwa 2/3 des Smartphone-Bildschirms während der Messung einnahm. Die Analyse hob außerdem Optimierungspotenziale in der Anwendungsentwicklung hervor, darunter die Integration fortschrittlicher Fehlerkorrekturalgorithmen und intuitiverer Benutzeroberflächen.

Diese Forschung trägt zur wachsenden Wissensbasis über den Einsatz mobiler Technologien in der Forstwirtschaft bei und liefert praktische Empfehlungen zur Verbesserung der Zuverlässigkeit und Effizienz smartphonebasierter Messwerkzeuge. Indem die Lücke zwischen professionellen Geräten und zugänglichen Technologien geschlossen wird, unterstreicht diese Studie das Potenzial von Smartphones, die Datenerhebung im Wald zu demokratisieren und die öffentliche Beteiligung an der Umweltüberwachung zu fördern.

Acknowledgements

I would like to express my sincere gratitude to Univ.Ass. Dipl.-Ing. Benjamin Wild for his invaluable scientific support and for inspiring the topic of this work. I am also deeply grateful to Senior Scientist Dipl.-Ing. Dr.techn. Markus Hollaus for his thorough guidance and unwavering support throughout the work phase.

Contents

1. Introduction

1.1. Motivation

As Corona [2016, p. 8] mentions in his publication:

> *"Forests provide a wide range of ecosystem services from which people benefit, and upon which all life depends."*

This highlights why everyone should take an interest in forests, their development, and their current state, as the entire population depends on them in one way or another. The various reasons for monitoring forests can be broadly categorized into global change issues, wildlife-related concerns, and economic considerations. These varied motivations inherently require different scales of investigation, ranging from global to local levels. This is also why there are so many different approaches, given the vast diversity of interests [Corona 2016].

The economy demands a variety of forest-related figures. For example, forest owners require information to improve forest management and ensure cost-efficient planning for activities like wood harvesting and tree planting. Other valuable figures include forest growth rates or the volume of wood per area (measured in m^3/ha). This data can help forest owners select more suitable tree species for their specific locality, considering factors such as temperature, soil type, and terrain shape, potentially increasing the revenue generated from their land. On a larger scale, organizations or countries are often interested in broader assessments to respond to significant changes in forestry [Sahashi 2002; Charlton et al. 2020].

The other important aspect concerns issues related to climate change and wildlife. This sector, as in other areas, has gained increasing importance for forestry in recent decades. The more we can learn from various datasets collected on forests or protected forests, the better we will understand how to minimize our impact on wildlife [Moomaw, Masino, and Faison 2019]. Diversified forests are vital for protecting species threatened with extinction. As Aguilar [2024] highlights the need to protect and restore diverse, healthy forest ecosystems to prevent biodiversity loss. In agriculture, monocultures—cultivating a single crop species—promote pest and disease outbreaks due to a lack of natural diversity, often requiring more pesticides and herbicides, which can harm the environment [Balogh 2021]. Similarly, in forestry, monocultures reduce biodiversity and increase vulnerability to pests and diseases, necessitating chemical interventions. Diverse forests enhance resilience and support a broader range of species, contributing to ecological health. Monitoring forest diversity is essential for conservation, enabling targeted actions to mitigate monoculture effects and promote biodiversity, which protects species and ensures sustainable forest resources for future generations [Gardner 2010].

To further illustrate the importance of forest diversity, their role in protecting landscapes and human settlements in challenging environments deserves attention. In mountainous regions, forests can be classified as protection forests as they can protect against avalanches, which is why data about the forest density, type and sizes of individual trees is crucial in assessing their health and ability to protect [Teich et al. 2012]. In small scales forest growth rates allow to quantify the carbon storage capacity of forests more exactly, which helps to understand better the importance of forests against global warming [Bello et al. 2015].

Beyond their localized protective functions, forests play an integral role in addressing global environmental challenges. On the global scale, datasets about forests are essential for understanding the connection between global warming and deforestation. Forests store between 70% and 90% of global above-ground biomass (AGB), making them critical for carbon cycling and biodiversity conservation [Houghton, Hall, and Goetz 2009]. Globally, forests hold approximately 861 gigatons of carbon, with 42% stored in living biomass, both above and below ground [Harris and Gibbs 2022]. This immense storage capacity underscores the vital role forests play in mitigating climate change and maintaining ecological balance. However, precise quantification of AGB remains challenging due to the uneven distribution of sampling data [H. Nguyen et al. 2019]. Advances in satellite-based technologies, such as optical sensors, have significantly improved the monitoring of forest cover changes and carbon dynamics on a global scale [Hansen et al. 2013].Additionally, the European Space Agency's Biomass satellite is expected to enhance global precision in measuring forest biomass, contributing to a deeper understanding of the carbon cycle [Scipal et al. 2010]. Addressing deforestation is paramount, as it directly contributes to carbon emissions and undermines efforts to mitigate climate change [Canadell and Raupach 2008]. Forest protection is essential, as they store significant amounts of carbon, playing a key role in combating global warming [Duncanson et al. 2023]. Remote sensing technologies and forest conservation strategies work hand in hand to mitigate the effects of deforestation while preserving biodiversity [Merzdorf Evans 2022].

Due to the importance of having accurate and timely data about forests, there have been signifiant advances in the field of forest monitoring. The next chapter aims to shed light on the state-of-the-art in this regard.

1.2. State of the art

National forest inventories play a fundamental role in advancing our understanding of forest data collection practices and the prioritization of relevant parameters across diverse regions. While certain core metrics are commonly used across different regions, their specific implementation varies to account for distinct ecological contexts and management goals. These variations often encompass the measurement of additional tree-specific parameters, reflecting localized priorities. Among the most frequently recorded parameters are the following [Stillhard et al. 2023; Hauk et al. 2020; Nagel 2017; M. A. Miller 2023]:

- Tree species
- Tree height
- Tree class
- Diameter at breast height (DBH)
- Trunk diameter in 30% of the height
- Shank quality class
- Type of utilization
- Crown boundary height
- Presence of cane rot
- Overgrowth or pre-growth
- Identification of dying trees
- Forking of the tree trunk
- Growth class
- Age group
- Stem damage
- Degree of decomposition
- Sun exposure

Given the extensive range of parameters recorded in forest inventories, this thesis narrows its focus to two key metrics: diameter at breast height (DBH) and tree height. These parameters are among the most critical in forest inventory due to their central role in estimating forest structure, biomass, and carbon storage capacity. Allometric models further underscore the significance of DBH and tree height measurements by providing an efficient and non-destructive means of estimating AGB and other critical metrics. These models rely on mathematical relationships that correlate measurable parameters, such as DBH and tree height, with complex or less accessible metrics like biomass. Widely used allometric equations take the form:

$$\log(M) = A + B \cdot \log(DBH) \tag{1.1}$$

where M represents biomass, and A and B are empirically derived parameters tailored to specific tree species or ecological zones [Zianis et al. 2005]. Platforms such as GlobAllomeTree provide access to species-specific equations, facilitating accurate assessments across varied climatic and vegetative conditions [Henry et al. 2013]. By leveraging data from destructive sampling methods to build these equations, allometric models enable large-scale biomass estimations crucial for forest monitoring and carbon stock assessments [Brede et al. 2022].

The standard definition of DBH refers to the diameter of a tree measured at a height of 1.3 m above the ground. However, slight variations in the specified measurement height exist across international guidelines. For instance, the U.S. Department of Agriculture recommends a measurement height of 4.5 ft (approximately 1.37 m) [M. A. Miller 2023], while most European forest inventories adhere to the 1.3 m standard [Stillhard et al. 2023; Hauk et al. 2020; Nagel 2017]. To ensure consistency with widely adopted European practices, this thesis employs a standardized measurement height of 1.3 m. Trees with a DBH of less than 5 cm are excluded from the analysis, as these are typically classified as seedlings or shrubs. Nevertheless, certain inventories apply alternative thresholds, such as a minimum DBH of 7 cm [Stillhard et al. 2023; Nagel 2017] or 5 inches (approximately 12.7 cm) [M. A. Miller 2023]. In Austria, a threshold of 10 cm is commonly used [Hauk et al. 2020]. These discrepancies underline the importance of establishing clear and consistent measurement protocols for comparability across studies.

Figure 1.1 illustrates several challenges associated with determining DBH under varying field conditions. For example, in cases where a tree forks below the designated measurement height (case b), each stem is typically treated as an independent individual. Similarly, cases involving inclined stems (cases c and d) demonstrate that the measurement height is determined along the stem's axis rather than strictly from a vertical reference. Case e highlights additional complexities, such as inconsistent ground reference points, which can further complicate accurate and standardized DBH measurements. These examples underscore the need for rigorous methodological standards to ensure the reliability of forest inventory data [Stillhard et al. 2023].

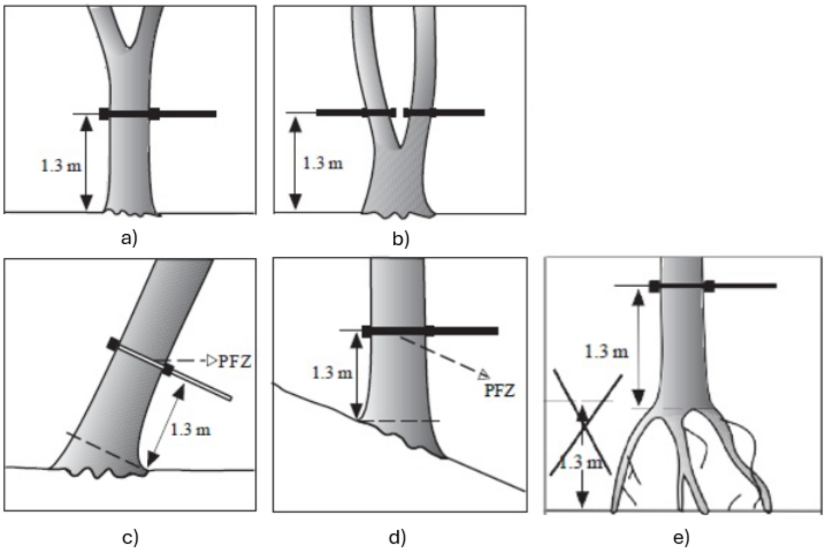

Figure 1.1.: Different kinds of DBH measurements adopted from Stillhard et al. [2023, p. 28] a) default case for DBH, b) forking of a tree trunk, c) and d) direction of the stem measuring height, e) difference between stem and roots

The definition of tree height is the distance between the base and the tip of the tree's crown [Hauk et al. 2020]. This value is rounded to decimetres, as measurements are typically not more precise. Seedlings are often categorized only into height classes [Hauk et al. 2020]. In the case of a broken crown or trunk, the height of the tree should be recorded as it would have been in an unbroken state [Hauk et al. 2020]. It is essential to note that when measuring tree height, the aim should not be directed at the crown edge, as this would only result in the apparent height rather than the true height. Instead, the highest point of the tree must be targeted (see Figure 1.2). Neglecting this can lead to a systematic overestimation of the height [Stillhard et al. 2023].

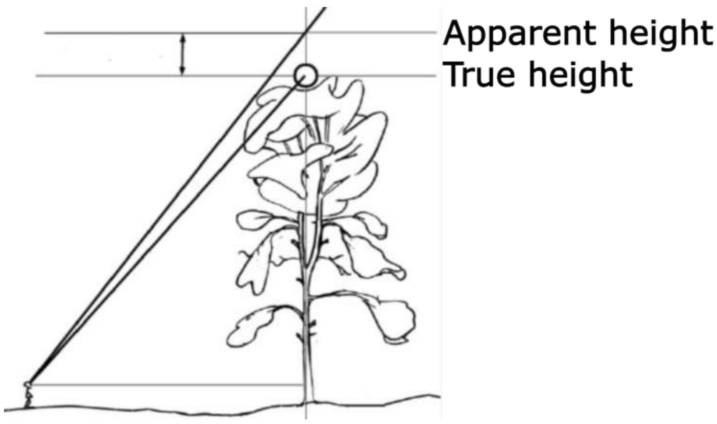

Figure 1.2.: Possible source of error for the height measurement adopted from Düggelin [2019]

The data collection for the national forest inventories takes place within designated survey areas, which are typically circular [Stillhard et al. 2023; Hauk et al. 2020; M. A. Miller 2023] but may also be square [Nagel 2017] in shape, ranging in size from 170 m² [M. A. Miller 2023] to 1 hectare [Nagel 2017]. Currently, national forest inventories suggest to determine the tree height using instruments such as a clinometer, relascope, or a Vertex. For measuring the DBH, tools like a diameter tape, measuring tape, or calipers are employed [Stillhard et al. 2023; Hauk et al. 2020; Nagel 2017; M. A. Miller 2023].

The clinometer is a fundamental tool, operating on the principle of measuring angles of inclination relative to gravity. By determining the angle between the observer and the top of a tree from a known horizontal distance, tree height can be calculated using trigonometric principles [M. A. Miller 2023]. Its simplicity and affordability (available for 140€ at Treemarker.co.uk, accessed: 2025.01.04) make it particularly suitable for basic forestry applications, especially in contexts where budget constraints are significant. This device is lightweight and robust, owing to its lack of electronic components, which enhances its durability under field conditions. However, the operation of a clinometer requires manual alignment with the target and precise reading of the displayed angle. While its design facilitates straightforward handling, accurate results depend heavily on the user's skill and steady hands. Additionally, the need for manual calculations to derive height values may introduce inefficiencies compared to more automated solutions [Mecholic 2024].

The relascope is a versatile optical instrument for measuring tree heights and diameters. Its design incorporates a system of prisms or lenses that project measurement scales directly onto the target, allowing users to estimate values with precision. The mirror relascope includes vertical measurement scales (degree, percent, and topographic) specifically designed for accurately determining tree height. The topographic scale enables direct height readings at varying distances, with height values adjusting proportionally to the observer's distance from the tree. This functionality makes the relascope a critical tool for comprehensive forestry assessments. The cost of a relascope is moderate (available for 2300€ at Silvanus.at, accessed: 2025.01.04), depending on the brand and specific features, but its multifunctionality and reliability often justify the investment for detailed surveys. Proper handling of the relascope requires careful calibration and precise alignment. Users must maintain a defined distance from the tree and account for terrain slope to ensure accurate readings. The primary advantages of the relascope lie in its ability to measure multiple forest parameters with a single device and its potential for delivering precise results [Bitterlich et al. 2021].

The Vertex is an advanced ultrasonic instrument for measuring tree heights and distances, crucial in forestry surveys. It calculates horizontal and slope distances by emitting ultrasonic signals between the device and a transponder fixed at the tree base, combined with inclination angle measurements. This enables accurate readings even in dense understory where line-of-sight methods fail. Calibration is required before use, especially when temperature or humidity conditions change, as these affect the speed of sound. The device allows the operator to measure tree height by recording the distance and angle to the transponder, then aiming at the treetop. Additional height points, such as commercial height, can be measured from the same position. While the Vertex ensures precise and efficient data collection by automating calculations, it is susceptible to signal interference from environmental noise, such as wind, rain, or insects, potentially leading to errors. Despite its advanced features, the Vertex is relatively moderately priced (available for 1500€ at Grube.at, accessed: 2025.01.06), offering an excellent balance of cost, accuracy, and efficiency for professional forestry tasks [Haglöf 2020].

Diameter tapes and measuring tapes are offering similar functionality with one key distinction. Measuring tapes require the user to calculate the DBH [cm] from the measured circumference U [cm] using the formula 1.2. In contrast, diameter tapes simplify this process by including a pre-calibrated diameter scale, allowing the DBH to be read directly without the need for manual conversion. This feature eliminates the calculation step, providing immediate results and enhancing convenience in field measurements. Both tools are used by wrapping the tape around the tree at breast height, ensuring it is placed perpendicular to the tree axis for accurate readings. They are lightweight, portable, and affordable (available for 30€ at Silvanus.at, accessed: 2025.01.05), making them suitable for estimating the DBH efficiently. Due to the typical tape length of 5 m, the maximum measurable diameter is limited to approximately 160 cm [M. A. Miller 2023; Stillhard et al. 2023].

$$DBH = \frac{U}{\pi} \tag{1.2}$$

Calipers are precision tools used to measure the DBH of a tree directly. The measurement is taken by positioning the two arms of the caliper across the tree trunk at breast height and ensuring they are perpendicular to the tree axis for accuracy. Calipers are highly accurate for small to medium-sized trees and are known for their durability and reliability in field conditions. While basic models are relatively affordable (available for 180€ at Silvanus.at, accessed: 2025.01.04), more advanced versions can be costly (available for 1900€ at Silvanus.at, accessed: 2025.01.04). However, their utility is limited to trees within the size range of the caliper arms, and larger models can be bulky to carry, posing challenges in dense forest environments [Stillhard et al. 2023].

In addition to conventional and well-established measuring devices, novel methods for generating tree parameters have emerged. While some of these methods are being tested to produce comprehensive datasets, they are sometimes experimental, maybe not user-friendly, or lack cost-effectiveness. In certain cases, commercially available measuring devices or software applications are either unavailable. Two primary categories of these innovative approaches include laser scanners and mobile devices, such as smartphones and tablets.

Laser scanning for data generation is generally divided into two stages: the on-site recording of data and the subsequent off-site evaluation. Regarding the recording of point clouds, various approaches are available. Forest areas can be captured using terrestrial laser scanning (TLS) from multiple scanning positions [Charlton et al. 2020; Cabo, Ordóñez, et al. 2018]. TLS devices represent a significant investment, with prices starting at several tens of thousands of euros. Moreover, they typically weigh 6 kg or more and require a tripod for operation [Trimble 2024], which can limit manoeuvrability in forest areas with difficult access. To address these challenges, studies have explored the use of portable laser scanners (PLS) [Proudman et al. 2022]. While PLS systems facilitate transportation and transition from static to continuous dynamic measurements, the weight of the device remains a concern. An alternative to carrying the instrument is the use of airborne laser scanning (ALS) or unmanned aerial vehicle (UAV) laser scanning [Lindberg and Hollaus 2012; Dalla Corte et al. 2020; Wieser et al. 2016]. These platforms can efficiently cover large areas. However, they involve substantial costs and require careful planning of flight routes. In addition to challenges during data acquisition, the evaluation of tree parameters relies on specialized software tools. Applications such as Stemfit [Charlton et al. 2020], 3DFin [Cabo, Ordóñez, et al. 2018], and OPALS [Otepka-Schremmer and Mandlburger 2020] enable the detailed analysis of point cloud data.

There is a significant demand for measuring devices that are not only cost-effective but also easy to use and transport, particularly for measuring tree parameters of national forest inventories. Mobile devices like smartphones and tablets are well-suited to meet this demand. These devices are often readily available or moderately priced, especially when compared to TLS systems. Various approaches have been developed to utilize mobile technologies for forest measurements. For instance, methods employing Ultra-Wideband (UWB) modules have been explored to measure the number of trees, DBH, and tree locations [Yuan et al. 2021; Sun et al. 2023]. Another innovative instrument has been designed to calculate DBH and tree height using angle and distance measurements, emphasizing ease of use [Yuan 2021]. Additionally, close-range photogrammetry is increasingly used to generate tree parameters. Research by Miller, Morgenroth and Gomez [2015] demonstrates that Structure-from-Motion (SfM) combined with multi-view stereo-photogrammetry is effective for evaluating tree heights, DBH, crown spread, and other parameters. A similar approach using smartphone videos, combined with clustering algorithms, has also shown promising results [Song et al. 2023]. Programs originally developed for indoor navigation, such as Microsoft Kinect and Google Tango, have been adapted for forestry applications. These systems use a combination of colour and near-infrared cameras, along with near-infrared laser projectors, to calculate DBH [Hyyppä et al. 2017]. However, a major limitation of these systems is that processing typically requires specialized software and is performed off-site, which can limit their practicality. Low-cost devices like smartphones provide numerous ways to measure tree parameters. For example, the combination of smartphone photography, close-range photogrammetry, and machine vision enables the estimation of DBH, crown diameter, and tree height [X. Wu et al. 2019; Ahamed et al. 2023]. A notable example for mobile application that calculates DBH by integrating "Light Detection And Ranging" (LiDAR) and image data exist [Wang et al. 2023; Tatsumi, Yamaguchi, and Furuya 2023]. The use of low-cost LiDAR sensors embedded in tablets has also shown great promise for generating point clouds and achieving accurate DBH measurements [Çakir et al. 2021]. For point clouds, diameters are calculated by fitting circles to the tree trunk using a least-squares minimization approach, ensuring accurate and reliable measurements. LiDAR sensors have demonstrated significant time and cost efficiency compared to traditional methods, with the added potential of involving citizen scientists in forest data collection efforts [Pace et al. 2022]. Citizen scientists, members of the public who contribute to scientific research, could play a vital role in expanding forest monitoring by using accessible tools, such as smartphones or tablets, to gather data. However, a major limitation lies in the fact that LiDAR sensors, essential for such measurements, are only available in a limited number of high-end smartphones and tablets. For example, LiDAR is available on iPhones from the Pro and Pro Max series starting with the 12th generation, as well as on a few Android devices such as the Samsung Galaxy S21 Ultra, Google Pixel 6 Pro, OnePlus 9 Pro, and a handful of others [Frey 2024]. These devices are not only expensive but also relatively uncommon, restricting the widespread participation of citizen scientists. The high cost and limited availability of such technology reduce its potential for large-scale adoption, particularly in regions where access to advanced devices is limited.

An alternative to point cloud-based DBH estimation relies on simple trigonometric principles. For calculating the DBH [m], two primary parameters are required: the distance to the tree c [m] and the opening angle γ [rad] to each side of the tree. These parameters form the basis of the straightforward formulas 1.3, 1.4, and 1.5, as described by Gruber and Joeckel [2017]. These formulas represent an analytical, closed-form solution. First, α [rad], the supplementary angle of γ, is calculated. Subsequently, the radius r [m] is determined, and doubling this value yields the DBH [m]. A visual representation of these calculations is provided in Figure 2.8.

$$\alpha = \pi - \gamma \tag{1.3}$$

$$r = \frac{c}{tan\frac{\alpha}{2} \cdot tan\frac{\alpha}{4}} \tag{1.4}$$

$$DBH = 2 \cdot r \tag{1.5}$$

There are several methods to determine the height of a tree h [m]. Most applications use an approach that involves measuring the distance to the tree d [m] and the angle ϕ [rad] between the highest point of the tree crown and the lowest point of the tree trunk. As described by Enterkine et al. [2022], the tree height can be calculated using the following formulas 1.6, 1.7 and 1.8, which represent an analytical, closed-form solution:

$$h = h_1 + h_2 \tag{1.6}$$

$$h_1 = d \cdot tan(\phi_1) \tag{1.7}$$

$$h_2 = d \cdot tan(\phi_2) \tag{1.8}$$

Here, d represents the horizontal distance to the tree measured at smartphone height. This is enclosed by the angles ϕ_1 [rad] and ϕ_2 [rad], whereby angle ϕ_1 extends from d to the tree crown and angle ϕ_2 extends from d to the start of the tree trunk. One might assume that the height at which the smartphone is held could influence the measurement, as individuals vary in height, leading to different measuring heights for holding the smartphone. However, this has no effect because the measurements are always taken horizontally to the tree. The angles ϕ_1 and ϕ_2 adjust proportionally to the measuring height, ensuring that the calculated tree height remains the same regardless of the smartphone's height.

1.3. Objectives of the work

The present work explores alternative methods to enable individuals to collect forest monitoring data using standard smartphones. This approach leverages the affordability, portability, and ease of use of such devices, making data collection accessible to a broader audience. Excluding the use of LiDAR sensors is a deliberate decision in this thesis to ensure inclusivity, as these sensors are available in only a small fraction of smartphones or tablets. Instead, the focus lies on empowering users to contribute to citizen science initiatives using widely available and affordable technology, thereby overcoming the barriers posed by high costs and limited device accessibility. To achieve this, it is equally important to actively motivate and engage individuals by emphasizing the societal and environmental benefits of their contributions.

The primary objective of this thesis is to evaluate the effectiveness of various smartphone applications in measuring tree parameters, specifically height and DBH. Attention is given to determining whether the genus of a tree influences the accuracy of the parameter estimation. Additionally, the thesis aims to identify the potential advantages and disadvantages of the applications under investigation. Of particular interest is whether any method demonstrates superior efficiency in execution or yields higher-quality results. Another key aspect of the evaluation is comparing the measurement times of these methods with those of TLS to assess whether they can achieve comparable or even faster results. Special emphasis is placed on identifying potential sources of error and verifying whether the theoretical assumptions underlying these methods align with practical outcomes. To this end, an error simulation is conducted to analyse how measurement inaccuracies propagate through to the final parameter estimations. This includes examining whether the expected strengths and limitations of the methods are observed in real-world scenarios. The quantitative and qualitative results gathered through this thesis will provide the foundation for addressing the overarching question: how might an "ideal" application for tree parameter measurement be designed?

Given the constraints and specific limitations associated with smartphone applications, a comprehensive analysis was conducted, resulting in the identification of six applications that meet the criteria. These selected applications are as follows:

- Arboreal Tree Height [Sandim et al. 2023; Sveaskog 2021; Arboreal 2024]
- ARTreeWatch [F. Wu et al. 2023]
- Geo-Quest
- GLOBE Observer [Campbell 2021; Enterkine et al. 2022]
- GreenLens [Feng et al. 2023; Feng et al. 2024a; Feng et al. 2024b]
- Working Trees [Ahamed et al. 2023]

The following chapters are structured to provide a comprehensive analysis and evaluation of the research objectives outlined above. Chapter 2 delves into the data and methods used in this thesis. It begins by describing the study area, providing the context for the data acquisition process. This is followed by a detailed overview of the tools and methods employed, including a description of smartphone applications, reference data collection procedures, and evaluation criteria. Chapter 3 presents the results and discussion. It is subdivided into qualitative and quantitative analyses. The qualitative analysis assesses the user-friendliness, robustness, and efficiency of the investigated applications. The quantitative analysis examines the accuracy and reliability of the measurements compared to reference data, supported by statistical evaluations. Furthermore, this chapter discusses the observed strengths and weaknesses of each application. Chapter 4 concludes the work by summarizing the findings and providing recommendations for future improvements and applications of smartphone-based tree measurement technologies. This structured approach ensures that each research question is addressed systematically and provides a clear progression from objectives to findings and implications.

2. Data and methods

2.1. Study area

For this research, a specific area within the Prater, a park located in Vienna's second district, was selected for data acquisition. The park encompasses diverse landscapes, including meadows, water surfaces, solitary trees, and forested areas. To simulate realistic measurement conditions, a forested area was chosen as the study site. This selection ensured a variety of tree species, DBH and tree heights while minimizing understory vegetation, which can interfere with measurements. Forests generally pose greater challenges for measurement compared to isolated trees in open meadows, where sufficient space allows for easier height estimation and definition. The study area is depicted in Figure 2.1, where all measured trees are shown in green with exemplary labelling. Unfortunately, the official tree cadastre of the city of Vienna [StadtWien 2020] does not provide data for this specific area, likely due to its large size and high tree density. The available cadastre trees are marked in red in Figure 2.1, also with exemplary labelling [StadtWien 2020]. As a result, no comparison with the official tree cadastre was conducted. For map creation, orthophoto data from Basemap.at [2021] was used.

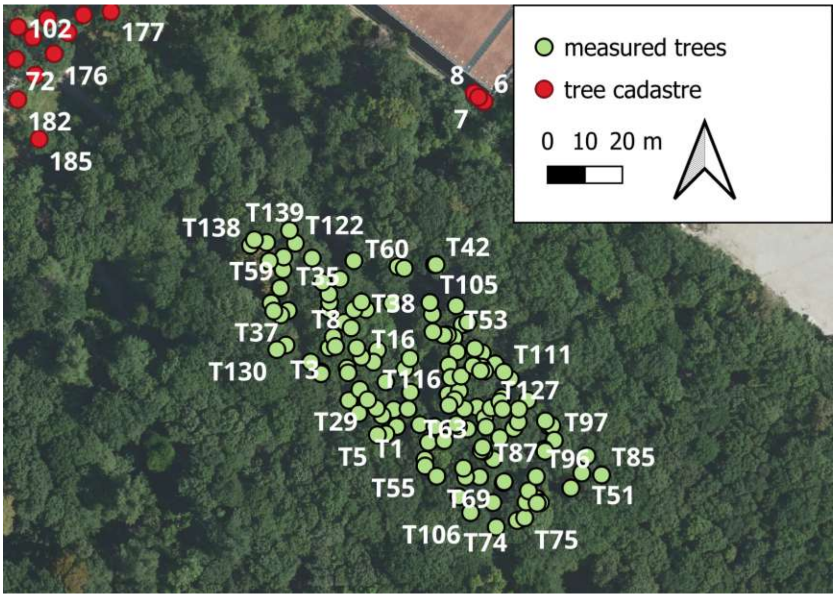

Figure 2.1.: Prater investigation area with exemplary labelling of measured trees (green) and trees from the Vienna tree cadastre (red) (data source: Stadt Wien – data.wien.gv.at). Displayed with an orthophoto (data source: basemap.at).

2.2. Reference data acquisition

To ensure reliable and comprehensive data comparisons, it was essential to employ accurate instruments for data collection. In this thesis, a combination of TLS and diameter tape measurements was utilized. The diameter tape was selected for measuring the DBH due to its high precision, while TLS provided the most accurate means of determining tree height and served as an additional independent estimate for the DBH.

The terrestrial laser scanning data were acquired using a RIEGL VZ-600i scanner. The scanner is georeferenced using its equipped GNSS antenna, connected to the Real-Time Kinematic (RTK) network provided by "Echtzeit Positionierung Austria" (EPOSA) [Eposa.at]. Data preprocessing, including point cloud registration, was carried out using the RiSCAN PRO software [Riegl 2024]. Tree heights were manually measured within the point clouds using the open-source software CloudCompare [Girardeau-Montaut 2024].

For the DBH estimation a classic diameter tape, the software 3D Forest Inventory (3DFin) [Cabo, Laino, et al. 2023] and OPALS [Otepka-Schremmer and Mandlburger 2020] were used. As described in 1.2 the DBH can be just read of the diameter tape. For larger tree diameters, there is a small hook to hang the tape on the bark in order to be able to measure straight.

3DFin [Cabo, Laino, et al. 2023; Laino et al. 2024] is a software package that can be integrated into CloudCompare [Girardeau-Montaut 2024] and QGIS [QGIS 2024], offering users three operational modes: basic, advanced, and expert. The primary difference between these modes lies in the number of parameters that can be configured by the user. In basic mode, most parameters are assigned default values, allowing users to modify only a fundamental subset of parameters that are considered the most critical. These include the search area for tree trunks, the clipping intensity, and whether the point cloud is already normalized. In contrast, advanced and expert modes provide access to a broader range of parameters for more detailed customization. Despite these differences, all modes follow the same underlying algorithmic structure, which consists of four main steps. The first step involves the height normalization of the point cloud. During this process, noise below the ground surface and above the tree canopy is filtered out. A Digital Terrain Model (DTM) is then generated, and the normalized height of each individual point in the point cloud is calculated. The second step focuses on the identification of tree trunks. This is achieved by defining a search area using horizontal stripes, followed by filtering out branches and clustering points. Small clusters are subsequently eliminated to isolate the trunks. In the third step, the entire tree is identified within the point cloud by determining the axis of the previously detected trunks, which serves to delineate the search area for each tree. Tree heights are then calculated by clustering the points associated with each tree. Finally, in the fourth step, tree diameters are determined by fitting circles to the trunk at various heights using a least squares minimization approach [Cabo, Laino, et al. 2023; Laino et al. 2024].

The DBH module of OPALS [Otepka-Schremmer and Mandlburger 2020] requires as input a file containing the approximate positions of tree trunks and the patch length. These positions are derived from the analysis performed in 3DFin [Cabo, Laino, et al. 2023] and subsequently used in this module. The process begins with the selection of relevant points in cylinders, makes a robust least-square fitting and minimize outliers. After computing the first cylinder, the software traces the trunk both along and opposite to the axis direction until the entire length of the tree is processed. The module outputs several parameters, including tree height, DBH and additional tree-related metrics [Otepka-Schremmer and Mandlburger 2020].

2.3. Investigated apps

A wide range of apps for measuring tree parameters exists. Tables 2.1 and 2.2 provide an overview of those compatible as of 2024.08.13 with the Galaxy M34 5G, which served as the test device for this analysis. This smartphone was selected, which will be discussed in more detail later (see chapter 2.4). Theoretically, additional apps are available, but some were excluded from this analysis because they are either restricted to iOS devices or require specialized hardware, such as lidar sensors, which are not available on most Android devices. Android's significantly larger global market share compared to iOS [StatCounter 2024] reinforces the decision to focus on Android-compatible apps. For example, the Arboreal Tree Height app, while available for Android, is not as feature-rich as its iOS-exclusive counterpart, Arboreal Tree, which offers more comprehensive functionality. The column *observed parameters* in the tables highlights which tree parameters each app can measure and evaluate. Most of the apps listed are free to use, with the exception of Arboreal Tree Height, which requires a paid subscription. The developers of these applications are distributed across the Northern Hemisphere, particularly in countries with extensive forested areas, such as Sweden and Austria. Minimum requirements for these apps typically include a specific Android version in combination with ARCore support. This compatibility and its implications for app functionality will also be described in detail later. Notably, GLOBE Observer is the only app that functions without ARCore.

App name	Observed parameters	Operating System	Costs	Developed by (Developed in)	required Android version	App access	Released on	Last updated	Species detection integrated
Arboreal Tree Height	Tree Height	Android and iOS*	6,99€ per year	Arboreal AB (SE)	≥ 7.0	Click here[1]	17.08.2019	21.07.2024	No
ARTreeWatch	Tree Height, DBH	Android	Free	F. Wu et al. 2023 (CN)	≥ 7.0	Not available on PlayStore	Not publicly released	-	Yes, but not automatically detected
Geo-Quest	Tree Height, DBH	Android and iOS	Free	C4C project (AT)	≥ 10.0	Click here[2]	-	17.06.2024	Yes
GLOBE Observer	Tree Height	Android and iOS	Free	NASA (US)	≥ 4.4	Click here[3]	20.04.2016	12.05.2023	No
GreenLens	DBH	Android	Free	Feng et al. 2024a (CN, US, GB)	≥ 7.0	Click here[4] Click here[5]	-	-	No
Working Trees	Tree Height, DBH	Android and iOS	Free	Working Trees Inc. (US)	-	Click here[6]	18.04.2024	30.07.2024	Yes, but not automatically detected

Table 2.1.: Compatible apps in alphabetical order part 1. *There exist apps from the same developer for iOS (Arboreal Forest and Arboreal - Tree) but these have more functionalities and can process lidar data. [1] play.google.com/store/apps/details?id=se.arboreal.height&hl=de_AT&gl=US [2] play.google.com/store/apps/details?id=com.iiasa.geoquest [3] play.google.com/store/apps/details?id=gov.nasa.globe.observer&hl=en_US [4] github.com/MingyueX/GreenLens [5] apkpure.com/p/com.cleeg.greenlens [6] play.google.com/store/apps/details?id=com.workingtrees.working_trees

App name	Georeferencing	Measurement principle	App documentation	References
Arboreal Tree Height	No	ARCore, ARKit	Poorly and hardly described	Sveaskog 2021 Sandim et al. 2023 Arboreal 2024
ARTreeWatch	Yes	ARCore, ARKit	Roughly available	F. Wu et al. 2023
Geo-Quest	Yes, but not accessible	ARCore, ARKit	Not available	-
GLOBE Observer	Yes	Magnetometer, gyroscope	Available	Enterkine et al. 2022 Campbell 2021
GreenLens	Yes	ARCore, ARKit	Available	Feng et al. 2024a Feng et al. 2024b Feng et al. 2023
Working Trees	Yes, but not accessible	ARCore, ARKit	Not available for Android*	Ahamed et al. 2023

Table 2.2.: Compatible apps in alphabetical order part 2
*The documentation for the evaluation of the figures and statistics for the publication is open source and the app description is only available for iOS.

Most apps are readily available on the Google Play Store, with the exceptions of ARTreeWatch, which is not yet publicly released, and GreenLens, which can only be downloaded from platforms like GitHub or ApkPure. Notably, Geo-Quest is a prototype currently under development as part of a research project. The *released on* column indicates the initial publication date of each app, while the *last updated* column provides insight into how actively each app is maintained and improved over time. Comparing these two columns reveals that several of the listed apps are regularly updated. In terms of tree species identification, three of the six apps allow for the addition of tree species data. However, only Geo-Quest includes automatic species detection, whereas the other two, ARTreeWatch and Working Trees, require users to identify species manually. Some of these apps also include functionality for *georeferencing* measured trees using the GNSS capabilities of the smartphone, enabling further analysis and visualization. This feature is either unavailable for Arboreal Tree Height or inaccessible for Geo-Quest and Working Trees. Here, it is only possible to view the location on a map. The availability, quality, and level of detail regarding the measurement principles and code documentation provided with these apps vary significantly. For instance, Geo-Quest lacks any form of documentation on its measurement methods or implementation details, possibly due to its status as a research project prototype. In contrast, ARTreeWatch includes process-level documentation. GreenLens goes a step further by providing open-source access to its entire codebase, ensuring full transparency and enabling users to review or adapt the app's implementation. Finally, the *measurement principle* column in the tables provides an overview of the key algorithms and sensor technologies utilized by each app.

The following information in this paragraph is all from the ARCore website of Google LLC [Google 2024a]. ARCore is an Augmented Reality (AR) platform developed by Google for Android and iOS devices. It allows developers to create apps that overlay digital content on the physical world. As of 2024.08.13, 977 smartphones supported ARCore [Google 2024b]. ARCore has some fundamental tools: motion tracking, environmental understanding, depth understanding and light estimation. For motion tracking Simultaneous Localization And Mapping (SLAM) is used to determine where the smartphone is located. It searches visually distinct feature points and calculates with these points the current position of the smartphone. Additionally, this data gets combined with the data from the Inertial Measurement Unit (IMU) to estimate the smartphone's orientation and position over time. For environmental understanding, ARCore uses the detected feature points to find clusters of them to detect geometric elements. The so called Depth API can only be used on smartphones that support it with sufficient processing power. It helps to estimate distances of the elements in the picture and to display the virtual objects in front of or behind real world objects. Some smartphones also come with depth sensor, like a Time of Fight (ToF) sensor. Light estimation helps to display virtual objects with realistic colour intensity, illumination, and shading by analysing the lighting conditions of the environment. ARCore detects the average intensity and colour correction of the current camera image, allowing virtual objects to be illuminated under the same conditions as their real-world surroundings.

This ensures that virtual objects blend seamlessly into their environment, enhancing the overall sense of realism.

All the apps mentioned, except for GLOBE Observer, utilize ARCore. Any deviations from this standard are detailed in the following descriptions of the apps.

Arboreal Tree Height

The workflow of the Arboreal Tree Height application is illustrated in Figure 2.2. Subplot (a) displays the landing page, where users can select their preferred units system, either metric or imperial. The measurement process begins by selecting "measure Height". In the next step, shown in subplot (b), the tree is marked from a close distance (approximately 1.3 meters) using a green sphere. The user is then instructed to move to a distance roughly equivalent to the height of the tree, which is tracked by the mobile device. In subplot (c), the user selects the base of the tree trunk, followed by marking the top of the tree in subplot (d). The application calculates the tree height based on the measured distance and the angle ϕ, as described in Chapter 1.2.

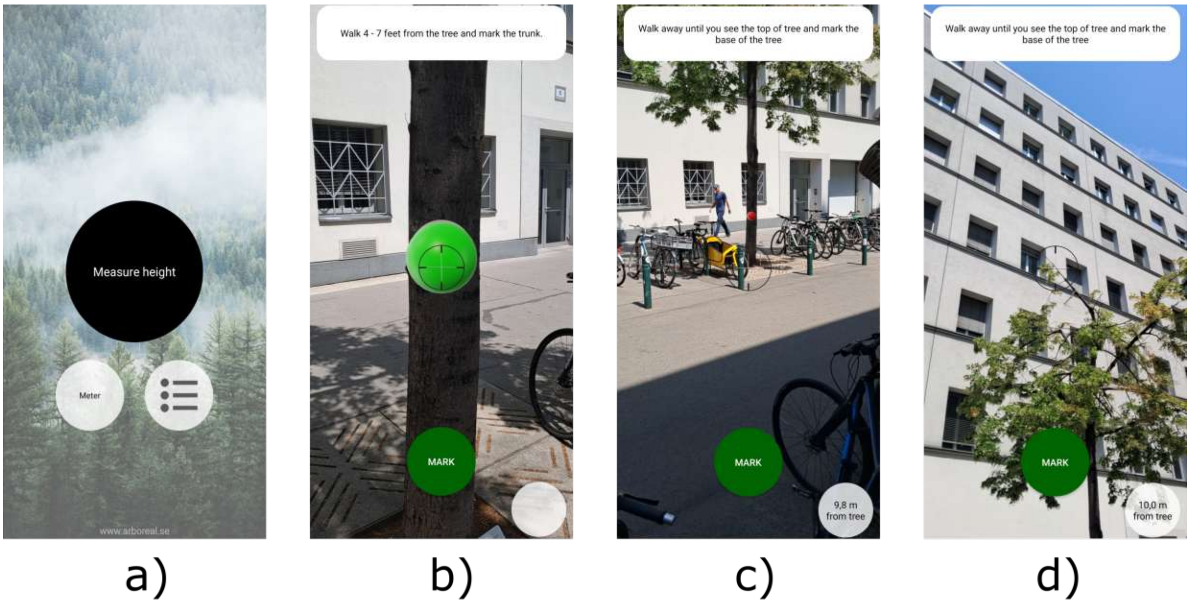

Figure 2.2.: Arboreal Tree Height workflow a) landing page and starting the measurement b) select the trunk by clicking on the green dot c) select the bottom of the trunk d) select the top of the trunk

ARTreeWatch

The ARTreeWatch app was developed using the Android Studio 4.0 development environment [F. Wu et al. 2023]. The workflow of the app is illustrated in Figure 2.3. Subplot (a) shows the landing page, which displays a map of the user's current location.

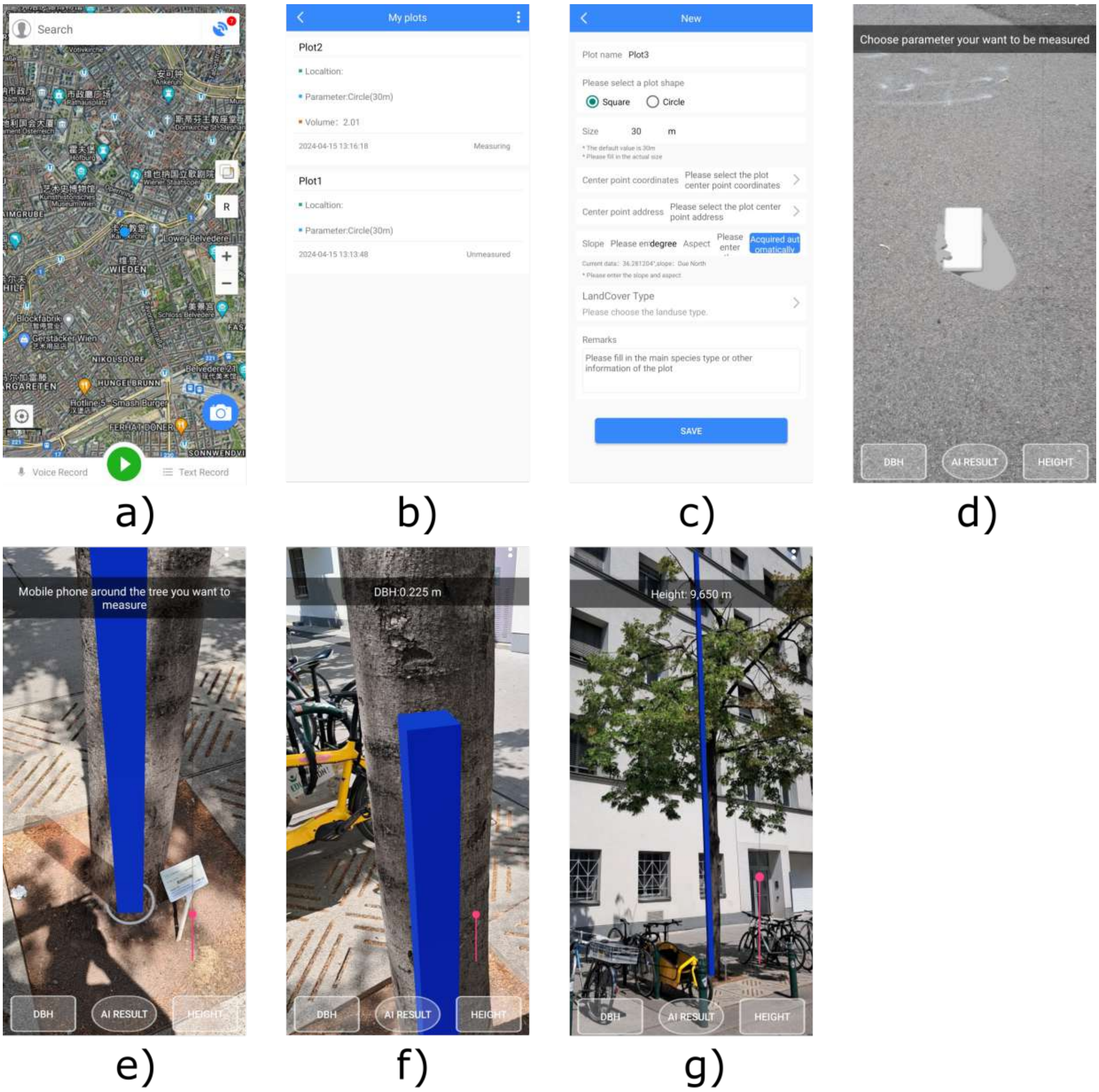

Figure 2.3.: ARTreeWatch workflow a) landing page with a map showing the current location b) overview of existing plots c) creating a new plot d) move the smartphone for initialisation e) select the bottom of the trunk and choose measuring mode f) move around the tree for DBH calculation g) move the slider till the bar reaches the top of the trunk

By selecting the camera icon, shown in (b), the user is presented with an overview of existing plots. If necessary, a new plot can be created (c) and metadata such as land cover can be added. The measurement process begins in (d), where the smartphone must be moved to initialize the system and determine its position in space. To continue, the user selects the base of the trunk and chooses the desired measuring mode, as shown in (e). For measuring the DBH, the DBH tool (f) generates a point cloud of the trunk by recording the stem while the user circles around the tree. The software fits a circle to the point cloud using the calculated data and displays the resulting DBH value. The height measurement begins after the DBH has been determined. The user is instructed to move approximately as far away from the tree as the height of the tree. Subplot (g) shows a slider that appears for height measurement, which can be adjusted until the bar aligns with the top of the trunk. The slider initially has a maximum height of 10 m. When this limit is reached, the slider resets, and the scale is doubled to extend the measurement range [F. Wu et al. 2023].

Geo-Quest

The Geo-Quest app is built using Unity, a cross-platform game engine developed by Unity Technologies, as the foundation for the mobile application [Unity 2024]. The app features several modules, including Tree-Quest, Forest-Quest, and Laxenburg Park Trees. Among these, Forest-Quest is inspired by the Bitterlich method [Bitterlich 1952]. The relevant module to this thesis is Tree-Quest.

The workflow of the Tree-Quest module is illustrated in Figure 2.4. Subplot (a) displays the landing page, where all available modules are listed. For the purposes of this thesis, the Tree-Quest module is selected. Once selected, a map is displayed (b), showing the user's current GNSS position. The user specifies the location of the tree to be measured and a blue circular marker appears at the chosen location. In subplot (c), the application begins searching for and calculating feature points necessary for distance measurement. This distance is used to estimate the DBH, as described in Chapter 1.2. In subplot (c), the application begins searching for and calculating feature points necessary for distance measurement. This distance is used to estimate the DBH, as described in Section 1.2. The user then selects a point on the tree trunk, which is highlighted as a tennis ball. At this stage (d), the opening angle is measured by selecting the left and right edges of the tree bark. Alternatively, the user can choose the automatic (A) mode instead of the manual (M) mode. In automatic mode, a point cloud of the trunk is generated by recording the stem as the user circles the tree. The software fits a circle into the point cloud to determine the DBH value. Once the DBH measurement is complete, the app transitions to height measurement (e). The user selects the base of the trunk, then moves to a distance approximately equal to the tree's height. This distance is tracked by the smartphone. The user then selects the top of the trunk (f), and the app calculates the height using the distance and the angle ϕ, as described in Chapter 1.2. Finally, subplot (g) displays the measured tree parameters, including DBH and height. Additionally, the app offers a questionnaire for users to complete at the end of the process. Subplot (h) depicts the first set of questions from the questionnaire, which addresses key aspects such as the tree's ID, whether the tree is alive, whether it is planted or wild, and the tree species. For species identification, the app attempts automatic recognition and prompts the user to verify whether the species was correctly identified.

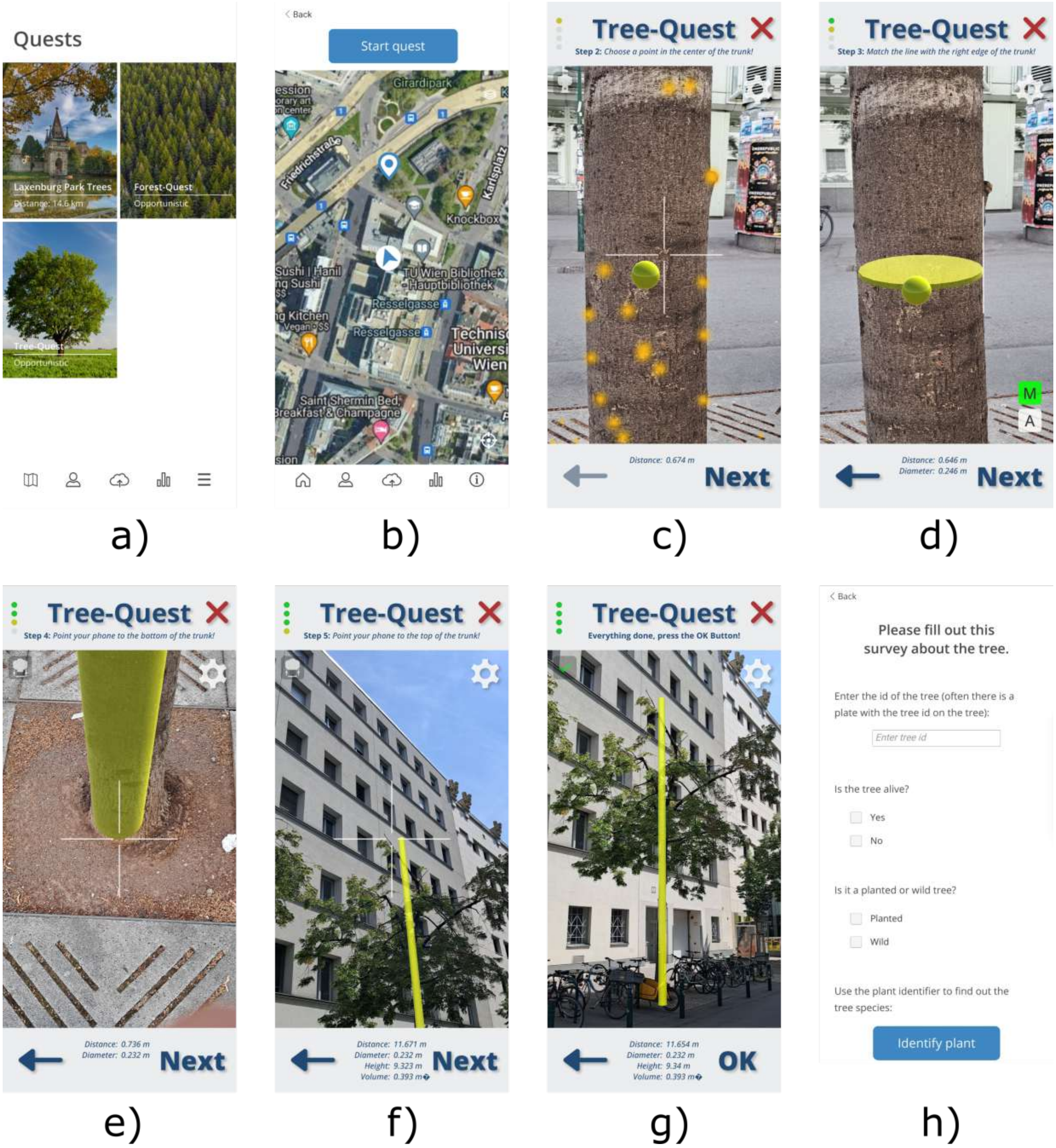

Figure 2.4.: Geo-Quest workflow of the Tree-Quest a) landing page with an overview of different Quests b) pick the tree location c) find feature points on the tree bark and set a point in the centre of the trunk (tennis ball) d) measure the left and right side of the tree bark e) select the bottom of the trunk f) select the top of the trunk g) measured tree data displayed h) option to enter further tree information, shows only the first part.

GLOBE Observer

GLOBE Observer is the only app tested that does not rely on ARCore or ARKit. Instead, it utilizes the smartphone's gyroscope and magnetometer to function as a clinometer. The app estimates stride length based on the user's height to calculate distances. This app is a bundle of multiple modules developed by NASA, designed to improve the understanding of various Earth parameters [Enterkine et al. 2022; Campbell 2021].

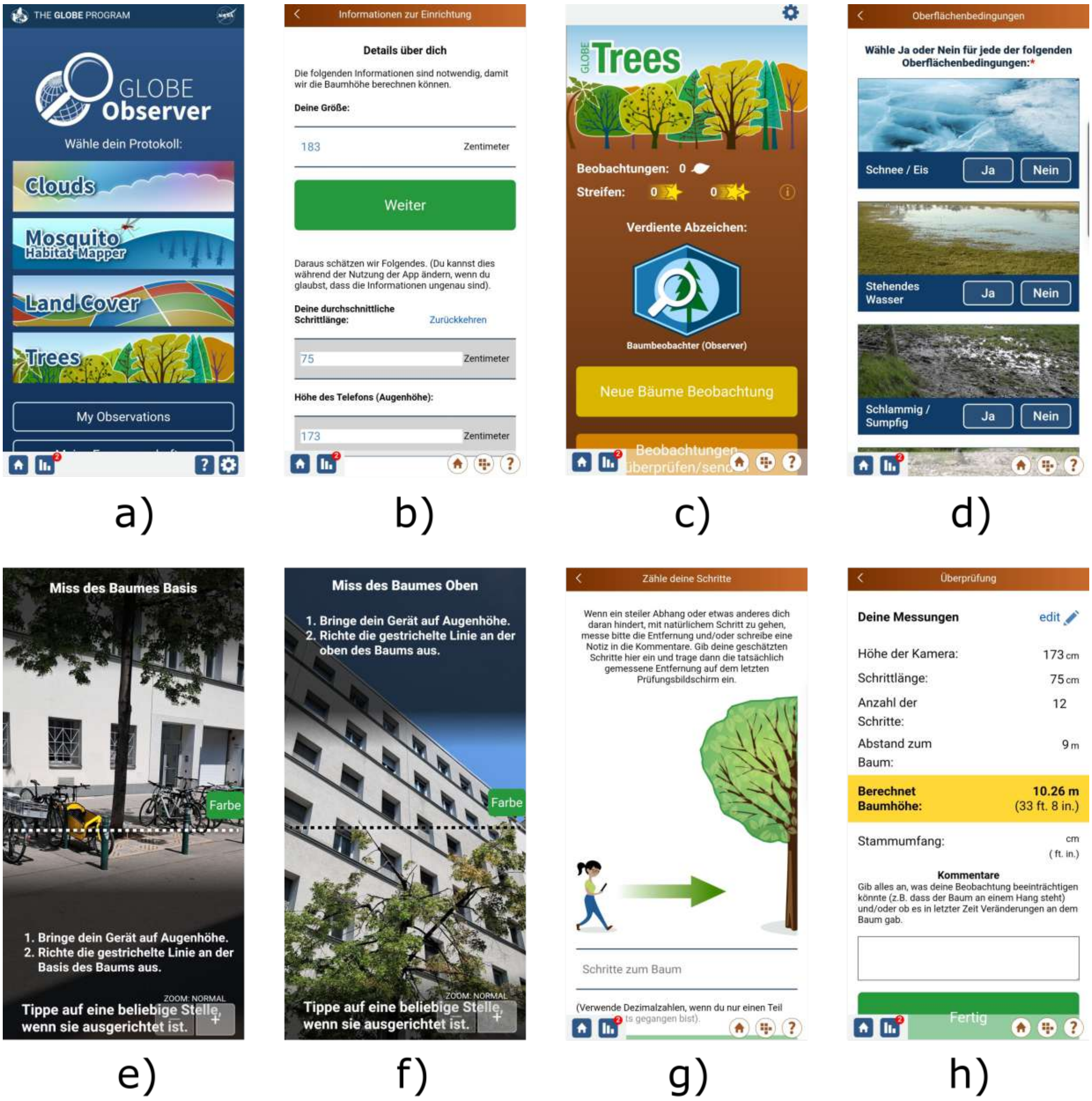

Figure 2.5.: GLOBE Observer workflow a) landing page with an overview of different applications b) entering personal height for scaling c) start tree measuring d) adding metadata, shows only the first part e) select the bottom of the trunk f) select the top of the trunk g) count steps to the tree h) result of the measurement

The workflow of the app is illustrated in Figure 2.5. Subplot (a) displays the landing page, which provides an overview of the different available modules. Upon selecting the "trees" module, the interface shown in (b) appears, where users are required to enter the personal height. In (c), a new measurement session can be initiated. The next step (d) involves adding metadata about the surrounding area, including weather conditions. The user is then instructed to position themselves at a distance from the tree approximately equal to its height. In subplot (e), the base of the tree is marked, followed by marking the top of the tree in (f). To estimate the distance to the tree, the user is required to count their steps toward it. Using the user's height, the app calculates an average stride length to determine the distance, as this is possible due to human body proportions. Finally, subplot (h) displays a summary of all measured values. Users have the option to adjust the stride length on this page, for example, if it has been measured independently or if the initial estimate requires refinement.

GreenLens

GreenLens is developed using Flutter, an open-source cross-platform user interface software development toolkit for the frontend. For backend processing, it employs OpenCV, an open-source computer vision library, and PyTorch Mobile, a mobile adaptation of the PyTorch machine learning framework. Additionally, ARCore is utilized. A neural network segments the trunk and calculates the DBH by identifying the two borders of the trunk and applying the principles of a pinhole camera [Feng et al. 2024a; Feng et al. 2023].

The workflow of the app is illustrated in Figure 2.6. Subplot (a) displays the landing page, where the user's profile is shown. After starting the process by pressing the camera button, the initialization step (b) requires the smartphone to be moved slowly. In step (c), the user adjusts the smartphone's position to align a green dot within a white box. The green dot indicates correct device orientation, perpendicular to the ground, and enables the capture button once the alignment conditions are satisfied. The DBH measurement can then be captured. This process takes a few seconds as the app identifies the trunk borders and calculates the DBH. The results are displayed in subplot (d). If the border detection is inaccurate, the entire process can be restarted [Feng et al. 2024a].

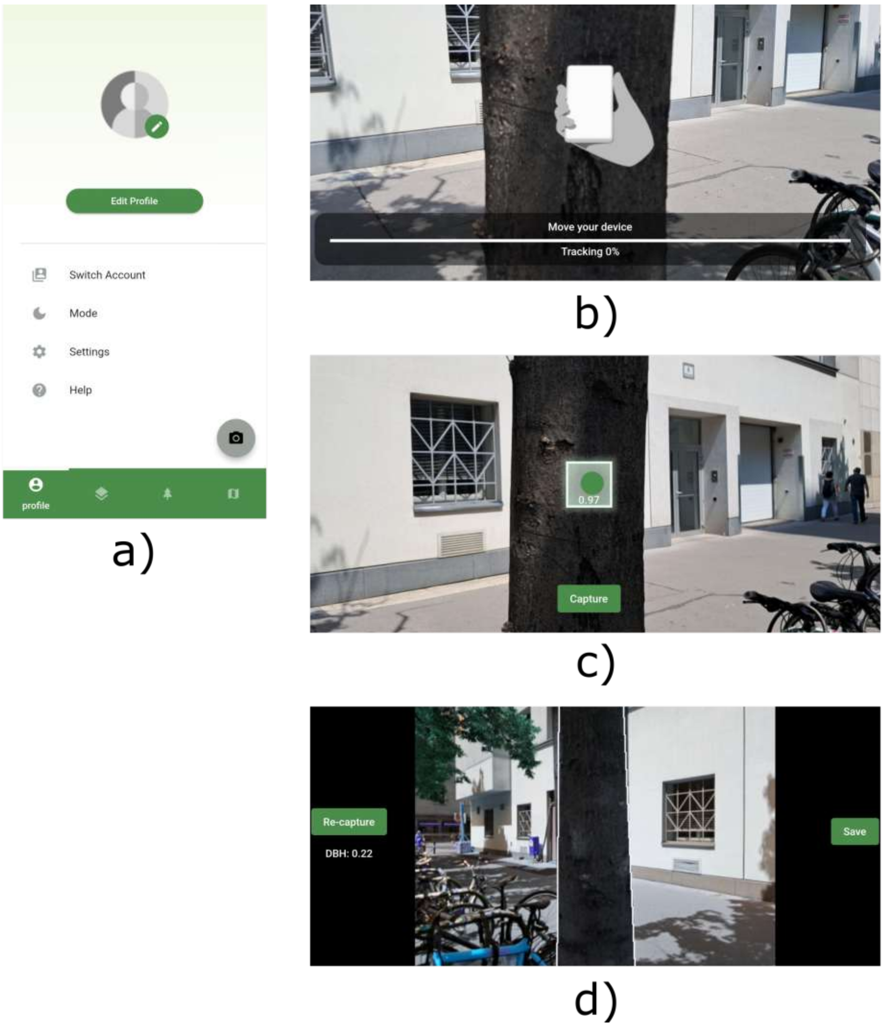

Figure 2.6.: GreenLens workflow a) landing page shows the user profile, start measuring with the camera button b) move the smartphone for initialisation c) moving the smartphone to get a green dot inside the box d) result and validation

Working Trees

The workflow of the Working Trees app is illustrated in Figure 2.7. At the start (a), the user is given the option to log in with an account or use the demo version. For this thesis, the demo version was used. The next step involves defining areas where different groups can be created (b). In step (c), additional information, such as the date, is added before starting a measurement within the newly created group (d). The measurement process begins with selecting a point at the base of the tree trunk (e). The user is then instructed to step backward until the top of the trunk can be selected, as shown in (f). This creates a visible line on the screen that represents the tree height and should extend to the highest point of the tree. For DBH calculation, the user selects the left and right edges of the tree bark at the height of a yellow dashed line. Finally, the tree species must be identified and selected (g) [Ahamed et al. 2023].

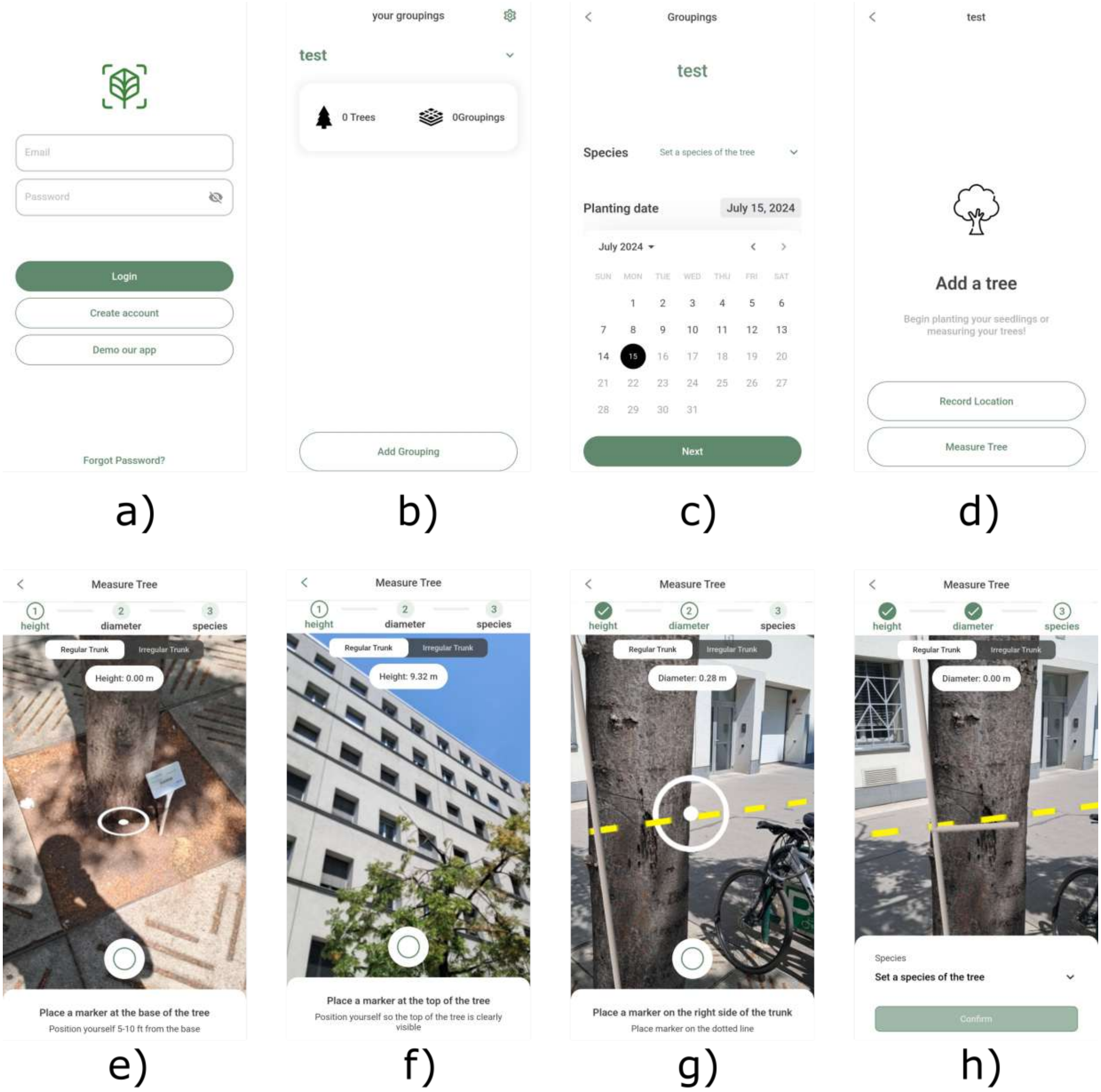

Figure 2.7.: Working Trees workflow a) landing page with login option b) grouping for different locations c) adding metadata d) start tree measuring e) select the bottom of the trunk f) select the top of the trunk g) measure the left and right side of the tree bark h) entering the tree species

2.4. Measurement procedure

A Samsung Galaxy M34 5G was used to carry out the app measurements. This is because it represents wildly used average hardware and the price is reasonable (available for 290€ at Amazon.de, accessed: 2024.12.04). The smartphone runs Android 14, is compatible with Google ARCore (see Chapter 2.3), and features a 6000 mAh battery. Like other smartphones in the mid-price segment, it does not include a lidar sensor.

The study area was mapped using a terrestrial laser scanner (RIEGL VZ-600i) (see Chapter 2.2). This mapping provided a database for comparison with app-based measurements and allowed for precise allocation of measurement data. While not all trees in the study area were measured with the apps, the focus was on trees with crowns that were not substantially obstructed from view at a distance. To ensure optimal visibility of the tree crowns, the measurements were carried out during the leaf-off period. This was necessary because limited visibility of the tree crown can lead to significant errors in height estimation. Efforts were made to include a diverse range of DBH values and a variety of tree species in the measurements. Tree species were identified using the “Pl@ntNet” app [Cirad et al. 2024]. To simplify the analysis and avoid introducing too many classifications, tree species were grouped by genus. This approach also accounted for potential limitations of the app, as distinguishing tree species solely based on trunk characteristics can be challenging. Before using the apps, the DBH was measured manually with a diameter tape to provide a reference for comparison.

All measured values were recorded in a table by a second person during the measurement process. Each tree was measured individually and comprehensively, using the same sequence of apps until all results were obtained. In case of obvious gross errors or app malfunctions, the measurement was immediately aborted and repeated. If a valid result could not be achieved after three attempts, the tree was excluded from the analysis for the respective measurement method. Any error exceeding 5 cm in the DBH was classified as a gross error, prompting a new measurement.

2.5. Evaluation of the apps

In order to enable a fair and objective evaluation of all apps, this step is divided into two main categories. On the one hand the qualitative and on the other hand the quantitative assessment.

Qualitative assessment

The qualitative evaluation is divided into several main areas: *user-friendliness*, advantages and disadvantages, consumption of time and energy and detailed description for each app. Although every effort was made to remain as objective as possible, this evaluation inevitably contains a certain degree of subjectivity and should be regarded as an initial point of reference.

The *user-friendliness* is divided into four categories: *robustness*, *user manual*, *user interface* (UI) and *data access*. Scores are assigned on a scale from one to three, where three indicates significant room for improvement and one represents a good result. *robustness* evaluates how well an app works, without errors, without starting to stutter, crashing or obviously delivering grossly incorrect results. It is important to note that apps with a broader range of functionalities and measurement parameters may naturally exhibit lower *robustness*. The *user manual* refers to how well the work instructions are documented, including the required behaviour during the measurement process and the key points to observe in order to avoid gross errors. The evaluation of the *UI* assesses the quality of the design and the intuitive navigation through the measurement process. *Data access* assesses whether data such as tree height, DBH, and tree position can be accessed solely during the measurement or also afterward.

The usage statistics primarily focus on *time consumption* and *energy consumption*. The term *initialization time* refers to the total time required to start or end the measurement process for DBH or tree height within the app. This period excludes the actual measurement process but begins when the app is opened or switched. Some apps retain specific settings and metadata from the previous measurement, while others do not, requiring the entire process to restart. This phase accounts for a significant portion of both energy and time, in addition to the measurement itself. Another factor, often underestimated, is the *robustness* of the app. Frequent crashes or incorrect results increase the time and energy required for measurements. Unfortunately, this aspect was not recorded separately, and as a result, these delays are also included in the *initialization time* To accurately represent energy and time consumption, the values are provided on a per-tree basis. These figures were derived by taking the total time and power consumption indicated in the phone settings and dividing them by the number of trees measured. Consequently, the reported values for *energy consumption* and *time consumption* always incorporate the *initialization time* It is important to note that the *initialization time* for certain apps can be reduced when measurements are performed using a single app. As mentioned in Section 2.4, the presence of a second person is essential to record data, ensuring the reported times for *time consumption* are achieved. This was particularly important as it eliminated the need to repeatedly lock, store, and unlock the smartphone in order to manually record measurements with pen and paper. This step is necessary to prevent data loss, especially when data cannot be retrieved off-site. Some apps lack this functionality, or in some cases, the association of data with individual trees may not be consistently guaranteed.

The pros and cons provide a quick overview of the app's key features. Special features are highlighted here so as not to lose sight of them as they have particular relevance. They also allow conclusions to be drawn later as to how an app could best be designed.

Quantitative assessment

First a visual analysis of the obtained results was conducted by plotting the obtained app results for DBH and tree height per app against their respective references. This helps to get a quick and intuitive overview over the achieved accuracies. Additionally, statistical metrics were calculated, as outlined in this section. The Formula 2.1 represents the computation of the mean error, where x_i [m] denotes the measured value for each tree and method, $\tilde{x}_i$ [m] represents the theoretically true value, and n [-] indicates the total number of measurements. The mean percentage error 2.2 is calculated similarly to the mean error but is expressed in a unit-free percentage, providing a clearer interpretation of measurement accuracy. Formula 2.3 represents the root mean square error ($RMSE$ [m]). This allows a statement about how much measured values scatter and how accurate and reliable the respective method is. Furthermore, a linear regression (2.4) is performed to analyse the relationship between the variables. The coefficient of determination R^2 [-] (see Formula 2.5) is calculated to quantify the proportion of variance in the dependent variable explained by the independent variable, providing insight into the model's goodness of fit. Here, $\bar{x}$ [m] denotes the mean of the measured values. In Chapter 3.2, the results are compared and evaluated based on these statistical metrics.

$$Mean\ error = \frac{1}{n}\sum_{i=1}^{n}(x_i - \tilde{x}_i) \tag{2.1}$$

$$Mean\ percent\ error = 100 \cdot \frac{1}{n}\sum_{i=1}^{n}\frac{(x_i - \tilde{x}_i)}{\tilde{x}_i} \tag{2.2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \tilde{x}_i)^2}{n}} \tag{2.3}$$

$$\hat{x}_i = k \cdot x_r + d \tag{2.4}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{2.5}$$

2.6. Error simulations

The exact implementation of DBH calculations across different apps is not documented. The approach described in Gruber and Joeckel [2017] provides a reasonable basis for conducting an error analysis. The transferability of these theoretical results to practical applications is also assessed and further explained subsequently. For reliable DBH results, it is crucial to accurately determine the parameters γ and c (see Formulas 1.3, 1.4, and 1.5). If these parameters are not measured precisely, the resulting error will directly propagate to the DBH calculation. To better understand these effects, refer to Figure 2.8, which provides an overview of the measurement geometry. The solid lines represent an ideal measurement without any errors. For instance, if the distance to the tree (c) is altered while the angle measurement (γ) remains constant, the resulting DBH error is shown in orange. Conversely, if the distance (c) remains constant while the angle measurement (γ) is altered, the resulting DBH error is shown in grey.

An analysis is also conducted to illustrate how varying error amounts affect DBH under different conditions. These conditions, specifically different tree diameters (10 to 40 cm), varying tree distances (30 to 90 cm), and opening angles (10° to 40°), are explicitly considered in the subsequent calculations and applied to the Formulas 1.3, 1.4, and 1.5. The various error curves and their effects on DBH are presented in Figure 3.7.

Additionally, these measurement scenarios are evaluated not only using the theoretical model but also through app-based measurements (see Figure 3.8). In this experiment, errors in the theoretical modelling were assessed using multiple measurements of a single tree. This was achieved by measuring the DBH multiple times from three different distances and angles relative to the tree. To ensure the results were not limited to this specific DBH, the measurements were standardized using the tree width relative to the screen width. Specifically, three scenarios were realized: 1/3, 2/3, and 3/3 (full screen). To guarantee accurate tree-width-to-screen-width ratios, transparent tape was temporarily applied to the smartphone screen for guidance. This experimental setup provides a link between theoretical considerations and real-world applications. It is only carried out with one app. The decision was made in favour of Geo-Quest. All results are detailed in Chapter 3.3 .

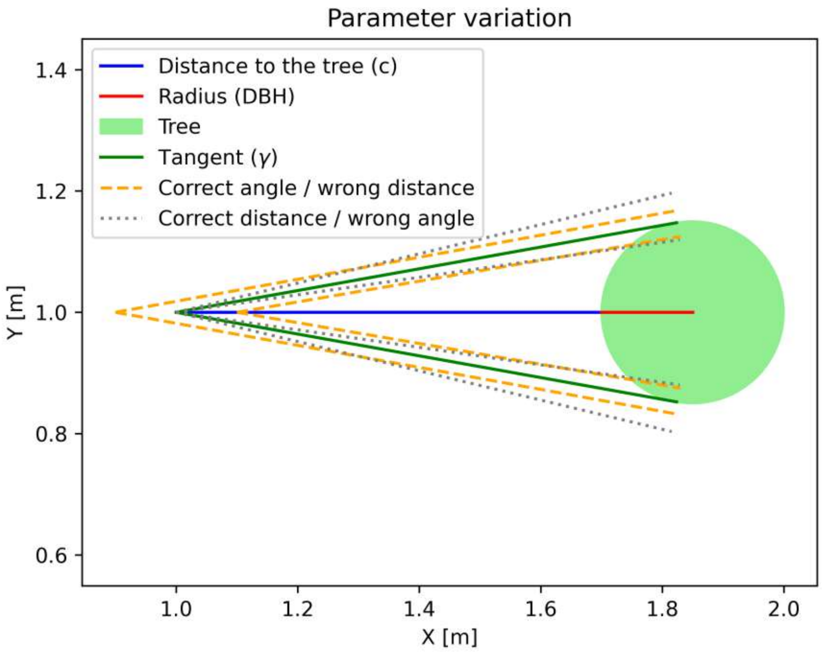

Figure 2.8.: Different kinds of parameter variation

For reliable tree height measurements, it is crucial to accurately determine the parameters ϕ and d (see Formulas 1.6, 1.7, and 1.8). Any inaccuracies in these parameters will directly impact the calculated tree height. A comparison of Formulas 1.4 and 1.7 reveals a similar mathematical relationship, expressed as $distance_1 = distance_2 \cdot \tan(angle)$. Both formulas rely on distances being multiplied by the tangent of angles. This relationship is explicitly evident in Formula 1.7. Formula 1.4 also aligns with this relationship when considering that α is the supplementary angle of the measured opening angle γ (see Formula 1.3). Building on this the error propagation analysis for DBH calculations can also provide insights into the error influences on tree height measurements.

3. Results and discussion

3.1. Qualitative analysis of the apps

Tables 3.1, 3.2, and 3.3 provide a comprehensive overview of all qualitative app evaluations.

The *user-friendliness* assessment (Table 3.1) indicates that the Arboreal Tree Height app performs exceptionally well in terms of *robustness*, while ARTreeWatch exhibits poor performance in this aspect. This disparity is not only linked to the app's structure and programming but also to its level of complexity. Apps that include a broader range of parameters inherently introduce more potential sources of error. This connection is clearly reflected in Table 2.1, which provides details on the analysed parameters. The *user manual* and *UI* categories generally do not present major issues for most apps and are rated favourably in most cases. In contrast, data accessibility often requires significant improvement. In ARTreeWatch, measurement data is only accessible during the active measurement process and although an export function is included, it remains non-operational. Overall, GLOBE Observer achieves the highest ratings in these categories, whereas ARTreeWatch has the most room for improvement.

User-friendliness	Robustness	User manual	User interface	Data access
Arboreal Tree Height	1	1	1	3
ARTreeWatch	3	3	3	3
Geo-Quest	2	1	1	3
GLOBE Observer	1	1	2	1
GreenLens	3	2	1	1
Working Trees	2	1	1	2

Table 3.1.: User-friendliness is categorized into robustness, user manual, and user interface, with each aspect rated on a scale of 1 to 3. For further details, refer to Chapter 2.5.

In addition to *user-friendliness*, energy and time efficiency are critical aspects of app evaluation. Table 3.2 focuses specifically on these parameters, highlighting significant differences between the apps. The data clearly demonstrate that avoiding the use of AR Core results in substantial energy savings. For example, the GLOBE Observer

	Energy consumption [mAh/tree]	Time consumption [min/tree]	Initialization time [min/tree]
Arboreal Tree Height	24	2.2	0.1
ARTreeWatch	54	2.5	0.3
Geo-Quest	23	1.7	0.2
GLOBE Observer	12	2.3	0.8
GreenLens	26	2.0	0.8
Working Trees	30	2.7	0.5

Table 3.2.: Time and energy consumption is calculated per tree. It must be borne in mind that the initialization time, measurement abort and restart and the amount of data recorded can have a significant influence on time and energy consumption (see chapter 2.5).

app, which does not rely on AR Core (see Table 2.2), consumes by far the least energy per tree. These savings even outweigh the benefits of shorter measurement times. In principle, most apps can support a full day of work on a fully charged battery, except for ARTreeWatch, which would only last for half a working day. High battery consumption during even occasional use is problematic and may deter users from engaging in citizen science. Some apps also require a longer *initialization time*. When combined with lower *robustness*, this can considerably increase overall *time consumption*. These factors not only affect operational efficiency but may also reduce user satisfaction. Such influences must be taken into account to ensure the usability of these apps in practical, real-world scenarios.

In addition to energy and time efficiency, the advantages and disadvantages of the apps provide valuable insights for possible further development. Table 3.3 summarizes the most significant strengths and weaknesses of each app. To create an optimal app, it would be beneficial to incorporate several features highlighted in the table. These include height determination using on-screen bars, as implemented in ARTreeWatch (see Figure 2.3), a quick and straightforward DBH measurement tool, as demonstrated by Geo-Quest (see Figure 2.4) and a well-structured system for data storage and parameter access, as seen in GLOBE Observer and GreenLens. Building on the key findings from the comparative evaluation, the following sections provide detailed descriptions of each app. These descriptions delve into the specific features, functionalities, and unique characteristics that influence their performance and usability.

	Pros	Cons
Arboreal Tree Height	- Easy to use	- Measures only tree height
ARTreeWatch	- Intuitive best high measurement	- Mixed languages - Lagging display - Non-robust DBH measurements
Geo-Quest	- Easy to use - Good DBH solutions	- Feature point calculation
GLOBE Observer	- Easy to use - Good data access	- DBH with measuring tape possible - Collect additional information
GreenLens	- Good data access	- Lagging display - Too much time
Working Trees	- Data access	- Challenging DBH measurement

Table 3.3.: Important pros and cons listed for each app.

Arboreal Tree Height

Arboreal Tree Height is among the most robust apps available. Measurements have consistently been successful, with no failures caused by app instability. The *UI* is attractively designed and highly intuitive, leaving no room for confusion. It is streamlined to include only the essentials, effectively minimizing potential sources of error. The sole adjustable setting allows the user to select between the metric and imperial systems, which can be done with a single tap on the landing page (see Figure 2.2 (a)). Since no additional steps are required to initiate a measurement and the app demonstrates excellent stability, both time and *energy consumption* remain largely unaffected by *initialization time* or measurement interruptions. Targeting with the black-and-white crosshairs works seamlessly against any background. Another notable strength is the clarity and simplicity of the app's instructions, which are consistently visible to the user. One marginal drawback, however, is that while measurements can be taken in either the metric or imperial system, the app always displays descriptions in feet. Additionally, tree height results are only shown immediately after measurement. There is no meaningful way to access the data later, and tree location information is entirely unavailable.

ARTreeWatch

ARTreeWatch requires significant time and effort to complete measurements and offers one of the poorest user experiences. This is primarily due to its poorly designed *UI*. The app simultaneously displays text in English and Chinese, with no option to adjust the language settings. Navigation on the landing page is suboptimal, making it unintuitive to begin measurements using the camera, and there are no instructions provided for the initial steps. At Figure 2.3 (d), where the measurement begins, the display starts occasionally lagging, likely due to the phone's high processing demands, which results in noticeably jerky images. The DBH measurement is highly unreliable, often providing incorrect calculations or failing entirely, requiring the process to be restarted. This can easily test the user's patience, particularly when a large number of trees need to be measured. Obtaining accurate results becomes even more challenging when dealing with trees that do not exhibit vertical growth (see Figure 1.1 (c)). Consequently, the time required to measure a tree is relatively long, which naturally results in higher power consumption. Conversely, the height measurement proves to be the most intuitive and reliable of all tested apps. This is largely due to the implementation of a blue bar and slider, which make it nearly impossible to record unrealistically high values since the height is always visualized. Adjustments can only be made in predefined increments (e.g., up to 10m, up to 20m, etc.), as described in Chapter 2.3. This feature minimizes the likelihood of inaccurate results, even when the tree crown is obscured or the user is inexperienced. The *initialization time* is within an acceptable range. Measurement data, however, is only available during the measurement process. While the app includes a function for exporting data, this feature is not yet operational. Additionally, the precise location of the tree is not really good accessible within the app.

Geo-Quest

The Geo-Quest app features a highly attractive and user friendly interface with a well suited *user manual*. It is intuitive and allows the user to quickly start measurements with the so-called Tree-Quest mode. As illustrated in Figure 2.4 (c), feature points are calculated on the tree bark during the process. This step is generally robust, provided the user adheres closely to the instructions. If the user stands too far away, the estimation of feature points becomes infeasible. Similarly, insufficient lighting such as at dusk can make it more challenging for the algorithm to detect these points. In addition to manual measurement of the opening angle (see Chapter 2.3), which performs reliably, the app offers an option to calculate the DBH using a point cloud, similar to ARTreeWatch. This method, however, exhibits reliability issues comparable to those found in ARTreeWatch and was therefore not pursued further. On rare occasions, a second attempt may be required for height measurements. This typically occurs when the smartphone's IMU drifts, resulting in the measured angle no longer corresponding to the actual distance. Such incidents usually arise if the smartphone is dropped during measurement or if the process takes an unusually long time to complete. The app's well designed *UI* significantly reduces the time required for measuring a single tree, enabling users to navigate the process efficiently. This streamlined workflow also ensures that *energy consumption* remains within an acceptable range. Overall, the instructions provided during measurement are clear, and the experience feels modern and functional. One area for improvement lies in data accessibility. While tree parameters and graphical positions on the map are accessible during the measurement process, they are not available afterward, though pictures are saved for later reference. Users can upload the collected data at the end, but they must contact the development team to access it further.

GLOBE Observer

NASA's GLOBE Observer operates without relying on ARCore support (see Chapter 2.3) and instead utilizes only the gyroscope and magnetometer for measuring the angle between the bottom and the top of the tree. This design makes it significantly more energy efficient than all other apps with comparable runtime (see values in Table 3.2). It also delivers one of the best overall user experiences and is exceptionally easy to use, thanks to its detailed *user manual* and intuitive *UI*. A notable drawback is the relatively long time required to initiate a measurement. This is attributed to the additional data collected during the process (see Figure 2.5 (a) to (d)). Naturally, this results in somewhat extended measurement durations, though the overall measurement time remains in the mid-range. The app is among the most robust, as it only requires the smartphone to measure angles, while the distance is calculated using the user's stride length. The instructions provided are exceptionally user-friendly, often supplemented by detailed sketches to guide the user effectively. This strength is further reflected in its well designed *UI*. One standout feature is the app's ability to provide users with full retrospective access to all recorded data, including positional information and tree parameters. Users can even visualize the entire dataset on an interactive map, making this app a comprehensive tool for tree measurement and data analysis.

GreenLens

GreenLens faces significant challenges in terms of *robustness*. Some settings in the main menu, such as "help," "settings," and mode," are non-functional. Additionally, there are issues with the measurement process (see Figure 2.6 (b) and (d)). The smartphone's *initialization time* is significantly prolonged due to the required movement during the setup process, as shown in (b). In some instances, the process completes within just 10 to 20 seconds for unclear reasons, while in others, the user may need to wait over a minute. This inconsistency can be frustrating and detracts from the overall user experience. Measurement accuracy is also hindered by gross errors, which are primarily caused by incorrect detection of the tree trunk in the image. These errors stem from two main factors: poor lighting conditions or a background that closely resembles the tree trunk and irregularities in the tree's shape, such as curves or bumps. Trees in the background can further confuse the algorithm. Fortunately, these errors are always visible in step 2.6 (d), enabling users to identify and address them. Nonetheless, this often requires multiple measurement attempts, leading to longer overall measurement times. Another drawback to *user friendliness* is that the display occasionally lags, resulting in jerky images and reducing the fluidity of the experience. On the positive side, the app is relatively straightforward to use, requiring little prior knowledge or instruction thanks to a well designed *UI*. The *user manual* provided is of average quality but sufficient for basic operation. An advantage of GreenLens is that it allows users to retrospectively access all collected data, including positional information and DBH, making it one of the more data accessible apps.

Working Trees

Working Trees provides a generally good user experience. The *UI* is visually appealing and highly intuitive, making it easy to navigate during the measurement process. The *user manual* is clear, easy to read, and consistently well explained throughout the measurement steps. One minor issue arises from the use of the metric system for measurements, while some descriptions specify measurements in feet (see Figure 2.7 (e)). The *initialization time* is generally acceptable, provided the user continues measuring within a single session. If the user switches between apps, the setup process must be repeated each time, which can feel inefficient and slightly frustrating. During the measurement process, the tree height measurement functions reliably, but the DBH measurement presents some challenges. Selecting the edges of the tree trunk can feel cumbersome, as the displayed points are overly large, making precise selection difficult (see Figure 2.7 (h)). Additionally, DBH measurements sometimes fail, requiring the user to retry. As a result, measurement times can increase, which in turn impacts *energy consumption*. Measurement data is visible during the process and is saved for later access. However, data retention is currently limited to the duration of the app session. Upon closing and reopening the app, the data is lost. This limitation is specific to the demo version, as the full version allows for permanent data saving.

3.2. Quantitative analysis

3.2.1. Reference data

Figure 3.1 presents the results of the DBH measurements using a diameter tape (see Chapter 2.2), performed by three different testers. Subplot (a) illustrates the consistency of measurements across testers for individual trees. The data points for each tree are closely grouped, indicating minimal variability between testers. The overall accuracy, as indicated by the $RMSE$, is exceptionally high, with a value of 0.17 cm. This suggests that all testers were able to achieve high repeatability in their measurements.

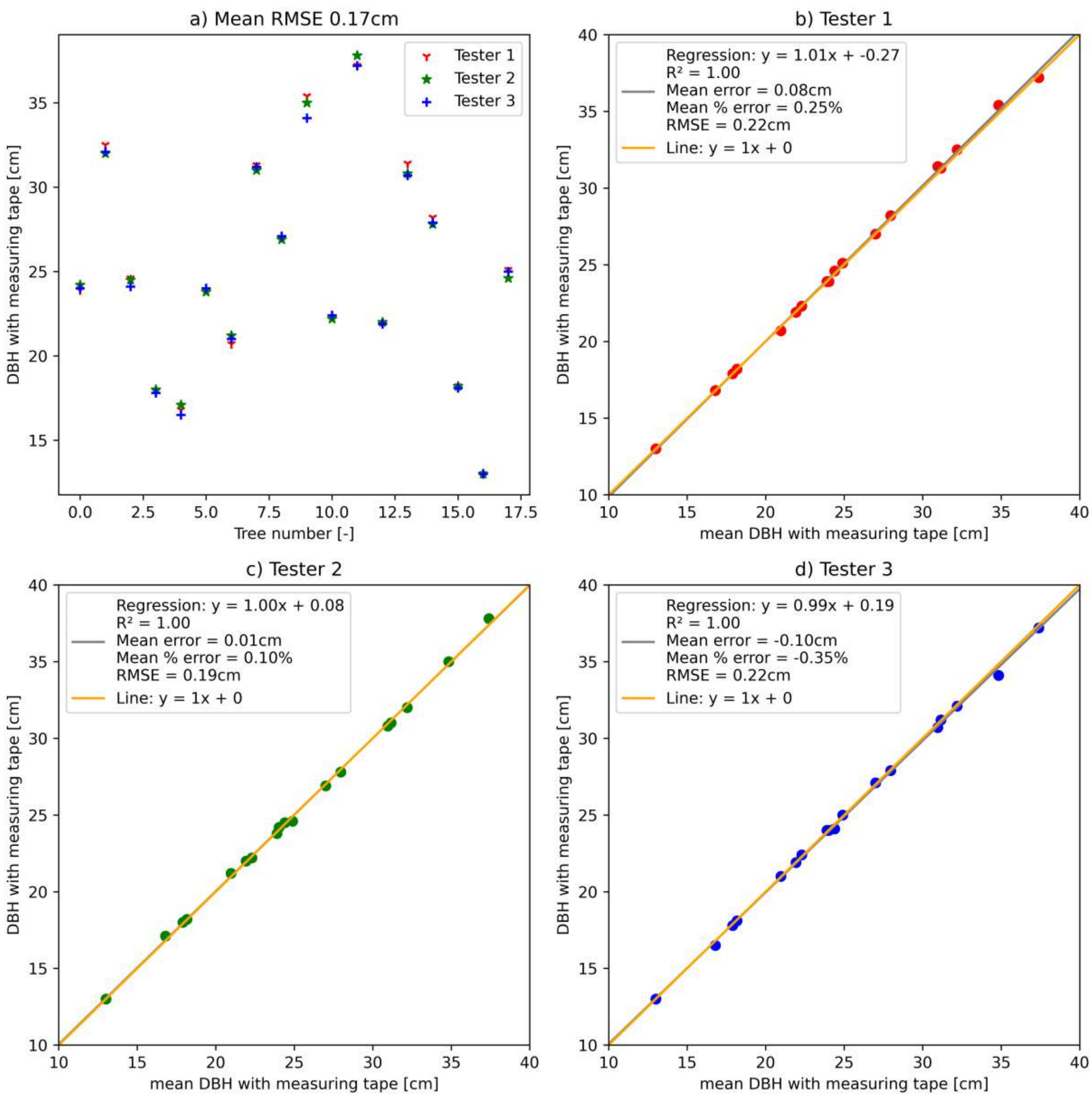

Figure 3.1.: Comparison of DBH measurements with a diameter tape. (a) Overall comparison of all testers across individual trees. (b) Accuracy for Tester 1 (geodesy student) relative to the mean DBH with measuring tape. (c) Accuracy for Tester 2 (environmental engineering student) relative to the mean DBH with measuring tape. (d) Accuracy for Tester 3 (geodesy researcher) relative to the mean DBH with measuring tape.

Subplots (b), (c), and (d) present detailed analyses of the measurements for each tester, showing consistently excellent results across all statistical metrics. The regression lines for all testers align almost perfectly with the ideal line ($y = 1x + 0$), and key metrics such as the R^2, $Mean\ error$ and $RMSE$ demonstrate a high level of agreement between measured and reference DBH values. For instance, the R^2 for all testers is 1.00, while the $RMSE$ ranges between 0.19 cm and 0.22 cm. $Mean\ errors$ are minimal, with values such as 0.01 cm for Tester 2 or -0.10 cm for Tester 3. These results confirm the precision and reliability of the diameter tape, regardless of the individual performing the measurements. The tape can thus be confidently used as a reference for all subsequent DBH measurements in this thesis. It is worth emphasizing that, while all testers had prior experience with various measurement tools, the diameter tape is straightforward enough that precise and accurate measurements can be achieved by virtually anyone after a brief introduction.

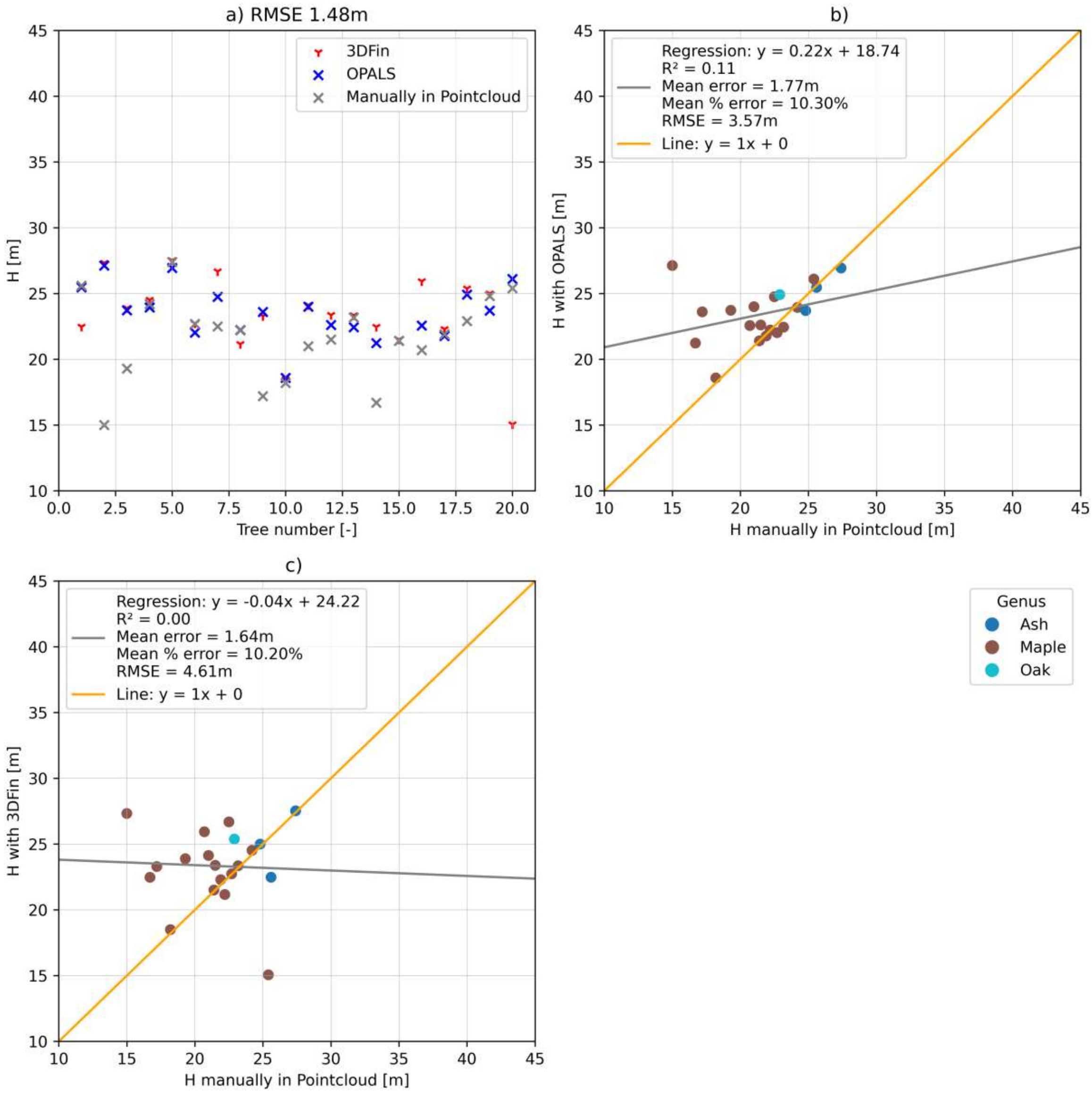

Figure 3.2.: Comparison of different height measurements (a) relations between all measurements (b) results for OPALS (c) results for 3DFin

Figure 3.2 compares tree height measurements obtained manually from the point cloud with those derived from software such as 3DFin and OPALS (see Chapter 2.2). Subplot (a) shows the relationship between all measurement methods. Approximately half of the measured trees exhibit significant deviations between the manual measurements and the software-derived values, while the other half shows closer agreement. Additionally, no clear trend can be observed for the genus, such as Ash, Maple, or Oak. Subplots (b) and (c) present detailed analyses of OPALS and 3DFin, respectively. Both regression lines deviate noticeably from the ideal line ($y = 1x + 0$), which is also reflected in the statistical metrics such as R^2, $Mean\ error$ and $RMSE$. While 3DFin and OPALS were initially considered as potential references for tree height measurements, the test results suggest that the current parameter settings of the software do not produce results comparable to the manual measurements. Nevertheless, improvements could likely be achieved by fine-tuning the software parameters or adjusting the point cloud data. For example, by segmenting individual trees to prevent potential occlusion by another tree from being incorrectly interpreted as height. On the other hand, it is also possible that the data quality is good, but the software algorithms could still be improved. However, this is certainly not a simple or trivial task. Since this thesis focuses on other aspects, such optimizations were not pursued. Instead, the manual point cloud measurements were used as the reference for all subsequent tree height comparisons. Although manual measurements are more time consuming and less economical, they remain the most accurate and reliable method within the scope of this thesis.

3.2.2. Results for the DBH

All DBH measurements generally provide consistent and reliable results, regardless of whether the data is analysed using point cloud software or an app.

Figure 3.3 illustrates the comparison between the reference measurements and those obtained from OPALS and 3DFin. Subplot (a) shows that the methods produce very similar results for the majority of the more than 50 analysed trees. For 3DFin, as seen in Subplot (b), the data aligns very closely with the expected regression line, with only minimal deviations. This is reflected in the low $Mean\ error$ of -0.4 cm and an $RMSE$ of 1.2 cm, indicating high precision. However, the random errors tend to increase slightly with larger DBH values, as evidenced by a subtle increase in data spread for larger diameters. In contrast, Subplot (c) demonstrates that OPALS produces measurements with slightly greater deviations from the reference. The slope of the regression line ($y = 0.89x + 1.58$) indicates a systematic underestimation of DBH values. This divergence becomes more pronounced as the tree diameters increase, resulting in increased variability compared to 3DFin. The larger dispersion in the data is also reflected in the higher $RMSE$ of 2.2 cm. Overall, while both methods show good agreement with the reference measurements, 3DFin demonstrates higher accuracy and precision, particularly for larger diameters, where OPALS tends to underestimate the DBH.

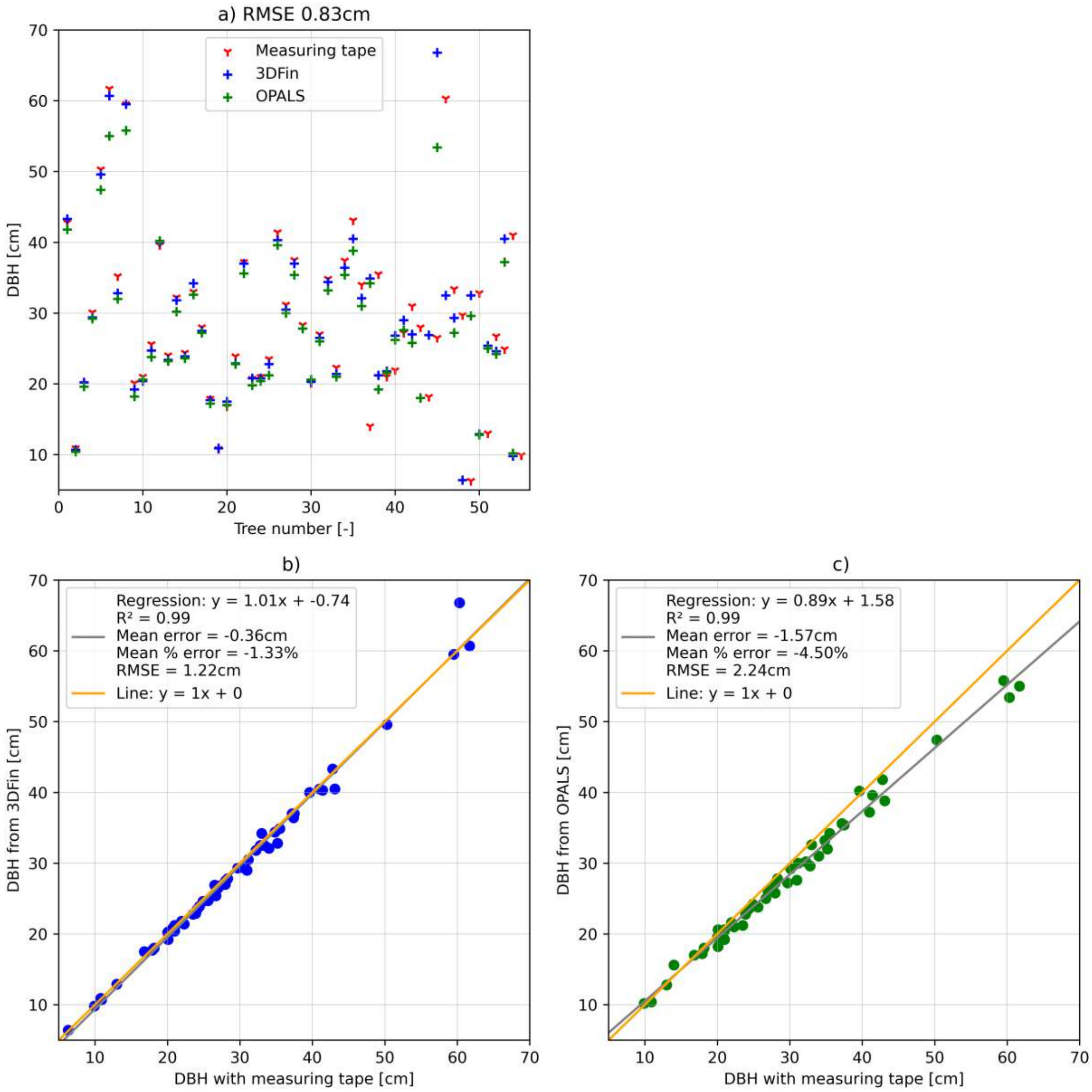

Figure 3.3.: Comparison of different DBH measurements (a) relations between reference and software data (b) results for OPALS (c) results for 3DFin

Figure 3.4 illustrates the performance of various apps in measuring DBH. Subplot (a) shows that the tape measure, Geo-Quest, and ARTreeWatch generally produce similar results, while GreenLens tends to overestimate DBH and Working Trees consistently underestimates it. Among the apps, ARTreeWatch delivers the most accurate results, as shown in Subplot (d). The fluctuations are minimal, with an $RMSE$ of 1.2 cm and a $Mean\ percentage\ error$ of just -0.3%. The regression line aligns almost perfectly with the ideal value, indicating high precision and reliability. Geo-Quest also performs well, as seen in Subplot (b). Although its statistical values are slightly worse than those of ARTreeWatch, with an $RMSE$ of 1.7 cm and a $Mean\ percentage\ error$ of -0.9%, the results are still highly acceptable for practical use. The slope of the regression line ($y = 0.96x + 0.73$) shows only a minor deviation from the ideal value.

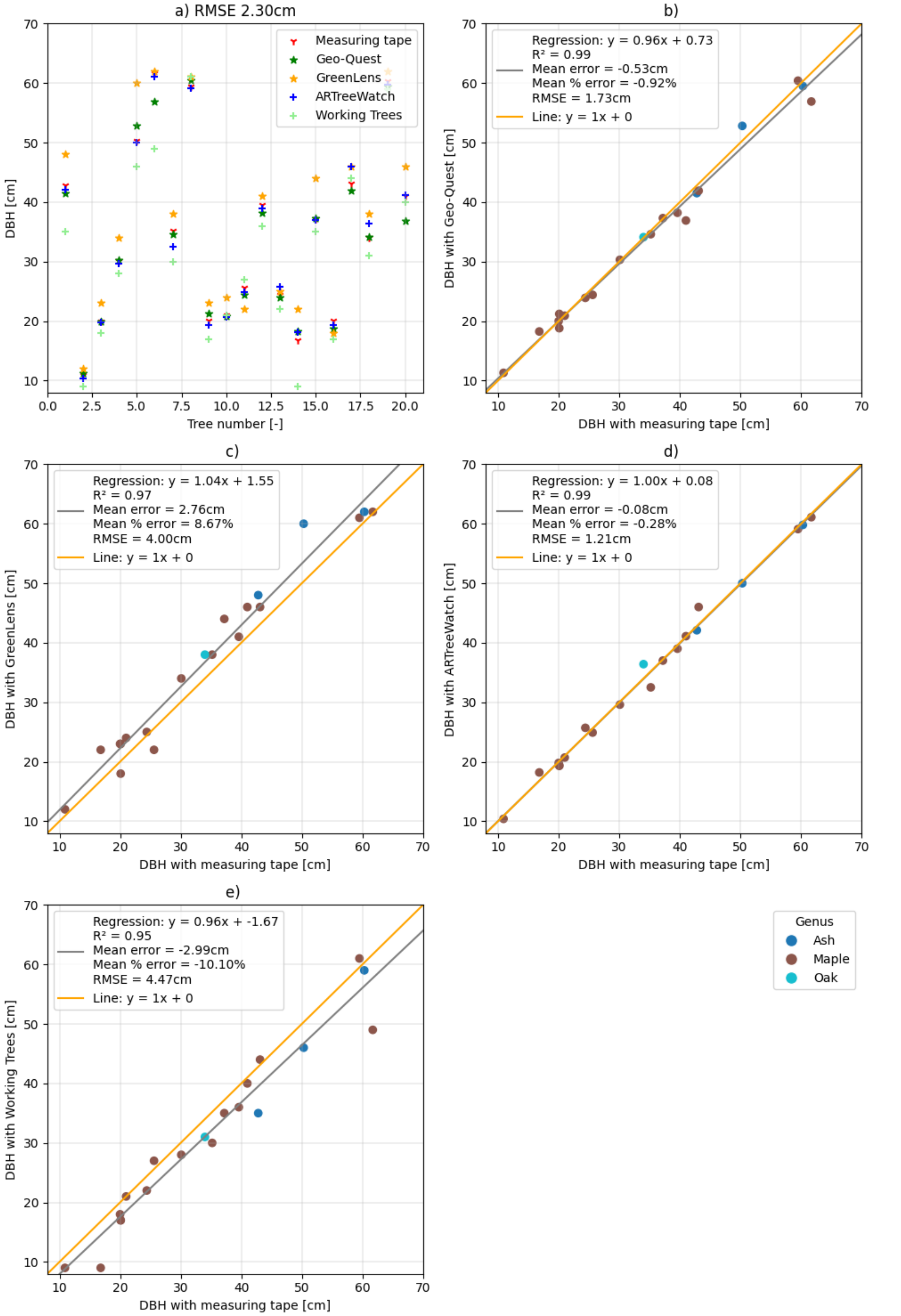

Figure 3.4.: Comparison of DBH measurements across different apps estimating DBH (a) relations between reference and app data (b) results for Geo-Quest (c) results for GreenLens (d) results for ARTreeWatch (e) results for Working Trees

These findings suggest that both Geo-Quest and ARTreeWatch provide results comparable to those of 3DFin (see Figure 3.3) and are suitable for practical DBH measurements. In contrast, GreenLens and Working Trees show significant deviations from the reference values. GreenLens, as depicted in Subplot (c), systematically overestimates DBH, with a *Mean percentage error* of 8.7% and an *RMSE* of 4 cm. The regression line reveals a nearly constant positive offset from the ideal value, indicating a systematic error. The opposite behaviour is observed with Working Trees in Subplot (e), where DBH values are consistently underestimated. This is reflected in a *Mean percentage error* of -10.1% and an *RMSE* of 4.5 cm. Lastly, no clear influence of the genus (Ash, Maple, or Oak) on the measurement results can be identified across the figure. This suggests that the deviations observed are more likely attributed to the individual apps rather than tree specific characteristics.

Figure 3.5 compares the results for the app Geo-Quest using a larger dataset to those presented in Subplot (b) of Figure 3.4, which used a smaller sample size. Despite the increase in the number of trees measured, the differences in the statistical metrics are minimal. The *Mean percentage error* improves by only 0.1%, and the *RMSE* decreases slightly by 0.2 cm. These results indicate that a sample size of 20 trees, as shown in Figure 3.4, is already sufficient to reliably assess Geo-Quest's accuracy, suggesting that the same sample size is likely adequate for evaluating the other apps as well. Consequently, future evaluations can rely on smaller, more manageable datasets without risking a loss in the validity of the conclusions.

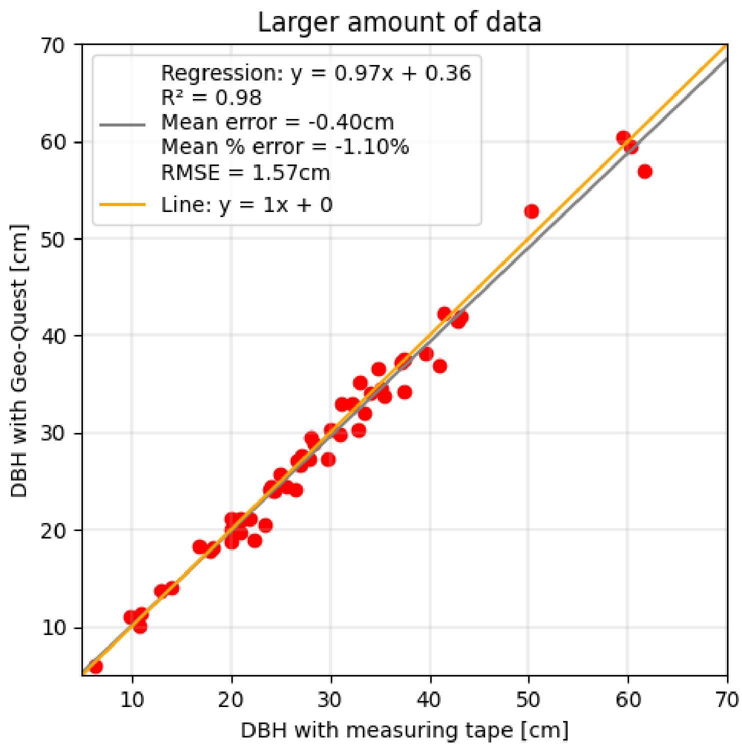

Figure 3.5.: Results for Geo-Quest with a bigger database

3.2.3. Results for the tree height

Figure 3.6 (a) provides an overview of the height measurements obtained from the different apps compared to the reference values. While the height values determined by the apps are generally close to each other, they do not always correspond to the actual tree heights. This suggests that while the distance to the tree is measured correctly, forest conditions likely pose challenges when determining the opening angle. Even though problematic trees were filtered out in advance (see Chapter 2.4), identifying the highest point of a tree may only be partially successful in dense forest stands. It is possible that the accuracy of height measurements could improve for isolated, free standing trees. However, for wooded areas, the current data suggests that significant improvements in accuracy are unlikely under similar conditions. The detailed evaluations in Subplots (b), (d), (e), and (f) reveal that the apps generally produce consistent results, with $RMSE$ values ranging from 3.4 m to 3.7 m and $Mean\ errors$ around 1 m. A notable exception is Arboreal Tree Height (c), which shows a significant outlier with a measured height of 41 m. Despite this outlier, the regression lines across all apps indicate a trend where smaller trees are measured with better accuracy, whereas taller trees tend to be overestimated. This pattern could be explained by the difficulty of identifying the tops of tall trees in forested areas, as previously described by Düggelin 2019 (see Chapter 1.2). Such challenges raise questions about the practical utility of these height measurements, given the observed fluctuations. Nevertheless, the results are significantly more accurate than height estimates made by untrained individuals. Interestingly, the method used by GLOBE Observer, which requires users to count steps and input body height or measure step length to calculate the tree distance (see Chapter 2.3), performs comparably to the more technically advanced approaches. This raises the question of whether it is always necessary to rely on technically complex and energy intensive programs (see Table 3.2) for determining the distance to the tree. One potential challenge for GLOBE Observer could be its performance on steep slopes, where determining the horizontal distance might be less accurate. However, this aspect would require further investigation, as the current study area is predominantly flat.

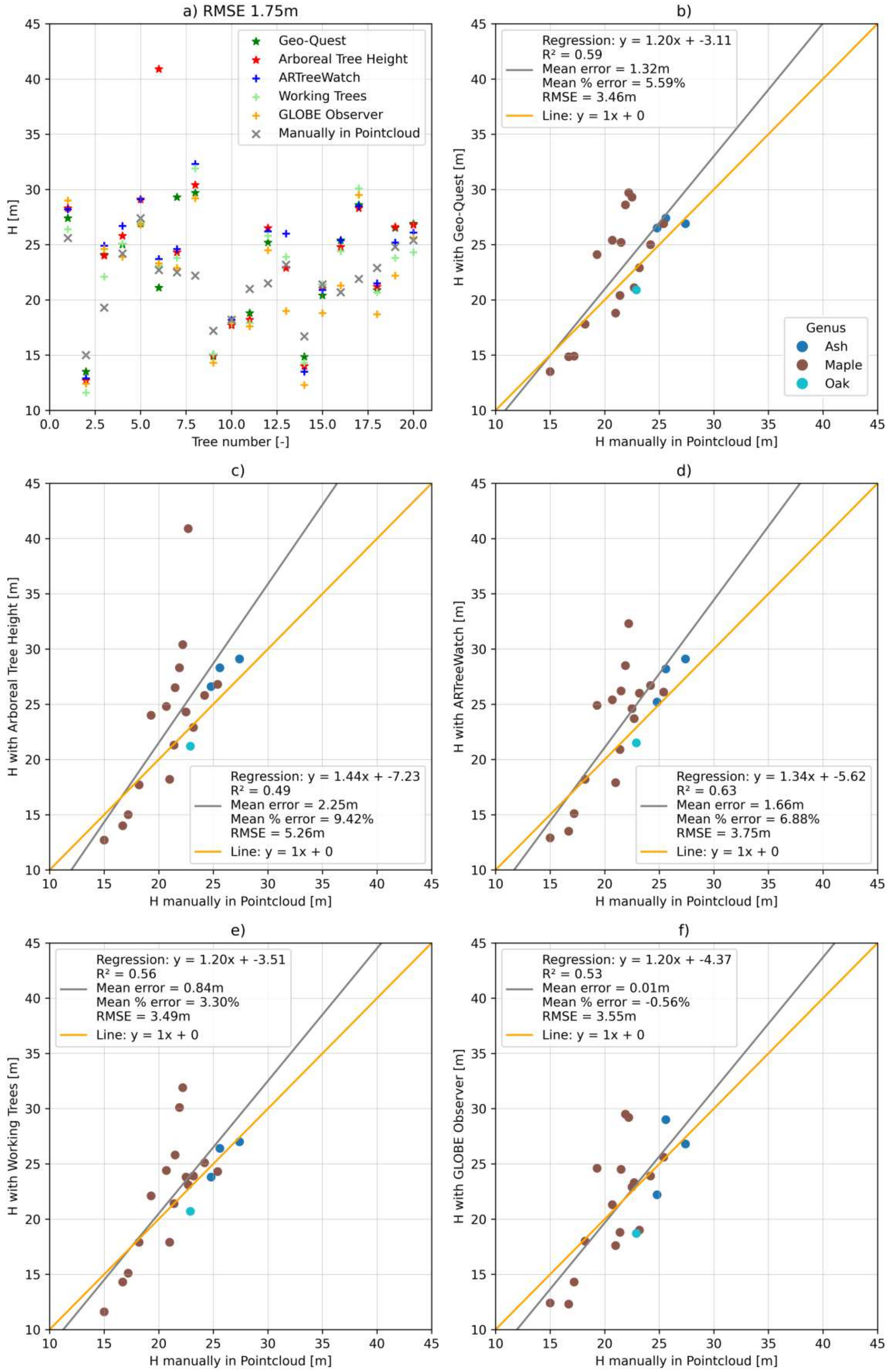

Figure 3.6.: Comparison of the tree height measurements across different apps estimating the tree height (a) relations between reference and app data (b) results for Geo-Quest (c) results for Arboreal Tree Height (d) results for ARTreeWatch (e) results for Working Trees (f) results for GLOBE Observer

3.3. Error analysis

Figure 3.7 provides a detailed analysis of how measurement errors theoretically affect the DBH. It is important to note that only absolute errors are considered here, regardless of their likelihood. The probability of such errors occurring is discussed in the following paragraph. Subplot (a) illustrates the DBH error as a function of the angle γ (see Formulas 1.3, 1.4 and 1.5) for different distances c (0.3 m to 0.9 m) and DBH values (10 cm to 40 cm). For instance, an angular error of 5° results in a DBH error of approximately 6 cm ($c = 0.5$ m and DBH = 20 cm). All curves exhibit similar patterns: the smaller the DBH and the shorter the distance c, the smaller the slope of the error. This indicates that small angles γ and short distances c result in lower theoretical errors. Subplot (b) shows the DBH error as a function of the distance c (see Formulas 1.3, 1.4 and 1.5) for different angles γ (10° to 40°) and DBH values (10 cm to 40 cm). For example, a distance error of 5 cm leads to a DBH error of approximately 5 cm ($\gamma = 40°$ and DBH = 40 cm). The curves in this plot exhibit a linear trend, with gradients that are equal for the same angles γ, regardless of the DBH. Therefore, the red, blue, green, and orange lines in (b) are overlapping. The slope of the error decreases with smaller angles γ, meaning that long distances c combined with small angles yield more accurate results. Overall, this error simulation analysis indicates that a medium distance and a small angle represent the best combination to minimize errors.

Beyond these theoretical absolute errors, it is also crucial to consider the probability of measurement deviations. At large distances and small angles, the likelihood of significant errors in angle or distance measurement increases. For instance, in the case of Geo-Quest, a greater distance from the tree results in a larger line for the angle measurement relative to the tree diameter (see Figure 2.4 d). This increases the difficulty of aiming accurately and worsens the distance measurement due to error propagation and the effects of grinding cuts. Trembling while measuring angles is independent of the distance and therefore results in similar absolute angular errors regardless of how far away the tree is. However, at shorter distances and larger angles, the effect of these errors is less pronounced because the error propagation over a shorter line segment is reduced. This suggests that the smallest theoretical errors occur at the largest real measurement errors, leading to the hypothesis that there is an optimal distance and angle where the total error is minimized. This optimal combination is also likely app-dependent.

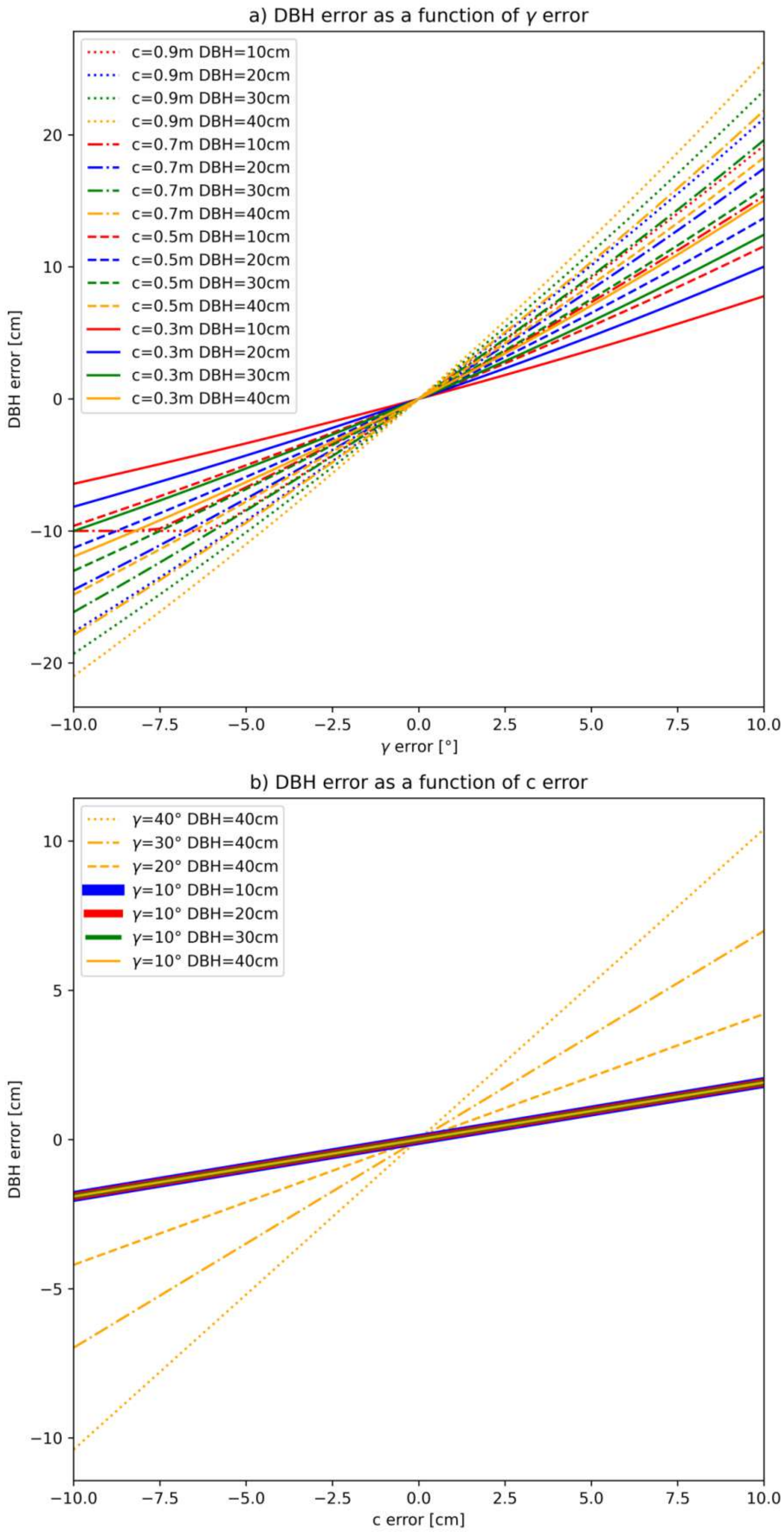

Figure 3.7.: (a) shows how the DBH is effected if the measurement of γ is erroneous. (b) shows how the DBH is effected if the measurement of c is erroneous.

The measured data in Figure 3.8 (a) can now be used to validate the theoretical considerations. In this example, a tree with a DBH of approximately 25.3 cm was measured from various distances with Geo-Quest. Instead of referencing the actual distance, the size of the tree on the screen was used as a reference to determine the optimal measurement distance (see Chapter 2.6).

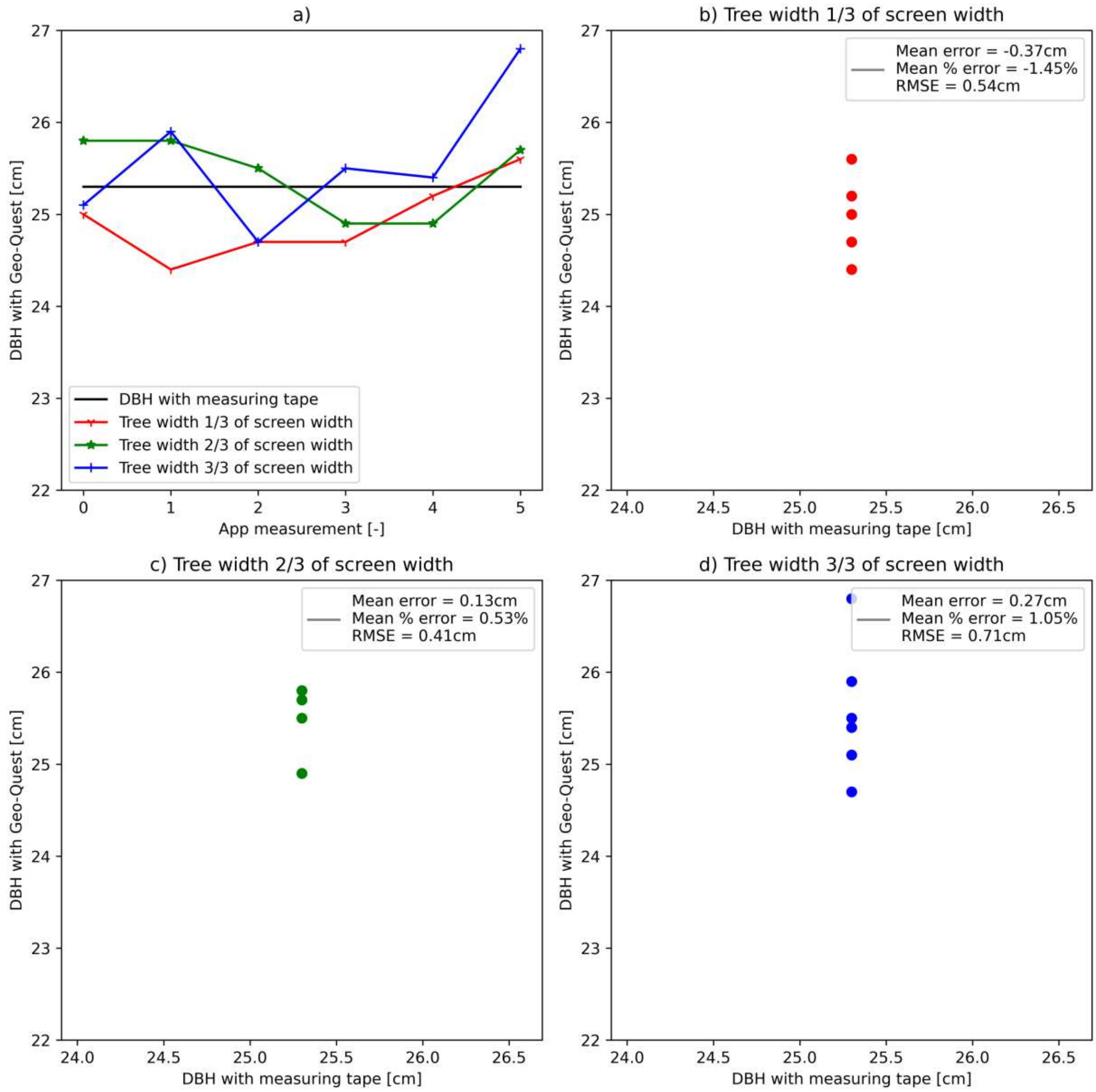

Figure 3.8.: Accuracy of different tree distances and angles displayed with different tree widths of the screen width a) different screen width filled with the tree compared to the diameter tape (b) tree width 1/3 of the screen width (c) tree width 2/3 of the screen width (d) tree width 3/3 of the screen width (full screen)

This approach ensures a consistent relationship between the visible size of the tree on the screen and the measurement accuracy. A closer examination of Subplots (b), (c), and (d) reveals that measurements where the tree trunk covers approximately 2/3 of the screen width (as shown in Subplot (c)) have the smallest scatter around the reference value, both visually and numerically. This suggests for Geo-Quest that when the tree covers about 2/3 of the screen, the measurements are most robust against errors. However, it is important to note that certain practical limitations may still affect the measurements. For instance, the feature point detection in Geo-Quest becomes not possible for very distant trees, as the structural details of the tree bark are harder to resolve. This imposes a maximum distance beyond which no measurements are possible, especially for trees with very large diameters. The other apps will also exhibit similar behaviour and maintain an optimal distance. However, this depends on the implementation of the measurement and calculation. Therefore, these aspects need to be further analysed.

Due to the similar mathematical relationships (see Chapter 2.6), it can also be inferred that height errors behave similarly to DBH errors. To summarize, achieving the best results requires a medium distance and a medium angle, which strike the right balance between minimizing errors and maintaining practical usability.

4. Conclusion and recommendations

Mobile devices without LiDAR sensors, in conjunction with appropriate applications, demonstrate strong potential for forest parameter measurement. These tools allow accurate determination of the DBH and tree positions, producing results comparable to 3D point clouds. Notably, ARTreeWatch and Geo-Quest emerged as the most reliable apps, frequently providing high quality data. However, the measurement of tree height in forested areas is inherently constrained by the visibility of the tree crowns. Additional research is necessary to assess the capabilities of these applications in environments with isolated trees.

The investigation found no significant differences in accuracy across various tree genera, underscoring the general applicability of these methods. Moreover, error models highlight their impact on DBH determination, suggesting that a tree should occupy approximately 2/3 of the screen width for optimal measurements in Geo-Quest. Although current data suggests that maintaining a measurement distance equivalent to the tree's height may enhance accuracy, this hypothesis requires further validation.

While app performances vary, ARTreeWatch stands out negatively due to its limited robustness and frequent interruptions, which can test user patience despite its intuitive height measurement using a slider. In contrast, apps like Geo-Quest, with effective DBH measurement tools based on opening angle calculations, provide a more reliable and efficient user experience. Most apps demonstrate acceptable energy consumption, allowing for a full day's operation on a standard battery, although ARTreeWatch is an exception, offering limited battery life.

Recommendations for developers include incorporating user-friendly features such as simplified height estimation methods like those in GLOBE Observer, which combines angle measurement with step counting for energy efficient, straightforward results. Enhanced visualization tools, such as adjustable height sliders seen in ARTreeWatch, can minimize gross errors. For DBH, techniques involving opening angle calculations, as implemented in Geo-Quest, should be prioritized. Furthermore, improving data accessibility and enabling seamless digital data transfers post measurement will support comprehensive analyses and integration with other forestry datasets.

When deciding which method makes sense for recording tree data, it is not only the cost of the measuring equipment and software that plays an important role. But also whether it is possible to work error free and how long it takes on average for one tree. In the case of the TLS, it took 48 minutes to scan the entire survey area. If the processing time in off site gets added, the result is around 108 minutes. If the observation area becomes larger, the measurement time naturally increases linearly. However, the evaluation time hardly increases with a larger survey area because the computer's actual computation time makes up only a small portion of the overall processing time in the office. Breaking these figures down to an individual tree reveals that the TLS requires on average only 0.8 min/tree, compared to an overall average of 2.2 min/tree for all apps. However, it should be noted here that no manual checking of the data is included.

By addressing these considerations, smartphone applications can advance their role as accessible, cost-effective alternatives for forest parameter measurement, even though their current measurement durations and accuracy levels are inferior to those achieved by traditional methods and may not fully satisfy professional foresters. Nonetheless, their inherent ease of use and affordability make them particularly well-suited for citizen science applications, where these advantages can significantly outweigh the limitations in precision and speed.

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