Interactive Visualization of the Impacts of Climate/Land Use Change and Response Measures using Augmented Reality

Dissertation
with the aim of achieving a doctoral degree
at the Faculty of Mathematics, Informatics and Natural Sciences
Department of Earth System Sciences
at University of Hamburg

submitted by
Vladimir Metelitsa

Hamburg, 2024

Department of Earth Sciences

Date of oral defense: 14.02.2025
Reviewers of the dissertation: Prof. Dr. Martina Neuburger
Dr. María Máñez Costa

Members of the examination commission: Prof. Dr. Martina Neuburger
Dr. María Máñez Costa
Prof. Dr. Frank Steinicke
Prof. Dr. Uwe A. Schneider
Dr. Martin Döring

Chair of the Subject Doctoral Committee
Earth System Sciences: Prof. Dr. Hermann Held

Dean of the MIN Faculty: Prof. Dr.-Ing. Norbert Ritter

Eidesstattliche Versicherung | Declaration on Oath

I hereby declare and affirm that this doctoral dissertation is my own work and that I have not used any aids and sources other than those indicated.

If electronic resources based on generative artificial intelligence (gAI) were used in the course of writing this dissertation, I confirm that my own work was the main and value-adding contribution and that complete documentation of all resources used is available in accordance with good scientific practice. I am responsible for any erroneous or distorted content, incorrect references, violations of data protection and copyright law or plagiarism that may have been generated by the gAI.

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.
Sofern im Zuge der Erstellung der vorliegenden Dissertationsschrift generative Künstliche Intelligenz (gKI) basierte elektronische Hilfsmittel verwendet wurden, versichere ich, dass meine eigene Leistung im Vordergrund stand und dass eine vollständige Dokumentation aller verwendeten Hilfsmittel gemäß der Guten wissenschaftlichen Praxis vorliegt. Ich trage die Verantwortung für eventuell durch die gKI generierte fehlerhafte oder verzerrte Inhalte, fehlerhafte Referenzen, Verstöße gegen das Datenschutz- und Urheberrecht oder Plagiate.

Ort, den | City, date Unterschrift | Signature

The best material model of a cat is another,
or preferably the same, cat
— Arturo Rosenblueth
in 'The Role of Models in Science',
Philosophy of Science (Oct 1945)

Summary

This dissertation investigates the potential of Augmented Reality (AR) as a medium for delivering climate services across diverse contexts and stakeholder groups. Through two in-depth case studies, the research demonstrates AR's capability to bridge the gap between complex climate science and practical decision-making while addressing the challenges of data scarcity and user engagement.

The first case study developed and validated a novel AR-based methodology for measuring urban tree carbon sequestration. The methodology demonstrated high accuracy compared to conventional forestry tools, achieving strong correlations for both tree diameter and height measurements. The resulting carbon sequestration estimates showed minimal deviation from conventional methods. User testing demonstrated strong acceptance, with high usability scores and the vast majority of users reporting increased understanding of carbon sequestration concepts.

The second case study implemented and evaluated an AR-based agricultural planning tool for small-scale producers in Novo Progresso, Brazil. This application successfully transformed complex climate model outputs into accessible visualizations that enabled farmers to explore climate impacts and adaptation strategies for their specific plots. The study demonstrated AR's effectiveness in data-scarce environments through innovative approaches to combining local knowledge with available climate data.

Both case studies validated AR's viability across multiple dimensions: as a data collection tool, as an interface for complex climate models, as a public engagement platform, and as a decision support system for domain experts. The research shows that AR can effectively serve both data-rich environments, where it enables precise measurements, and data-poor environments, where it facilitates user input and visualization. The successful implementation across different contexts, from urban environments to rural agricultural settings, demonstrates AR's adaptability as a medium for climate services.

This research makes several novel contributions to the field: it provides the first comprehensive evaluation of AR as a medium for climate services, develops new methodologies for environmental measurement using smartphone AR, and demonstrates effective approaches for implementing climate services in data-scarce environments. The findings suggest that AR technology can play a crucial role in democratizing access to climate information and supporting evidence-based environmental decision-making across different sectors of society.

The dissertation concludes that AR represents a viable and versatile medium for climate service delivery, capable of addressing key challenges in making climate information accessible and actionable for diverse user groups. These findings have significant implications for the future development of climate services and the broader field of climate change communication and adaptation planning.

Zusammenfassung

Diese Dissertation untersucht das Potenzial von Augmented Reality (AR) als Medium zur Bereitstellung von Klimadienstleistungen in unterschiedlichen Kontexten und für verschiedene Interessengruppen. Anhand von zwei detaillierten Fallstudien wird aufgezeigt, wie AR dazu beitragen kann, die Kluft zwischen komplexer Klimawissenschaft und praktischer Entscheidungsfindung zu überbrücken und dabei Herausforderungen wie Datenknappheit und Benutzerengagement zu adressieren.

In der ersten Fallstudie wurde eine neuartige, AR-basierte Methodik zur Messung der Kohlenstoffbindung städtischer Bäume entwickelt und validiert. Die Methodik zeigte im Vergleich zu herkömmlichen forstwirtschaftlichen Werkzeugen eine hohe Genauigkeit und erzielte starke Korrelationen bei der Messung von Baumdurchmesser und -höhe. Die Schätzungen zur Kohlenstoffbindung wichen dabei nur minimal von etablierten Methoden ab. Benutzertests ergaben eine hohe Akzeptanz der Methode: Sie erhielt hervorragende Bewertungen hinsichtlich der Benutzerfreundlichkeit, und die Mehrheit der Teilnehmer berichtete von einem besseren Verständnis der Konzepte zur Kohlenstoffbindung.

Die zweite Fallstudie implementierte und bewertete ein AR-basiertes Planungstool für Kleinbauern in Novo Progresso, Brasilien. Die Anwendung ermöglichte es den Landwirten, komplexe Klimamodell-Ausgaben in leicht zugängliche Visualisierungen zu übersetzen. Dies unterstützte sie dabei, Klimafolgen und geeignete Anpassungsstrategien für ihre spezifischen Parzellen besser zu verstehen und zu planen. Die Studie zeigte insbesondere die Effektivität von AR in datenarmen Umgebungen, indem innovative Ansätze zur Kombination von lokalem Wissen mit verfügbaren Klimadaten genutzt wurden.

Beide Fallstudien validierten die Vielseitigkeit von AR in mehreren Dimensionen: als Werkzeug zur Datenerfassung, als Schnittstelle für komplexe Klimamodelle, als Plattform für öffentliches Engagement sowie als Entscheidungshilfe für Fachexperten. Die Forschung zeigt, dass AR sowohl in datenreichen Umgebungen, in denen präzise Messungen ermöglicht werden, als auch in datenarmen Umgebungen, in denen Benutzereingaben und Visualisierungen erleichtert werden, effektiv eingesetzt werden kann. Der erfolgreiche Einsatz in unterschiedlichen Kontexten – von städtischen Gebieten bis hin zu landwirtschaftlich geprägten Regionen – demonstriert die Anpassungsfähigkeit von AR als Medium für Klimadienstleistungen.

Diese Forschung leistet mehrere wesentliche Beiträge zum Fachgebiet: Sie bietet die erste umfassende Bewertung von AR als Medium für Klimadienstleistungen, entwickelt innovative Methoden für Umweltmessungen mittels Smartphone-AR und zeigt effektive Ansätze zur Implementierung von Klimadienstleistungen in datenarmen Umgebungen. Die Ergebnisse deuten darauf hin, dass AR-Technologie eine Schlüsselrolle bei der Demokratisierung des Zugangs zu Klimainformationen und der Förderung evidenzbasierter Umweltentscheidungen in verschiedenen Gesellschaftssektoren spielen kann.

Die Dissertation schließt mit dem Fazit, dass AR ein praktikables und vielseitiges Medium für die Bereitstellung von Klimadienstleistungen darstellt. Es ist in der Lage, zentrale Herausforderungen bei der Zugänglichmachung und Nutzbarmachung von Klimainformationen für diverse Benutzergruppen zu bewältigen. Diese Ergebnisse haben bedeutende Implikationen für die zukünftige Entwicklung von Klimadienstleistungen sowie für die Weiterentwicklung der Klimakommunikation und der Anpassungsplanung.

Acknowledgement

First and foremost, I would like to express my deepest gratitude to my supervisors María, Martina, and my panel chair Frank. Their unwavering support, expert guidance, and insightful feedback have been instrumental in shaping this research journey. Their mentorship has not only enhanced the scientific rigor of this work but also profoundly influenced my academic and professional growth.

I extend my sincere thanks to Leam, whose support and invaluable insights were crucial in conceptualization of the tree carbon sequestration study. His expertise and collaborative spirit significantly enriched the research methodology and findings.

My heartfelt appreciation goes to Carlos and Lea for their essential assistance with stakeholder consultations in Novo Progresso, Para, Brazil. Their local knowledge and support were pivotal in understanding the socio-environmental dynamics and engaging with community perspectives.

To my family, whose unconditional love, patience, and encouragement have been my constant source of strength throughout this challenging academic pursuit – your belief in me has been my cornerstone.

I am deeply grateful to the graduate school SICSS for providing a comprehensive and structured academic environment. The courses and programmatic support were invaluable to my research development. Special thanks to Berit from the graduate school, whose kindness, availability, and helpful approach made navigating academic challenges so much more manageable and enjoyable.

I would also like to acknowledge the broader scientific community, research institutions, and funding bodies that made this research possible. Special thanks to my colleagues and peers at CLICCS, GERICS, hereon and the University of Hamburg who provided critical feedback, engaged in stimulating discussions, and created a supportive academic environment.

This research would not have been possible without the cooperation of local communities, especially those in Novo Progresso, who generously shared their time, knowledge, and experiences.

To all friends, colleagues, acquaintances and study participants who volunteered to test the prototype applications and share valuable feedback - million thanks.

Finally, I am grateful to everyone who directly or indirectly contributed to this thesis, supporting me through this transformative academic journey.

List of publications

The tree main chapters composing this dissertation are either in review, been submitted to or are to be submitted to peer-reviewed scientific journals.

Chapter Number	Title	Authors	Status	Journal	Impact Factor
2	*Estimation of Tree Carbon Sequestration Using Smartphone LiDAR, Photogrammetry and Computer Vision*	Vladimir Metelitsa, Leam Martes	Accepted	Remote Sensing	4.2
3	*The Usability of TreeCarbonAR, a Smartphone-based Augmented Reality Application for Tree Carbon Sequestration Estimation*	Vladimir Metelitsa, María Máñez Costa	Submitted	Environmental Modeling & Software	4.8
4	*An Evaluation of Feasibility and Stakeholder Utility of an Augmented Reality Climate Service for Small-Scale Rural Producers in Novo Progresso, Pará, Brazil*	Vladimir Metelitsa, Carlos Tello, Martina Neuburger, María Máñez Costa	Prepared for submission		

Other publications in peer-reviewed scientific journals not included in this dissertation:

- Tello, C., **Metelitsa, V.**, & Neuburger, M. The role of social and traditional media in the Amazon forest: in search of pluriversal discourses (in preparation)

Other publications and contributions not included in this dissertation (gray literature):

- Contribution to the development of the EU Horizon 2000 project NAIAD web-based E-Guide
  Metelitsa V., Gómez E., Vay L., Mayor B., Cauweenbergh N., Máñez M., Kozinc D. López Gunn E. (2021) "Deliverable 5.3 E-Guide Outline". EU Horizon 2020 NAIAD Project

Declaration of authorship

I, Vladimir Metelitsa, born in Minsk, Belarus on the 18th of May, 1992, hereby declare my share in the authorship of the dissertation chapters (research articles), which are either published, submitted, or are to be submitted to peer-reviewed journals, as following:

Chapter	Title	First author contribution (Vladimir Metelitsa)	Co-author contributions
2	*Estimation of Tree Carbon Sequestration Using Smartphone LiDAR, Photogrammetry and Computer Vision*	**Conceptualization** (predominantly) **Methodology** (predominantly) **Software Development** (completely) **Data Collection** (completely) **Analysis of the results** (completely) **Manuscript Writing** (completely)	**Conceptualization** Leam Martes **Methodology** Leam Martes
3	*The Usability of TreeCarbonAR, a Smartphone-based Augmented Reality Application for Tree Carbon Sequestration Estimation*	**Conceptualization** (predominantly) **Methodology** (predominantly) **Software Development** (completely) **Data Collection** (completely)	**Conceptualization** Leam Martes María Máñez Costa **Methodology** Leam Martes **Writing-review and editing** María Máñez Costa

		Analysis of the results (completely) **Manuscript Writing** (completely)	
4	*An Evaluation of Feasibility and Stakeholder Utility of an Augmented Reality Climate Service for Small-Scale Rural Producers in Novo Progresso, Pará, Brazil*	**Conceptualization** (partially) **Methodology** (completely) **Data Curation** (completely) **Software Development** (completely) **Analysis of the results** (completely) **Manuscript Writing** (completely)	**Conceptualization** Carlos Tello Martina Neuburger **Data Collection (Interviews)** Carlos Tello

Table of contents

CHAPTER 1 *INTRODUCTION* I

THE POTENTIAL OF AR FOR CLIMATE SERVICES 8
RESEARCH QUESTIONS 9
STRUCTURE OF THE THESIS 17
REFERENCES 19

CHAPTER 2 *ESTIMATION OF TREE CARBON SEQUESTRATION USING SMARTPHONE LIDAR, PHOTOGRAMMETRY AND COMPUTER VISION* **21**

1. INTRODUCTION 24
    1.1 Background 24
2. METHODS 27
    2.1 Study area 27
    2.2 Development of the mobile application 27
        2.2.1 System Architecture and Core Technologies 27
        2.2.2 Tree Detection and Measurement Process 28
        2.2.3 Carbon Sequestration Calculation 33
    2.3 Mobile application data collection 34
    2.4 Conventional survey methods data collection 35
    2.5 Statistical analysis 36
3. RESULTS 37
    3.1 Measurement time 37
    3.2 Accuracy of DHB estimates 38
    3.3 Accuracy of height estimates 39
    3.4 Accuracy of biomass and final carbon sequestration calculations 40
4. DISCUSSION 41
    4.1 Limitations 42
    4.2 Future Research Directions 43
    4.3 Policy Implications 43
5. CONCLUSION 44

APPENDIX A: EXPLANATION OF TREE DIAMETER EQUATION 45
REFERENCES 47

CHAPTER 3 *THE USABILITY OF TREECARBONAR, A SMARTPHONE-BASED AUGMENTED REALITY APPLICATION FOR TREE CARBON SEQUESTRATION ESTIMATION* **54**

1. INTRODUCTION 56
2. BACKGROUND 57
3. METHODOLOGY 59
    3.1 Initial Application Design 59
    3.2 Internal Testing Round 63
    3.3 Revised Application Design and Functionality 64
    3.4 User Testing Process 66
4. RESULTS 68
    4.1 First iteration 68
    4.2 Changes made based on feedback from first iteration 70
    4.3 Results from second iteration 72
5. DISCUSSION 77

6.0 CONCLUSION 79
REFERENCES 81

Appendix A: Survey Questions 87

CHAPTER 4 *AN EVALUATION OF FEASIBILITY AND STAKEHOLDER UTILITY OF AN AUGMENTED REALITY CLIMATE SERVICE FOR SMALL-SCALE RURAL PRODUCERS IN NOVO PROGRESSO, PARÁ, BRAZIL* **93**

1. Introduction 96
2. Background 97
   2.1 Historical Context of Novo Progresso 97
   2.2 Current Challenges 100
   2.3 Climate Change Impacts on Agriculture 102
   2.4 The Potential for AR Climate Services in the region 103
3. Methods 107
   3.1 Initial Field Observations and Stakeholder Engagement 108
   3.2 Initial Data Collection and Processing 109
   3.3 Development of the AR Climate Service Application Prototype 111
   3.5 Stakeholder Engagement and Usability Testing 114
   3.6 Data Analysis 115
4. Results 115
   4.1 Initial Reception and General Assessment 116
   4.2 Identified Areas for Enhancement 116
5. Discussion 117
   5.1 Planned Improvements Based on Expert Feedback 117
   5.2 Innovating Climate Services for the Amazon 118
   5.3 Bridging the Digital Divide 119
   5.4 Customization and Local Relevance 119
   5.5 Potential Impacts on Land Use and Forest Management 119
   5.6 Ethical Considerations and Limitations 120
   5.7 Scaling and Integration 121
   5.8 Future Research Directions 121
6. Conclusion 122
References 124

CHAPTER 5 *CONCLUSIONS, LIMITATIONS AND FUTURE RESEARCH* **129**

Conclusions 131
Addressing the Research Questions 132
Limitations 136
Future Research 139

List of Tables

Table 1: Which chapters address the various research questions.. 16
Table 2: Comparison of DHB results to previous studies using smartphone methods 38
Table 3: Comparison of tree height results to previous studies using smartphone methods...... 40
Table 4: Comparison of the results of the two iterations.. 75
Table 5: Comparison of SUS values to literature 78

List of Figures

Figure 1: The Reality-Virtuality Continuum (from Milgram et al., 1994)...................................... 3
Figure 2: The flow used in estimating carbon sequestration in the mobile app 29
Figure 3 *Approaches to estimate DBH: (a) Theoretical approach applying the trigonometric law of cosines; (b) Novel suggested approach based on intersecting chords theorem*...................... 31
Figure 4: Estimation of the tree height using the mobile application, based on the tan tree height estimation method commonly used with clinometers and hypsometers........................ 32
Figure 5: DBH measured using LiDAR (left) and photogrammetry (right) showed good agreement with ground truth from conventional methods. The solid line shows a theoretical perfect correlation fit, while the dotted lines show a linear fit model for our measurements... 39
Figure 6: Scatter plots comparing the measured tree heights from LiDAR (left) and photogrammetry (right) apps with those measured using a hypsometer. The solid line represents a perfect correlation fit (app measured height = conventional tools measured height), while the dotted line shows a linear fit for our data.. 40
Figure 7: Scatter plots comparing the estimated biomass (left) and carbon sequestration (right) from the app using LiDAR with those using data from conventional tools................................ 41
Figure 8: Path from point cloud to tree circle to diameter calculation. 46
Figure 9: Development process for TreeCarbonAR 59
Figure 10: The initial design of the application, before the first internal testing round. (a) One of the steps of the tutorial on first launch; (b) Measurement of tree height; (c) Result screen with ability to change the management strategy 63
Figure 11: The design of the application, before user testing, showing the new DBH measurement method. 66
Figure 12: Distribution of SUS scores across both iterations... 74
Figure 13: Improvement between iterations across the SUS categories..................................... 75
Figure 14: Original 3D prototype placed on table, using an iPad Pro device. 112
Figure 15: Second Prototype of the AR climate service. Screenshots are translated to English, protype used Brazilian Portuguese.. 114

Abbreviations

AGB	Above-ground Biomass
AR	Augmented Reality
AR5	Fifth Assessment Report
CI	Confidence Interval
CO_2	Carbon Dioxide
DBH	Diameter at Breast Height
HAR	Hand-held Augmented Reality
HCI	Human-Computer Interaction
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
MR	Mixed Reality
NBS	Nature-Based Solutions
NGO	Non-governmental Organization
PIN	National Integration Program
REDD+	Reducing emissions from deforestation and forest degradation in developing countries
RMSE	Root Mean Squared Error
SD	Standard Deviation

SUS	System Usability Score
ToF	Time-of-flight
VR	Virtual Reality
WMO	World Meteorological Organization
XR	Extended Reality

Chapter 1

Introduction

This thesis is a pilot study of the use of augmented reality (AR) to provide interactive climate services to non-scientists, thereby allowing for a whole new class of users to participate in the climate change debate as well as assess climate impacts of different scenarios and trade-offs between various response measures. I seek to demonstrate that AR is an effective technology to help users to understand concepts that were previously shrouded under a veil of scientific intricacy.

Climate services, as defined by the European Commission (2015, p. 10), are the "transformation of climate-related data – together with other relevant information – into customized products such as projections, forecasts, information, trends, economic analysis, assessment, counselling on best practices development and evaluation of solutions and any other service in relation to climate that may be of use to society at large." Climate services are considered key to a successful transition to a green economy and to building more resilient societies (European Commission, 2015, p. 7). The availability of climate services with accessible interfaces could help shape climate adaptation planning and limit climate risks (National Research Council, 2001). The importance of climate services has been widely recognized by the European Union (European Commission, 2015), the United States of America (National Research Council, 2001), China (China Meteorological Administration, 2015) and the World Meteorological Organization (2011).

Climate services play a vital role in helping society understand, prepare for, and respond to climate-related challenges, serving a diverse range of stakeholders with distinct needs and priorities. Policy makers at local, national, and international levels require comprehensive climate information to develop evidence-based adaptation strategies and make informed decisions about resource allocation. Meanwhile, urban planners and infrastructure developers need detailed spatial and temporal climate projections to ensure future developments are resilient to changing conditions. Agricultural stakeholders, including farmers and agribusiness managers, depend on seasonal forecasts and long-term climate projections to optimize crop selection, planting times, and resource management. Furthermore, emergency response teams and disaster management authorities rely on climate services to anticipate and prepare for extreme weather events and their potential impacts on vulnerable communities.

Traditional climate services primarily utilize web-based platforms, static maps, technical reports, and conventional 2D visualizations to communicate climate information. While these media have proven valuable for delivering basic climate data and projections, they often fall short in meeting the complex needs of diverse stakeholders. Web platforms, though accessible, frequently present data in formats that require significant expertise to interpret, limiting their utility for non-technical users. Static maps and reports, while detailed and authoritative, can struggle to convey the dynamic nature of climate processes and their interactions with human systems. Furthermore, conventional visualization methods often fail to effectively communicate the spatial and temporal complexity of climate phenomena, making it challenging for stakeholders to fully grasp the implications for their specific contexts and needs.

These limitations in current climate service delivery mechanisms have created a notable gap between the available climate information and stakeholders' ability to effectively utilize it for decision-making. Policy makers often struggle to translate technical climate projections into actionable policies, while urban planners face challenges in visualizing how climate changes might impact specific infrastructure projects over time. Agricultural stakeholders, particularly smaller-scale farmers, may find it difficult to interpret complex climate data in relation to their local conditions and specific crop requirements. The disconnect between available climate information and user needs highlights the importance of exploring new approaches to climate service delivery, particularly those that can provide more intuitive, interactive, and context-specific ways of engaging with climate data.

Most climate service tools intended for stakeholders simplify the interface, making the tools more user-friendly, but they are still seldom understandable for someone without an educational background or work experience in the subject matter, and in effect inaccessible for non-scientists. It is important for the simulations to be co-developed with stakeholders, through workshops guiding the development process based on stakeholders' needs and incorporating their feedback. The effectiveness of applications developed in this way should also be tested with stakeholder participation.

Over the last few decades, new technologies have been emerging, allowing for a range of experiences mixing the real and virtual worlds. These new technologies offer an innovative way to transmit information in an increasingly interactive way. This family of technologies, often referred to as "Extended Reality", includes virtual reality (VR), mixed reality (MR) and augmented reality. These technologies can be arranged on a continuum between reality and fully virtual environments. On this continuum VR is on the opposite end of reality, while augmented reality technologies are only one step away from reality towards virtual environments (Milgram *et al.*, 1994, Figure 1).

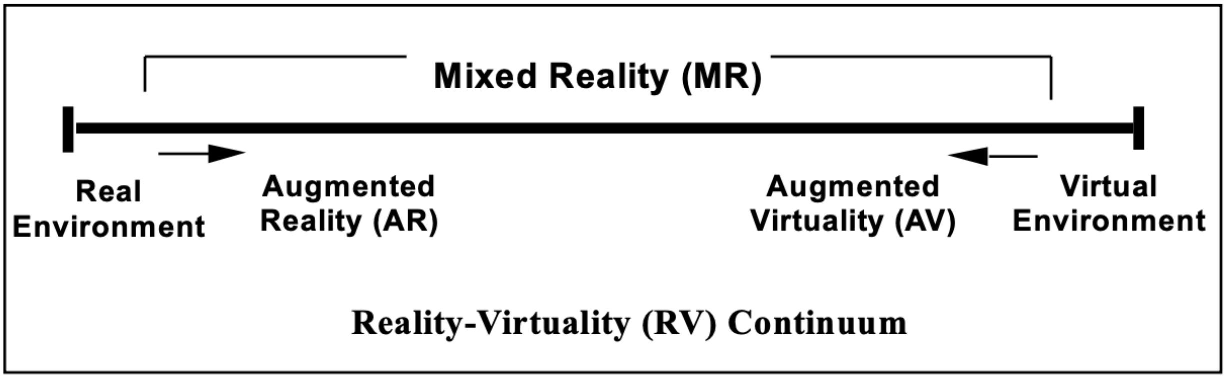


Figure 1*: The Reality-Virtuality Continuum (from Milgram et al., 1994)*

AR is a rapidly growing technology field, which allows users to see information or objects blended into their environment. Unlike VR, it does not aim to replace the user's environment with a completely different one, but rather to provide useful information about their surroundings or to show how an object would blend in that environment. In other words, AR aims to "augment", enhance or enrich our experience of reality. Examples of uses include help with navigation in maps, trying out furniture in your home before buying it, exploring animals from up-close for educational purposes, explaining medical implants to patients through simulations shown on their own bodies, city planning with interactive visualizations and many more.

AR appears particularly well suited for transferring knowledge on environmental issues, as it allows people to view their own environment at the same time as the superimposed 3D objects and information, and interact with both real-world and virtual objects simultaneously. Unlike previous visualisation technologies, AR allows the user to more naturally interact with the object in their own environment using their own hands rather than using a mouse cursor on a computer screen. Winn (2002) shows that the physical interaction that is offered by AR allows for a better cognition and recall than traditional textbooks or computer simulations.

In addition to being more accessible and easier to understand, AR as a visualisation medium has the potential to be more impactful in influencing change. Seeing impacts in their own environment is more likely to leave an impression on the users and influence them to make changes.

There have already been several studies on the effectiveness of extended reality technologies in science education. Many of the studies done into the use of extended reality technologies in relation to climate change communication were in the form of 360-degree videos played on a VR helmet. For example, Markowitz (2018) used this method to teach the effects of climate change on ocean acidification, and found the technology to lead to knowledge gain, more climate science curiosity and more positive attitudes towards the environment, based on a survey done before and after the viewing of the VR simulation. In a rare example of a study using interactive VR, Huang *et al.* (2019), used the results of an ecological model (LANDIS-II) to create an interactive model of a forest under two different climate scenarios. Unfortunately, the study only discusses the creation of the simulation, rather than testing it on a user group and reporting on its effectiveness.

Much less research has been done into the use of AR in science education. One such study compared the effectiveness of a physical ball-and-stick model of an amino acid with an AR model in a chemistry university classroom (Chen, 2006). The study found students to enjoy the portability, adaptability, interactivity and additional details of the AR model, but also not to like the marker technology used, as it was hard to get it to be recognised by their device and to work at some angles. Another study (Theodorou *et al.*, 2018) used AR (also marker based) to demonstrate the concept of renewable energy to 4th, 5th and 6th graders, and found it to have a large positive effect on the students' engagement and understanding of the material compared to regular lectures not including AR.

Despite some notable research exploring AR's potential in educational contexts, where studies have demonstrated its effectiveness in enhancing student engagement, spatial understanding, and knowledge retention across various disciplines, there is a striking absence of research investigating AR applications specifically for climate services. Therefore, the potential of AR as a tool for delivering effective climate services to professional stakeholders remains largely unexplored. This research gap is particularly noteworthy given AR's demonstrated capabilities in visualizing complex spatial data, enabling interactive exploration of layered information, and providing context-specific insights – all features that could significantly enhance the delivery and comprehension of climate information. There is therefore both a challenge and an opportunity for investigating how AR technology could be leveraged to transform the way climate services are delivered and consumed by diverse stakeholder groups.

Raaphorst et al. (2020) were pioneering researchers who first recognized the transformative potential of AR for climate services, highlighting innovative visualization approaches like Daan Roosengaarde's 'Waterlicht' installation as early examples of how immersive technologies could engage stakeholders in understanding complex climate risks.

This research project investigates two different AR types: in-situ AR and table top AR. In-situ AR helps users understand the impacts and effects of measures on their location, rather than having to understand more abstract global statistics and figures. Table top AR provides a bird's-eye view of a larger area, to visualise larger scale interactions. AR allows for visualisation to be interactive, enabling the user to switch between different scenarios (e.g., ones representing the different RCP climate scenarios) and apply different response measures.

Both of these AR types avoid one of the most common pain-points in AR implementations: the reliance on a so-called "AR Marker" for positioning the superimposed objects. When using markers (usually a QR code or bar code printed on a card), a camera built into the AR device of the user is used to identify the location of the marker and then replace said marker with an object or animation. This technology has several drawbacks: it only works when the marker is placed the right side up, well within view of the camera and in well-lit conditions. Even if all these requirements are met, slight shaking of the mobile device or changes in lighting conditions can interrupt the simulation. By basing the visualisation on the location (using the GPS instead of a printed marker) or anchoring it to a flat surface, this common issue of AR applications is avoided all together.

To achieve the widest accessibility, the AR visualisation developed for our case studies will be in the form of applications for the iOS and Android mobile platforms. They will use Hand-held AR (HAR) rather than a Head-Mounted Display (HMD), as there is no clear difference in engagement or interactivity, with HAR being more accessible, more user-friendly and only requiring a smartphone. HAR technology is already widely used in the construction and warehousing industries and as such familiar to many smartphone users in the form of maps, furniture shopping apps and popular games. The number of users of mobile AR applications on is estimated to be in excess of a billion as of 2024 (ARtillery Intelligence, 2024). In effect, the use of HAR (rather than VR) will allow for the simulation to be accessible to a large percentage of the 4.6 billion smartphone users (GSMA, 2024), as that will be all they need to use the app.

The applications use the Unity engine combined with the ARKit framework on iOS (Apple, n.d.) and the ARCore library on Android (Google, n.d.) which provide the groundwork of implementing

AR experiences. Unity is chosen both because of its ubiquity in the development of 3D visualization applications and because it allows to considerably reduce the development time, as a large portion of the code can be reused between iOS and Android, whereas normally two separate codebases in two different programming languages (most commonly Swift on iOS and Kotlin on Android) would be required.

Chen (2005) narrowed down the complicated issue of visualisation of science for end-users to ten main problems. AR has the potential to address, or at least contribute to the resolution of, eight of these issues. More specifically, *in-situ* AR resolves the issue of Usability (problem 1), by providing information about the exact location of the user's interest instead of more general data. Problem 2, the need to understand advanced concepts to even know what data would be useful to the actor, is at least partially addressed by the ability to group many different useful pieces of information that the user may not even know they needed into a single simulation with a more simple and general title. Using AR instead of scientific publications, infographics or charts also helps reduce the issue of Required Previous Knowledge (problem 3), as it is usually much easier to understand and interpret direct changes to own environment than reading figures. For example, if the data being modelled is sea level rise, it is much easier for a user to understand the change if they are able to look down and see water up to their knees, rather than looking at map showing an increase of 20 cm in their location or even more abstract regional or country-level data. The issue of end-users and decision makers not necessarily seeing the value in having visualisations (problem 4) is also at least in part addressed, as AR simulations can act as an excellent showcase of how widely accessible and easy to understand scientific knowledge can be made. The issue of Scalability that exists in flat diagrams (problem 6) is very elegantly handled by AR simulations, as they are innately 3-dimensional and interactive, allowing the user to get closer to the information they want to see and see it in more detail, while not seeing the information that they do not need. The issue of Aesthetics and Visual Appeal (problem 7) can also be solved by AR, as it allows the data to be seen as realistic objects and changes, rather than lines and points on a diagram. The issues of using dynamics (problem 8) and causality/inference (problem 9) are both handled by the interactivity of the visualisations, letting users change parameters while instantly seeing the impact of the changes they made. While the issue of presenting large volumes of information (problem 10) is inherently well solved by Human-Computer Interaction (HCI) approaches such as AR, as discussed by Chen (2005).

The novelty of this research project stems from its use of *in-situ* AR, a technology that has garnered little research so far, and none within the field of climate services. Furthermore, interactive AR, even without the *in-situ* aspect, has not yet been applied in the field of climate change. The only examples are either 360-degree non-interactive videos played over VR headsets or blending of environments to demonstrate concepts in classrooms. The use of interactive models within climate services is in itself rather novel, as most are targeted at users with some knowledge of the subject matter, and therefore not very accessible.

The Potential of AR for Climate Services

Augmented Reality technology presents compelling opportunities to transform the delivery and consumption of climate services. By overlaying digital information onto the real world through mobile devices, AR offers unique advantages for making complex climate data more accessible, interactive, and actionable for diverse users. This technology is particularly well-suited for climate services due to several key characteristics.

First, AR enables highly localized information delivery. Unlike traditional climate services that often present regional or country-level data, AR applications can provide information specific to a user's exact location by leveraging device sensors and GPS capabilities. This allows users to see climate impacts and projections directly in their immediate environment, making abstract concepts more tangible and personally relevant.

Second, AR excels at visualizing complex data in intuitive ways. Rather than requiring users to interpret technical charts or statistics, AR can present climate information through interactive 3D visualizations overlaid on the real world. This visual approach makes complex climate concepts more understandable for non-expert users while maintaining scientific accuracy. For instance, AR can show how projected sea level rise would affect specific locations or visualize carbon sequestration by individual trees in urban environments.

Third, AR supports real-time data collection and analysis through mobile device sensors. Modern smartphones equipped with cameras, LiDAR sensors, and other measurement tools can gather environmental data while providing immediate feedback through AR interfaces. This capability enables users to actively participate in environmental monitoring while receiving instant analysis and contextualization of their measurements.

Fourth, AR applications can function effectively even in areas with limited infrastructure. Many AR climate services can operate offline once installed, requiring only periodic internet connectivity for updates. This makes them particularly valuable for delivering climate information in rural or developing regions where internet access may be unreliable.

Finally, AR's interactive nature encourages active engagement with climate information. Users can explore different scenarios, test various adaptation strategies, and see the potential outcomes of different decisions in real time. This hands-on approach can help bridge the gap between climate science and practical decision-making, supporting more informed choices about climate adaptation and mitigation.

These capabilities make AR a promising medium for democratizing access to climate services while maintaining scientific rigor. As mobile devices become increasingly powerful and AR technology continues to mature, the potential for developing effective, user-friendly climate services through AR will only grow.

Research Questions

This study evaluates Augmented Reality's potential as a medium for climate services through six research questions that examine technical, practical, and user-cantered aspects of AR implementation. Together, the questions form a comprehensive framework for assessing whether and how AR can serve as an effective platform for delivering climate services.

Research Question 1: To what extent can Augmented Reality serve as a viable medium for climate services?

This foundational question investigates AR's suitability for delivering climate services, examining both technological capabilities and user acceptance. It examines whether AR technology can effectively bridge the gap between complex climate data and practical user needs while maintaining scientific accuracy and accessibility. Three sub questions guide this investigation:

RQ1.1: What characteristics of AR make it suitable for climate service delivery?
This sub question examines the inherent features of AR technology that could make it particularly effective for delivering climate services. It explores how AR's ability to overlay digital information on the real world, its interactive nature, and its capacity for real-time visualization could enhance the delivery of climate information. The question considers both technical aspects (such as spatial awareness and visualization capabilities) and user experience factors (such as intuitive interaction and engaging presentation).

RQ1.2: What types of climate services can be effectively implemented using AR technology?
This sub question explores suitable applications across environmental monitoring, decision support, and public education, identifying factors that influence successful implementation.

RQ1.3: What are the key requirements for successful AR climate service implementation?
This sub question identifies the critical factors and conditions necessary for effective AR climate service deployment. It examines technical requirements (such as sensor capabilities and processing power), user requirements (such as interface design and accessibility), and contextual requirements (such as data availability and infrastructure needs). This understanding is essential for developing guidelines for successful AR climate service implementation.

These questions form the basis for evaluating AR's potential through practical case studies, considering both opportunities and limitations in diverse contexts.

Research Question 2: Can Augmented Reality technologies reliably collect environmental data for use in climate services?
This research question investigates the potential of AR technology as a data collection tool for climate services, focusing specifically on the ability of smartphone-based AR systems to gather environmental measurements. It examines whether AR can serve as a reliable alternative or complement to traditional measurement methods while offering advantages in accessibility, efficiency, and ease of use. The investigation is guided by three sub questions:

RQ2.1: What level of accuracy can smartphone-based AR achieve in collecting environmental measurements compared to conventional methods?
This sub question quantifies the precision and reliability of AR-based measurements against established methodologies. It involves rigorous comparative testing between AR measurements and traditional tools, examining factors such as systematic errors, measurement consistency, and

accuracy under different conditions. The question is crucial for establishing whether AR-based measurements can meet the scientific standards required for climate services.

RQ2.2: What are the key technical and practical limitations of using AR for environmental data collection?
This sub question examines the constraints and challenges that affect AR-based environmental measurements. It investigates how various environmental and technical factors might impact measurement accuracy and reliability. Understanding these limitations is essential for defining the appropriate use cases for AR-based measurements and developing strategies to optimize their effectiveness in different scenarios.

RQ2.3: How can AR data collection methods be adapted for different environmental contexts and measurement needs?
This sub question explores how AR measurement techniques can be optimized for various environmental settings and measurement requirements. It investigates the adaptability of AR measurement methods to different types of environmental data collection, considering factors such as scale, complexity, and environmental conditions. This includes examining how AR applications can be designed to accommodate different measurement scenarios while maintaining accuracy and usability.

This research question is particularly significant as it investigates the fundamental capability of AR to collect and utilize local data in settings with poor pre-existing data availability. The findings from this research question will inform both the technical development of AR applications and their practical implementation in environmental monitoring and climate service contexts.

Research Question 3: Can complex climate model outputs be effectively translated into interactive AR visualizations?
This research question examines AR's potential to transform sophisticated climate model data and projections into accessible, interactive visualizations that maintain scientific validity while being understandable to users. The investigation is guided by three sub questions:

RQ3.1: What approaches can be used to transform complex model outputs into meaningful AR experiences? This sub question explores methodologies for converting climate model data into interactive AR visualizations. It examines different visualization techniques, interaction paradigms, and user interface approaches that can effectively communicate complex climate information. The question addresses how to balance scientific accuracy with user comprehension, investigating ways to present multi-dimensional data in an intuitive and engaging format through AR.

RQ3.2: How can model uncertainty and variability be effectively communicated through AR? This sub question investigates techniques for representing the inherent uncertainty and variability in climate model projections through AR visualization. It explores how AR can help users understand and work with probabilistic information and ranges of potential outcomes, examining ways to communicate confidence levels and variability without overwhelming users or oversimplifying the underlying science.

RQ3.3: What level of model complexity can be effectively represented in AR interfaces? This sub question examines the boundaries of complexity that can be meaningfully represented in AR visualizations. It investigates how to determine appropriate levels of detail and complexity in AR representations of climate model outputs, considering both technical limitations and user cognitive load. This includes exploring how different user groups might require different levels of complexity in the visualization of model outputs.

This research question is vital for understanding how AR can serve as an effective medium for communicating complex climate information. The ability to translate sophisticated climate model outputs into comprehensible, interactive visualizations is crucial for making climate information more accessible and actionable for different stakeholder groups, from policy makers to the general public. The insights gained from this question will help establish good practices for developing AR-based climate service visualizations that effectively bridge the gap between scientific complexity and practical utility.

Research Question 4: Can AR climate services effectively engage and inform the general public?
This research question investigates AR's potential as a tool for public engagement with climate information. It examines whether AR technology can make complex climate concepts more accessible and meaningful to non-expert users, exploring how interactive, engaging experiences might enhance public understanding and engagement with climate-related issues. The question addresses the broader challenge of democratizing access to climate information and supporting informed public participation in climate-related decision-making.
The investigation is guided by three sub questions:

RQ4.1: How do non-expert users understand and interact with climate information presented through AR?
This sub question examines how members of the general public interpret and engage with climate information when it is presented through AR interfaces. It investigates user comprehension, engagement patterns, and potential barriers to understanding. The question explores how different presentation methods and interaction designs might affect user understanding and engagement with climate concepts.

RQ4.2: What design approaches best support public engagement with climate information in AR?
This sub question identifies effective design strategies for public-facing AR climate services. It examines how various design elements - from visualization techniques to interaction methods - can be optimized to enhance public engagement and understanding. This includes investigating how to make complex information accessible without oversimplification and how to maintain user interest while ensuring scientific accuracy.

RQ4.3: Can AR climate services lead to improved understanding of climate concepts among the general public?
This sub question investigates whether AR presentations of climate information can enhance public comprehension of key climate concepts compared to traditional communication methods. It explores how AR's unique capabilities might help overcome common barriers to understanding climate information and whether these improvements in understanding can support more informed decision-making and engagement with climate issues.

This research question is crucial for understanding AR's potential role in climate communication and public engagement. As climate change increasingly affects daily life, finding effective ways to communicate climate information to the general public becomes ever more important. Understanding how AR can contribute to this goal is essential for developing more effective climate services that can reach and engage broader audiences.

Research Question 5: Can AR climate services support decision-making for domain experts in non-climate fields?

This research question explores how AR climate services can assist professionals who need to incorporate climate considerations into their decision-making but whose primary expertise lies in other domains. It examines whether AR can effectively bridge the gap between domain expertise

and climate knowledge, making climate information more accessible and actionable for professionals in fields such as agriculture, urban planning, and resource management.
The investigation is guided by three sub questions:

RQ5.1: How do professional stakeholders integrate AR climate services into their decision-making processes?
This sub question examines how domain experts incorporate AR-based climate information into their existing professional practices and decision-making frameworks. It investigates how AR tools can complement professional expertise and existing decision-making processes, exploring the ways in which different stakeholder groups might utilize climate information presented through AR to inform their work.

RQ5.2: What specific requirements do domain experts have for AR climate services?
This sub question identifies the unique needs and preferences of professional users in different fields. It examines what features, information types, and interaction methods would be most valuable for domain experts, considering how AR climate services can be tailored to specific professional contexts and decision-making needs. This includes investigating how climate information can be presented in ways that align with professional workflows and domain-specific considerations.

RQ5.3: Can AR effectively bridge the gap between domain expertise and climate knowledge?
This sub question investigates whether AR can successfully translate climate information into formats that are meaningful and applicable within specific professional contexts. It explores how AR can help domain experts connect climate information to their area of expertise, examining whether AR's visualization and interaction capabilities can help professionals better understand and apply climate considerations in their work.

This research question is essential for understanding how AR climate services can support practical decision-making across different professional sectors. As climate considerations become increasingly important across various fields, finding effective ways to integrate climate information into professional decision-making becomes crucial. The insights gained from this question will help inform the development of AR climate services that can effectively serve professional users while respecting and complementing their domain expertise.

Research Question 6: Can effective AR climate services be implemented in lesser developed countries and data-scarce environments?

This research question investigates the feasibility and effectiveness of implementing AR climate services in regions with limited data availability and infrastructure. It examines how AR technologies can be adapted to function effectively in challenging environments while still providing meaningful climate services to local stakeholders. The question addresses the important challenge of ensuring that innovative climate service technologies can serve communities regardless of their resource constraints or development status.

The investigation is guided by four sub questions:

RQ6.1: What strategies can be employed to develop useful AR climate services in regions with limited environmental data and infrastructure?

This sub question explores approaches for creating effective AR applications in data-scarce environments. It examines how AR services can be designed to function with limited data inputs while still providing valuable information to users. The question investigates methods for combining available data with local knowledge and alternative information sources to create meaningful climate services.

RQ6.2: How can AR applications be adapted to meet the specific needs and constraints of users in developing regions?

This sub question tailors AR climate services to particular contexts of developing regions. It examines how applications can be designed to account for factors such as limited internet connectivity, device availability, and varying levels of technical literacy. This includes investigating how to create interfaces and interactions that are appropriate for local contexts and user capabilities.

RQ6.3: Can AR climate services effectively bridge data and resource gaps in lesser developed countries while remaining accessible and useful?

This sub question investigates whether AR technology can help overcome limitations in traditional climate service delivery in developing regions. It examines how AR might provide alternative ways of gathering, presenting, and utilizing climate information in resource-constrained environments, exploring whether AR can offer advantages over conventional approaches in these contexts.

RQ6.4: What are the key technological, social, and infrastructural considerations for implementing AR climate services in developing regions?

This sub question examines the broader context of implementing AR climate services in developing regions. It investigates various factors that need to be considered for successful implementation, from technical requirements and infrastructure needs to social and cultural considerations. This includes exploring how AR services can be designed to be sustainable and effective within existing resource constraints.

This research question is crucial for understanding how AR climate services can be made accessible and useful in regions where traditional climate services might be limited or unavailable. It addresses the important goal of ensuring that innovative climate service technologies can benefit communities regardless of their resource constraints or development status, contributing to more equitable access to climate information globally.

Together, these research questions form a comprehensive framework for evaluating AR's potential as a medium for climate services. They progress from fundamental questions about technical viability and data collection capabilities to practical considerations about implementation and user engagement, culminating in addressing the broader challenge of deployment in resource-constrained environments. This systematic approach enables the investigation of AR's potential across multiple dimensions: technical feasibility, user acceptance, practical utility, and adaptability to different contexts. By addressing these questions through concrete case studies, this research aims to establish whether and how AR can serve as an effective medium for delivering climate services to diverse stakeholder groups, from urban citizens to rural producers, and from the general public to domain experts. The answers to these questions will help guide the future development and implementation of AR-based climate services while identifying both opportunities and limitations in their application.

Table 1: *Which chapters address the various research questions*

Chapter	RQ1	RQ2	RQ3	RQ4	RQ5	RQ6
2		X				
3	X		X	X		
4	X		X		X	X

Structure of the thesis

This thesis consists of three main chapters exploring different applications and contexts for AR-based climate services, bookended by an introduction and a conclusion. Each chapter investigates distinct aspects of AR's potential as a medium for climate services while building towards a comprehensive understanding of its viability and effectiveness across different contexts.

Chapter 2 presents a novel methodology for estimating tree carbon sequestration using smartphone LiDAR, photogrammetry, and computer vision technologies. The study developed and validated a mobile application that integrates these technologies to measure key dendrometric parameters (tree height and diameter) and calculate carbon sequestration potential. Field trials with 153 trees across urban and forested environments demonstrated exceptional accuracy, with measurements showing strong correlation with conventional forestry tools. The application achieved these results while reducing measurement time to less than 20% of conventional methods. This chapter establishes the technical foundation for AR climate services by demonstrating that smartphone-based AR applications can reliably collect environmental data with accuracy comparable to traditional methods while significantly improving accessibility and efficiency. The methodology and initial results of this study were also presented at the international scientific conference EGU 2022 in Vienna.

Chapter 3 evaluates the usability and effectiveness of TreeCarbonAR, an expanded AR application building upon the measurement methodology developed in Chapter 2. This enhanced application not only measures carbon sequestration but also translates these measurements into relatable terms by comparing them to everyday activities like kilometres driven or water boiled in a kettle. The application additionally incorporates different forest management strategies, allowing users to explore how various approaches would affect carbon sequestration potential. Through two iterations of user testing with 41 and 53 participants respectively, the study assessed how non-expert users interact with and understand climate information presented through AR. The application underwent significant refinements based on initial user feedback, resulting in improved usability scores and enhanced user understanding of carbon sequestration concepts. This chapter demonstrates AR's potential to bridge the gap between complex climate science and public understanding, showing how AR can make abstract environmental concepts tangible and accessible to non-expert users. The concept and initial results of this study were also presented at the international scientific conference of the International Environmental Modelling and Software Society (iEMSs) 2022 in Brussels.

Chapter 4 investigates the feasibility and utility of AR climate services in a fundamentally different context - supporting agricultural decision-making by small-scale rural producers in Novo Progresso, Pará, Brazil. The study developed and evaluated a table-based AR application that allows farmers to visualize climate projections and test different adaptation strategies for their agricultural plots. Despite challenges including limited infrastructure and data scarcity, the application successfully engaged rural producers and supported their decision-making processes. The study demonstrates AR's adaptability as a medium for climate services in developing regions and data-poor environments, showing how AR can effectively combine local knowledge with climate projections to support practical decision-making. The initial concept of this results was presented at the iEMSs 2022 conference (Brussels) while more advanced progress was presented at the EGU 2024 conference (Vienna).

Together, these chapters provide a comprehensive examination of AR's potential as a medium for climate services. From precise environmental measurement to public engagement to agricultural decision support, the research demonstrates AR's versatility across different applications, user groups, and contexts. The progression from technical validation to user engagement to real-world implementation in a developing region provides compelling evidence for AR's viability as a medium for delivering climate services while highlighting important considerations for its effective deployment.

References

Bijak, S., & Sarzyński, J. (2015). Accuracy of smartphone applications in the field measurements of tree height. *Folia Forestalia Polonica*, *57*(4), 240–244. https://doi.org/10.1515/ffp-2015-0025

Apple. (n.d) ARKit Framework. Accessed at https://developer.apple.com/documentation/arkit

Artillery Intelligence (2024). Mobile AR Usage & Consumer Attitudes, Wave 8.

Theodorou, P., Kydonakis, P., Botzori, M., Botzori, M., & Skanavis, C. (2018). Augmented Reality Proves to be a Breakthrough in Environmental Education.

Chen, C. (2005). Top 10 unsolved information visualization problems. *IEEE Computer Graphics and Applications*, *25*(4), 12–16. https://doi.org/10.1109/MCG.2005.91

Chen, Y.-C. (2006). A study of comparing the use of augmented reality and physical models in chemistry education. *In Proceedings of the 2006 ACM international conference on Virtual reality continuum and its applications (VRCIA '06). Association for Computing Machinery, New York, NY, USA,* 369–372. https://doi.org/10.1145/1128923.1128990

Raaphorst, K., Koers, G., Ellen, G. J., Oen, A., Kalsnes, B., van Well, L., Koerth, J., & van der Brugge, R. (2020). Mind the Gap: Towards a Typology of Climate Service Usability Gaps. *Sustainability*, *12*(4), Article 4. https://doi.org/10.3390/su12041512

China Meteorological Administration (2015) China Framework for Climate Services.

European Commission. (2015) A European Research and Innovation Roadmap for Climate Services. https://data.europa.eu/doi/10.2777/750202

Huang, J., Lucash, M. S., Scheller, R. M. & Klippel A. (2019). Visualizing Ecological Data in Virtual Reality. 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), 2019, pp. 1311-1312, doi: 10.1109/VR.2019.8797771.

Google (n.d) ARCore Library. Accessed at https://developers.google.com/ar

GSMA. (2024). *The State of Mobile Internet Connectivity Report 2024*. https://www.gsma.com/r/somic/

Markowitz, D. M., Laha, R., Perone, B. P., Pea, R. D., & Bailenson, J. N. (2018). Immersive Virtual Reality field trips facilitate learning about climate change. *Frontiers in Psychology*, *9* (NOV). https://doi.org/10.3389/fpsyg.2018.02364

Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1994). Augmented reality: a class of displays on the reality-virtuality continuum. *Telemanipulator and Telepresence Technologies*, *2351*, 282–292. https://doi.org/10.1117/12.197321

National Research Council (NRC). (2001) A Climate Services Vision: First Steps Toward the Future, The National Academies Press, Washington, D. C.

Winn, W. (2002). Learning in Artificial Environments: Embodiment, Embeddedness and Dynamic Adaptation. *Tech., Inst., Cognition & learning*, 1, 87-114. 372

World Meteorological Organization. (2011). Climate Change for Action: A Global Framework for Climate Services – Empowering the Most Vulnerable.

Chapter 2

Estimation of Tree Carbon Sequestration Using Smartphone LiDAR, Photogrammetry and Computer Vision

Estimation of Tree Carbon Sequestration Using Smartphone LiDAR, Photogrammetry and Computer Vision

Vladimir Metelitsa[1, 3, §], Leam Martes[2, 3]

[1] Climate Service Center Germany (GERICS), Helmholtz-Zentrum hereon GmbH, Fischertwiete 1, 20095 Hamburg
[2] Institute for Wood Science-World Forestry, Center for Earth System Research and Sustainability (CEN)
[3] Center for Earth System Research and Sustainability (CEN), Universität Hamburg
[§] Corresponding author; E-Mail: vladimir.metelitsa@hereon.de

Vladimir Metelitsa ORCiD: 0000-0003-0984-9249
Leam Martes ORCiD: 0000-0001-9931-1308

Keywords: LiDAR, Carbon Sequestration, Urban Forestry, Smartphone Applications, Dendrometry, Forest Inventory, Photogrammetry, Augmented Reality, Mobile Sensing, Nature-based Solutions

Abstract

This study presents and validates a novel method for estimating tree carbon sequestration by integrating smartphone Light Detection and Ranging (LiDAR), photogrammetry, and computer vision technologies with on-device processing. Using a custom-developed mobile application, we compared the accuracy and efficiency of LiDAR-based measurements against both conventional forestry tools (D-tape and hypsometer) and photogrammetry-only smartphone measurements. In field trials comprising 153 trees across urban and forested environments, the LiDAR-enabled application demonstrated exceptional accuracy in measuring key dendrometric parameters, with Diameter at Breast Height (DBH) showing strong correlation with conventional methods ($R^2 = 0.99$, RMSE = 1.54 cm), and tree height measurements achieving even higher accuracy ($R^2 = 0.99$, RMSE = 0.43 m). The photogrammetry-only implementation showed slightly lower but still robust accuracy (DBH: $R^2 = 0.96$, RMSE = 3.39 cm). The mobile application proved to be significantly faster, reducing measurement time to less than 20% of conventional methods, averaging 45.3 seconds per tree compared to 4 minutes using traditional tools. Carbon sequestration estimates derived from these measurements showed only some deviation from those based on conventional measurements ($R^2 = 0.99$), though accuracy was lower for trees under 10 cm diameter. The user-friendly design of the mobile application, coupled with its efficiency and accuracy, has the potential to revolutionize the evaluation of nature-based solutions, promote environmental stewardship, and democratize environmental decision-making, thereby enabling a broader spectrum of non-scientific users to utilize forest data for decision-making processes in areas such as urban planning.

1. Introduction

Trees play a crucial role in the carbon cycle by capturing atmospheric carbon dioxide (CO_2) via photosynthesis and storing it in their biomass, thereby acting as carbon sinks (Bonan, 2008). This process of carbon sequestration is an important contributor to mitigation of climate change (Pachauri *et al.*, 2014). An accurate estimation of the amount of carbon sequestrated by trees is imperative to understanding and managing the global carbon balance as well as to developing effective forest management and climate mitigation strategies. However, current methods for measuring forest carbon stocks face significant challenges in terms of efficiency, accessibility, and scalability. Traditional methods of measuring the carbon sequestration of a forest involve on-site field surveys, which are labour-intensive, time-consuming, require specialized equipment and expertise. They can occasionally be inaccurate due to the complex structure of forest canopies. A modern alternative to conventional forest surveys is the use of Light Detection and Ranging (LiDAR) and similar technologies. LiDAR, a remote-sensing technology, enables the collection of three-dimensional point clouds depicting the device's surroundings. These point clouds can be processed to extract accurate measurements, including important properties of trees such as their height and diameter at breast height (DBH), thereby enabling the estimation of the carbon sequestration potential of trees. Previously, this technology has been expensive, necessitating bulky tools and requiring a complex analysis of the resultant point cloud data. However, recent technological advancements have enabled the integration of LiDAR into select smartphones, tablets and other mobile devices. This progression not only permits data collection comparable to large-scale LiDARs (albeit at a reduced range and resolution), but also enables immediate on-site processing, courtesy of the on-board processing power inherent in modern mobile devices and their ability to execute custom code. This study explores the potential of a smartphone application, which integrates LiDAR, machine vision/learning, and photogrammetry with on-device processing, in the estimation of the carbon sequestration of trees, as compared to conventional forest inventory survey tools.

1.1 Background

The application of remote sensing in forest surveys and carbon sequestration measurement has evolved significantly over the past decades. Various methods have been developed and refined, from traditional ground-based tools to sophisticated aerial systems. However, the exploration of smartphone-based measurement systems, particularly those incorporating smartphone LiDAR, a burgeoning technology in this context, remains in its early stages despite their potential for democratizing forest measurements.

LiDAR, an active remote sensing technology, has gained significant popularity in forest surveys, owing to its capacity to produce highly accurate, detailed 3D data on the vertical structure of vegetation. LiDAR systems operate by emitting laser pulses that ricochet off objects and return to a sensor. This sensor measures the time taken for the pulse to return (time-of-flight), thereby calculating the distance to the object. By scanning a forest area with multiple laser pulses, LiDAR creates a high-resolution point cloud representing the structure and spatial distribution of trees and forest vegetation.

Airborne LiDAR offers the benefit of rapidly and efficiently covering large forest areas, making it ideal for large-scale mapping and monitoring projects (e.g. Leitold *et al.*, 2015). It can survey thousands of hectares in a single flight, allowing researchers to create detailed 3D models of entire forest landscapes. However, airborne LiDAR's main limitation is its lower spatial resolution compared to terrestrial LiDAR, meaning it cannot capture fine-scale details such as individual tree crowns or small canopy gaps. Despite this, airborne LiDAR is extensively utilized for forest inventory and mapping, providing accurate, high-resolution data over large areas and facilitating swift assessments of forest structure and biomass.

Terrestrial LiDAR systems offer substantially higher spatial resolution and can capture detailed information about individual trees and their spatial arrangements (Heo et al., 2019). These systems, typically mounted on tripods or vehicles, enable researchers to generate highly accurate 3D models of individual trees and forest plots from multiple angles. This detailed point-cloud data supports precise dendrometry measurements, canopy cover, and forest structure changes over time. However, terrestrial LiDAR's main drawback is the significant time and resources required for data collection, particularly over larger areas. The equipment is also costly and requires specialized expertise for operation and data processing.

While these conventional LiDAR approaches have revolutionized forest surveying by providing unprecedented detail about forest structure, their widespread adoption remains limited by cost and complexity. This has created a significant gap between the potential of LiDAR technology and its practical accessibility for routine forest monitoring. Conventional forest survey tools, therefore, remain significantly more frequently used.

Smartphone LiDAR holds a potential for creating a unique niche within forest surveys due to its portability, accessibility, and affordability, while maintaining sufficient accuracy to gather data on the studied area. Therefore, it could democratize processes previously reserved for a small subset of the population, enabling a broader group, including non-scientists, to participate. Despite being a promising technology, the use of smartphone LiDAR for forest surveys and similar applications has not been subject to extensive scientific research or further development so far.

Early research in this field has shown encouraging results. Gollob (2021) undertook a first examination of the potential of using smartphone LiDAR for DBH estimation. This study demonstrated that smartphone LiDAR could achieve acceptable accuracy for DBH measurements. However, this first study only featured the use of a mobile device for collecting point clouds, while processing was performed on an external computer upon completion of the data collection. The study already demonstrated that the data collected could be quite accurate. Tatsumi, Yamaguchi & Furuya (2022) studied the potential of the iPhone LiDAR in forest surveys, for mapping and measuring tree trunks, with near real time on device processing. Their method required circle fitting to the tree trunk, obtained by walking all the way around the tree. They found the LiDAR to be reasonably accurate, but suggested improvements in occlusion handling (nearby branches/vegetation). Holcomb, Tong and Keshav (2023) used a more advanced method of measuring tree diameter that uses only a single image of a tree, with filters and rotation applied to, for the extraction of the tree trunk from its surroundings on the image. The study also found the readings to be accurate, but with decreasing accuracy as the tree trunk size increases. The application in the study interestingly did not technically measure DBH, but rather the diameter at the height the smartphone was held at. This is arguably not always a good substitute for DBH, as DBH is an important metric frequently used for comparison and in forestry formulas. The study paid particular attention to the issue of tree trunk occlusion, in forested settings, and had good results in trunk detection even in heavily forested areas.

Bijak & Sarzyński (2015) reviewed two different smartphone applications that measure the height of trees. They found the concept to be promising as it allowed for fast and easy measurements, but requiring further improvement as the measurements frequently showed a systematic underestimation of tree heights in the range of 1 to 2.5 meters. It is worth noting that the applications reviewed for that study did not provide automatic tree distance measurement, requiring the user to measure their distance from the tree and enter it in the application. Additionally, the applications did not account for the tree incline or a potential incline of the ground plane.

To date, no research has integrated smartphone LiDAR with photogrammetry and computer vision for comprehensive tree measurement, or provided immediate carbon sequestration calculations through on-device processing. Furthermore, the use of augmented reality for measurement guidance remains understudied. This research addresses these gaps by developing and validating a novel mobile application that combines these technologies for efficient and accurate tree carbon estimation.

2. Methods

2.1 Study area

The study sampled trees in three different areas/plots within the city of Hamburg, Germany. The three areas were an urban park (Eilbek Park and surroundings), a more densely wooded urban forest and a stretch of street trees lining pedestrian walkways (Wandsbek area). These sites were selected due to their diversity of local tree species and levels of density, thus presenting a comprehensive portrayal of potential tree carbon sequestration within an urban context. Moreover, these divergent locations also allowed for diverse measurement scenarios, to identify potential contextual issues with the application use.

2.2 Development of the mobile application

We developed a user-friendly mobile application aimed at enabling swift and straightforward determination of key dendrometric measurements without requiring intricate knowledge about the underlying mechanisms. The application utilizes an augmented reality interface overlaying the user's environment from images captured by the smartphone's rear camera. The primary purpose of the application is to automate the process of measuring the DBH and tree height, the two critical variables for the calculation of tree biomass, for the estimation of carbon sequestration. To ensure maximum accessibility for users, the application supports both LiDAR-enabled smartphones and phones without LiDAR, relying exclusively on photogrammetry for the latter.

2.2.1 System Architecture and Core Technologies

The application was developed using two parallel implementations: an iOS version written in Swift and SwiftUI and an Android version developed in Kotlin. Both versions utilize their respective platform's augmented reality frameworks (ARKit for iOS, ARCore for Android) to enable spatial awareness and measurement capabilities. The system architecture comprises four primary components that work in concert to deliver accurate measurements and a seamless user experience.

The first component is the sensing module, which manages all data acquisition from device sensors. For iOS devices, this includes integration with the LiDAR sensor for depth mapping and point cloud generation. Both implementations process the camera feed for photogrammetry and computer vision analysis, while simultaneously tracking device motion and orientation through the inertial measurement unit (IMU) sensors. The sensing module also handles ground plane detection and tracking, which is crucial for accurate height measurements and slope compensation.

The processing module forms the computational core of the application, handling real-time analysis of sensor data. This module processes and filters point cloud data, executes tree trunk detection and segmentation algorithms, performs geometric calculations for DBH and height measurements, and computes biomass and carbon sequestration estimates. All processing is performed on-device, eliminating the need for network connectivity or external computing resources.

The user interface module delivers an augmented reality overlay that guides users through the measurement process. This module provides real-time feedback on measurement quality, visual confirmation of tree detection, and clear presentation of measurement results. The interface adapts dynamically to measurement conditions, offering guidance for optimal positioning and alerting users to potential measurement issues.

The data management module handles all aspects of measurement data persistence and retrieval. This includes local storage of measurements and calculations, export functionality for further analysis, and management of calibration data. The module implements data validation protocols to ensure measurement integrity and maintains a structured format for measurement history and analysis.

These components are tightly integrated through a modular architecture that enables efficient data flow while maintaining system reliability and responsiveness. The architecture was designed with extensibility in mind, allowing for future enhancements such as additional measurement parameters or improved analysis algorithms

2.2.2 Tree Detection and Measurement Process

The measurement workflow comprises several sequential processes, each employing specific technologies to optimize accuracy, Figure 2 outlines the steps.

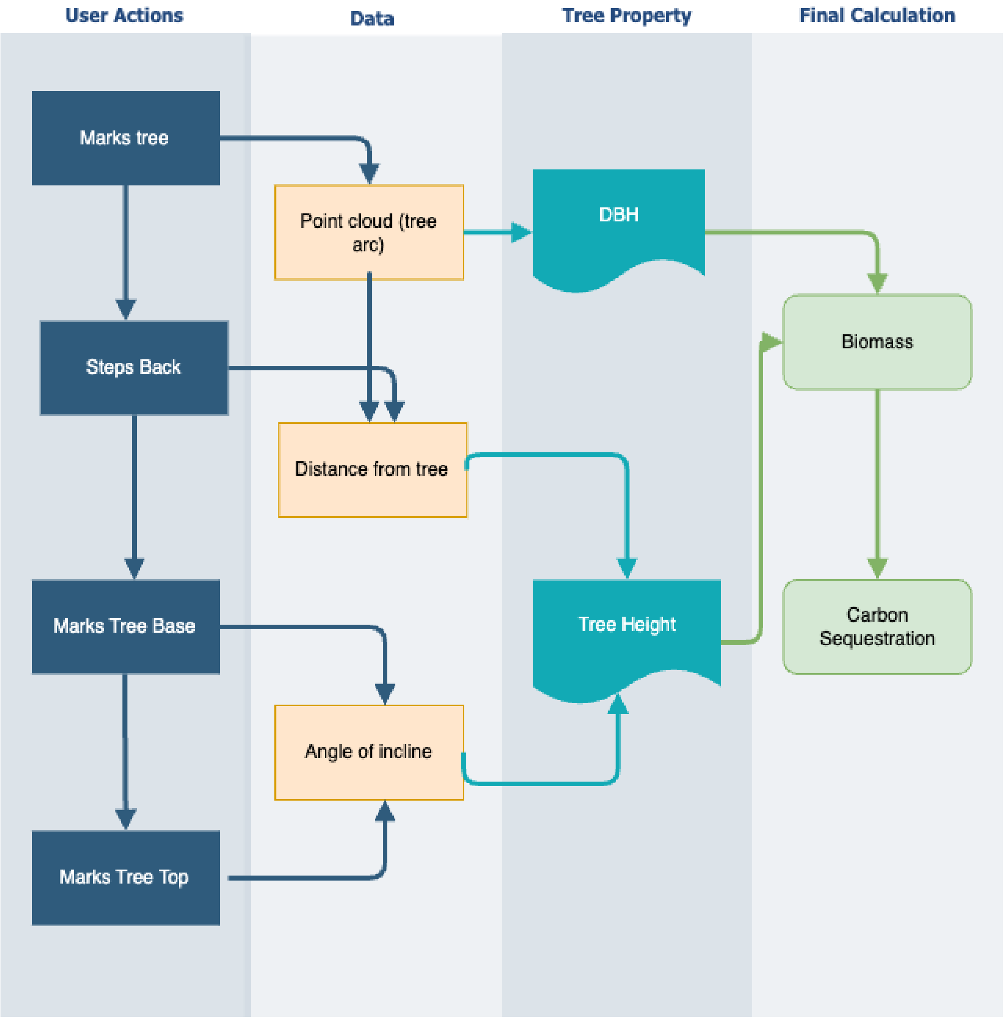


Figure 2: *The flow used in estimating carbon sequestration in the mobile app*

The first step in measuring the tree's DBH is to clearly identify the position, orientation and scale of the tree trunk. To identify the tree in the user environment, a machine learning/vision instance segmentation model is applied to the photo frame that is on the screen when the user taps the "measure" button.

The instance segmentation model used was YOLOv7-seg (Wang, Bochkovskiy & Liao, 2022), an open-source state-of-the-art object detection and segmentation model. This machine vision model was trained on a vast dataset of tree trunk images, enabling it to discern tree trunks on a frame taken from the device camera. Using the depth point cloud data, the identified tree trunk is then "extracted" from its surrounding. While this step is not mandatory for the measurement, it significantly enhances the application's performance in densely forested areas and for trees

with multiple branches that partially obscure the trunk. For this purpose, numerous images in the training data set contain trunks occluded by branches or other vegetation.
If the application fails to identify a tree trunk in the image, the user is guided to adjust their position to achieve a clearer view and try again. Once a tree trunk is detected, the application superimposes an outline on the identified trunk to signal successful detection and readiness for measurement.

To measure the DBH, the application effectively has to draw a straight line at breast height (1.3m above ground). The line's length can then be determined by either measurement from the LiDAR or a pixel counting method, similar to what is commonly used in smartphone digital ruler applications. The iPhone LiDAR has previously been measured to have an accuracy to the nearest centimetre for objects larger than 10 cm (Luetzenburg, Kroon & Bjørk, 2021).

Given that trees do not grow strictly perpendicularly to the ground, it is important to measure the diameter perpendicular to the tree trunk, rather than parallel to the forest floor. The tree's angle to the ground is estimated by the application, based on the angle of trunk to the ground plane and the diameter line is aligned accordingly.

In theory, to measure DBH simple trigonometry could be used (Figure 3a). Two opposing edges of the tree (adjusted for angle to the ground) are taken as the two edges of the triangle and the location of the user's phone camera as the third. Since we know the angle of the triangle on the side of the phone as well as the length of the two lines connecting the user's device to the tree, we can easily determine the length of the last side of the triangle, which is the diameter of the tree. Due to trees cross sections not being perfect circles, and the parallax effect of photos, the measured through line is not exactly the same as the diameter of the tree trunk, a one side depth cloud of a tree trunk does not include a full half of a trunk.

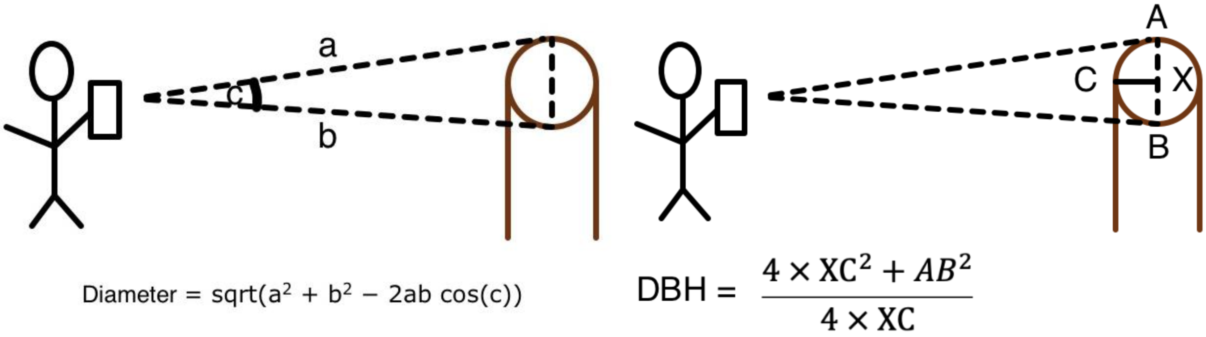


Figure 3 *Approaches to estimate DBH: (a) Theoretical approach applying the trigonometric law of cosines; (b) Novel suggested approach based on intersecting chords theorem*

Instead, we developed a novel method to avoid this parallax effect (Figure 3b). We extract the arc of the tree and some lengths from the point cloud to obtain a closer estimate of the true diameter. Our suggested equation to calculate DBH is as follows:

$$\mathrm{DBH} \;=\; \frac{4 \times \mathrm{XC}^2 + AB^2}{4 \times \mathrm{XC}}$$

Where AB is the chord connecting the outer visible parts of the tree along the point cloud arc, and XC is the distance from the chord AB to the closest to the user point of the point cloud C. An explanation of how the equation is derived is given in Appendix A.

While this is in practice a very similar measurement, accounting for the parallax effect improves the accuracy of measurements by a few per cent. This is especially noticeable on smaller trees, where this pseudo-systematic error is more visible. This method still assumes that the tree has a cylindrical shape, but this is a mostly reasonable simplification, as both previous studies (e.g., Holcomb *et al.,* 2023) as well as the IPCC guidelines for tree surveys (Eggleston *et al.*, 2006) make the same assumption. On devices without LiDAR, depth from motion combined with pixel counting is used to achieve the same effect.

The height of the tree is estimated by applying geometric principles similar to those used in conventional methods, such as a clinometer and hypsometers. However, the mobile application automates this process. After the measurement of the DBH, a cross-hair is displayed in the centre of the screen and the user is instructed to take a few steps back (as this is usually required to see the tree top) roughly half or more of the height of the tree and to tilt the device upwards until the tree's top aligns with the cross hair and to tap a button to confirm. Then the user tilts the phone downwards towards the tree roots and similarly marks the bottom of the tree. Internally the application undertakes ground plane estimation, measures the tree's angle to the ground and the phone's angle to the tree's top. The distance from the tree to the user is derived either from the LiDAR (if the user is less than 5 meters away from the tree) or Simultaneous Localization and Mapping (SLAM) APIs of the mobile platform if the user is not. These parameters are used to calculate the tree height (Figure 4).

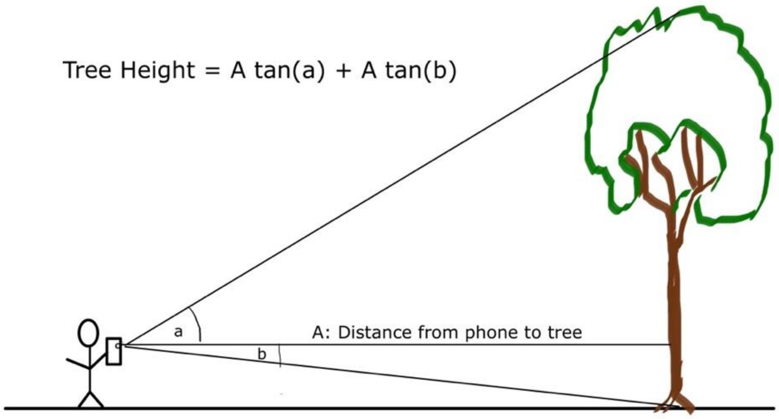


Figure 4: *Estimation of the tree height using the mobile application, based on the tan tree height estimation method commonly used with clinometers and hypsometers*

During the tree height measurement step, an image of the tree is captured and analysed through a machine vision model to determine the tree species. This is important as distinct tree species have different carbon storage capacities. The model uses a MobileNetV2 convolutional neural network architecture (Sandler et al, 2018). MobileNetV2 was chosen for its high efficiency on mobile devices, making it a great fit for real time processing on phones and tablets. This model was trained on a collection of 25,000 tree images pre-classified by species common to Germany and Central Europe, compiled from several publicly available datasets (Yang *et al.*, 2023; Carpentier *et al.*, 2018) supplemented with photographs collected during this study. The dataset was split 75-15-15 into a training, testing and validation sample. The model outputs a probability distribution of different tree species, with the highest being selected if the confidence threshold of 80% is reached. If the threshold is not met, a secondary pre-trained model classifies if the tree is coniferous or deciduous. This fallback model was trained with the same dataset, but with binary classification, ensuring that when specific species identification is not successful, the broader taxonomic category can still inform carbon sequestration calculations. The user interface clearly indicates on the result screen when this fallback classification is used.

Lastly, the DBH and height measurements are incorporated into an allometric equation for the tree type to estimate the biomass and, subsequently, the carbon sequestration. The specifics of this calculation are discussed in more detail in the next section.

2.2.3 Carbon Sequestration Calculation

The application performs real-time carbon sequestration estimation through a series of calculations that follow established forestry protocols. This process begins with the selection of appropriate allometric equations based on the detected species. The equations used in this study are primarily derived from the Zianis et al. (2005, Appendix A, pp. 18-39) study, which provides biomass models specifically validated for European urban trees in temperate climates. For species not covered in the Zianis study, allometric equations from McPherson (2016) are used instead. These equations predict dry biomass directly, as they were developed through destructive sampling where trees were harvested, dried, and weighed to establish the relationships between tree dimensions and biomass. In the rare cases where species-specific equations are not available, either due to limitations in species detection from machine vision or absence from both studies, the application falls back to estimating the volume (Dik, 1984; Jansen, Sevenster & Faber, 1996) and multiplying it by the average wood density for the type of tree (coniferous of deciduous) across most common species (Zanne *et al.*, 2009).

Some allometric equations require basal area, to calculate it the following equation is used:

$$BA = \pi \times \left(\frac{DBH}{2}\right)^2$$

where BA is the basal area in cm^2 and DBH is the diameter at breast height in centimetres. This equation is simply an adaptation of the equation for the area of a circle.

To account for below-ground biomass, the model applies a root-to-shoot ratio of 0.26, which is widely accepted in forestry literature (Cairns *et al.*,1997; Nowak & Crane, 2002). Therefore, the total biomass is calculated by multiplying the above-ground biomass by 1.26 to include root systems.

The carbon content estimation follows IPCC guidelines (Eggleston *et al.*, 2006), which establish that 50% of a tree's dry biomass consists of carbon. This conversion factor has been extensively validated across multiple studies and is recognized as a reliable approximation for carbon content estimation in trees.

The final step converts stored carbon to CO_2 equivalent using the molecular weight ratio. Since CO_2 comprises one carbon atom (atomic weight 12) and two oxygen atoms (atomic weight 16 each), the molecular weight ratio of CO_2 to C is:

$$CO_2 = Carbon + 2 \times Oxygen = 12 + 16 \times 2 = 44$$

$$Ratio\ of\ C\ to\ CO_2 = \frac{44}{12} = 3.667$$

To calculate the CO_2 sequestered by the tree we simply multiply the carbon stored by this ratio. Therefore, the final equation to convert biomass to carbon sequestered is as follows:

$$CO_2\ sequestered = AGB \times 1.26 \times 0.5 \times 3.667$$

where AGB is the aboveground dry biomass in kilograms.

For trees smaller than 10 cm in diameter, the accuracy of measurements is reduced due to limitations in both the LiDAR sensor resolution and the standard allometric equations. This is recognized as a limitation of the current implementation, and users are notified when measuring trees in this size range that results may have increased uncertainty. All calculations are performed instantaneously on the device, allowing for immediate feedback and verification of results.

2.3 Mobile application data collection

Data collection with the application involves “scanning” the tree by selecting (tapping) it on the screen, taking a few steps back and tilting the phone towards the top and bottom of the tree when the app guides the user to. No further steps are required, as the application takes care of the measurement of the tree parameters, calculation of biomass, and estimation of the carbon sequestration of the tree. An augmented reality user interface guides the user during the measurement process, providing real-time feedback on potential issues such as trunk visibility, measurement height, and device orientation/angle. Common actions like starting a new measurement or cancelling the current measurement are presented as buttons on the bottom centre of the screen.

The measurement was performed twice, once using a smartphone with a LiDAR (iPhone 14 Pro Max) and once with a smartphone without a LiDAR (Samsung Galaxy S21). The iPhone 14 Pro's

LiDAR is identical to those found in previous iPhone Pros and all iPads Pro 2020 and newer. While Apple does not directly share the specifications of the sensor, teardowns reveal it to be a Sony 0.03 mega pixels CMOS image sensor with a resolution of 640 x 480 pixels at 15 frames per second (TechInsights, 2020). The LiDAR's range is approximately 5 meters, requiring the surveyed object to be within this distance for successful measurement.

2.4 Conventional survey methods data collection

Additional field measurements were conducted to collect the biophysical parameters of the same trees, using conventional forest survey methods, to validate the app-derived estimates. Conventional survey methods are widely believed to be very accurate and commonly serve as ground-truth for forest studies (Tatsumi, Yamaguchi & Furuya, 2022; Holcomb *et al.,* 2023).

Tree height was measured using a hypsometer range finder. Hypsometers are precision handheld instruments that are used to measure the height of trees using laser. The device internally uses trigonometry to calculate the height of a tree based on the angle of elevation and the distance from the observer to the tree (Larsen, 1987). In this research the Trimble LaserAce 1000 Rangefinder was used, set to the three-point method that collects three data points: the distance of the observer from the tree, the angle of the observer to the base of the tree and the angle of the observer to the top of the tree.

The measurer stood at a distance from the tree base that was at least half of the tree height, ensuring a clear line of sight to the tree top. The device was pointed at the middle of the tree, the base and the top of the three.

DBH was measured for each tree using a diameter tape, also known as a D-tape or forestry tape (Avery & Burkhart, 2015). DBH measurements were taken at a standard height of 1.3 meters (4.5 feet) above the ground on the uphill side of the tree. The diameter tape was wrapped around the tree at the specified height, and the diameter was recorded directly from the tape's calibrated scale. This is effectively a streamlined approach to the old method of wrapping a piece of string around the tree and measuring the length of the string using tape, and doing simple calculations to convert the circumference to the diameter.

The collected tree biophysical data was used to calculate the tree biomass and carbon sequestration using allometric equations relevant to the tree type (as assessed by the measurer). Subsequently, the carbon content of the biomass was calculated, assuming that 50 per cent of the biomass consists of carbon (Eggleston *et al.*, 2006).

The time taken to process each tree with each method was measured using a digital stopwatch and recorded along with the dendrometric measurements.

2.5 Statistical analysis

The degree of agreement between the mobile application measurements and conventional methods was assessed through several complementary approaches. Linear regression analysis was performed to evaluate the relationship between the two measurement methods, with conventional measurements serving as the independent variable and mobile application measurements as the dependent variable. The coefficient of determination (R^2) was calculated to quantify the proportion of variance in the mobile application measurements that could be explained by the conventional measurements. The regression models were assessed for their adherence to underlying assumptions, including normality of residuals, homoscedasticity, and linearity.

To quantify measurement accuracy, both absolute and relative error metrics were calculated. The Root Mean Square Error (RMSE) was computed using:

$$RMSE = \sqrt{\frac{1}{n}\sum(x_{app} - x_{conv})^2}$$

Where n is the number of trees measured (sample size), x_{app} is the measurement using the app and x_{conv} is the measurement done using the conventional survey method.

The percent RMSE (%RMSE) was calculated to facilitate comparison across different measurement scales:

$$\%RMSE = \frac{RMSE}{\bar{x}_{conv}} \times 100$$

Where $\bar{x}_{conv}$ represents the mean of conventional measurements.

All statistical analyses were performed using R statistical software (version 4.2.0, R Core Team, 2024). The significance level (α) was set at 0.05 for all statistical tests. Confidence intervals were calculated at the 95% level. Visualization of results was accomplished using the ggplot2 package.

3. Results

In all one hundred and fifty-three tested trees both the phone with the LiDAR and the phone solely relying on photogrammetry were able to detect the tree trunk, calculate the DHB and height and provide an estimate for the carbon sequestration. In 151 cases (98.7% of the sample), the initial measurement position yielded successful results. In two cases (1.3%), dense understory vegetation initially impeded accurate measurements. However, the application's AR guidance system successfully directed the user to alternative measurement positions, approximately 1.5 meters lateral to the original position, from which complete measurements were obtained.

3.1 Measurement time

The measurement time using the mobile application was significantly faster than using conventional methods. The average time to make a measurement using the application (including calculation processing time) was 45.3 seconds per tree (SD = 12.8 seconds, range: 20-78 seconds. In contrast, conventional measurement methods required a mean time of 240.6 seconds per tree (SD = 35.2 seconds, range: 185-315 seconds) to complete the same set of measurements, with an additional mean time of 60.3 seconds (SD = 15.4 seconds) for manual calculation of carbon sequestration values.

This means that a survey using the application would take less than a fifth of the time that conventional survey methods would (95% CI: 78.9-83.5%). This efficiency gain was consistent across different tree sizes and measurement conditions, with only a slight increase in measurement time (mean increase: 8.4 seconds, SD = 3.2 seconds) observed for trees in densely vegetated areas requiring alternative measurement positions.

This is, however, likely an underestimate of the efficiency difference, as it does not account for several benefits that a real-life use of this method would provide. The conventional method involves doing manual post-processing of measurements and carbon sequestration calculations, while the mobile application performs these computations automatically in real-time. Measuring the diameter of trees can sometimes be difficult in a forest context, as the tree can be relatively inaccessible or harder to reach due to surrounding vegetation and other hazards. Additionally, if several trees are in close proximity, conventional survey methods would require walking up to each one to measure them, while the application could measure all of them from the same spot as long as they are less than 5 metres away or with minimal walking. It can sometimes be hard to identify the top of a tree, and not confuse it with branches of surrounding trees on the viewfinder of a hypsometer, but this issue does not affect the mobile application as it gives a much wider view of the tree on the screen. Finally, in densely forested locations it might be harder to read the scale on analogue tools, while the mobile application is less dependent on good lighting. Conversely, hypsometers can theoretically be used in darkness, while the application cannot, but in practice accurate measurements cannot be made in the dark due to difficulty pointing at the top and bottom of the tree without good vision.

These findings have important implications for large-scale forest inventories and carbon stock assessments, where measurement time directly impacts project feasibility and cost-effectiveness. The substantial reduction in measurement time, coupled with automated data processing and storage, represents a significant advancement in forestry measurement efficiency.

3.2 Accuracy of DHB estimates

There was a good match (Figure 5) between the ground truth measurements from the D-tape with those of the mobile application using LiDAR (R^2: 0.99), while the photogrammetry only implementation performed slightly worse than the LiDAR implementation (R^2: 0.96). The RMSE for the LiDAR and photogrammetry implementations are 1.54cm (5.26%) and 3.39cm (11.6%) respectively. On trees with a diameter of 30cm and larger, the LiDAR implementation only slightly differs from the measurements with D-tape. The accuracy on trees below 7cm diameter was lower using LiDAR than photogrammetry, therefore in the future the app should automatically fallback to photogrammetry when measuring such small trees. Table 2 shows a comparison of results of this study with previous research measuring DBH using smartphone methods.

Table 2: *Comparison of DHB results to previous studies using smartphone methods*

Study	Device used	On-device processing	Sample size and range	RMSE (RMSE%)
This study (LiDAR)	iPhone 14 Pro	Yes	153 trees; 6-82cm	1.54cm (5.26%)
This study (no LiDAR)	Samsung S21	Yes	153 trees; 6-82cm	3.39cm (11.6%)
Tatsumi *et al.* 2022	iPhone 13 Pro	Yes	672 trees; 5-70cm	2.3cm (10.3%)
Holcomb *et al. 2*023	Huawei P30	Yes	97 trees; 6-104cm	3.7cm (8.0%)
Gollob *et al.* 2021	iPad Pro (2020)	No	424 trees; 5-59cm	3.13cm (12%)

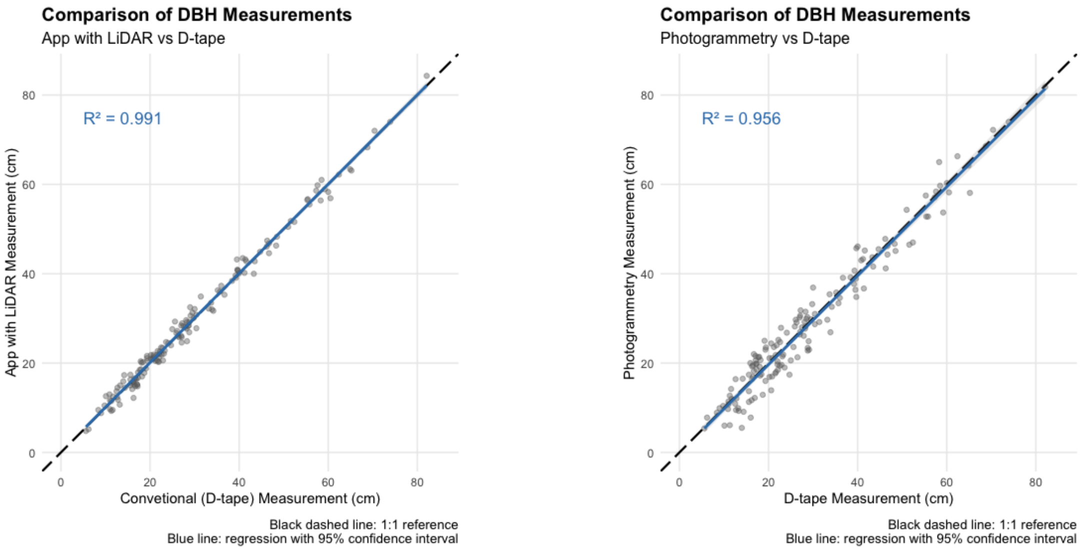


Figure 5: *DBH measured using LiDAR (left) and photogrammetry (right) showed good agreement with ground truth from conventional methods. The solid line shows a theoretical perfect correlation fit, while the dotted lines show a linear fit model for our measurements.*

3.3 Accuracy of height estimates

The measurements of the tree height showed a high similarity to those obtained from the hypsometer (R^2: 0.99). For the LiDAR app the RMSE was 0.46m with RMSE% of 2.72%. The photogrammetry app showed a slightly lower R^2 of 0.98 and an RMSE of 0.63m (RMSE% of 3.73%)(Figure 6). It is worth mentioning that hypsometers themselves have a degree of error, as they rely on the user's accurate aiming with the device and consistent technique between trees. The inaccuracy in conventional survey tools such as clinometers themselves has been estimated to be as low as 0% but also as high as 10-15% for tall trees (Larsen, 1987). It is notable that the errors being larger for taller trees is also consistent with how conventional survey tools operate (Larsen, 1987). Table 3 compares the results with previous smartphone-based tree height measurement studies.

Table 3: *Comparison of tree height results to previous studies using smartphone methods*

Study	Device used	Sample size and range	RMSE (RMSE%)
This study (LiDAR)	iPhone 14 Pro	153 trees; 4-28m	0.46m (2.72%)
This study (No LiDAR)	Samsung S21	153 trees; 4-28m	0.63m (3.73%)
Bijak & Sarzyński, 2015	Motorola XT1068	90 trees; 12-28m	1.01m (2.5%) 2.46m (7.2%)
Itoh et al., 2010	iPhone 3G	61 trees; 5-30m	0.7m-3.0m (7.9%-10.1%)
Xinmei, Aijun & Tinting, 2020	Unknown	55 trees; 2-14m	0.267m (5.8%)

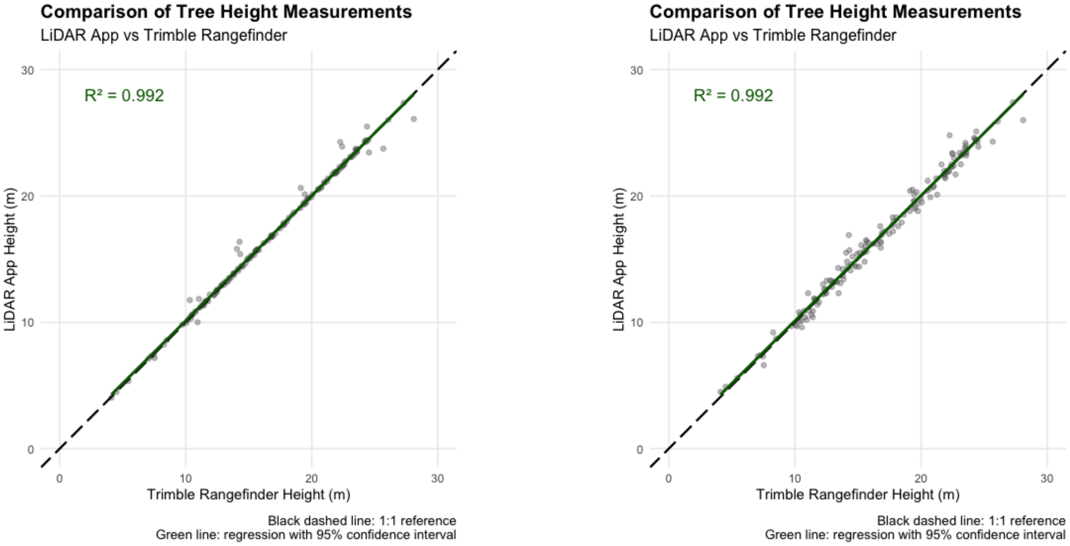


Figure 6: *Scatter plots comparing the measured tree heights from LiDAR (left) and photogrammetry (right) apps with those measured using a hypsometer. The solid line represents a perfect correlation fit (app measured height = conventional tools measured height), while the dotted line shows a linear fit for our data.*

3.4 Accuracy of biomass and final carbon sequestration calculations

As the input data into the calculation for the biomass and carbon sequestration for the trees was very similar to the ones obtained from conventional survey tools, the results were clearly very comparable (Figure 7). The R^2 for both biomass and CO_2 the app with LiDAR is 0.99 while with photogrammetry app is 0.97. The R^2 for biomass and CO_2 sequestration are identical as the CO_2 sequestration calculation is simply a multiplication of the biomass, so they are directly related. The RMSE for the LiDAR app is 76.66 (RMSE% 10.95), while the photogrammetry app RMSE is

144.89 (RMSE% 20.65). The RMSE% for the biomass is higher than that of DBH or height likely due to allometric equations often using exponentials.

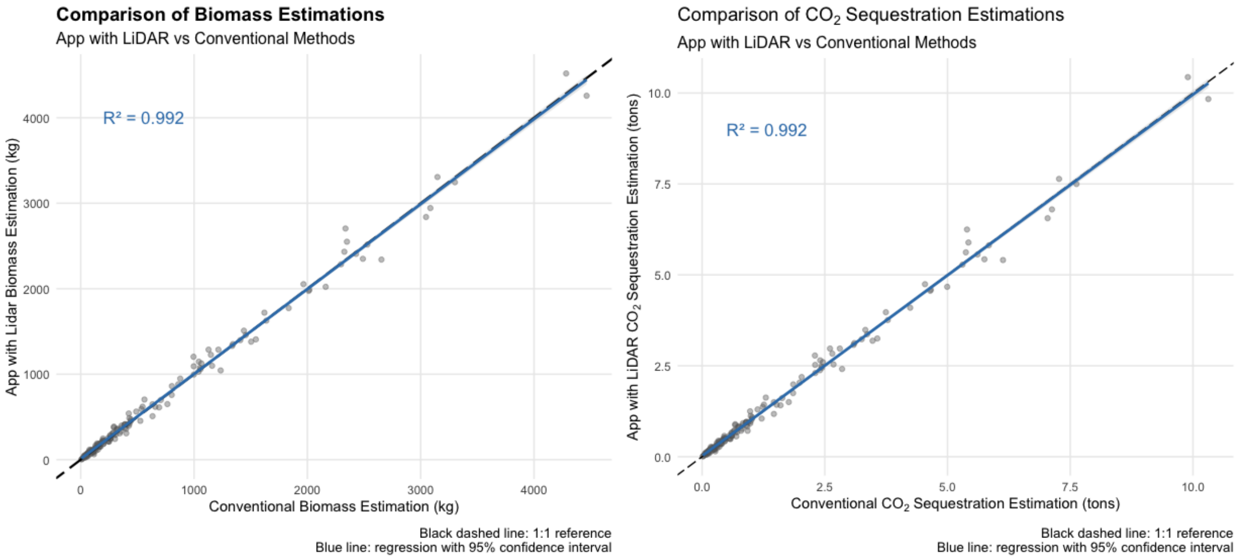


Figure 7: *Scatter plots comparing the estimated biomass (left) and carbon sequestration (right) from the app using LiDAR with those using data from conventional tools.*

4. Discussion

The presented novel approach to estimating the carbon sequestration of trees demonstrated considerable advantages over conventional methods in terms of efficiency and accessibility. It is also significantly more convenient, not requiring any specialized heavy tools, only a portable smartphone or tablet. Future improvements in mobile LiDAR potentially extending the range of the readings could allow for even more advanced uses, such as surveys of whole areas of forests from a single position. The study also showed that while having a LiDAR definitely improves the accuracy of the results, data derived from devices with only a camera is still reasonably accurate, only a few per cent away from the results obtained from commonly used forestry tools. The implications of these findings extend far beyond the research community, potentially reshaping the evaluation of nature-based solutions (NBS) and empowering non-scientists in decision-making and planning processes.

NBS are “actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (IUCN, 2016). The ability to accurately assess the carbon sequestration potential of trees is pivotal in evaluating the effectiveness of these solutions. By providing fast, accurate, and user-friendly means of carbon sequestration estimation, the developed mobile application facilitates the collection of essential data on a scale previously unachievable. This could significantly expedite the evaluation and implementation of NBS, potentially leading to more effective climate change mitigation and adaptation strategies and a more sustainable future.

Moreover, this approach presents a powerful tool for public engagement and education. As demonstrated in this study, its user-friendly design and augmented reality guidance make it accessible even to those without a background in science or forestry. Consequently, this could empower a wide range of individuals and communities to participate actively in environmental decision-making and planning. From urban developers considering the placement of green spaces to mitigate the heat island effect, to farmers evaluating agroforestry potentials on their land, or school students undertaking a local reforestation project, the application offers valuable insights.

Additionally, the app could foster a deeper appreciation of the value of trees and forests within the wider public. By making abstract concepts such as carbon sequestration tangible and accessible, it may encourage greater public support for forest conservation and NBS, thereby playing a crucial role in promoting environmental stewardship.

However, while the app proved reliable in this study, the current version is not without limitations. For example, the accuracy was significantly lower when measuring smaller trees using LiDAR. Future iterations of the app should aim to address these limitations, while ongoing validation against traditional methods remains critical.

4.1 Limitations

The algorithm, while providing accurate measurements for most types of trees, poses a few limitations. The implementation discussed in this study is unable to correctly handle trees, which have a trunk that splits in two or more parts. While handling these kinds of trees is theoretically possible by measuring each part separately, it is unclear how the resulting measurements should further be used in the estimate of the tree biomass as a two-part tree is not factually the same as two trees. Additionally, the DHB measurement of very small trees is less accurate than of larger trees, as the curvature is less apparent and the inaccuracy of the sensors is more obvious on smaller objects than larger ones. This is somewhat alleviated by the accuracy of the tree height measurements for smaller trees being highly accurate. Finally, while the application is able to handle tree trunks partially covered by foliage (a common scenario in densely populated forests), it cannot handle scenarios where the trunk is almost completely or entirely covered by vegetation or obstructed by other trees, as this scenario does not provide for clear view of the trunk to measure its diameter graphically.

4.2 Future Research Directions

The successful application of mobile LiDAR technology for assessing carbon sequestration in trees opens up several avenues for future research. Some possible directions include:

4.2.1 Investigating the effects of different forest management practices

Mobile LiDAR can be employed to evaluate the impact of various forest management practices on tree carbon sequestration. Understanding the outcomes of different management strategies can help develop good practices for maximizing carbon storage in forests (Nabuurs et al., 2007).

4.2.2 Monitoring changes in carbon sequestration over time

Using mobile LiDAR technology to monitor tree growth and changes in biomass over time can provide valuable insights into the temporal dynamics of carbon sequestration. This information can help decision-makers in designing effective climate change mitigation and adaptation policies.

4.2.3 Assessing the role of urban trees in carbon sequestration

Urban trees also play a significant role in carbon sequestration (Onyili, *et al.*, 2023). Mobile LiDAR can be utilized to assess the carbon storage potential of urban trees, helping guide urban planning and green infrastructure development for climate change mitigation and adaptation (McPherson et al., 2010).

4.3 Policy Implications

The development of accessible, accurate forest measurement technology has significant implications for environmental policy and climate action. The ability to rapidly and accurately quantify forest carbon stocks could support the implementation of carbon credit programmes, urban forestry initiatives, and climate adaptation strategies. The technology's accessibility could also facilitate more widespread adoption of forest carbon monitoring, potentially supporting the expansion of nature-based climate solutions. Furthermore, it can facilitate engagement of local communities and indigenous peoples in decision-making relating to REDD+ and other forest management projects thereby enhancing transparency and integrity of forest carbon crediting mechanisms.

5. Conclusion

In conclusion, the mobile application method described in this study marks an important step forward in carbon sequestration estimation, offering a promising tool for public engagement in environmental decision-making and NBS evaluation. By democratizing the measurement of tree carbon sequestration, it holds the potential to drive forward not only scientific understanding, but also societal engagement with climate change mitigation strategies. The use of smartphone LiDAR technology for determining the carbon sequestration provided by trees offers a promising and accurate approach for assessing and monitoring forest carbon dynamics. Future research can build upon this work to explore the impact of forest management practices, monitor changes in carbon sequestration over time, and evaluate the role of urban trees in carbon storage. Collectively, these efforts can contribute to the development of effective strategies for mitigating climate change and promoting sustainable forest management.

Appendix A: Explanation of tree diameter equation

This section gives a more thorough explanation of how the equation used to calculate the tree diameter based on the arc of the tree obtained from the depth point cloud from the mobile device LiDAR is derived. The equation is simply a reworked form of the Intersecting Chord Theorem from Euclidian Geometry. The Intersecting Chord Theorem is a fundamental concept in geometry, that elucidates the relationship between the lengths of segments formed when two chords intersect within a circle. The theorem asserts that if two chords intersect each other inside a circle, the products of the lengths of the segments of each chord are equal. For example, consider two chords, AB and CD, intersecting at a point X inside a circle. The theorem states that the product of the lengths of the segments of one chord (AX × XB) will be equal to the product of the lengths of the segments of the other chord (CX × XD). Mathematically, this can be represented as AX × XB = CX × XD. It is closely related to other theorems such as the Power of a Point Theorem and the Secant-Secant Theorem, which also explore relationships within a circular context. It offers an elegant and powerful tool for solving problems involving circles and their internal chord structures, like we have in tree arcs.

Figure 8 shows how the arc is approximated into a circle from point cloud data, and subsequently used for calculation. We approximate the arc into a circle (in dotted line on figure) and draw a line connecting the two extremes of the arc to create a chord (AB), add a point representing the centre of the circle (M) and a line representing the diameter of the circle, perpendicular to AB (CD). We now have two intersecting chords: the connecting line of the two extremes of the arc AB and the diameter line CD. From the Intersecting Chord Theorem, we know that the product of the lengths of the segments of the diameter line is equal to the segments of our chord, or $\mathrm{AX} \times \mathrm{XC} = \mathrm{XC} \times \mathrm{XD}$. Since the diameter line intersects our chord in the middle, the two segments have of our chord have the same length therefore $\mathrm{AX} = \mathrm{XB} = \frac{1}{2}\mathrm{AB}$. If we rewrite the original equation in terms of UV we have: $\frac{1}{2}\,\mathrm{AB} \times \frac{1}{2}\,\mathrm{AB} = \mathrm{XC} \times \mathrm{XD}$. We can then divide both sides by XC, giving us $\mathrm{XD} = \frac{1}{4 \times \mathrm{XC}} \times \mathrm{AB}^2$. Now we can use this to calculate the diameter (CD):

$$\mathrm{Diameter} = \mathrm{CD} = \mathrm{XC} + \mathrm{XD} = \mathrm{XC} + \frac{AB^2}{4 \times \mathrm{XC}} = \frac{4 \times \mathrm{XC}^2 + AB^2}{4 \times \mathrm{XC}}$$

We are now able to calculate the diameter based on only two known variables: XC (the length of the segment connecting the near-most point of the tree to the user to the chord of the two extremities of the constructed arc) and AB (the length of the chord).

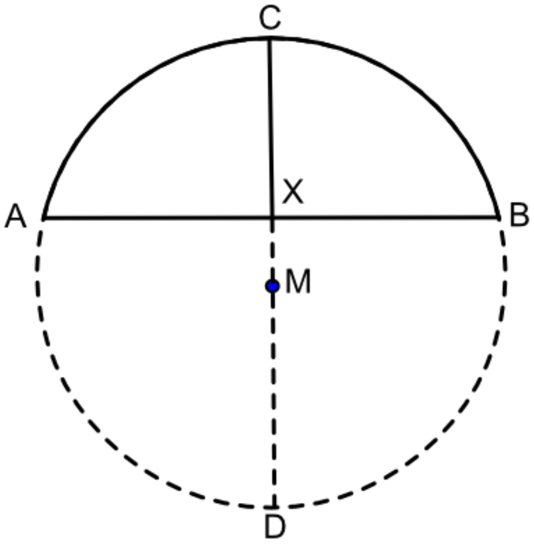


Figure 8: *Path from point cloud to tree circle to diameter calculation.*

Funding

This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy—EXC 2037 'CLICCS—Climate, Climatic Change, and Society'—Project Number: 390683824, contribution to the Center for Earth System Research and Sustainability (CEN) of Universität Hamburg.

References

Avery, T. E., & Burkhart, H. E. (2015). *Forest Measurements: Fifth Edition*. Waveland Press.

Bijak, S., & Sarzyński, J. (2015). Accuracy of smartphone applications in the field measurements of tree height. *Folia Forestalia Polonica*, *57*(4), 240–244. https://doi.org/10.1515/ffp-2015-0025

Bonan, G. B. (2008). Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *Science*, *320*(5882), 1444–1449. https://doi.org/10.1126/science.1155121

Carpentier, M., Giguère, P., & Gaudreault, J. (2018). *Tree Species Identification from Bark Images Using Convolutional Neural Networks* (arXiv:1803.00949). arXiv. https://doi.org/10.48550/arXiv.1803.00949

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Eds.). (2016). *Nature-based solutions to address global societal challenges*. IUCN International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2016.13.en

Dik, E. J. (1984). *De schatting van het houtvolume van staande bomen van een aantal in de bosbouw gebruikte soorten = Estimating the wood volumes of standing trees in forestry practice*. https://research.wur.nl/en/publications/de-schatting-van-het-houtvolume-van-staande-bomen-van-een-aantal-

Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. https://www.osti.gov/etdeweb/biblio/20880391

Forrester, D. I., Tachauer, I. H. H., Annighoefer, P., Barbeito, I., Pretzsch, H., Ruiz-Peinado, R., Stark, H., Vacchiano, G., Zlatanov, T., Chakraborty, T., Saha, S., & Sileshi, G. W. (2017). Generalized biomass and leaf area allometric equations for European tree species incorporating stand structure, tree age and climate. Forest Ecology and Management, 396, 160–175. https://doi.org/10.1016/j.foreco.2017.04.011

Gollob, C., Ritter, T., Kraßnitzer, R., Tockner, A., & Nothdurft, A. (2021). Measurement of Forest Inventory Parameters with Apple iPad Pro and Integrated LiDAR Technology. *Remote Sensing*, *13*(16), Article 16. https://doi.org/10.3390/rs13163129

Heo, H. K., Lee, D. K., Park, J. H., & Thorne, J. H. (2019). Estimating the heights and diameters at breast height of trees in an urban park and along a street using mobile LiDAR. *Landscape and Ecological Engineering*, *15*(3), 253–263. https://doi.org/10.1007/s11355-019-00379-6

Holcomb, A., Tong, L., & Keshav, S. (2023). Robust Single-Image Tree Diameter Estimation with Mobile Phones. *Remote Sensing*, *15*(3), Article 3. https://doi.org/10.3390/rs15030772

Houghton, J. T., & Intergovernmental Panel on Climate Change (Eds.). (2001). *Climate change 2001: The scientific basis: contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Itoh, T., Eizawa, J., Yano, N., Matsue, K., & Naito, K. (2010). Development of Software to Measure Tree Heights on the Smartphone. *Journal of the Japanese Forest Society*, *92*(4), 221–225. https://doi.org/10.4005/jjfs.92.221

Jansen, J. J., Sevenster, J., & Faber, J. (1996). *Opbrengsttabellen voor belangrijke boomsoorten in Nederland*. https://research.wur.nl/en/publications/opbrengsttabellen-voor-belangrijke-boomsoorten-in-nederland

Larsen, D. R., Hann, D. W., & Stearns-Smith, S. C. (1987). Accuracy and Precision of the Tangent Method of Measuring Tree Height. *Western Journal of Applied Forestry*, *2*(1), 26–28. https://doi.org/10.1093/wjaf/2.1.26

Lefsky, M. A., Cohen, W. B., Parker, G. G., & Harding, D. J. (2002). Lidar Remote Sensing for Ecosystem Studies: Lidar, an emerging remote sensing technology that directly measures the three-dimensional distribution of plant canopies, can accurately estimate vegetation structural attributes and should be of particular interest to forest, landscape, and global ecologists. *BioScience*, *52*(1), 19–30. https://doi.org/10.1641/0006-3568(2002)052[0019:LRSFES]2.0.CO;2

Leitold, V., Keller, M., Morton, D. C., Cook, B. D., & Shimabukuro, Y. E. (2015). Airborne lidar-based estimates of tropical forest structure in complex terrain: Opportunities and trade-offs for REDD+. Carbon Balance and Management, 10(1), 3. https://doi.org/10.1186/s13021-015-0013-x

Luetzenburg, G., Kroon, A., & Bjørk, A. A. (2021). Evaluation of the Apple iPhone 12 Pro LiDAR for an Application in Geosciences. *Scientific Reports*, *11*(1), Article 1. https://doi.org/10.1038/s41598-021-01763-9

Luyssaert, S., Inglima, I., Jung, M., Richardson, A. D., Reichstein, M., Papale, D., Piao, S. L., Schulze, E.-D., Wingate, L., Matteucci, G., Aragao, L., Aubinet, M., Beer, C., Bernhofer, C., Black, K. G., Bonal, D., Bonnefond, J.-M., Chambers, J., Ciais, P., … Janssens, I. A. (2007). CO2 balance of boreal, temperate, and tropical forests derived from a global database. *Global Change Biology*, *13*(12), 2509–2537. https://doi.org/10.1111/j.1365-2486.2007.01439.x

McPherson, E. G., Simpson, J. R., Xiao, Q., & Wu, C. (2011). Million trees Los Angeles canopy cover and benefit assessment. *Landscape and Urban Planning*, *99*(1), 40–50. https://doi.org/10.1016/j.landurbplan.2010.08.011

McPherson, E. G., Doorn, N. S. van, & Peper, P. J. (2016). Urban tree database and allometric equations. *Gen. Tech. Rep. PSW-GTR-253. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 86 p.*, *253*. https://doi.org/10.2737/PSW-GTR-253

Nabuurs, G. J., Andrasko, K., Benitez-Ponce, P., Boer, R., Dutschke, M., Elsiddig, E., Ford-Robertson, J., Matsumoto, M., Oyhantcabal, W., Achard, F., Anaya, C., Brinkman, S., Higuchi, N., Hoogwijk, M., Lecocq, F., Rose, S., Schlamadinger, B., Filho, B. S. S., Sohngen, B., … Calvo, E. (2007). *Forestry In B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, & L. A. Meyer (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*

Nowak, D. J., Crane, D. E., & Stevens, J. C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening*, *4*(3), 115–123. https://doi.org/10.1016/j.ufug.2006.01.007

Onyili, A. C., Ezenwenyi, J. U., Nzekwe, C. J., & Ezenwankwo, S. O. (2023). Potentials of Urban Trees and their Roles in Carbon Sequestration. *E-Proceedings of the Faculty of Agriculture International Conference*, 261–264.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J. A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N. K., Edenhofer, O., Elgizouli, I., Field, C. B., Forster, P., Friedlingstein, P., Fuglestvedt, J., Gomez-Echeverri, L., Hallegatte, S., … van Ypserle, J.-P. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In R. K. Pachauri & L. Meyer (Eds.), *EPIC3Geneva, Switzerland, IPCC, 151 p., pp. 151, ISBN: 978-92-9169-143-2* (p. 151). IPCC. https://epic.awi.de/id/eprint/37530/

Tatsumi, S., Yamaguchi, K., & Furuya, N. (2022). ForestScanner: A mobile application for measuring and mapping trees with LiDAR-equipped iPhone and iPad. *Methods in Ecology and Evolution*, *n/a*(n/a). https://doi.org/10.1111/2041-210X.13900

TechInsights [@techinsightsinc]. (2020, March 28). *TechInsights has begun the teardown process of #Apple iPad Pro (Model A2068). Our early findings indicate a 4.18 mm x 4.30 mm (18.0 mm^2) #Sony ToF sensor with 0.03 MP resolution & 10 µm pitch pixels within the #LiDAR system. Our analysis continues with in-depth reports to follow. Https://t.co/zg7HIc9wYW* [Tweet]. Twitter. https://twitter.com/techinsightsinc/status/1244050881705844737

Xinmei, W., Aijun, X., & Tingting, Y. (2020). Passive Measurement Method of Tree Height and Crown Diameter Using a Smartphone. *IEEE Access*, *8*, 11669–11678. https://doi.org/10.1109/ACCESS.2020.2965216

Yang, T., Zhou, S., Huang, Z., Xu, A., Ye, J., & Yin, J. (2023). Urban street tree dataset for image classification and instance segmentation. *Computers and Electronics in Agriculture*, *209*, 107852. https://doi.org/10.1016/j.compag.2023.107852

Zanne, A. E., Lopez-Gonzalez, G., Coomes, D. A., Ilic, J., Jansen, S., Lewis, S. L., Miller, R. B., Swenson, N. G., Wiemann, M. C., & Chave, J. (2009). *Data from: Towards a worldwide wood economics spectrum* (Version 5, p. 2123413 bytes) [Dataset]. Dryad. https://doi.org/10.5061/DRYAD.234

Zianis, D., Muukkonen, P., Mäkipää, R., & Mencuccini, M. (2005). Biomass and stem volume equations for tree species in Europe. Silva Fennica Monographs, 2005(4), 1–63. https://doi.org/10.14214/sf.sfm4

Chapter 3

The Usability of TreeCarbonAR, a Smartphone-based Augmented Reality Application for Tree Carbon Sequestration Estimation

The Usability of TreeCarbonAR, a Smartphone-based Augmented Reality Application for Tree Carbon Sequestration Estimation

Vladimir Metelitsa[1, 3, §], Leam Martes[2, 3], María Máñez Costa[1]

[1] Climate Service Center Germany (GERICS), Helmholtz-Zentrum hereon GmbH, Fischertwiete 1, 20095 Hamburg
[2] Universität Hamburg, Institute of Geography, Bundesstraße 55, 20146, Hamburg, Germany
[3] Center for Earth System Research and Sustainability (CEN), Universität Hamburg
[§] Corresponding author; E-Mail: vladimir.metelitsa@hereon.de

Vladimir Metelitsa ORCiD: 0000-0003-0984-9249
Leam Martes ORCiD: 0000-0001-9931-1308
María Máñez Costa ORCiD: 0000-0001-5415-0811

Abstract

This study introduces TreeCarbonAR, an innovative augmented reality (AR) smartphone application designed to enhance understanding of urban tree carbon sequestration. Integrating AR technology with LiDAR sensors and computer vision, TreeCarbonAR allows users to measure individual trees and visualise their carbon storage potential in real-time. The application underwent three iterations of development and two stages of user testing, with 41 and 53 participants respectively, to evaluate its effectiveness as a climate service tool. Using the System Usability Scale (SUS) and custom questionnaires, we assessed the application's usability and its impact on users' comprehension of carbon sequestration concepts. Results showed a significant improvement in usability between iterations, with SUS scores increasing from 79.3 to 86.4. By the second iteration, 92% of users reported an increased understanding of carbon sequestration, demonstrating the application's effectiveness in communicating complex environmental concepts. The integration of forest management strategy simulations further engaged users in exploring the long-term impacts of different approaches to urban forestry. This study contributes to the growing field of innovative climate services by showcasing the potential of AR technology to bridge the gap between scientific knowledge and public understanding. TreeCarbonAR offers a model for developing user-friendly, technology-driven tools that can play a crucial role in fostering informed public participation in urban forestry and broader environmental decision-making processes.

Keywords: Augmented Reality, Carbon Sequestration, Urban Forestry, Climate Services, Smartphone Application, LiDAR, Computer Vision, Public Engagement, Nature-based Solutions

1. Introduction

Human induced climate change is one the defining challenges of our time, threatening ecosystems, economies and human well-being (Masson-Delmotte *et al.*, 2021). In the last decades, different strategies have been considered to reduced Green House Gasses Emissions and mitigate climate change. Nature-based solutions (NBS) are one of those measures, already accounting for as much as 40% of climate measures in urban areas, as they have emerged as a promising strategy for carbon sequestration and climate mitigation in urban environments (Kabisch et al., 2016; Goodwin *et al.*, 2023). However, the implementation of such strategies usually requires layered decision-making processes that are traditionally top-down and the domain of politicians and policymakers. There is growing recognition of the need to democratize these environmental decision-making processes and to empower citizens to participate meaningfully in climate action. Climate services – tools and applications that translate climate data into actionable information – have the potential to bridge the gap between scientific knowledge and public understanding (Buontempo et al., 2020).

Recent advancements in smartphone technology, particularly in Augmented Reality (AR), LiDAR sensors, sensor fusion, and computer vision, offer new opportunities for developing accessible and engaging climate services. These technologies can transform abstract concepts like carbon sequestration into tangible, interactive experiences for users. By combining these capabilities, it may be possible to create tools that give the general public a better understanding of climate change and support evidence-based decision-making in urban planning and NBS assessment.

This study introduces TreeCarbonAR, a smartphone-based AR application designed to facilitate the use of climate related information for non-experts. TreeCarbonAR estimates the carbon sequestration potential of individual trees. The application utilizes the phone's sensors to measure dendrometric properties and employs machine vision to identify tree species, providing users with real-time estimates of carbon storage. By offering comparisons to everyday activities and simulating various management strategies, TreeCarbonAR aims to make the concept of carbon sequestration more relatable and actionable for non-expert users.

The primary objective of this research is to evaluate the usefulness and usability TreeCarbonAR in the context of enhancing public understanding of carbon sequestration and supporting environmental decision-making. Through an iterative co-design process and user testing, we seek to answer the following research questions:

1. How do non-expert users perceive and interact with an AR-based tool for estimating tree carbon sequestration?
2. What are the key usability factors that influence user engagement with such a climate service application?
3. How can iterative co-design improvements based on user feedback enhance the effectiveness of the application in communicating complex environmental concepts?

By addressing these questions, this study contributes to the growing body of research on climate services and public engagement in environmental decision-making. The findings have implications for the design of future mobile applications aimed at democratizing access to environmental data and supporting evidence-based urban planning and NBS assessment.

2. Background

Recent developments in mobile technology have opened new avenues for engaging and interactive climate services as well as citizen science. In particular, smartphones, which are now equipped with an array of sensors and ever-increasing computational power, have become powerful tools for engaging the public in environmental monitoring and data collection. Sandim et al. (2020) already demonstrated this potential of mobile applications in the field of urban tree inventory, while Luna et al. (2018) showcased their effectiveness in facilitating citizen participation in biodiversity monitoring. These studies highlight the growing role of mobile technology in democratizing environmental data collection and analysis.

Climate services, as defined by the World Meteorological Organization (2013), provide climate information to assist decision-making by individuals and organizations. These services play a crucial role in helping societies adapt to climate variability and change (Hewitt et al., 2012). While existing climate services have shown promise in information dissemination, the tools that provide immediate, personalized feedback about their surroundings in an interactive and engaging manner remain scarce. This gap presents an opportunity for innovative applications that not only enable data collection but also improve the users' understanding about the environmental significance of their surroundings.

The recent addition of LiDAR sensors in select smartphones and tablets as well as improvements in computer vision algorithms are creating new possibilities for environmental applications. Gollob et al. (2021) demonstrated the potential of smartphone LiDAR for forest inventory tasks, achieving promising accuracy in tree measurements. Meanwhile, Carvalho (2022) showed the capabilities of deep learning models in tree species identification from smartphone images. While these studies illustrate the technical feasibility of using smartphones for tree measurement and identification, there remains a need to integrate these capabilities into user-friendly climate service that can provide meaningful information, such as carbon sequestration, to non-expert users.

Augmented Reality (AR), an extended reality technology, has emerged as a powerful medium for enhancing user engagement and understanding in a variety of fields, including environmental education. While the use of AR in climate services has not yet received much attention in academic literature, Akçayır & Akçayır (2017) conducted a comprehensive review of AR in education, highlighting its potential to increase the learner's motivation and understanding of complex concepts. Sharma *et al.* (2021) demonstrated how AR could be used for environmental education in the classroom, helping make abstract projections more tangible for users. Despite these advancements, the application of AR for delivering climate services, and specifically for quantifying and visualizing carbon sequestration by individual trees in real-time remains largely unexplored.

The design of climate services, particularly those aimed at non-expert users, requires careful consideration of user experience (UX) principles. Different scholars (Daniels, Bharwani & Butterfield (2019); Máñez Costa *et al.* (2022); Harrs *et al.* (2024)) emphasized the importance of co-design processes in developing climate services that meet user needs, while others (Eggeling *et al.* (2022); Reveco-Umaña (2023); Christel *et al.* (2018); Vincent *et al.* (2018); Hewitson *et al.* (2017) further highlighted the significance of usability testing in refining climate service applications, demonstrating how iterative design can improve user engagement and understanding. These studies underscore the need for user-cantered design approaches in developing climate service applications, especially when targeting non-expert users.

Public understanding of carbon sequestration, particularly in the context of urban trees, is crucial for fostering support for green infrastructure initiatives to mitigate the effects of climate change. Jeong *et al.* (2023) explored urban residents' perceptions of tree benefits, finding that while people generally value trees, they often underestimate their role in climate change mitigation. García-Antúnez *et al.* (2023) further investigated public perceptions of carbon sequestration and storage in urban greenery, highlighting the importance of these perceptions for the social acceptability of carbon-oriented nature-based solutions. Their study underscores the need for effective communication strategies to enhance public understanding of the climate mitigation potential of urban trees.

The literature reveals a growing potential for mobile applications in delivering climate services, particularly when leveraging technologies like AR and advanced smartphone sensors (Raaphorst *et al.*, 2020). However, there is a clear need for tools that can effectively communicate complex environmental concepts, such as carbon sequestration, to the general public in an interactive and personalized manner. The development of user-friendly applications that integrate these technologies to provide immediate, personalized feedback on the environmental impact of individual trees could significantly enhance public understanding and engagement with urban forestry and climate change mitigation efforts and represent a novel approach to climate services in a new medium. This study aims to address this gap by developing and evaluating TreeCarbonAR, focusing on its usability and effectiveness as an AR-based climate service for communicating complex environmental concepts to non-expert users.

3. Methodology

The development and testing of the TreeCarbonAR app took place over three distinct iterations, two of which involved user testing (Figure 9). The following sections describe in detail the prototyping and testing of the application.

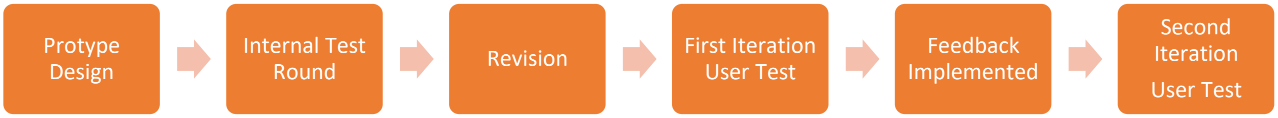


Figure 9: *Development process for TreeCarbonAR*

3.1 Initial Application Design

The initial prototype version of the TreeCarbonAR app was developed with a focus on simplicity and ease of use, aiming to provide non-expert users with an intuitive tool for estimating tree carbon sequestration. The application was built using Swift with ARKit for iOS devices and Kotlin with ARCore for Android platforms to enable AR functionality. Key aspects of the application's interface and functionality as they were in the first prototype are illustrated in Figure 10.

When launching the application, users were presented with a brief description of the app functionality and an overview of the various tree management strategies (Figure 10a). This tutorial and introductory information were designed to provide context and prepare users for the measurement process.

To calculate the carbon stored in the tree, two key tree measurements are needed: the tree height and Diameter at Breast Height (DBH). A measurement process was implemented entirely within an AR environment, where users viewed their surroundings through their device's camera with superimposed instructions and interactive elements.

The initial measurement process was composed of two steps as follows. First, to measure the DBH users were instructed to walk around the tree while pointing their device in the direction of the tree trunk. As they circled the tree, the application collected depth cloud data to determine the tree's shape and extract the DHB. This "circumnavigation method" was designed to capture a comprehensive view of the tree's girth. Second, after completing the circumference measurement, to measure the tree height, users are directed to step away from the tree a distance similar to that of the height of the tree. Users are then prompted to point their device at the tree's base and then its top (Figure 10b). Using principles of trigonometry, the application calculated the tree's height using two triangles, based on the user's distance from the tree (forming one side of the triangles) and the angle between this line and the top and bottom of the tree forming two angles.

Finally, TreeCarbonAR's initial design would recognize the tree type using computer vision techniques. This functionality was essential for accurate carbon sequestration estimation, as different tree species have varying carbon storage capacities. The tree type recognition system was developed using a convolutional neural network (CNN) architecture, specifically a deep learning model based on the MobileNetV2 architecture (Sandler et al., 2018). This choice was motivated by MobileNetV2's efficiency on mobile devices while maintaining high accuracy, making it suitable for real-time processing on smartphones.

The model was trained on a diverse dataset of tree images, containing 25,000 images of various trees pre-classified by species, which are common in urban environments. The image dataset was based on datasets available in literature (Yang *et al.*, 2023; Carpentier *et al.*, 2018) combined with photos taken by the authors of the study. The dataset included images of tree bark, foliage and overall tree structure to ensure robust recognition across different seasons, photo angles and growth stages. Data augmentation techniques, such as random rotations, flips, and colour jittering, were employed to enhance the model's generalization capabilities, and ensure that it works correctly in different levels of lighting and with potential obstructions or angled photos.

During the measurement process, two snapshots of the tree are taken, one at the base at the end of the circumference measurement and one from far away when the tree top is marked by the user. These images are then processed through the trained CNN model to classify the tree type. The model outputs a probability distribution across known tree species, with the highest probability being selected as the identified type.

To improve accuracy and user experience, the initial design also incorporated a confidence threshold of 80 per cent. If the model's confidence in its prediction fell below this threshold, the application would prompt the user to take additional photos. If the processing of the new photo still does not reach the confidence threshold, then the application falls back to only detecting the tree kind (coniferous vs deciduous); which allows to provide a measurement, but decreases the accuracy. This is based on a second pre-trained CNN model which was trained on the same image dataset but classified into only coniferous or deciduous. If this fallback model is used, it is communicated to the user on the results screen alongside the results by a bright orange warning on the top.

This integration of this computer vision-based tree type recognition system with the AR measurement interface and on-device carbon sequestration calculation algorithms formed a key component of TreeCarbonAR's innovative approach to climate services in urban forestry.

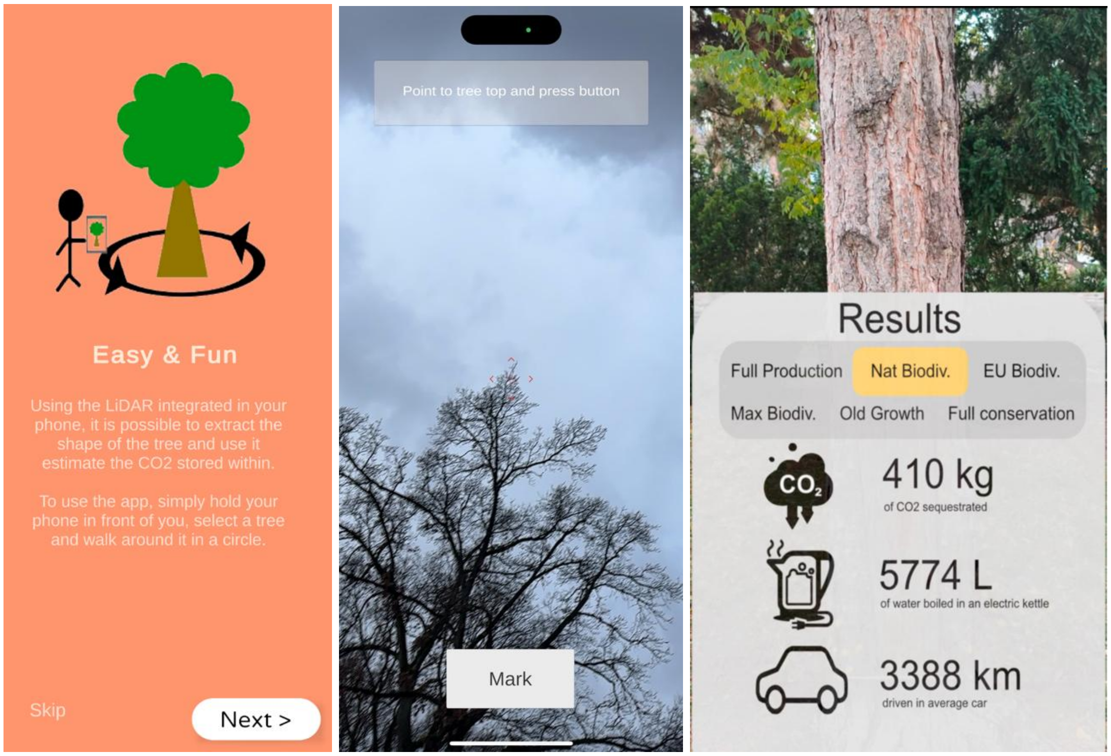
Once this process is complete, users are shown a screen with an estimate of the carbon stored in the tree, as well as some daily life figures such as a comparison with the energy used for boiling a kettle of water or the emissions from driving a car (Figure 10c). Following the measurement process, users could switch between different management strategies directly from the results screen. The application would update the estimated carbon sequestration based on the strategy selected by the user. This provides the user with immediate feedback on how various approaches could impact the tree's carbon storage potential.

A key feature of TreeCarbonAR was the inclusion of six different management scenarios, based on the research by Martes & Köhl (2022). These scenarios were designed to illustrate how different forest management approaches could impact carbon sequestration. The six scenarios included in the application were:

1. Full Conservation: The forest is completely protected from harvesting, allowing trees to grow naturally and store carbon through their full life cycle.
2. Maximum Biodiversity Protection: A conservation-focused approach that protects 40% of the forest from harvesting, prioritizing biodiversity and natural carbon storage over timber production.
3. Old Growth Forest Protection: Focuses on preserving mature forests by protecting all stands older than 120 years while allowing managed harvesting in younger areas.
4. EU Biodiversity: Following European Union recommendations, 10% of the forest is protected from harvesting to balance conservation with sustainable forest management.
5. National Biodiversity: Based on national guidelines, 5% of the forest is protected from harvesting to preserve biodiversity while allowing sustainable forestry in the remaining area.
6. Full Production: The entire forest area is managed for sustainable timber production, with no areas exclusively set aside for conservation.

These management strategies were presented to users through a multi-select slider at the top of the results screen. Users could switch between scenarios by tapping on the scenario of interest, with the selected strategy being highlighted. As users switched between scenarios, the application dynamically updated the displayed carbon sequestration figures, allowing for immediate comparison of the impacts of different management approaches. The impacts of each management scenario were pre-computed, allowing for quick and responsive updates within the application without requiring running the full BEKLIFUH model on device.

By incorporating these management strategies, TreeCarbonAR aimed to provide users with a more comprehensive understanding of forest carbon dynamics and the potential impacts of different policy decisions on carbon sequestration. This feature was designed to enhance the educational value of the application and to illustrate the complexities involved the management of green zones.



Using the LiDAR integrated in your phone, it is possible to extract the shape of the tree and use it estimate the CO2 stored within.

To use the app, simply hold your phone in front of you, select a tree and walk around it in a circle.

410 kg of CO2 sequestrated

5774 L of water boiled in an electric kettle

3388 km driven in average car

Figure 10: *The initial design of the application, before the first internal testing round. (a) One of the steps of the tutorial on first launch; (b) Measurement of tree height; (c) Result screen with ability to change the management strategy*

Particular attention was paid throughout the design process to using simple to understand, not overly scientific language and intuitive icons to ensure accessibility for non-expert users. Similarly, the user interface was kept minimal, with clear instructions guiding users through each step of the measurement process. This initial prototype served as a foundation for user testing and subsequent iterations.

3.2 Internal Testing Round

Following the development of the prototype of TreeCarbonAR, an internal testing round was conducted to validate the application's functionality and identify any potential issues before proceeding to a wider user testing. This phase involved approximately 10 participants, including the study's scientists, PhD students from the University of Hamburg, as well as acquaintances, family members, friends, and colleagues of the researchers. While no specific criteria were used to select the participants, the group of testers provided a range of perspectives and levels of expertise.

During this phase, which lasted several weeks, participants used the application to measure various trees and provided feedback on their experiences. The testing process was qualitative in nature, with no formal quantitative data collection. Testers were encouraged to provide open-ended feedback on all aspects of the application, including ease of use, clarity of instructions, and any technical issues encountered. In addition to general functionality testing, the main investigator conducted a comparative analysis of the application's measurement accuracy against commonly used forest survey tools to assess what uncertainties to provide with the results. The results of this accuracy assessment are discussed in detail in Metelitsa & Martes (2025).

The internal testing round revealed a significant limitation in the initial design: the "circumnavigation method" for measuring a tree diameter proved impractical in many real-world scenarios, particularly in more densely forested areas. While street trees are usually easy to circumnavigate, in more natural contexts, trees can be sharply inclined, on a slope, or having obstacles near them, making it harder to do the measurement. This finding led to a design change in the measurement logic, allowing for measurement from only one side of the tree in subsequent versions of the application.

Besides the circumnavigation issue, the testing also uncovered minor user interface (UI) and user experience (UX) issues. These were primarily related to the clarity of instructions and the intuitiveness of certain interface elements. However, no other major functional issues were identified, indicating that the core measurement and calculation features of the application were working as intended.

This internal testing round proved invaluable in identifying key areas for improvement before moving on to a wider user testing. The feedback gathered during this phase informed refinements to the application's design and functionality, particularly in terms of the tree measurement process and UI enhancements.

3.3 Revised Application Design and Functionality

Following the internal testing round, the TreeCarbonAR application underwent revisions, primarily focusing on improving the tree measurement process. The key modification addressed the limitations of the initial "circumnavigation method" for measuring the diameter at breast height, which had proved impractical in densely forested areas or trees that were inclined at an angle or on perilous terrain.

The revised measurement process maintained the original method for tree height calculation but introduced a novel approach for DBH measurement. Instead of requiring users to walk around the entire tree, the new method leverages the device's LiDAR sensor to “scan” the curvature of the tree from a single vantage point (Figure 11). This point cloud data is then processed on device to extract a chord of the two visible edges of tree curvature and the visible depth of the tree. These are used with the Intersecting Chord Theorem to calculate the tree's diameter. This mathematical approach, detailed in Metelitsa & Martes (2025), allows for accurate DBH estimation without the need for a full circumnavigation of the tree.

This change in the methodology addressed the primary issue identified during the internal testing. Users can now measure trees by selecting any easily accessible side of the trunk, making the application more versatile and user-friendly, particularly in densely forested areas or situations where obstacles prevent full access around a tree.

The user interface and experience underwent minor revisions based on feedback from the internal testing round. These adjustments primarily focused on improving the clarity of instructions and enhancing the intuitiveness of certain interface elements. However, the overall structure and flow of the application remained largely unchanged. No new features or functionalities were added to the application in this revision. The core features, including the presentation of carbon sequestration data and the exploration of different management strategies, remained consistent with the initial design. Similarly, there were no changes to the technology stack or frameworks used in the application's development.

Importantly, the accuracy of the measurements was a key consideration throughout the revision process. Continued accuracy assessments were conducted following the change in methodology. As reported in Metelitsa & Martes (2025), these assessments revealed that the new measurement approach not only maintained but actually slightly improved the accuracy of DBH measurements compared to the initial method. This is likely due to the initial approach not sufficiently accounting for the parallax effect in scanning the tree curvature.

This revised design of TreeCarbonAR represents a clear improvement in usability in challenging measurement scenarios. By addressing the key limitation identified in the internal testing round while maintaining the application's core features and improving measurement accuracy, the revised version of TreeCarbonAR was well-positioned for a wider user testing and potential real-world application in urban forestry and public engagement with carbon sequestration concepts.


Approach a tree, aim at it using the marker, and tap 'Mark' to begin measurement

Figure 11*: The design of the application, before* user testing, showing the new DBH measurement method*.*

3.4 User Testing Process

Following the revision of TreeCarbonAR based on the internal testing feedback, a first iteration user testing phase was conducted to evaluate the application's usefulness, effectiveness, usability, and potential impact on user’s understanding of carbon sequestration. This phase involved a larger, more diverse group of participants to gain broader insights into the application's performance in real-world conditions.

A total of 41 participants were involved in this user testing phase. The study was advertised through various environmental newsletters, environmental communities on social media platforms such as Reddit, regional classifieds and chat groups. This recruitment strategy aimed to attract individuals with an interest in environmental issues, but not necessarily expertise in forestry or carbon sequestration. Demographic data was not collected from participants to simplify compliance with privacy regulations.

Participants, who volunteered for the study, were provided with the prototype TreeCarbonAR application, along with instructions for its use and a survey to be completed after trying out the application. The testing protocol was designed to allow participants to use the application in their own environments and on their own time, simulating real-world usage scenarios. This approach provided insights into how the application would perform across a variety of settings and user contexts.

Participants were instructed to measure a minimum of two trees using the application before completing the survey. This requirement ensured that users had sufficient experience with the application to provide informed feedback. The testing period extended over several months, allowing participants ample time to use the application under various conditions and reflect on their experiences.

Data collection for this user testing phase was primarily conducted through an online survey. The survey was designed to gather both quantitative and qualitative feedback on various aspects of the application, including its usability, the clarity of information provided, and its effectiveness in communicating concepts related to carbon sequestration.

The survey included a mix of Likert scale questions to quantify user experiences and open-ended questions to capture more nuanced feedback and suggestions for improvement. Key areas of focus in the survey included:

1. Ease of use and intuitiveness of the application interface
2. Clarity of instructions for tree measurement
3. Understanding of carbon sequestration concepts presented in the app
4. Perceived usefulness of the management strategy simulations
5. Overall user satisfaction and likelihood of continued use

The survey also included the ten questions composing the commonly used System Usability Scale (SUS) to assess the application’s usability, to avoid confusion the word “system” has been replaced with “app” in each question.

By collecting this range of data, the study aimed to gain a comprehensive understanding of the application's strengths and areas for potential improvement from the perspective of its target users.

The data collected from the user testing survey was analysed using a combination of quantitative and qualitative methods. Responses to Likert scale questions were analysed statistically to identify trends in user experiences and perceptions. Open-ended responses were subjected to thematic analysis to identify common themes, unique insights, and specific suggestions for improvement.

This user testing process provided valuable insights into the real-world performance and user reception of TreeCarbonAR, informing both its immediate refinement and future development directions. The findings from this phase were crucial in assessing the application's potential as a tool for enhancing public understanding of, and engagement with, urban tree carbon sequestration.

4. Results

4.1 First iteration

The initial version of TreeCarbonAR was subjected to comprehensive user testing to evaluate its effectiveness as a climate service tool and its potential to enhance public understanding of carbon sequestration. A total of 41 users participated in this first round of testing. The evaluation process employed the System Usability Scale (SUS) to assess the application's overall usability, complemented by custom questions designed to probe specific aspects of the app's functionality and user experience.

The application's usability was generally well-received, with a mean SUS score of 79.3 (median: 77.5, SD: 11.94, Range: 47.5-100). The individual scores for each question are shown in Table 4. According to established SUS score interpretation guidelines (Bangor et al., 2009), this score falls within the "Good" range, very near the “Excellent” range, indicating that users found the application relatively intuitive and easy to navigate. This positive reception was particularly evident in users' responses to the AR-guided measurement process. Participants likened the experience to a game, noting that the interactive nature of the measurements encouraged them to engage with more trees than they had initially planned.

In terms of its primary function as a climate service tool, TreeCarbonAR demonstrated promising results. When asked about their understanding of carbon sequestration, 85% of users reported an increase in comprehension after using the application. In this context ‘increase in comprehension’ corresponds to marks 4 or 5 on the Likert scale. This improvement was frequently attributed to the app's visual representation of carbon storage and its dynamic illustration of how storage capacity changes with tree size. Users often commented on how this feature effectively conveyed the significance of urban forests in climate change mitigation, translating abstract concepts into tangible, relatable information.

The inclusion of various management strategies in the application was generally appreciated by users, who found this feature informative and thought-provoking. However, this aspect also revealed areas for potential improvement. Several users (n=5) expressed a desire for more readily accessible information about each strategy, noting that they had to return to the start screen to refresh their understanding of different approaches as they forgot the meaning of the different strategies by the time they could select them. This feedback suggested a need for more seamless integration of strategy descriptions within the user interface.

While the overall reception was positive, users identified several areas for enhancement. A common suggestion was the implementation of a feature to review past measurements (n=11), which would allow users compare different trees over time. Additionally, multiple participants expressed interest in the ability to share their results with friends or on social media (n=5).

Several users suggested implementing a feature to compare measurements between two different trees directly within the application. This feedback indicated that users were engaging deeply with the concept of carbon sequestration and were interested in exploring variations across different tree species or sizes.

In terms of the application's effectiveness in promoting environmental awareness, users reported that using TreeCarbonAR heightened their appreciation for urban trees. Several participants noted that the experience made them more attentive to the trees in their local environment and more curious about their potential for carbon sequestration.

Despite these areas for improvement, the first iteration of TreeCarbonAR demonstrated significant potential as a climate service tool. Its ability to engage users through interactive AR technology while simultaneously educating them about carbon sequestration represents a novel approach to climate science communication. The high percentage of users reporting increased understanding of carbon sequestration concepts suggests that the application successfully bridges the gap between complex climate science and public engagement.

The feedback gathered from this first iteration provided valuable insights for refining the application, pointing towards specific features and modifications that could enhance its effectiveness and user experience. These suggestions formed the basis for the subsequent revision of TreeCarbonAR, setting the stage for the second round of testing.

4.2 Changes made based on feedback from first iteration

Following the first iteration of user testing, we undertook a comprehensive revision of TreeCarbonAR, addressing key areas of feedback to enhance the application's functionality, usability and usefulness. The changes implemented were directly informed by user suggestions and observed areas for improvement, with the aim of creating a more engaging and informative climate service tool.

A primary focus of the revision was the presentation and accessibility of information about management strategies. In response to users' requests for more readily available strategy descriptions, two significant changes were implemented. First, when users select or change management strategies, the application now displays a concise description of the chosen strategy directly on the selection screen. This immediate feedback allows users to quickly understand the implications of their selection without navigating away from their current task. Second, an additional "info" button was integrated into the interface, providing access to more detailed descriptions of all available strategies. This feature caters to users seeking a deeper understanding of forest management approaches, while maintaining a clean and uncluttered main interface.

To address the frequently requested feature of reviewing past measurements, a new "Results" section was added to the main menu. This section displays a full list of all previously measured trees, and including information such as the tree's location, species, a photograph taken during the measurement process, and the calculated values. Users can access more detailed information about each tree by selecting individual entries. Importantly, this feature also allows users to revisit past measurements and apply different management strategies.

The ability to share results was another key user request that was implemented in the revised version. By integrating with the device's native share functionality (“Share sheet”), TreeCarbonAR now allows users to disseminate their findings through any social media applications installed on their device. This feature not only satisfies users' desire to share their discoveries but also has the potential to increase the application's reach and impact, promoting wider engagement with urban forestry and carbon sequestration concepts.

In response to suggestions for a more guided user experience, particularly for first-time users, a comprehensive step-by-step tutorial was developed and integrated into the application. This tutorial guides new users through the measurement process and introduces them to key features of the app, helping to lower the initial learning curve.

To provide more context for the carbon sequestration values, more detailed comparisons were added to relate these values to everyday activities. For example, the carbon sequestration of a tree could now be expressed in terms of miles flown or hours of television watched. These relatable comparisons aim to make the abstract concept of carbon sequestration more tangible and meaningful to users.

While not explicitly requested by users, we also took this opportunity to optimize the application's performance and refine the user interface. This included improvements to the AR measurement interface, enhancements to data processing speed, and refinements to the visual design for improved clarity and aesthetic appeal.

These changes collectively represent a significant evolution of TreeCarbonAR, addressing the major points of user feedback while maintaining the core functionality that was well-received in the initial version. The revised application aims to offer a more comprehensive, user-friendly, and educational experience, setting the stage for the second round of user testing to evaluate the effectiveness of these improvements.

4.3 Results from second iteration

Following the implementation of changes based on user feedback from the first iteration, TreeCarbonAR underwent a second round of user testing to evaluate the effectiveness of these modifications and to further assess the application's potential as a climate service tool. This second iteration involved 53 participants, representing a slight increase in sample size compared to the first round of testing. The evaluation methodology remained consistent with the first iteration, employing the SUS alongside custom questions tailored to assess specific aspects of the application's functionality and user experience.

Analysis of users' prior experience revealed that 31% of participants had previously used AR applications, showing a slight increase from the first iteration (27%). This percentage aligns with findings from Smink *et al.* (2020). Only 7.3% of participants reported previous experience with carbon sequestration estimation, a notably low figure. Furthermore, 63% of participants indicated they had previously made climate change mitigation-related decisions in their private or professional lives, suggesting that while the user base was environmentally conscious and actively engaged in climate action, specific experience with carbon sequestration tools was limited. This combination of characteristics - high environmental engagement but limited technical experience - made the participant group particularly suitable for evaluating TreeCarbonAR's effectiveness as a climate service tool for non-expert users.

The results from the second iteration demonstrated a marked improvement in overall user satisfaction and usability. The mean SUS score increased significantly from 79.3 in the first iteration to 86.4 in the second (Median: 87.5, SD: 8.04, Range: 77.5-100), with the scores being distributed more towards the higher scores (Figure 12). This shift moves the application from the "Good" range to the "Excellent" range on the SUS scale, indicating a substantial enhancement in user experience and ease of use. The improvement in SUS score suggests that the changes implemented in response to initial feedback were largely successful in addressing user concerns and enhancing the overall functionality of the application.

The SUS questions were also grouped into three thematic categories: 'Learnability & Ease of Use' (Q3, Q4, Q7, Q10), 'Complexity & System Integration' (Q2, Q5, Q6, Q8), and 'User Confidence & Satisfaction' (Q1, Q9). The categories were chosen to represent different aspects of the user experience, with Learnability focusing on how easily users could start using the system, Complexity examining the technical coherence of the application, and User Confidence capturing the overall user satisfaction with the tool. Figure 13 shows the improvement in each of these thematic categories between iterations, with Complexity & System Integration showing the largest improvement, followed by Learnability & Ease of Use, and User Confidence & Satisfaction.

One of the most notable improvements was observed in users' understanding of carbon sequestration concepts. In the first iteration, 85% of users reported an increased understanding of carbon sequestration after using the application. This figure rose to 92% in the second iteration, suggesting that the additional context and improved presentation of information had a positive impact on the application's educational value. Users frequently commented on the effectiveness of the comparisons that related carbon sequestration to everyday activities, with many noting that these analogies helped to make the abstract concept more tangible and relatable.

The revised presentation of management strategies was particularly well-received. Users reported feeling more confident in understanding and comparing different forest management approaches. The immediate availability of strategy descriptions upon selection, coupled with the option to access more detailed information, appeared to significantly enhance user engagement with this feature. Many users noted that they found themselves experimenting with different strategies and contemplating the long-term impacts of forest management decisions, indicating a deeper level of engagement with the subject matter.

The newly implemented "Results" section, which allows users to review past measurements, proved to be a popular addition. Users appreciated the ability to track their measurements over time and compare different trees. This feature appeared to encourage continued use of the application, with several users likening the experience to building a personal forest inventory. The integration of social media sharing capabilities also received positive feedback, with users expressing enthusiasm about sharing their findings with their social networks.

Despite the generally positive feedback, the second iteration also revealed new areas for potential improvement. A suggested addition was a community feature that would allow users to see and compare measurements from other users in their area (possibly as a map), suggesting an interest in broader community engagement around urban forestry and carbon sequestration. A final suggested feature is to be able to compare measurements of the same tree over time.

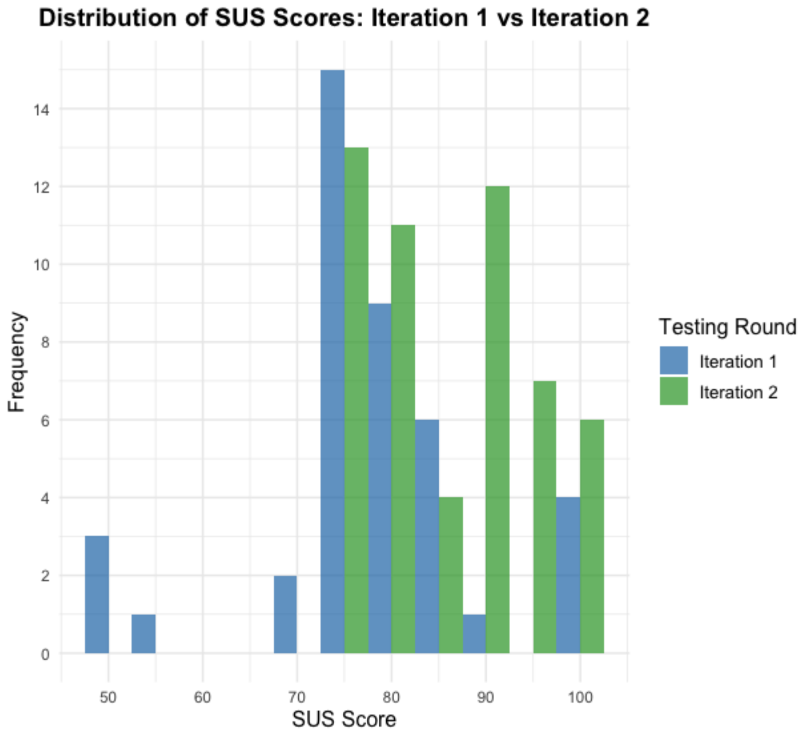


Figure 12: *Distribution of SUS scores across both iterations*

In terms of the application's effectiveness as a climate service tool, the second iteration results are particularly encouraging. The high percentage of users reporting increased understanding of carbon sequestration, coupled with the evident enthusiasm for sharing results and engaging with forest management concepts, suggests that TreeCarbonAR is successfully bridging the gap between complex climate science and public engagement. The application appears to be effective not only in educating users about carbon sequestration but also in fostering a sense of connection to urban forests and their role in climate change mitigation.

Overall, the results from the second iteration demonstrate significant improvements in usability, user engagement, and educational value compared to the first iteration. The changes implemented in response to initial user feedback appear to have successfully addressed many of the identified issues while maintaining and enhancing the aspects of the application that users found most valuable. These results suggest that TreeCarbonAR has evolved into a more effective and user-friendly climate service tool, with potential for fostering greater public understanding and engagement with urban forestry and carbon sequestration concepts.

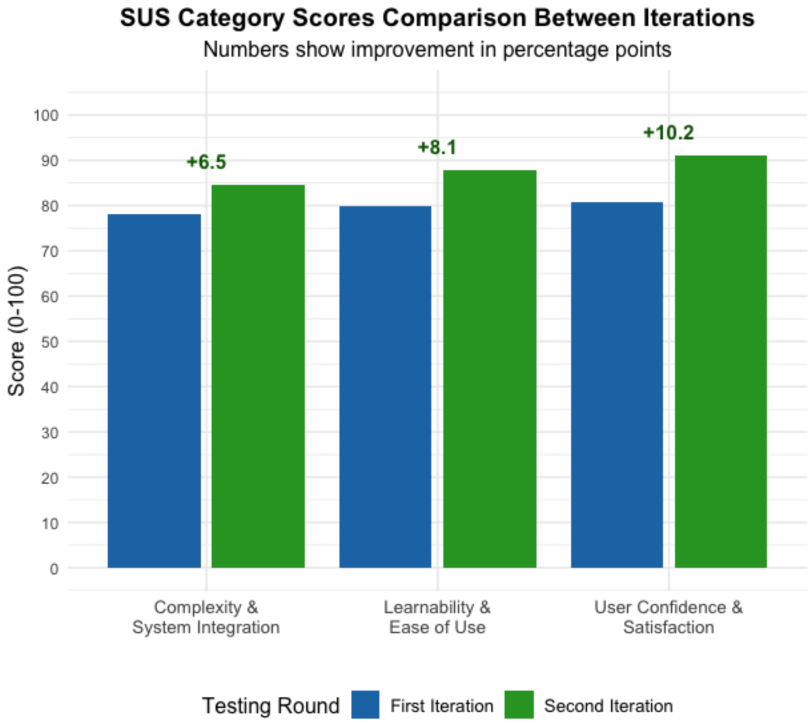


Figure 13*: Improvement between iterations across the SUS categories*

Across both iterations, TreeCarbonAR demonstrated its effectiveness as a climate service tool for enhancing public understanding of carbon sequestration. The improvements made between iterations successfully addressed the main concerns raised by users and resulted in a more engaging and informative application. The high usability scores and positive user feedback suggest that TreeCarbonAR successfully bridges the gap between complex climate science and public engagement, offering an accessible and interactive way for non-experts to engage with concepts of carbon sequestration and forest management.

Table 4: *Comparison of the results of the two iterations*

Question	Iteration 1	Iteration 2	Difference
Have you used any Augmented Reality (AR) applications before?	28%	31%	+3%
Have you estimated carbon sequestration before?	3%	7.3%	+4.3%
Have you made climate change mitigation related decisions in your private or professional life before?	67%	63%	-4%
The application was stable (no crashes)	4.12	4.53	+0.41
The instructions were hard to follow	2.02	1.72	-0.3

I easily understood the results communicated by the application	4.17	4.55	+0.38
I found the results interesting and useful	4.34	4.53	+0.19
It is easy for me to connect the things I learned with what I already know	3.85	4.49	+0.64
This information was more difficult to understand than I would like for it to be	2.02	1.72	-0.3
I learned some things that were surprising or unexpected	3.85	3.83	-0.02
I want AR applications to be used in other contexts as well	4.19	4.26	+0.07
Using the AR application was fun	4.37	4.55	+0.18
I think that I would like to use this app frequently (SUS 1)	4.27	4.71	+0.44
I found the app unnecessarily complex (SUS 2)	1.98	1.77	-0.21
I thought the app was easy to use (SUS 3)	4.24	4.54	+0.3
I think that I would need assistance to be able to use this app (SUS 4)	1.95	1.68	-0.27
I found the various functions in this app were well integrated (SUS 5)	4.37	4.49	+0.12
I thought there was too much inconsistency in this app (SUS 6)	1.87	1.69	-0.18
I would imagine that most people would learn to use this app very quickly (SUS 7)	4.39	4.92	+0.53
I found the app very cumbersome to use (SUS 8)	2.00	1.57	-0.43
I felt very confident using the app (SUS 9)	4.19	4.56	+0.37
I needed to learn a lot of things before I could get going with this app (SUS 10)	1.93	1.96	+0.03
The app increased my understanding of carbon sequestration in trees	4.17	4.34	+0.17
The app changed my perception of trees and their role in combating climate change	4.17	4.28	+0.09
The app helped me visualize the amount of carbon stored in trees	4.37	4.56	+0.19
Comparing tree carbon sequestration to daily activities made the concept more relatable	4.14	4.51	+0.37
The app motivated me to take more climate-positive actions	3.66	3.63	-0.03
I would be interested in using this app to survey trees in my neighbourhood or local parks	3.97	4.28	+0.31

5. Discussion

The results of this study demonstrate the potential of AR applications as effective climate service tools, particularly in the context of urban forestry and carbon sequestration education. TreeCarbonAR, through its iterative development and testing process, has shown significant promise in bridging the gap between complex climate science and public understanding.

The marked improvement in usability scores between the first and second iterations, with the SUS score increasing from 79.3 to 86.4, underscores the importance of user-cantered design in developing climate service applications. This aligns with the findings of Christel et al. (2018), who emphasized the value of co-design processes in climate service development. The iterative approach employed in this study, incorporating user feedback to refine the application, proved effective in enhancing user experience and engagement. Table 5 shows a comparison to select SUS studies in literature.

The high percentage of users reporting increased understanding of carbon sequestration concepts suggests that TreeCarbonAR addresses the knowledge gap identified by García-Antúnez *et al*. (2023) regarding public perceptions of carbon sequestration in urban greenery. By providing immediate, personalized feedback on individual trees, TreeCarbonAR makes the abstract concept of carbon sequestration more tangible and relatable to users.

The integration of AR technology with smartphone LiDAR and computer vision capabilities represents a novel approach in climate services, allowing for more accessible tools in urban tree inventory and NBS assessment. While previous studies such as Gollob *et al*. (2021) and Carvalho *et al*. (2020) demonstrated the technical feasibility of using smartphones for some tree measurements and species identification, TreeCarbonAR extends these capabilities into an interactive tool for carbon sequestration estimation.

The positive reception of the management strategy simulations in TreeCarbonAR highlights the potential of such applications in fostering public engagement with complex environmental decision-making processes. By allowing users to explore different management scenarios and their impacts on carbon sequestration, the application provides a unique platform for experiential learning about forest management. This feature aligns with the growing recognition of the need to democratize environmental decision-making.

One limitation of this study is the lack of long-term engagement data. While the results show positive short-term impacts on user understanding and engagement, further research is needed to assess the long-term effects of such applications on public knowledge and behaviour related to urban forestry and climate change mitigation.

Table 5*: Comparison of SUS values to literature*

Application	Type	SUS Score	Reference
TreeCarbonAR (1st iteration)	AR-based climate service	79.3	This study
TreeCarbonAR (2nd iteration)		86.4	This study
Fish conservation IARLS	AR-based fish conservation learning application	78	Lin *et al*. (2011)
VLE	Online learning platform	58.6	Vertesi *et al.* (2018)
360ED Alphabet AR	AR Educational apps	88.75	Tasfia *et al.* (2023)
Color Quest AR		50.75	
Magic Book AR		19.375	

Note: SUS scores typically range from 0 to 100, with higher scores indicating better usability. Scores above 68 are considered above average, while scores above 80 are considered excellent.

Additionally, the self-selection of participants may have resulted in a sample biased towards individuals already interested in environmental issues and ones that are more tech savvy. Future studies should aim to include a more diverse range of participants to better assess effectiveness across different demographics and levels of prior environmental engagement.

Despite these limitations, TreeCarbonAR demonstrates the potential of AR-based climate service applications in enhancing public understanding and engagement with urban forestry and carbon sequestration. By making complex scientific concepts accessible and interactive, such tools can play a crucial role in building public support for nature-based solutions to climate change.

This study contributes to the growing body of research on innovative climate services and public engagement with climate action. The success of TreeCarbonAR in improving user understanding of carbon sequestration and forest management strategies suggests that similar approaches could be effective for other environmental and climate-related concepts. Future research should explore the potential of AR and smartphone technology in addressing other aspects of climate change communication and mitigation planning, particularly in urban contexts where public engagement is crucial for successful implementation of nature-based solutions.

6.0 Conclusion

This study demonstrates the potential of AR applications as effective climate service tools, particularly in the context of urban forestry and carbon sequestration education. TreeCarbonAR, through its innovative integration of AR technology, smartphone LiDAR, and computer vision capabilities, offers a novel approach to bridging the gap between complex climate science and public understanding.

The iterative development and testing process of TreeCarbonAR yielded significant improvements in usability and effectiveness. The increase in SUS scores from 79.3 to 86.4 between iterations underscores the value of user-cantered design in developing climate service applications. More importantly, the high percentage of users reporting increased understanding of carbon sequestration concepts highlights the application's success in making abstract environmental concepts tangible and relatable to non-expert users.

TreeCarbonAR's ability to provide immediate, personalized feedback on individual trees' carbon sequestration potential, coupled with its interactive management strategy simulations, represents a significant advancement in public engagement tools for urban forestry and climate change mitigation. By allowing users to explore the impacts of different forest management scenarios, the application fosters a deeper understanding of the complexities involved in environmental decision-making.

The positive reception of TreeCarbonAR suggests that similar AR-based approaches could be effective for communicating other environmental and climate-related concepts. This study contributes to the growing body of research on innovative climate services and provides a model for developing user-friendly, technology-driven tools for environmental education and engagement.

However, the research also reveals areas for future development, including the incorporation of more personalized features, community engagement elements, and long-term impact assessment. These directions for future research underscore the dynamic nature of climate service development and the ongoing need for innovation in this field.

TreeCarbonAR demonstrates the potential of AR technology to transform how the public engages with and understands complex environmental issues. By making the invisible visible and the abstract tangible, such applications can play a crucial role in building public support for nature-based solutions to climate change. As cities worldwide grapple with the challenges of climate change mitigation and adaptation, tools like TreeCarbonAR offer a promising avenue for fostering informed public participation in urban forestry and broader environmental decision-making processes.

Funding

This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy - EXC 2037 ’CLICCS - Climate, Climatic Change, and Society’ - Project Number: 390683824, contribution to the Center for Earth System Research and Sustainability (CEN) of Universität Hamburg.

References

Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review*, *20*, 1–11. https://doi.org/10.1016/j.edurev.2016.11.002

Bangor, A., Kortum, P., & Miller, J. (2009). *Determining what individual SUS scores mean: Adding an adjective rating scale. J. Usability Studies, 4(3), 114–123. https://dl.acm.org/doi/10.5555/2835587.2835589*

Brooke, J. (1996). SUS: A “Quick and Dirty” Usability Scale. In *Usability Evaluation In Industry*. CRC Press.

Buontempo, C., Hanlon, H. M., Bruno Soares, M., Christel, I., Soubeyroux, J.-M., Viel, C., Calmanti, S., Bosi, L., Falloon, P., Palin, E. J., Vanvyve, E., Torralba, V., Gonzalez-Reviriego, N., Doblas-Reyes, F., Pope, E. C. D., Newton, P., & Liggins, F. (2018). What have we learnt from EUPORIAS climate service prototypes? *Climate Services*, *9*, 21–32. https://doi.org/10.1016/j.cliser.2017.06.003

Carvalho, M. de A., Marcato, J., Martins, J. A. C., Zamboni, P., Costa, C. S., Siqueira, H. L., Araújo, M. S., Gonçalves, D. N., Furuya, D. E. G., Osco, L. P., Ramos, A. P. M., Li, J., de Castro, A. A., & Gonçalves, W. N. (2022). A deep learning-based mobile application for tree species mapping in RGB images. *International Journal of Applied Earth Observation and Geoinformation*, *114*, 103045. https://doi.org/10.1016/j.jag.2022.103045

Carpentier, M., Giguère, P., & Gaudreault, J. (2018). *Tree Species Identification from Bark Images Using Convolutional Neural Networks* (arXiv:1803.00949). arXiv. https://doi.org/10.48550/arXiv.1803.00949

Christel, I., Hemment, D., Bojovic, D., Cucchietti, F., Calvo, L., Stefaner, M., & Buontempo, C. (2018). Introducing design in the development of effective climate services. *Climate Services*, *9*, 111–121. https://doi.org/10.1016/j.cliser.2017.06.002

Daniels, E., Bharwani, S., & Butterfield, R. (2019). *The Tandem framework: A holistic approach to co-designing climate services*. Stockholm Environment Institute. https://www.jstor.org/stable/resrep23003

Eggeling, J., Rydenfält, C., Kingma, B., Toftum, J., & Gao, C. (2022). The usability of ClimApp: A personalized thermal stress warning tool. *Climate Services*, *27*, 100310. https://doi.org/10.1016/j.cliser.2022.100310

García-Antúnez, O., Lampinen, J., Raymond, C. M., Gulsrud, N. M., & Olafsson, A. S. (2023). Unpacking public perceptions of carbon sequestration and storage in urban greenery: Implications for the social acceptability of carbon-oriented nature-based solutions. *Nature-Based Solutions*, *4*, 100087. https://doi.org/10.1016/j.nbsj.2023.100087

Goodwin, S., Olazabal, M., Castro, A. J. & Pascual, U. Global mapping of urban nature-based solutions for climate change adaptation. *Nat. Sustain.* **6**, 1–12 (2023).

Gollob, C., Ritter, T., Kraßnitzer, R., Tockner, A., & Nothdurft, A. (2021). Measurement of Forest Inventory Parameters with Apple iPad Pro and Integrated LiDAR Technology. *Remote Sensing*, *13*(16), Article 16. https://doi.org/10.3390/rs13163129

Harrs, J.-A., Reinhart, V., Vögt, V., Scheib, J. P. P., Tewes, T., Pohl, T., & Rechid, D. (2024). Integration of climate information into urban climate change adaptation: A case study of municipal processes in Constance. *Climate Services*, *35*, 100495. https://doi.org/10.1016/j.cliser.2024.100495

Hewitson, B., Waagsaether, K., Wohland, J., Kloppers, K., & Kara, T. (2017). Climate information websites: An evolving landscape. *WIREs Climate Change*, *8*(5), e470. https://doi.org/10.1002/wcc.470

Hewitt, C., Mason, S., & Walland, D. (2012). The Global Framework for Climate Services. *Nature Climate Change*, *2*(12), 831–832. https://doi.org/10.1038/nclimate1745

Jeong, N.-R., Han, S.-W., & Ko, B. (2023). Understanding Urban Residents' Perceptions of Street Trees to Develop Sustainable Maintenance Guidelines in the Seoul Metropolitan Area, Korea. *Forests*, *14*(4), Article 4. https://doi.org/10.3390/f14040837

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., Haase, D., Knapp, S., Korn, H., Stadler, J., Zaunberger, K., & Bonn, A. (2016). Nature-based solutions to climate change mitigation and adaptation in urban areas: Perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society*, *21*(2). https://www.jstor.org/stable/26270403

Kortum, P., Acemyan, C. Z., & Oswald, F. L. (2021). Is It Time to Go Positive? Assessing the Positively Worded System Usability Scale (SUS). *Human Factors*, *63*(6), 987–998. https://doi.org/10.1177/0018720819881556

Lin, H.-C. K., Hsieh, M.-C., Wang, C.-H., Sie, Z.-Y., & Chang, S.-H. (2011). Establishment and usability evaluation of an interactive AR learning system on conservation of fish. *The Turkish Online Journal of Educational Technology*, *10*(4).

Luna, S., Gold, M., Albert, A., Ceccaroni, L., Claramunt, B., Danylo, O., Haklay, M., Kottmann, R., Kyba, C., Piera, J., Radicchi, A., Schade, S., & Sturm, U. (2018, August 30). *Developing mobile applications for environmental and biodiversity citizen science: Considerations* *and recommendations*. JRC Publications Repository. https://doi.org/10.1007/978-3-319-76445-0_2

Máñez Costa, M., Oen, A. M. P., Schmid Neset, T.-S., Celliers, L., Suhari, M., Huang-Lachmann, J.-T., Pimentel, R., Blair, B., Jeuring, J., Rodriguez-Camino, E., Photiadou, C., Jerez Columbié, Y., Gao, C., Tudose, N. C., Cheval, S., Votsis, A., West, J. J., Lee, K., Shaffrey, L., … Schuck-Zöller, S. (2022). *Co-production of Climate Services: A diversity of approaches and good practice from the ERA4CS projects (2017–2021)*. Linköping University Electronic Press. https://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-182887

Martes, L., & Köhl, M. (2022). Improving the Contribution of Forests to Carbon Neutrality under Different Policies—A Case Study from the Hamburg Metropolitan Area. *Sustainability*, *14*(4), Article 4. https://doi.org/10.3390/su14042088

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, Ö., Yu, R., & Zhou, B. (Eds.). (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://doi.org/10.1017/9781009157896

Metelitsa, V. & Martes, L. (2024). Estimation of tree carbon sequestration using smartphone LiDAR, photogrammetry and computer vision. [In Review]

Ordóñez, C., Threlfall, C. G., Kendal, D., Hochuli, D. F., Davern, M., Fuller, R. A., van der Ree, R., & Livesley, S. J. (2019). Urban forest governance and decision-making: A systematic review and synthesis of the perspectives of municipal managers. *Landscape and Urban Planning*, *189*, 166–180. https://doi.org/10.1016/j.landurbplan.2019.04.020

Raaphorst, K., Koers, G., Ellen, G. J., Oen, A., Kalsnes, B., van Well, L., Koerth, J., & van der Brugge, R. (2020). Mind the Gap: Towards a Typology of Climate Service Usability Gaps. *Sustainability*, *12*(4), Article 4. https://doi.org/10.3390/su12041512

Reveco-Umaña, C. (2023). Exploring the use of climate information as practice. *Climate Services*, *30*, 100396. https://doi.org/10.1016/j.cliser.2023.100396

Sandim, A., Amaro, M., Silva, M. E., Cunha, J., Morais, S., Marques, A., Ferreira, A., Lousada, J. L., & Fonseca, T. (2023). New Technologies for Expedited Forest Inventory Using Smartphone Applications. *Forests*, *14*(8), Article 8. https://doi.org/10.3390/f14081553

Sandler, M., Howard, A., Zhu, M., Zhmoginov, A., & Chen, L.-C. (2019). *MobileNetV2: Inverted Residuals and Linear Bottlenecks* (arXiv:1801.04381). arXiv. https://doi.org/10.48550/arXiv.1801.04381

Sharma, B., Singh, N. P., Mantri, A., Gargrish, S., Tuli, N., & Sharma, S. (2021). Save the Earth: Teaching Environment Studies using Augmented Reality. *2021 6th International Conference on Signal Processing, Computing and Control (ISPCC)*, 336–339. https://doi.org/10.1109/ISPCC53510.2021.9609463

Smink, A. R., van Reijmersdal, E. A., & van Noort, G. (2022). Consumers' Use of Augmented Reality Apps: Prevalence, User Characteristics, and Gratifications. *Journal of Advertising*, *51*(1), 85–94. https://doi.org/10.1080/00913367.2021.1973622

Tasfia, S., Islam, M.N., Nusrat, S.A., Jahan, N. (2023). Evaluating Usability of AR-based Learning Applications for Children Using SUS and Heuristic Evaluation. In: Kaiser, M.S., Waheed, S., Bandyopadhyay, A., Mahmud, M., Ray, K. (eds) Proceedings of the Fourth International Conference on Trends in Computational and Cognitive Engineering. Lecture Notes in Networks and Systems, vol 618. Springer, Singapore. https://doi.org/10.1007/978-981-19-9483-8_8

Vertesi, A., Dogan, H., & Stefanidis, A. (2020). Usability Evaluation of Virtual Learning Environments: A University Case Study. In P. Isaias, D. G. Sampson, & D. Ifenthaler (Eds.), *Online Teaching and Learning in Higher Education* (pp. 161–183). Springer International Publishing. https://doi.org/10.1007/978-3-030-48190-2_9

Vincent, K., Daly, M., Scannell, C., & Leathes, B. (2018). What can climate services learn from theory and practice of co-production? *Climate Services*, *12*, 48–58. https://doi.org/10.1016/j.cliser.2018.11.001

Yang, T., Zhou, S., Huang, Z., Xu, A., Ye, J., & Yin, J. (2023). Urban street tree dataset for image classification and instance segmentation. *Computers and Electronics in Agriculture*, *209*, 107852. https://doi.org/10.1016/j.compag.2023.107852

Appendix A: Survey Questions

Dear Participant,

Thank you for taking the time to complete this survey about your experience with our Tree Carbon Sequestration Augmented Reality (AR) application. Your feedback is invaluable in helping us improve the app and assess its effectiveness in educating users about the role of trees in climate mitigation.

About the app

Our AR app allows users to measure the height and diameter of trees using their smartphone. The app then uses these measurements to estimate the amount of carbon sequestered by the tree and compares it to everyday activities, such as boiling a kettle of water or driving a car for a certain distance. This innovative approach aims to make the concept of carbon sequestration more tangible and relatable.

Purpose of the survey

The purpose of this survey is to:

1. Evaluate the usability and functionality of the AR app
2. Assess the effectiveness of the app in educating users about carbon sequestration and climate change mitigation
3. Gather insights on how the app influences users' perceptions of trees and climate action
4. Collect suggestions for improvements and additional features

Confidentiality and data use

Your responses will be kept strictly confidential and will only be used for the purpose of improving the app and for academic research related to climate change services and AR technology. No personally identifiable information will be collected or shared.

Survey structure

The survey consists of multiple-choice questions and a few open-ended questions. It should take approximately 10-15 minutes to complete. There are no right or wrong answers – we are interested in your honest opinions and feedback.

Voluntary participation

Your participation in this survey is entirely voluntary. You may choose to skip any questions you are not comfortable answering or exit the survey at any time. incomplete surveys will not be logged or used.

Thank you again for your participation. Your input will help us enhance this educational and decision-making tool and contribute to broader climate change awareness efforts.

Let's begin!

Have you used any Augmented Reality (AR) applications before? ☐ Yes ☐ No

Have you estimated carbon sequestration before? ☐ Yes ☐ No

Have you made climate change mitigation related decisions in your private or professional life before? ☐ Yes ☐ No

Question	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The application was stable (no crashes)					
The instructions were hard to follow					
I easily understood the results communicated by the application					
I found the results interesting and useful					
It is easy for me to connect the things I learned with what I already know					
This information was more difficult to understand than I would like for it to be					
I learned some things that were surprising or unexpected					
I want AR applications to be used in other contexts as well					
Using the AR application was fun					
I think that I would like to use this app frequently					

I found the app unnecessarily complex					
I thought the app was easy to use					
I think that I would need assistance to be able to use this app					
I found the various functions in this app were well integrated					
I thought there was too much inconsistency in this app					
I would imagine that most people would learn to use this app very quickly					
I found the app very cumbersome to use					
I felt very confident using the app					
I needed to learn a lot of things before I could get going with this app					
The app increased my understanding of carbon sequestration in trees					
The app changed my perception of trees and their role in combating climate change					
The app helped me visualize the amount of carbon stored in trees					
Comparing tree carbon sequestration to daily activities made the concept more relatable					
The app motivated me to take more climate-positive actions					
I would be interested in using this app to survey trees in my neighbourhood or local parks					

Can you consider some ways to enhance the user interface?

Would you propose some additional features/functionality to enhance your usage of the application?

Can you suggest any ways to improve the app's effectiveness in educating about carbon sequestration and climate action?

How would you use the knowledge gained from this app in your daily life or decision-making?

Would you recommend the app to your family and friends? Why?

Chapter 4

An Evaluation of Feasibility and Stakeholder Utility of an Augmented Reality Climate Service for Small-Scale Rural Producers in Novo Progresso, Pará, Brazil

An Evaluation of Feasibility and Stakeholder Utility of an Augmented Reality Climate Service for Small-Scale Rural Producers in Novo Progresso, Pará, Brazil

Vladimir Metelitsa[1, 3, §], Carlos Tello[2, 3], Martina Neuburger[2,3]

[1] Climate Service Center Germany (GERICS), Helmholtz-Zentrum hereon GmbH, Fischertwiete 1, 20095 Hamburg
[2] Universität Hamburg, Institute of Geography, Bundesstraße 55, 20146, Hamburg, Germany
[3] Center for Earth System Research and Sustainability (CEN), Universität Hamburg
[§] Corresponding author; E-Mail: vladimir.metelitsa@hereon.de

Vladimir Metelitsa ORCiD: 0000-0003-0984-9249
Carlos Tello ORCiD: 0000-0001-5259-7177
Martina Neuburger ORCiD: 0000-0003-4767-3352

Keywords: Agricultural Frontier, Brazilian Amazon, rural producers, climate service, augmented reality, land use change

Abstract

The Brazilian Amazon is experiencing significant environmental and agricultural challenges due to climate change and anthropogenic activities. In Novo Progresso, Pará, where agricultural expansion and environmental conservation objectives frequently conflict, small-scale farmers face increasing difficulties in agricultural decision-making due to changing weather patterns and limited access to climate information. This study presents the development and evaluation of an Augmented Reality (AR) climate service application designed to support agricultural adaptation strategies. The table-top AR application was developed based on extensive field observations and stakeholder interviews. The application allows farmers to visualize the area, select their land plots, input agricultural data relevant to their production, and explore potential localized climate change impacts and adaptation strategies. Expert evaluation by local agricultural authorities and stakeholders indicated strong potential for the tool. Suggested improvements included the integration of consolidated areas, pluviometric data, and soil fertility information. While the application shows promise in supporting agricultural decision-making, careful attention must be paid to ensuring it remains targeted toward small-scale producers rather than enabling large-scale agricultural expansion. This study demonstrates the feasibility and utility of AR technology for delivering climate services in rural developing regions, while highlighting the importance of incorporating local context and stakeholder needs in technological solutions for climate adaptation.

1. Introduction

The Brazilian Amazon, a region of immense ecological importance, faces significant challenges due to climate change and anthropogenic activities (Lovejoy & Nobre, 2019; Gatti *et al.*, 2021; Castellanos *et al.*, 2022). Among its most vulnerable inhabitants are small-scale agricultural producers, whose livelihoods depend directly on predictable weather patterns and sustainable land use (Brondizio & Moran, 2008). As rainfall patterns shift and temperatures rise, these farmers must adapt their practices to maintain productivity and ensure food security (Marengo *et al.*, 2018). However, the complexity of climate projections and the diversity of potential adaptation strategies make it difficult for individual farmers to take informed decisions about their agricultural practices. At the same time, these producers are often blamed for the destruction of the Amazonian biome (Fearnside, 2008; Cavalho *et al.*, 2019).

This study focuses on the municipality of Novo Progresso in the state of Pará, a region that has gained international attention due to its high rates of deforestation and land use changes (Yanai *et al.*, 2017; Sauer, 2018). Here, we propose and evaluate an innovative approach to climate services: an Augmented Reality (AR) mobile application designed to provide localized projections of the impact of climate change on agricultural production and adaptation strategies to small-scale farmers. By helping them optimize their existing agricultural land, such tools could potentially reduce the pressure to expand into forested areas.

Meteorological records show increasing variability in rainfall patterns and more frequent extreme weather events in the region, impacting crop cultivation. While local producers may not always perceive long-term climate changes (Tello, Schröder & Neuburger, 2022; Brondizio & Moran, 2008), data shows more frequent occurrence of both prolonged droughts and intense rainfall events (Marengo et al., 2018; Castellanos *et al.*, 2022). Multiple adaptation strategies exist, such as crop rotations, improved irrigation strategies, switching to different crops, or modifying fertilizer use, assessing the benefits and trade-offs of these different response measures is complicated. Additionally, due to the social and power dynamics in the region, these decisions sometimes need to be made at the community scale, requiring tools that can support collective decision-making processes.

On the other hand, the development of climate services in this area are constrained by the lack of data on crucial factors such as the specific crops cultivated, soil types, and the agricultural strategies already being implemented. This study attempts to address these challenges by providing an interactive tool to farmers that allows them to assess the impacts of climate change and test different response measures for their own fields.

The choice of hand-held mobile AR technology for this climate service is driven by several factors. First, while personal computers are relatively uncommon in the region, smartphone ownership is widespread among rural producers, making a mobile application an ideal delivery method. According to the Brazilian Institute of Geography and Statistics, as of 2023, 96.7% of Brazilian households had smartphones, while only 39% had access to computers - a figure that had decreased from 45.9% in 2016 (IBGE, 2024). Second, the immediate local relevance possible with AR technology offers clear benefits over more generalized country-wide or global statistics. Finally, by allowing producers to input data about their own agricultural plots, we overcome the typical limitation of the lack of localized cultivation data.

This study aims to evaluate whether an AR climate service for agriculture would be both feasible and useful to stakeholders in the Novo Progresso region. To our knowledge, this represents the first attempts to implement AR climate services in rural areas of developing countries, making this research both novel and potentially impactful. We hope to contribute to the growing field of climate services and provide valuable insights into the potential of AR technology to support climate adaptation in agriculture, particularly in developing regions facing significant climate challenges.

2. Background

2.1 Historical Context of Novo Progresso

Novo Progresso is a municipality located in the Southwest of the Amazonian state of Pará, situated along the margins of the federal road BR-163. Its territory covers 38,162.002 km², and according to the latest census (2022), it contains 33,638 inhabitants (IBGE, 2023). The region's development trajectory exemplifies the complex socio-environmental dynamics that have shaped the Brazilian Amazon over the past half-century. The region's history is deeply intertwined with national developmental policies and resource exploitation, particularly since the 1960s when the Brazilian government initiated ambitious plans to integrate the Amazon into the national economy - policies that would lead to extensive deforestation and social transformation. The municipality's history is intrinsically connected with the Amazon resource extraction and Brazilian developmental projects (Araujo & Melo, 2008; Torres et al., 2017).

The area was first inhabited by Indigenous communities and "*riberinhos*," who settled by the Tapajos River in the middle of the 19th century. By the 1950s, rubber tapping and mining extraction brought new inhabitants to the region (Novo Progresso, 2023). However, the most significant transformation began in the early 1970s, when the military government initiated ambitious plans to integrate the Amazon into the national economy through development and colonization projects (Torres et al., 2017).

The construction of the BR-163 highway, connecting Cuiabá in Mato Grosso to Santarém in Pará, marked a crucial turning point. Initiated in 1971, this massive infrastructure project was part of the National Integration Program (PIN), designed under the slogan "*integrar para não entregar*" (integrate not to surrender) (Torres *et al.*, 2017). The initial phase, between 1971 and 1976, involved clearing approximately 1,700 kilometres of forest, with these efforts converging at the former 1085-kilometre mark, now known as Municipality of Novo Progresso (Novo Progresso, 2023). The BR-163 highway aimed to link key areas of production and distribution while boosting colonization, economic growth, and border security (Rodrigues & Nahum, 2023). To facilitate this development, the government established Decree 1.164/1971, which granted federal control over a 200-kilometre strip adjacent to established, under construction or proposed federal roads. This was followed by Federal Law 6.338/1976, which established the legal framework for land ownership and introduced the legal structure reaffirming the "settlement of government lands". This gave ownership to individuals engaged in active cultivation and habitation on the land up to 100 hectares as long as this land was productive (Torres et al., 2017). The highway's construction not only facilitated access to the region's abundant natural resources but also spurred a wave of migration that would fundamentally alter the social and ecological landscape of Novo Progresso. Unlike other areas of the Amazon, the land regularization process in Novo Progresso created opportunities for the establishment of extensive landholdings. This distinctive pattern led to the emergence of large landowners and triggered significant migration and land-use issues. The process also intensified existing environmental problems related to deforestation, mining, and logging (Bandeira Castelo et al., 2020; Rodrigues & Nahum, 2023; Torres et al., 2017).

The first pioneers, arriving between 1976 and 1990, responded to government incentives and promises of land ownership (Tello, Schröder & Neuburger, 2022). They faced the daunting task of establishing themselves in the dense Amazon rainforest with limited infrastructure and support. Through clearing forest land for agriculture and cattle ranching, these early settlers laid the foundations for future development while initiating a pattern of deforestation that would escalate in subsequent decades.

By 2000, the BR-163 established itself as a key commodity corridor, facilitating production and distribution while driving the expansion of the agricultural frontier (Deutsch & Fletcher, 2022; Rodrigues & Nahum, 2023), directly impacting the socio-environmental dynamics of Novo Progresso. This transformation aligns with what Coelho et al. (2019) define as the Amazonian agricultural frontier: a scenario of socio-environmental and economic relations resulting from the expansion of the farming and mining sectors, alongside urbanization, service networks, and state interventions in its different spheres.

In response to growing land and environmental issues and agricultural expansion, the federal government created settlement projects through the National Institute for Colonisation and Agrarian Reform (INCRA) to redistribute the land and create environmentally protected areas in the municipality. In 1997, the INCRA created the settlement projects (*Projeto de Assentamento Federal "PA"*) Nova Fronteira and Santa Júlia, and in 2006, it created the settlements (*Projeto de Desenvolvimento Sustentável "PDS"*) Nelson de Oliveira and Terra Nossa. Furthermore, the recognition of Baú Kayapó indigenous land in 1991 and the creation of the Jamanxim Environmental Preservation Area (APA) in 2017 helped shape some of the dynamics of land use and management in the area.

Despite these conservation efforts, Novo Progresso's socio-environmental dynamic of agricultural expansion, illegal mining, logging, and resource extraction has placed it among the ten most deforested municipalities in the Amazon, with accumulated deforestation of 7,646.05 km² from 2007 to date (PRODES, 2023).

From 2004 onwards, the region has seen a shift towards larger-scale agricultural operations, particularly the expansion of soybean cultivation. The completion of the BR-163 highway's paving in 2021 accelerated this trend by improving market access and enabling more intensive land use. This period coincided with significant changes in national environmental policy. The election of President Jair Bolsonaro in 2019 marked a shift in the government's approach to Amazon conservation, characterized by reduced funding for monitoring and conservation programmes (Vale *et al.*, 2021; Ferrante & Fearnside, 2019). Under his administration, environmental protection agencies saw their budgets and enforcement capabilities significantly diminished, creating conditions that further enabled agricultural expansion and deforestation in regions like Novo Progresso. This period has also seen increased tension between agricultural expansion and conservation efforts, exemplified by events like the "Day of Fire" in 2019, where coordinated burning of forest areas drew international condemnation (Aragao, 2021).

The expansion of soy and cattle production in the region has overwhelmed protection and conservation projects, creating a complex challenge for sustainable development and environmental preservation. The municipality's history reflects the broader challenges of reconciling economic development with environmental sustainability in one of the world's most critical ecosystems. The legacy of these historical processes continues to shape the region's social, economic, and environmental dynamics, providing the complex backdrop against which current efforts to promote sustainable agriculture and climate resilience must operate.

2.2 Current Challenges

Today, Novo Progresso faces a complex web of interconnected challenges that stem from its historical development and its position at the forefront of the agricultural frontier in the Amazon. Deforestation remains one of the most pressing issues in the municipality. According to data from the Program for Monitoring Brazilian Amazon Forest by Satellite (PRODES, 2024), Novo Progresso has lost over 7,600 square kilometres of forest since 2007, placing it among the ten most deforested municipalities in the Brazilian Amazon. This extensive forest loss not only threatens biodiversity and ecosystem services but also contributes significantly to climate change through carbon emissions.

The landscape of Novo Progresso has undergone a dramatic transformation over the past decades. What was once primarily dense rainforest has become a mosaic of pastures, croplands, and fragmented forest patches. The expansion of soybean cultivation has been particularly notable in recent years, driven by global demand and improved transportation infrastructure. This shift in land use has profound implications for local ecosystems, soil health, and water cycles.

Climate change poses an increasingly severe threat to both natural ecosystems and agricultural productivity in the region. Shifting rainfall patterns are altering the traditionally predictable wet and dry seasons, making agricultural planning more challenging, extreme weather events, including both droughts and flooding. These changes not only affect crop yields but also exacerbate soil erosion and degradation, creating a cycle of declining agricultural productivity.

Land tenure issues continue to complicate sustainable development efforts in Novo Progresso. The history of unplanned colonization and unclear property rights has led to ongoing conflicts over land ownership. Illegal land grabbing remains a significant problem, with public lands often being appropriated for private use. The challenges of regularizing land titles through programmes like Terra Legal have left many farmers in a state of legal uncertainty, which can discourage long-term investments in sustainable practices.

The effectiveness of environmental policies and their enforcement has fluctuated over time, often reflecting changes in national political priorities. During periods of reduced enforcement, the region has seen spikes in deforestation and land use changes. The creation of protected areas, such as the Jamanxim National Forest, has led to conflicts with local landowners and ongoing debates about the balance between conservation and economic development.

Agricultural practices in the region face multiple challenges. Many small-scale farmers lack access to technical assistance and may struggle to implement sustainable farming methods. The predominance of extensive cattle ranching, while culturally significant, often leads to low productivity and continued pressure on forest resources. The transition to more intensive agriculture, particularly soybean cultivation, brings its own set of environmental challenges, including potential soil degradation.

Access to markets remains a significant issue for many producers in Novo Progresso. While the paving of the BR-163 highway has improved transportation links, many smaller farmers still struggle to get their products to market efficiently. This can lead to economic instability and pressure to expand agricultural areas to increase production.

The social fabric of Novo Progresso reflects its history of migration and rapid development. The community includes a mix of long-term residents, more recent arrivals, and indigenous populations, each with their own perspectives on land use and development. Balancing these diverse interests while promoting sustainable development remains an ongoing challenge.

Lastly, the municipality faces significant gaps in basic infrastructure and services. Despite progress, many areas still lack reliable electricity, internet connectivity, and healthcare facilities. Education and training opportunities, particularly in sustainable agricultural practices and environmental management, are often limited.

These multifaceted challenges underscore the complexity of promoting sustainable development in Novo Progresso. Any efforts to address climate change and improve agricultural practices must navigate this intricate landscape of environmental, social, and economic issues.

2.3 Climate Change Impacts on Agriculture

Rural producers in Novo Progresso are particularly vulnerable to the impacts of climate change, with shifting weather patterns having potentially transformative impacts on farming practices and crop yields. These changes pose significant challenges to their livelihoods and the overall food security of the region.

One of the potentially most significant impacts is the change in rainfall patterns. Historically, the region experienced predictable wet and dry seasons, which provided a reliable framework for agricultural planning. However, these patterns have become increasingly erratic. Climate change could delay the onset of the rainy season, lead to longer dry spells during traditional wet seasons, and more intense rainfall events (Castellanos, 2022). These may changes disrupt traditional planting schedules and increase the risk of crop failures. The unpredictability of rainfall could make irrigation planning particularly challenging, especially for small-scale farmers who lack access to sophisticated irrigation systems.

Rising temperatures pose another potential significant challenge for agriculture in Novo Progresso. The region has experienced a gradual increase in average temperatures over the past few decades, a trend that climate models predict will continue (Lange & Büchner, 2021). Higher temperatures lead to increased evapotranspiration, resulting in water stress for crops even when rainfall amounts remain constant. This may be particularly problematic for the region's expanding soybean cultivation, as soybeans are sensitive to heat stress during flowering and pod-filling stages. The warmer temperatures may affect livestock, reducing milk production in dairy cattle and increasing heat-related stress in all farm animals.

The frequency and intensity of extreme weather events have also increased, posing additional challenges to agriculture. Prolonged droughts, which can last for weeks or even months, have become more common, with a potential to lead to crop failures and reduced pasture quality for livestock. On the other hand, intense downpours that can cause flooding and soil erosion. These extreme events not only damage crops directly but also contribute to long-term soil degradation, reducing the land's productive capacity over time.

Soil degradation, exacerbated by climate change, represents a growing concern. The combination of higher temperatures, more intense rainfall events, and longer dry spells accelerates erosion and alters soil chemistry. The loss of soil organic matter reduces water-holding capacity, making crops more vulnerable to drought stress. Changes in soil microbial communities due to altered temperature and moisture regimes may affect nutrient cycling, potentially reducing soil fertility over time.

The changing climate could also influence in the prevalence and distribution of pests and diseases that affect crops and livestock (Guégan et al, 2022; Milman, 2022). Warmer temperatures can allow certain pests to expand their ranges, while changes in rainfall patterns can create more favourable conditions for the spread of fungal diseases. This may force farmers to adapt their pest management strategies.

These climate change impacts are not occurring in isolation but are interacting with other environmental and socio-economic challenges in the region. For instance, the ongoing deforestation in and around Novo Progresso may be exacerbating local climate change impacts by altering microclimates and reducing rainfall through decreased evapotranspiration. Similarly, the expansion of large-scale monocultures, particularly soybeans, may be making the agricultural system as a whole more vulnerable to climate shocks.

The ability of farmers to adapt to these changes is often limited by factors such as lack of access to climate information, limited financial resources for implementing new technologies or practices, and in some cases, insecure land tenure that discourages long-term investments in climate resilience. Small-scale farmers are particularly vulnerable, as they often lack the resources to implement adaptation strategies such as improved irrigation systems or drought-resistant crop varieties.

In this context, the need for effective climate services becomes apparent. Providing farmers with accurate, localized climate information and guidance on adaptation strategies could play a crucial role in building the resilience of the agricultural sector in Novo Progresso. However, developing and implementing such services in this complex and rapidly changing environment presents significant challenges, which this study aims to address through the innovative use of Augmented Reality technology.

2.4 The Potential for AR Climate Services in the region

In the face of the significant climate-related challenges confronting agriculture in Novo Progresso, climate services have emerged as a promising tool for supporting adaptation and resilience. Climate services, which provide tailored climate information to support decision-making, have the potential to empower farmers with the knowledge they need to navigate the increasingly unpredictable weather patterns and long-term climate trends affecting their livelihoods.

The concept of climate services encompasses a wide range of activities, from the provision of basic weather forecasts to complex, long-term climate projections and associated agricultural advisories. In the context of Novo Progresso, effective climate services could include seasonal rainfall forecasts, heat stress warnings for livestock, guidance on optimal planting dates based on climate projections, and advice on climate-resilient crop varieties and farming practices.

However, the implementation of such services in regions like Novo Progresso faces several significant challenges. One of the primary obstacles is data scarcity. The Amazon region, in general, suffers from a lack of dense, long-term weather monitoring networks. In Novo Progresso specifically, there are few weather stations, and historical records are often incomplete or of questionable quality. This lack of local data makes it difficult to produce fine-scale climate projections and to validate climate models for the region. As a result, existing climate information products have to rely on coarse-resolution data that may not capture the local microclimates that are so crucial for agricultural decision-making.

Access to technology presents another challenge. While smartphone ownership is widespread among farmers in the region, access to computers and high-speed internet is limited, particularly in more remote areas. This digital divide can make it difficult to deliver complex climate information in formats that are easily accessible and understandable to all farmers. Moreover, the lack of consistent internet connectivity can hinder real-time updates and interactive features that could enhance the usefulness of climate services.

The diverse agricultural practices in Novo Progresso further complicate the development of effective climate services. The region hosts a variety of crops, from traditional subsistence agriculture to large-scale soybean production, each with its own specific climate sensitivities. Soil types also vary considerably across the landscape, affecting water retention and nutrient availability. This diversity means that climate information needs to be highly localized and tailored to specific agricultural contexts to be truly useful.

Another crucial factor to consider is the social and power dynamics in the region. In Novo Progresso, as in many rural communities, agricultural decisions are often made not just at the individual farm level but also at the community level. This collective decision-making process can be influenced by local power structures, cultural norms, and shared resources such as water for irrigation. Effective climate services need to take these social dynamics into account, potentially providing information and tools that can support community-level adaptation strategies.

Despite these challenges, the potential benefits of well-designed climate services for Novo Progresso are significant. By providing farmers with more accurate and timely climate information, such services could help reduce crop losses due to extreme weather events, optimize the use of inputs like water and fertilizer, and support the gradual transition to more climate-resilient agricultural practices. Moreover, by empowering farmers with knowledge, climate services could help build adaptive capacity within the community, making the agricultural sector as a whole more resilient to future climate changes.

The key to realizing these benefits lies in developing climate services that are not only scientifically robust but also user-friendly, accessible, and relevant to the local context. This requires a participatory approach to service design, involving farmers and other local stakeholders from the outset to ensure that the information provided meets their needs and is presented in a format they can easily use and understand.

It is in this context that innovative technologies like AR offer exciting possibilities. By leveraging the widespread availability of smartphones and providing an intuitive, visual interface for complex climate information, AR-based climate services could potentially overcome many of the challenges faced by traditional approaches. The next section will explore in more detail how AR technology could be applied to create effective climate services for the farmers of Novo Progresso.

In the quest to develop effective climate services for the farmers of Novo Progresso, AR technology emerges as a promising and innovative solution. AR, which overlays digital information on the real world through a device's camera, offers a unique opportunity to address many of the challenges faced in implementing traditional climate services in this complex region. The potential of AR in this context lies in its ability to provide intuitive, location-specific climate and agricultural information directly to users through their smartphones. This approach leverages existing technology that is already widely adopted in the region, overcoming one of the primary barriers to the implementation of climate services in rural areas. Even in areas with limited internet connectivity, AR applications can be designed to function offline, with periodic updates when connection is available, ensuring consistent access to critical information.

One of the most significant advantages of AR for climate services is its capacity for highly localized information delivery. By using the smartphone's GPS and camera, an AR application can provide information specific to the exact location where the farmer is standing. This could allow farmers to point their phones at a particular field and instantly see overlaid information about soil moisture levels, crop health, projected rainfall, or optimal planting dates for that specific plot. This level of localization is crucial in a region like Novo Progresso, where microclimates and soil conditions can vary significantly over short distances.

AR technology also offers a solution to the challenge of data scarcity in the region. By allowing users to input their own agricultural data – such as crop types, planting dates, and observed weather conditions – an AR application can build a more comprehensive and accurate local database over time. This participatory approach not only improves the quality of the climate service but also engages farmers more deeply in the process of understanding and adapting to climate change.

The visual nature of AR presents complex climate and agricultural data in a more intuitive and accessible format. Instead of trying to interpret tables of numbers or complex charts, farmers could see visual representations of climate projections overlaid on their actual fields. For example, changing colours could represent projected soil moisture levels, or virtual crops could demonstrate expected growth under different climate scenarios. This visual approach can make complex information more understandable and actionable, particularly for users with limited formal education.

Furthermore, AR applications have the potential to facilitate community-level decision-making, which is crucial in the social context of Novo Progresso. By allowing users to share and view each other's inputs and scenarios, an AR climate service could support collaborative planning and adaptation strategies. Farmers could virtually 'visit' each other's fields, share successful practices, and collectively visualize the potential impacts of different adaptation strategies on their community.

The interactive nature of AR also allows for real-time updates and scenario testing. Farmers could experiment with different crop choices, planting dates, or management practices and immediately see projected outcomes based on climate forecasts. This feature could be particularly valuable in helping farmers navigate the increasing unpredictability of weather patterns in the region.

However, the implementation of AR-based climate services in Novo Progresso is not without challenges. The development of such an application requires careful consideration of user needs, technological limitations, and local socio-economic contexts. Issues such as data privacy, the digital literacy of users, and the accuracy of climate projections at very local scales all need to be addressed.

Moreover, for an AR climate service to be truly effective, it needs to be part of a broader system of agricultural support. This could include integration with extension services, links to markets and financial services, and connections to broader climate adaptation initiatives in the region. The technology should be seen as a tool to enhance and facilitate human expertise and local knowledge, not as a replacement for them.

Despite these challenges, the potential of AR to revolutionize climate services in regions like Novo Progresso is significant. By providing highly localized, visual, and interactive climate information, AR technology could play a crucial role in building the resilience of small-scale farmers in the face of climate change. This study aims to explore whether these potential advantages can be realized in practice, and whether an AR-based climate service can effectively support agricultural adaptation in the complex socio-ecological system of Novo Progresso.

As we move forward with this research, we will need to carefully evaluate not just the technological feasibility of such a system, but also its social acceptability, economic viability, and ultimate impact on agricultural practices and livelihoods in the region. The insights gained from this study could have far-reaching implications, not just for Novo Progresso, but for the development of climate services in rural areas across the developing world.

3. Methods

This study aimed to develop a digital tool tailored for rural producers in the municipality of Novo Progresso, Pará. The methodology included four phases: active observation, input data collection, prototype development, and stakeholder engagement in the prototype testing.

The first phase, active observation, involved field visits to understand the local context, including agricultural practices and baseline of stakeholder understanding of climate change impacts. This phase was crucial in identifying specific needs and constraints that would inform the tool's development.

The second phase focused on input data collection, gathering essential information about local agricultural practices, land use patterns, and climate projections. This included collecting spatial data about land plots, administrative boundaries, and restricted areas, as well as agricultural and climate data necessary for developing accurate projections.

The third phase encompassed the prototype development of the AR application. This involved designing the user interface and implementing the functionality tying the interface to the underlying model outputs.

The final phase consisted of stakeholder engagement in prototype testing, where the application was presented to local experts and government representatives. This phase included hands-on testing sessions and semi-structured interviews to gather feedback on the application's utility and areas for improvement.

3.1 Initial Field Observations and Stakeholder Engagement

Initial data collection from March to May 2022 consisted of discussions and direct observation involving rural producers in the region (Tello, Schröder & Neuburger, 2022). These discussions provided qualitative insights essential for the tool's contextual relevance. The field observations were conducted at small-scale fields in the proximity of Novo Progresso.

During this phase, we engaged with rural producers through field visits to their properties and informal conversations about their agricultural practices. These interactions focused on understanding the producers' history in the area, current agricultural practices, challenges and discussing producers' decision-making processes regarding land use and agricultural management.

A notable finding from these interactions was the producers' perception of climate change. Most producers initially expressed scepticism about climate change impacts, often stating that "the climate doesn't change" or that the "weather is optimal for production." However, when discussing specific long-term observations, the producers would describe changes in rainfall across years and some past adverse weather events. These observations align with meteorological records from the region, which confirm slight changes in precipitation patterns and an increase in drought frequency over the past decades. This disconnect between perceived and observed climate changes highlighted the need for a tool that could help visualize and contextualize these long-term patterns.

The observations revealed a strong emotional and professional connection to agricultural work. Rural producers demonstrated genuine enthusiasm for their profession and expressed a desire for their children to continue benefiting from the land in the future. They exhibited remarkable attention to detail in their agricultural practices, often discussing subtle optimizations and improvements in their production methods. This meticulous approach to agricultural optimization suggested that a detailed, data-driven tool would be well-received by this audience. Through active observation, several key factors influencing agricultural practices were identified. Land relief emerged as a crucial consideration, particularly for mechanized production of crops like soy and corn. Land size and characteristics were found to strongly influence production choices: large, flat parcels were typically used for soy production, while smaller plots with varied relief were more commonly used for cattle ranching. The smallest plots, primarily in settlement areas, were generally devoted to milk and fruit production. The distance from plots to the federal road BR-163 was also identified as a significant factor in land use decisions.

These observations also highlighted the importance of local reference points, such as the BR-163 highway, in how producers navigate and discuss their landscape. This insight directly influenced the decision to include prominent geographical features in the application's visual display. Additionally, discussions with producers revealed the need to incorporate local agricultural terminology and land use categories that reflect the specific context of Novo Progresso.

The insights gathered during this phase were instrumental in ensuring that the subsequent development of the AR application would address real user needs and constraints, rather than imposing external assumptions about what might be useful for the community. The producers' detail-oriented approach to agriculture, combined with their strong connection to the land and concern for its future viability, suggested that a sophisticated yet accessible tool for agricultural planning would be valuable for this community.

3.2 Initial Data Collection and Processing

A significant component of the prototype development planning involved gathering and processing spatial and administrative data from various sources. A primary source of preliminary data was the Pará state portal for land property management (SEMAS, n.d) - which maintains comprehensive records of land plots and their characteristics in the region. This database contains detailed information about land plot boundaries and associated properties, which was identified as crucial for the planned application. The goal was to allow farmers to simply select their pre-defined plots within the future application, rather than requiring them to manually delineate their fields.

Since the SEMAS portal only permits viewing individual plots without direct data download capabilities, we developed an automated tool to systematically collect information about all fields within and slightly beyond the study area. This expanded collection area was necessary to account for fields that either lie on the periphery or span multiple administrative regions. The tool extracted the geographical location and shape data for each field, creating a comprehensive database of land parcels in the region.

The initial data gathering phase was strongly influenced by input from rural producers, who helped identify essential data types and functionalities. Their practical experience and understanding of local conditions proved invaluable in determining what information would be most useful for agricultural decision-making in the planned application.

Based on this stakeholder input, several key data categories were identified as necessary for the prototype development. These included land ownership boundaries through both *Imóveis Rurais* (*Terra Legal*) and CAR properties data, providing clear delineation of land limits. Land cover and conservation information was also identified as important, encompassing categories such as forest reserves, permanent conservation areas, and restricted-use zones.

The data collection process also included hydrography data to represent water resources, along with the boundaries of protected areas and military zones. Administrative boundaries at both municipal and state levels were gathered to provide political and administrative context. Road network data, with particular emphasis on the BR-163 highway, was identified as crucial due to its role in agricultural logistics and as a key reference point for local navigation.

Special attention was paid to collecting data about socially and environmentally sensitive zones. This included information about settlement areas and embargoed zones - areas where owners have been penalized by federal authorities (IBAMA) for illegal activities, resulting in restricted market access. This information was identified as crucial for understanding land use limitations and opportunities in the region during the prototype development phase.

During the pilot phase, the application utilized representative but non-final datasets to validate the initial prototype's conceptual framework. The preliminary version focused on integrating climate variables such as rainfall and temperature patterns from ISIMIP 3b (Lange & Büchner, 2021), with crop change projections aligned with existing scientific literature (Müller *et al*, 2019). Recognizing the need for enhanced precision, an expanded prototype is developed after the pilot phase, and will incorporate outputs from the Environmental Policy Integrated Climate (EPIC) model (Williams *et al.*, 1989), with specific crop selections strategically identified through stakeholder consultations.

3.3 Development of the AR Climate Service Application Prototype

Following the initial data collection phase, to address the unique challenges of providing climate services in Novo Progresso, we developed the first prototype of the table top AR mobile application. Using Unity 3D engine as the development platform, the prototype integrated the previously gathered regional data layers relevant to Novo Progresso, with a particular focus on geographical and land use aspects.

Initial development efforts explored a 3D rendering of the area that included elevation and relief data, aiming to provide users with a more complete representation of the landscape (Figure 14). However, this approach was ultimately abandoned in favour of a flat, 2D rendering (Figure 15). This decision was driven by two key factors: the 3D version proved more challenging for users to interpret effectively, and more critically, performance testing indicated that the 3D rendering might not function properly on older smartphone models common in the region.

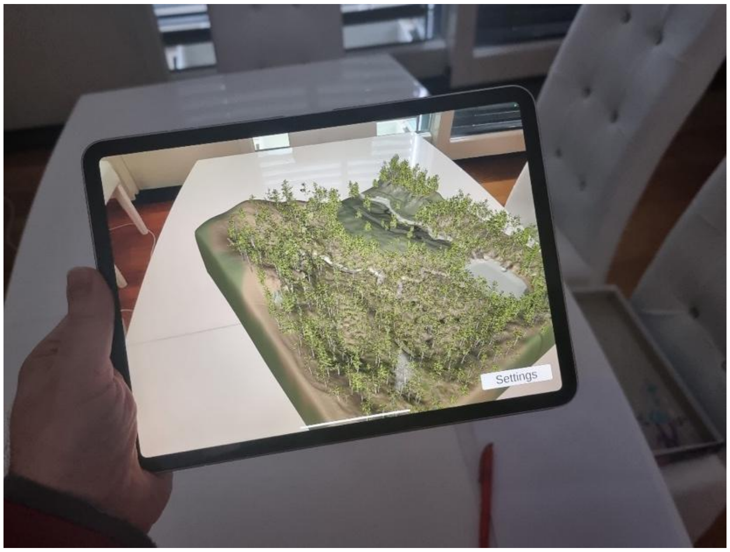


Figure 14: *Original 3D prototype placed on table, using an iPad Pro device.*

The prototype leveraged the platform AR libraries, ARKit for iOS devices and ARCore for Android devices, to implement marker-less AR functionality that enables users to project the application onto any flat surface without requiring physical markers. A key feature incorporated into the prototype was the ability to toggle between AR mode, where the overview is projected onto a table or other flat surface, and a flat mode that displays the information directly on the smartphone screen. This dual-mode functionality was implemented not only for user convenience but also to enable future evaluation of the comparative usefulness of AR versus traditional mobile app interfaces.

The core functionality of the prototype centered on an interactive overview of the Novo Progresso region, visualizing the previously collected data layers. The interface presented clearly delineated land plots showing individual agricultural parcels, administrative borders including municipal boundaries, and important geographical features. To integrate legal and environmental considerations identified during the data collection phase, the prototype also incorporated visualization of exclusion zones such as protected areas, military zones, and "áreas ambargadas." The BR-163 highway, identified during stakeholder engagement as a crucial reference point serving both as a reference point for users and as a key factor in understanding land use patterns in the region, is prominently displayed in the visualization.

User interaction in the prototype was designed around smartphone touch screen controls, with careful consideration given to creating an intuitive and accessible interface suitable for users with varying levels of technical literacy. The prototype implements a simple "touch-to-edit" system where users can select any plot to access an edit interface with dropdown menus for data input.

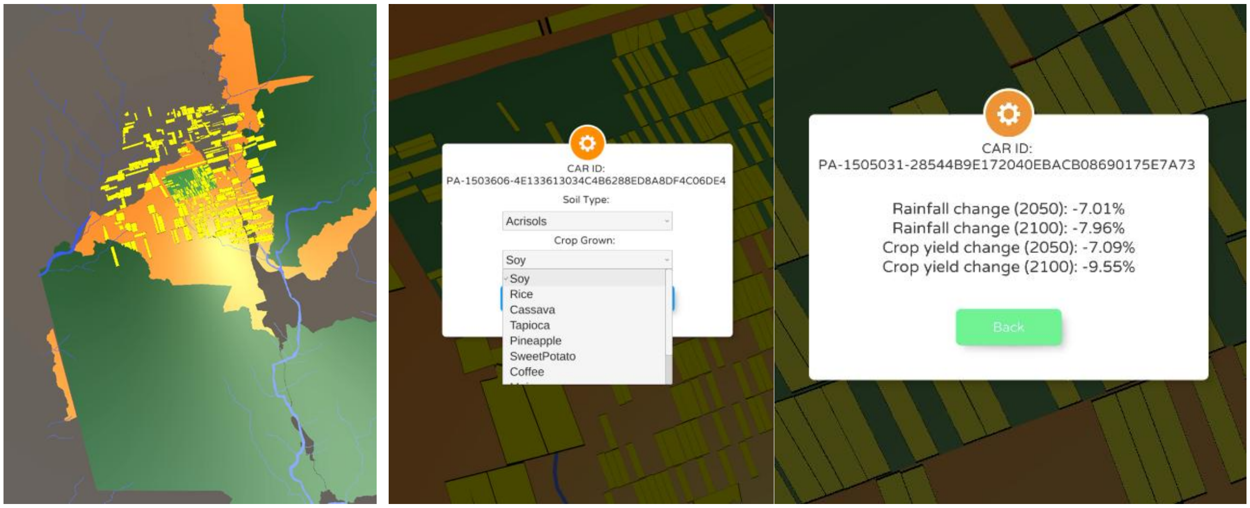
The information collected through this interface is comprehensive, covering key aspects of agricultural practice and land use. Through the edit interface, users can input detailed information about their agricultural practices. This includes specifying current land use through selections such as various crop types and relief. The interface also captures information about soil types, recognizing their crucial role in determining land productivity potential and climate vulnerabilities. Users can further detail their current management practices, including information about the use of irrigation and fertilizers.

This collected information serves as the foundation for the prototype's projection functionality. Using embedded climate model outputs, the application displays localized projections of climate impacts on agricultural productivity specific to each plot. These projections help farmers visualize how climate change might affect their current agricultural practices. The prototype also includes a scenario-testing feature, allowing users to experiment with different agricultural strategies. By modifying inputs such as crop selection or management practices, users can explore projected outcomes under various climate scenarios, providing a practical tool for exploring potential adaptation strategies.

The development of these data input and projection features was guided by the consultations with local stakeholders, ensuring that both the categories and options presented are directly relevant to the agricultural context of Novo Progresso. Throughout the prototype development, we maintained a careful balance between collecting comprehensive data and maintaining an intuitive, user-friendly interface that would not overwhelm users.

A key feature of the application is its ability to function fully offline, addressing the challenge of unreliable internet connectivity in rural Brazil. To achieve this, all necessary data, including baseline climate information and projection models, are embedded within the application. This design choice ensures that farmers can access critical information even in areas with no internet connection.

Updates to the underlying data and models are managed through periodic application updates, which users can download when they have internet access. In workshop settings, the application utilizes inter-device connectivity to allow data exchange between users without requiring internet access.



CAR ID:
PA-1503606-4E133613034C4B6288ED8A8DF4C06DE4
Soil Type: Acrisols
Crop Grown: Soy

CAR ID:
PA-1505031-28544B9E172040EBACB08690175E7A73

Rainfall change (2050): -7.01%
Rainfall change (2100): -7.96%
Crop yield change (2050): -7.09%
Crop yield change (2100): -9.55%

Figure 15: *Second Prototype of the AR climate service. Screenshots are translated to English, protype used Brazilian Portuguese*

3.5 Stakeholder Engagement and Usability Testing

Following the initial development phase, the prototype underwent a structured evaluation process to assess its utility and identify areas for improvement through a series of detailed feedback sessions with stakeholders in Novo Progresso's agricultural sector.

Four local experts were selected for these consultation sessions, representing different aspects of agricultural governance and support in the region:

- the Municipal Secretary of Agriculture, who provides oversight of local agricultural policy;
- the President of the Rural Producers Union, representing the interests and perspectives of local farmers;
- a local congressman (*vereador*), offering insights into the broader political and development context;
- the EMATER Pará representative in Novo Progresso, bringing expertise in agricultural extension services and rural development.

Each expert participated in an individual feedback session, where they were first introduced to the application and its features, then given time to interact with the prototype. The sessions were designed to allow experts to explore the application's functionality in a way that reflected how end-users would interact with it. All participants provided their prior informed consent before the sessions for their feedback to be used in the further development of the application.

These sessions were structured to gather feedback on multiple aspects of the prototype, including its technical functionality, user interface design, the relevance of the information provided and its potential utility for local farmers. The experts were encouraged to provide both immediate feedback during their interaction with the prototype and more detailed reflections through semi-structured interviews following the hands-on session.

This expert consultation phase was crucial in validating the design choices made during development and identifying necessary refinements before wider deployment to the farming community. The insights gathered from these sessions directly informed subsequent iterations of the application, ensuring its alignment with local needs and practices.

3.6 Data Analysis

The observational data and interview responses were analysed using a thematic analysis approach. Key themes were identified related to the application's usability, the relevance of the information provided, and potential improvements. These findings were used to refine the application and inform future development directions.

This methodology allowed us to develop and evaluate an AR-based climate service that is tailored to the specific needs and constraints of small-scale farmers in Novo Progresso. By combining mobile technologies with a participatory design process, we aimed to create a tool that can effectively support agricultural decision-making in the face of climate change.

4. Results

The evaluation of the AR-based climate service prototype through expert consultation sessions yielded valuable insights into both its potential utility and areas requiring enhancement. The feedback from key stakeholders - including representatives from the Municipal Secretary of Agriculture, the Rural Producers Union, local government, and EMATER Pará - provided a comprehensive assessment of the prototype's functionality and its potential role in supporting agricultural decision-making in Novo Progresso.

4.1 Initial Reception and General Assessment

The prototype garnered significant interest from all consulted experts, who recognized its potential value for local agricultural planning and climate adaptation. The AR functionality and offline capability were particularly well-received, with experts noting these features' relevance to the local context. The basic visualization of land plots and geographic features was confirmed as accurate and useful, validating our initial data collection and integration approach.

4.2 Identified Areas for Enhancement

The expert feedback revealed several crucial areas for improvement, each reflecting different aspects of agricultural practice and planning in Novo Progresso.

A key recommendation was the incorporation of "áreas consolidadas" (consolidated areas) into the visualization. These areas, representing the productive regions within land plots, were identified as crucial for understanding current agricultural land use patterns. Experts emphasized that this information would provide a more accurate picture of agricultural potential and constraints within each plot.

The lack of local weather monitoring infrastructure emerged as a significant concern, leading to a recommendation for incorporating a pluviometric index. Experts suggested utilizing data from surrounding weather stations to provide real-time weather forecasting capabilities. This addition was seen as particularly valuable for agricultural planning and risk management, given the region's dependence on rainfall patterns for agricultural success.

Soil fertility emerged as another critical data gap in the current prototype. Experts emphasized that soil fertility information is fundamental for informed decision-making about both crop selection and livestock management. This feedback highlighted the need to integrate soil quality data into the application's agricultural advisory capabilities.

A notable suggestion was the expansion of the application's scope to include cross-sectoral agricultural information. Experts identified several important agricultural activities in the region that could benefit from integration into the tool, including apiculture, pisciculture, pork production, livestock rearing, and fruit production - particularly cacao and açaí cultivation. They also pointed to existing databases from organizations such as IBGE, the State Secretary of Agriculture, and SICAR as potential data sources for this expansion.

The expert consultations provided important clarification regarding the significance of "áreas embargadas" (embargoed areas) in the region. These areas, resulting from legal infractions such as unauthorized logging or burning, carry significant economic implications for landowners. The experts explained that the presence of embargoed areas on a property restricts the landowner's ability to participate in commercial markets, effectively limiting their economic opportunities. This insight emphasized the importance of clearly displaying such regulatory information within the application.

Throughout the feedback sessions, experts consistently emphasized the importance of integrating local agricultural knowledge and practices into the application. Their suggestions reflected a deep understanding of the region's agricultural dynamics and the specific challenges faced by local producers. This feedback underscored the value of our expert consultation approach in ensuring the tool's relevance and utility for its intended users.

5. Discussion

The development and evaluation of an AR-based climate service application for Novo Progresso represent a step forward in providing localized, accessible climate information to small-scale rural producers in the Amazon region. The results of this study highlight both the potential of AR technology in agricultural decision-making and the specific needs of farmers in this complex socio-ecological context.

5.1 Planned Improvements Based on Expert Feedback

The expert consultations provided a clear direction for enhancing the prototype's functionality and relevance. Based on the feedback, several key improvements were identified for implementation in future iterations of the application.

A primary enhancement planned was the inclusion of consolidated area mapping. This update would enable the application to clearly present areas designated for production within individual plots, providing users with a more accurate representation of agricultural land use potential. This addition would help users better understand the productive capacity of their land while ensuring compliance with local regulations.

To address the critical need for weather information, the application would be enhanced to incorporate data from nearby weather stations. While acknowledging the current limitations in data availability and quality from these stations, the plan included developing a synthesized real-time pluviometric index. This feature would aggregate available data to provide users with the best possible precipitation information for agricultural planning, even with existing data deficiencies.

The addition of a soil fertility module was identified as another crucial improvement. This enhancement would integrate soil quality data from available governmental resources, allowing users to better understand their land's agricultural potential and limitations. This information would be particularly valuable for making informed decisions about crop selection and management practices.

A more comprehensive data integration feature was also planned, introducing the ability to cross-reference different types of agricultural data. This overlay system would enable users to visualize combined information across various agricultural sectors, providing a more holistic view for decision-making. Such integration would be particularly valuable for diversified agricultural operations and community-level planning.

These planned improvements were specifically designed to enhance the tool's practical utility for Novo Progresso's rural community, addressing the gaps identified through expert consultations while building on the prototype's existing strengths. The improvements reflect a commitment to developing a tool that not only provides climate information but also integrates seamlessly with local agricultural practices and decision-making processes.

5.2 Innovating Climate Services for the Amazon

This AR application helps fill a critical gap in climate services for the Amazon region. Prior research and the expert consultations confirmed that while numerous climate services exist globally, few target specific needs of small-scale farmers in frontier regions like Novo Progresso. The positive reception by diverse stakeholders underscores the demand for tailored, localized information in this area. The application's ability to provide plot-specific projections and scenario testing capabilities offers a level of detail and interactivity previously unavailable to many farmers in the region.

The use of AR technology in this context proved to be more than just a novelty. While the initial 3D rendering was abandoned in favour of a more accessible 2D representation, the ability to project a visual representation of the landscape onto a flat surface facilitated a more intuitive understanding of spatial relationships and land use patterns. This feature could be particularly valuable in community-level discussions and planning sessions, allowing multiple stakeholders to literally gather around a shared vision of their landscape and its potential futures.

5.3 Bridging the Digital Divide

One of the most significant advantages of this application is its ability to function offline. In a region where internet connectivity is often unreliable, this feature ensures that critical climate information remains accessible to farmers regardless of their location or connectivity status. This approach could serve as a model for developing digital tools for other rural or remote areas facing similar infrastructure challenges.

The toggle feature between AR and flat modes also demonstrates a thoughtful approach to technology adoption. By allowing users to choose their preferred interface, the application caters to varying levels of technological comfort and different use contexts. This flexibility could be crucial in ensuring widespread adoption and sustained use of the tool.

5.4 Customization and Local Relevance

The expert feedback highlighting the need for additional features - including the pluviometric index, soil fertility data, and cross-sectoral agricultural information - reflects the diverse and evolving agricultural practices in Novo Progresso. This input underscores the importance of continuous engagement with local stakeholders in the development of climate services. The requested additions also point to critical data gaps that need to be addressed to support informed decision-making in the region.

The interest in incorporating "áreas consolidadas" into the application, as emphasized by the expert consultations, highlights the complex regulatory environment in which these rural producers operate. By integrating this information, the tool could not only support agricultural decision-making but also aid in compliance with environmental regulations, potentially contributing to more sustainable land use practices.

5.5 Potential Impacts on Land Use and Forest Management

One promising potential feature of such an application is its ability to support more efficient and sustainable use of existing agricultural lands. This aligns with our field observations that rural producers have a strong connection to their land and desire to maintain its productivity for future generations. By providing producers with tools to optimize their current plots based on climate projections and incorporating the planned soil fertility module, the application could potentially reduce the pressure to clear new land for agriculture. This could contribute to slowing deforestation rates in the region, addressing one of the most pressing environmental concerns in the Amazon.

However, it is important to consider potential unintended consequences. The expert feedback regarding "áreas embargadas" highlighted the complex relationship between regulatory compliance and economic opportunity in the region. If the application leads to increased agricultural productivity, it could potentially make farming more profitable, which might inadvertently incentivize further agricultural expansion. This risk is particularly significant if the tool becomes an asset for large-scale commercial agricultural operations rather than serving its intended purpose of supporting small-scale rural producers.

To mitigate this risk, it is crucial that future development of the application remains firmly focused on meeting specific needs of small-scale producers. This includes maintaining features and interfaces that are most relevant to smaller operations, such as diverse crop management and sustainable practices, rather than optimizing for large-scale monoculture production. The planned cross-referencing of agricultural data should be designed to support diversified small-scale farming rather than commercial-scale operations. This targeted approach is essential to ensure the tool serves its intended purpose of supporting sustainable local agriculture rather than potentially contributing to larger-scale agricultural expansion and associated deforestation.

5.6 Ethical Considerations and Limitations

While the prototype shows great promise, several ethical considerations warrant attention. Data privacy and security should be prioritized, especially given the sensitive nature of land use information in a region with a history of land conflicts. The offline functionality of the application helps address some security concerns by keeping data local, but additional safeguards may be needed as more data sources are integrated.

Care must be taken to ensure that the tool doesn't exacerbate existing inequalities by disproportionately benefiting producers who are already more technologically adept or have access to better resources. Our observations of varying technological literacy levels among rural producers emphasize the importance of maintaining a simple, intuitive interface even as new features are added.

The reliance on user-inputted data, while necessary given the data scarcity in the region, presents limitations. The accuracy of the projections and agricultural advice provided by the application depends on the accuracy of user inputs. Future iterations of the tool, particularly the integration of weather station data and soil fertility information from governmental sources, will help address some of these limitations. The application may also benefit from the integration of remote sensing data or other external data sources to validate and complement user inputs.

5.7 Scaling and Integration

The positive reception of this AR application in Novo Progresso suggests potential for scaling to neighbouring regions facing similar challenges. However, our detailed understanding of the local context, gained through field observations and expert consultations, indicates that such expansion would require careful adaptation to local contexts, including different crops, soil types, and socio-economic conditions.

Integration with existing agricultural extension services and climate adaptation programmes could significantly enhance the impact of this tool. The involvement of EMATER and the Municipal Secretary of Agriculture in the evaluation process provides a foundation for such integration. The application could serve as a valuable complement to traditional extension services, providing a visual and interactive platform for discussing climate adaptation strategies.

5.8 Future Research Directions

This study opens up several avenues for future research. Long-term studies on the impact of the application on agricultural practices, productivity, and land use changes would be valuable. The planned improvements, particularly the integration of cross-sectoral agricultural data, will provide rich opportunities for studying how farmers use comprehensive information in their decision-making processes. Additionally, exploring ways to incorporate more data sources, including real-time weather data and satellite imagery, could enhance the tool's accuracy and utility. The challenges identified during expert consultations, such as the limitations of current weather monitoring infrastructure, point to specific areas where technological innovation could make significant contributions.

This AR-based climate service application developed for Novo Progresso demonstrates the potential of innovative technologies to address complex environmental and agricultural challenges. By providing localized, accessible, and interactive climate information, while responding to specific local needs identified through expert consultation, this tool has the potential to empower small-scale farmers in their decision-making and contribute to more sustainable land use practices in this critical region of the Amazon.

6. Conclusion

This study set out to evaluate the feasibility and utility of an AR climate service for small-scale agricultural producers in Novo Progresso, Pará, in the Brazilian Amazon. Through field observations, stakeholder engagement, and expert consultations, our research demonstrates that such a service is not only technically feasible but also responds to genuine needs within the local agricultural community.

The development process, from initial field observations to prototype testing, revealed key insights about the relationship between rural producers and climate information. While many producers initially expressed scepticism about climate change, their detailed observations of shifting weather patterns and concern for long-term land productivity indicated a clear need for tools to support climate adaptation. This understanding shaped the development of an application that bridges the gap between local agricultural knowledge and climate projections.

The successful implementation of the AR-based mobile application proves that it is possible to create a functional, offline-capable climate service tool that leverages AR technology in a rural, developing context. The decision to move from 3D to 2D visualization, prioritizing accessibility and performance on available devices, exemplifies the importance of adapting technological solutions to local contexts. The application's offline functionality directly addresses the infrastructure challenges identified during field observations.

The expert consultation process involving key stakeholders provided crucial validation of the approach while identifying specific improvements needed to enhance the tool's utility. Stakeholders' feedback, particularly regarding the integration of consolidated areas, pluviometric data, and soil fertility information, outlines a clear pathway for developing the application into a comprehensive agricultural decision-making tool. The utility of the AR climate service is evidenced by the enthusiastic response from users and their engagement with the application's features.

Importantly, the study highlighted the need to carefully target the application's development toward supporting small-scale producers rather than large-scale commercial agriculture. This focus is crucial for ensuring the tool contributes to sustainable agricultural practices rather than potentially incentivizing further deforestation through agricultural expansion.

While challenges remain, particularly in terms of data integration and the need to maintain simplicity while adding functionality, this study provides strong evidence that AR-based climate services can effectively support agricultural decision-making in frontier regions like Novo Progresso. The planned improvements, based on expert feedback, will further enhance the tool's utility while maintaining its accessibility for small-scale producers.

This research not only validates the concept of AR climate services for agriculture in the Amazon region but also demonstrates the importance of grounding technological solutions in local realities and needs. As climate change continues to pose significant challenges to agricultural communities worldwide, tools like the prototype from this study, developed with careful attention to local context and user needs, could play a crucial role in supporting sustainable agriculture and climate resilience in vulnerable regions.

Funding

This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy—EXC 2037 ’CLICCS—Climate, Climatic Change, and Society’—Project Number: 390683824, contribution to the Center for Earth System Research and Sustainability (CEN) of Universität Hamburg.

References

Aragao, T. (2021). *O "Dia do Fogo" nunca acabou na Amazônia*. ISA - Instituto Socioambiental. Retrieved October 26, 2024, from https://site-antigo.socioambiental.org/pt-br/noticias-socioambientais/o-dia-do-fogo-nunca-acabou-na-amazonia

Araujo, P. T. M., & Melo, A. S. S. A. (2008). Instituições Ambientais E Desmatamento Na Amazônia Legal Brasileira: Uma Análise Exploratória Em Nível De Município. *46th Congress, July 20-23, 2008, Rio Branco, Acre, Brazil*, Article 113384. https://ideas.repec.org//p/ags/sbrfsr/113384.html

Brondizio, E. S., & Moran, E. F. (2008). Human dimensions of climate change: The vulnerability of small farmers in the Amazon. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1498), 1803–1809. https://doi.org/10.1098/rstb.2007.0025

Bandeira Castelo, T., Adami, M., & Nascimento Dos Santos, R. B. (2020). Fronteira Agrícola e a política de priorização dos municípios no combate ao desmatamento no estado do Pará, Amazônia. *Estudos Sociedade e Agricultura*, *28*(2), 434. https://doi.org/10.36920/esa-v28n2-8

Carvalho, W. D., Mustin, K., Hilário, R. R., Vasconcelos, I. M., Eilers, V., & Fearnside, P. M. (2019). Deforestation control in the Brazilian Amazon: A conservation struggle being lost as agreements and regulations are subverted and bypassed. Perspectives in Ecology and Conservation, 17(3), 122–130. https://doi.org/10.1016/j.pecon.2019.06.002

Castellanos, E., M.F. Lemos, L. Astigarraga, N. Chacón, N. Cuvi, C. Huggel, L. Miranda, M. Moncassim Vale, J.P. Ometto, P.L. Peri, J.C. Postigo, L. Ramajo, L. Roco, and M. Rusticucci, 2022: Central and South America. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the

Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1689–1816, doi:10.1017/9781009325844.014.

Coelho, A. dos S., Dos Santos, L. F. M., Barros, M. N. R., Gomes, A. R., Adami, M., Marcuartú, B. C., Santos, L. B., & Damasceno, J. R. P. (2019). Usos da terra e dinâmicas territoriais na Faixa de Fronteira da Amazônia Legal: Uma análise comparativa. *Revista Brasileira de Desenvolvimento Regional*, *6*(3), 67. https://doi.org/10.7867/2317-5443.2018v6n3p67-92

Deutsch, S., & Fletcher, R. (2022). The 'Bolsonaro bridge': Violence, visibility, and the 2019 Amazon fires. *Environmental Science & Policy*, *132*, 60–68. https://doi.org/10.1016/j.envsci.2022.02.012

Fearnside, P. M. (2008). The Roles and Movements of Actors in the Deforestation of Brazilian Amazonia. Ecology and Society, 13(1). https://www.jstor.org/stable/26267941

Ferrante, L., & Fearnside, P. M. (2019). Brazil’s new president and ‘ruralists’ threaten Amazonia’s environment, traditional peoples and the global climate. *Environmental Conservation*, *46*(4), 261–263. https://doi.org/10.1017/S0376892919000213

Gatti, L. V., Basso, L. S., Miller, J. B., Gloor, M., Gatti Domingues, L., Cassol, H. L. G., Tejada, G., Aragão, L. E. O. C., Nobre, C., Peters, W., Marani, L., Arai, E., Sanches, A. H., Corrêa, S. M., Anderson, L., Von Randow, C., Correia, C. S. C., Crispim, S. P., & Neves, R. A. L. (2021). Amazonia as a carbon source linked to deforestation and climate change. Nature, 595(7867), 388–393. https://doi.org/10.1038/s41586-021-03629-6

Guégan, J.-F., de Thoisy, B., Gomez-Gallego, M., & Jactel, H. (2023). World forests, global change, and emerging pests and pathogens. *Current Opinion in Environmental Sustainability*, *61*, 101266. https://doi.org/10.1016/j.cosust.2023.101266

IBGE. (2023). *IBGE: Cidades e Estados*. Instituto Brasileiro de Geografia e Estatística. https://www.ibge.gov.br/cidades-e-estados/pa/novo-progresso.html

IBGE. (2024). Acesso à internet e à televisão e posse de telefone móvel celular para uso pessoal 2023 / IBGE, Coordenação de Pesquisas por Amostra de Domicílios. ISBN: 9788524046223 https://biblioteca.ibge.gov.br/index.php/biblioteca-catalogo?view=detalhes&id=2102107

IPCC (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Lange, S., & Büchner, M. (2021): ISIMIP3b bias-adjusted atmospheric climate input data (v1.1). ISIMIP Repository. https://doi.org/10.48364/ISIMIP.842396.1

Lovejoy, T. E., & Nobre, C. (2019). Amazon tipping point: Last chance for action. Science Advances, 5(12), eaba2949. https://doi.org/10.1126/sciadv.aba2949

Marengo, J. A., Souza, C. M., Thonicke, K., Burton, C., Halladay, K., Betts, R. A., Alves, L. M., & Soares, W. R. (2018). Changes in Climate and Land Use Over the Amazon Region: Current and Future Variability and Trends. Frontiers in Earth Science, 6. https://doi.org/10.3389/feart.2018.00228

Milman, O. (2022). *The Insect Crisis: The Fall of the Tiny Empires That Run the World* (First Edition). W. W. Norton & Company.

Müller, C., Elliott, J., Kelly, D., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., Folberth, C., Hoek, S., Izaurralde, R. C., Jones, C. D., Khabarov, N., Lawrence, P., Liu, W., Olin, S., Pugh, T. A. M., Reddy, A., Rosenzweig, C., Ruane, A. C., … Yang, H. (2019). The Global Gridded Crop Model Intercomparison phase 1 simulation dataset. *Scientific Data*, *6*(1), 50. https://doi.org/10.1038/s41597-019-0023-8

Novo Progresso. (2023). *Historia: Novo Progresso*. Prefeitura Municipal de Novo Progresso | Gestão 2021-2024. https://novoprogresso.pa.gov.br/o-municipio/historia/

PRODES. (2023). *TerraBrasilis project, accumulated deforestation*. http://terrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/legal_amazon/increments

Rodrigues, J. C., & Nahum, J. S. (2023). The concession of the BR-163 highway in the Brazilian Amazon: Corporatization of territory and conflicts. *DIE ERDE – Journal of the Geographical Society of Berlin*. https://doi.org/10.12854/erde-2022-624

Torres, M., Doblas, J., & Alarcon, D. F. (2017). *Dono é quem desmata: Conexões entre grilagem e desmatamento no sudoeste paraense*. Accessed on Nov 15 2024 at https://site-antigo.socioambiental.org/sites/blog.socioambiental.org/files/nsa/arquivos/dono_e_quem_desmata_conexoes_entre_gril1.pdf

Sauer, S. (2018). Soy expansion into the agricultural frontiers of the Brazilian Amazon: The agribusiness economy and its social and environmental conflicts. Land Use Policy, 79, 326–338. https://doi.org/10.1016/j.landusepol.2018.08.030

SEMAS, n.d. CAR data. Accessed on the 10 April 2022 at http://car.semas.pa.gov.br//consulta/mapa

Vale, M. M., Berenguer, E., Argollo de Menezes, M., Viveiros de Castro, E. B., Pugliese de Siqueira, L., & Portela, R. de C. Q. (2021). The COVID-19 pandemic as an opportunity to weaken environmental protection in Brazil. *Biological Conservation*, *255*, 108994. https://doi.org/10.1016/j.biocon.2021.108994

Williams, J. R., Jones, C. A., Kiniry, J. R., & Spanel, D. A. (1989). *The EPIC Crop Growth Model*. https://doi.org/10.13031/2013.31032

Yanai, A. M., Nogueira, E. M., de Alencastro Graça, P. M. L., & Fearnside, P. M. (2017). Deforestation and Carbon Stock Loss in Brazil's Amazonian Settlements. Environmental Management, 59(3), 393–409. https://doi.org/10.1007/s00267-016-0783-2

Chapter 5

Conclusions, Limitations and Future Research

Conclusions

This dissertation offers an initial exploration of Augmented Reality for delivering climate services across diverse contexts, stakeholder groups, and data environments. Through two case studies, my research provides strong empirical evidence for AR's potential to bridge the gap between complex climate science and practical decision-making at multiple scales. The results indicate that AR is a viable and versatile medium.

The first case study established both the technical validity and user acceptance of in-situ AR applications for climate services. The proposed novel measurement methodology achieved high accuracy in tree measurements, with R^2 values of 0.99 for diameter at breast height and 0.99 for tree height measurements, resulting in carbon sequestration estimates that deviated less than 11% from conventional methods. This technical validation was complemented by strong user acceptance, evidenced by a System Usability Scale score of 86.4 with 92% of users reporting increased understanding of carbon sequestration concepts. These results demonstrate that AR-based application can not only collect reliable environmental data but also effectively communicate complex environmental concepts to non-expert users.

The second case study, conducted in the Novo Progresso, Para, in the Brazilian Amazon, validated AR's applicability in a fundamentally different context - both in terms of geographic setting and user requirements. This research showed that AR climate services can be effectively adapted for users with varying levels of technological familiarity, through the successful implementation of a table-top AR visualization for agricultural planning in a developing region. The positive reception among rural producers suggests that AR can transcend technological and educational barriers when appropriately designed for its target audience. Additionally, it showed an approach to handle data gaps, through two-way knowledge exchange with stakeholders right in the application.

Together, these case studies demonstrate AR's flexibility as a medium for climate services across several key dimensions. The research shows AR's effectiveness both for collecting new environmental data through device sensors, as demonstrated in the tree measurement application, and for visualizing existing data in meaningful ways, as shown in the agricultural planning tool. The successful adaptation of AR applications to serve diverse user groups, from urban citizens to rural producers with varying levels of technical expertise and different decision-making needs, demonstrates the medium's versatility across user contexts. The effectiveness of both in-situ AR for real-time environmental measurements and table-top AR for planning and visualization further illustrates the adaptability of AR as an implementation approach. Moreover, AR climate services proved capable of functioning effectively both in data-rich environments where they can collect precise measurements and in data-poor environments where they facilitate user input and visualization, showing the medium's flexibility across different data environments.

This research represents a significant step forward in understanding how AR can serve as a medium for climate services. The consistent success across different applications, contexts, and user groups suggests that AR is not merely a technological novelty but a robust platform for delivering climate information and supporting climate-related decision-making. The high levels of user acceptance and demonstrated ability to increase understanding of complex climate concepts indicate that AR can play a valuable role in democratizing access to climate information and supporting evidence-based decision-making across different sectors of society.

Addressing the Research Questions

This dissertation explored six fundamental research questions about the potential of Augmented Reality as a medium for climate services. These questions investigated AR's viability across different dimensions: as a general medium for climate services, as a data collection tool, as an interface for complex climate models, as a public engagement platform, as a decision support system for domain experts, and as a solution for data-scarce environments in developing regions. The findings for each research question, detailed below, collectively build a comprehensive understanding of AR's capabilities and limitations in climate service delivery. They demonstrate how different approaches to AR implementation can address various challenges in climate service provision while serving diverse user groups and contexts.

RQ1: To what extent can Augmented Reality serve as a viable medium for climate services?

Research Question 1 investigated the viability of Augmented Reality as a medium for climate services. The findings strongly support AR's potential as a viable medium, as demonstrated through two distinct and successful implementations. The first case study, focused on urban tree carbon sequestration measurement, showed that AR can effectively support in-situ data collection and real-time analysis, enabling immediate feedback to users through the device's sensors and on-device processing. The second case study, implementing agricultural planning tools in the Brazilian Amazon, demonstrated the ability to combine local knowledge through user inputs with complex agricultural and climate model, turning the outputs into accessible visualization of projections to support decision-making on adaptation strategies with table-top interactions. These fundamentally different applications - one collecting environmental data through device sensors and providing immediate analysis, the other integrating user expertise with EPIC model outputs - demonstrate AR's flexibility as a medium for climate services. The successful implementation across such different use cases, user groups, and technological approaches provides strong evidence that AR can serve as a viable medium for climate service delivery. Particularly noteworthy is AR's ability to adapt to different usage contexts while maintaining high levels of user engagement and understanding, suggesting that AR's potential as a climate service medium extends beyond any single application type or user group.

RQ2: Can Augmented Reality technologies reliably collect environmental data for use in climate services?

Research Question 2 examined whether AR technologies could reliably collect environmental data for use in climate services. The findings from the tree measurement case study provided strong empirical evidence for AR's capacity to collect accurate environmental measurements. The novel AR-based measurement methodology achieved exceptional accuracy when compared to conventional forestry tools, with correlation coefficients (R^2) of 0.99 for diameter at breast height (DBH) and 0.99 for tree height measurements. These measurements translated into robust carbon dioxide sequestration estimates that aligned well with those performed using conventional methods ($R^2 = 0.99$). The study also identified important boundary conditions for reliable data collection, including limitations with very small trees, multi-trunk structures, and certain environmental conditions. However, these limitations were well-defined and could be clearly communicated to users, ensuring appropriate application of the technology. Importantly, the methodology proved robust enough to function effectively even without specialized hardware like LiDAR sensors, demonstrating the potential for widespread deployment. These results confirm that AR technologies can indeed collect environmental data with sufficient accuracy for climate service applications, while offering significant advantages in terms of speed, accessibility, and ease of use compared to traditional measurement methods.

RQ3: Can complex climate model outputs be effectively translated into interactive AR visualizations?

Research Question 3 investigated whether complex climate model outputs could be effectively translated into interactive AR visualizations. The agricultural planning case study in the Brazilian Amazon provided compelling evidence for this possibility. The study successfully transformed complex EPIC model outputs into accessible AR visualizations that enabled rural producers to explore potential climate impacts on their specific agricultural plots. The application effectively simplified multifaceted climate projections into interactive, table-top visualizations that allowed users to explore different adaptation strategies and their potential outcomes. Users could input data about their specific plots and receive visualizations of climate impacts under various scenarios, demonstrating that AR can successfully bridge the gap between complex climate modeling and practical decision-making needs. The high level of user engagement and understanding reported in the study suggests that AR's visual and interactive nature provides an effective medium for making complex climate model outputs accessible to non-expert users. Particularly noteworthy was the application's ability to maintain scientific validity while presenting information in a format that supported practical decision-making, showing that complexity reduction through AR visualization does not necessarily compromise the utility of climate model outputs.

RQ4: Can AR climate services effectively engage and inform the general public?

Research Question 4 explored whether AR climate services could effectively engage and inform the general public. The tree carbon sequestration application provided strong evidence for AR's effectiveness in public engagement with climate information. The high System Usability Scale score of 86.4 achieved in the second iteration of testing demonstrates that members of the general public could effectively interact with the AR interface despite having no prior experience with similar tools (only 31% of users reported using AR applications before). More significantly, 92% of users reported an increased understanding of carbon sequestration concepts after using the application, indicating AR's potential as an educational medium for complex environmental concepts. The success in translating abstract concepts like carbon sequestration into tangible, interactive experiences that users could relate to their immediate environment demonstrates AR's capacity to make climate science more accessible and meaningful to non-expert users. The application's ability to maintain user engagement while providing scientifically accurate information suggests that AR can effectively bridge the gap between scientific accuracy and public accessibility. This is particularly noteworthy given the challenge of communicating complex environmental concepts to general audiences, indicating that AR could serve as a valuable tool for broader climate science communication and public engagement.

RQ5: Can AR climate services support decision-making for domain experts in non-climate fields?

Research Question 5 explored whether AR climate services could support decision-making for domain experts working outside the climate field. The Brazilian Amazon case study provided strong evidence for this possibility through its successful engagement with rural producers - experts in agriculture but not in climate science. The study demonstrated that AR could effectively bridge the gap between agricultural expertise and climate knowledge by allowing producers to apply their local agricultural knowledge while exploring climate impacts and adaptation strategies. The application's success in combining users' deep understanding of their agricultural context with climate projections showed that AR can serve as an effective interface between domain expertise and climate science. Particularly noteworthy was how the table-top AR visualization enabled producers to explore different adaptation strategies in the context of their specific agricultural conditions, demonstrating that AR can successfully support complex decision-making processes by integrating domain expertise with climate information. The positive reception among rural producers indicates that AR can effectively serve as a decision support tool even for stakeholders who, while experts in their field, may have limited experience with climate science or digital technologies.

RQ6: Can effective AR climate services be implemented in lesser developed countries and data-scarce environments?

Research Question 6 examined whether effective AR climate services could be implemented in lesser developed countries and data-scarce environments. The Brazilian Amazon case study provided compelling evidence for this possibility, demonstrating successful implementation in a region facing both data scarcity and infrastructure limitations. Despite the absence of local weather stations, limited availability of high-resolution climate data and lack of information on the agricultural production of individual rural producers, the study showed that AR applications could effectively combine available regional data with user inputs to provide a meaningful climate service. The application's offline functionality addressed the challenge of unreliable internet connectivity in rural areas, while its implementation on widely-available smartphones, rather than requiring specialized equipment or personal computers, demonstrated AR applications' accessibility in developing regions. Particularly significant was the application's ability to integrate local knowledge with available climate data, showing how AR can help bridge data gaps through user participation and two-way knowledge exchange. The study's success in engaging rural producers in climate adaptation planning, despite these constraints, indicates that AR climate services can be effectively adapted to function in resource-limited settings without compromising their utility as decision support tools. These findings suggest that AR's flexibility as a medium makes it particularly suitable for developing regions where traditional climate services might be limited by data or infrastructure constraints.

Limitations

While this research demonstrates the viability of AR as a medium for climate services, several important limitations should be acknowledged. These limitations span technical constraints, methodological considerations, and challenges in impact assessment.

Impact of the COVID-19 Pandemic

The COVID-19 pandemic significantly impacted this research, necessitating substantial methodological adaptations and creating various operational challenges. The original research design emphasized extensive stakeholder engagement through in-person fieldwork, which was considered crucial given the novel nature of AR technology and the importance of building trust with stakeholders, particularly in developing regions.

The pandemic's impact manifested in several critical ways. First, the inability to conduct initial stakeholder consultations prior to prototype development meant that early design decisions could not benefit from direct user input about specific needs, priority adaptation strategies, and local sociocultural contexts. This limitation was particularly significant for AR applications, where user context and local requirements are crucial for effective implementation. The research methodology had to be substantially revised, requiring more iterations of development and testing to compensate for the lack of initial stakeholder insight.

Second, the research faced cascading delays due to its dependence on data from other CLICCS C2 projects, which were themselves impacted by pandemic-related fieldwork restrictions. The first usable dataset only became available in April 2022, significantly later than planned, and some anticipated data never materialized as connected projects modified their scope in response to pandemic constraints. This delayed start and reduced data availability necessitated a more focused approach on fewer case studies than initially planned.

Alternative methodologies were explored, including the possibility of simulating study sites using Virtual Reality and testing AR applications within those virtual environments. However, these alternatives were ultimately rejected as they would have compromised the research's core objective of developing locally relevant tools informed by community knowledge. The absence of real stakeholder input and actual field conditions would have severely limited the validity and applicability of the findings.

The pandemic also forced modifications to the testing and evaluation processes. For the first case study, the original plan for in-person workshops and interviews had to be replaced with detailed usage guides and online surveys. While this approach successfully gathered valuable feedback, it potentially limited the depth of user interaction and observation possible in face-to-face settings. The second case study faced additional challenges beyond the pandemic. While initial pilot testing was conducted in Brazil in mid-2022, subsequent political instability following presidential elections disrupted established institutional contacts, forcing the rescheduling and eventual cancellation of planned field visits. The loss of key contacts in the Ministry of Agriculture and EMATER due to political changes required building new relationships, further complicating the research process.

These pandemic-related limitations and adaptations should be considered when interpreting the research findings. While the modified methodology still produced valuable results, the reduced opportunity for direct stakeholder engagement in the early stages of development may have impacted the initial design choices and necessitated more iterations than might otherwise have been required.

Technical Limitations

AR, as a rather novel field, relies on many still developing technologies and as such can still pose limitations. For example, the tree measurement methodology, while highly accurate for most scenarios, faces certain constraints in specific situations. The application shows reduced accuracy when measuring very small trees and does not support the measurement of trees with multi-trunk structures. Additionally, while the methodology was validated on trees common in Western urban environments, its applicability to tropical species or trees with significantly different morphological characteristics remains untested. This limitation in validation could affect the methodology's global applicability, but could be addressed through machine vision training. While the applications were designed to function without requiring specialized hardware (for example, providing fallback options for devices without depth sensors, such as a LiDAR) and to operate in various lighting conditions, optimal performance still depends on adequate lighting for camera functionality. This could potentially limit usage during certain times of day or weather conditions. This is an inherent issue of handheld AR at the current state of technology.

Data and Infrastructure Constraints

To provide high quality visualizations, many kinds of data are required, which may not necessarily be available, and infrastructural issues may mean that the data cannot be obtained even at a theoretical level. In the Brazilian Amazon case study, while smartphone availability proved not to be a barrier (with widespread device ownership among rural producers), the lack of local weather stations and reliable climate data presented challenges for providing highly localized climate projections. Additionally, information on the environmental properties of fields and agricultural practices of individual rural producers was not available either. This was overcome with a two-way knowledge exchange approach in the case study, but in many cases this may not be possible. This highlights how AR applications, despite their technological sophistication, remain dependent on the quality and availability of underlying data resources.

Methodological Limitations

The first case study faces limitations related to participant sampling. The self-selection of participants could have resulted in samples biased toward individuals with greater interest in environmental issues or higher technological aptitude. Furthermore, the relatively small sample sizes in both studies, while sufficient for initial validation, may limit the generalizability of the findings to broader populations.

Another limitation of this research caused by its duration is the inability to assess long-term impacts of AR climate services on user behaviour and decision-making. While both applications demonstrated user interest and immediate positive effects on user understanding (with 92% of users reporting increased comprehension in the tree measurement study), the translation of this enhanced understanding into sustained behavioural change or modified decision-making practices remains unknown. This limitation is particularly relevant given the applications' aims of supporting climate action and environmental decision-making.

Cross-Cultural Considerations

Although the research spans two different geographical and cultural contexts, the applications' design and testing primarily occurred within specific cultural frameworks. The assumptions about user interaction, information presentation, and decision-making processes may not translate equally well across all cultural contexts, potentially limiting the global applicability of the findings.

These limitations, while significant, do not diminish the overall findings regarding AR's potential as a medium for climate services. Rather, they provide important context for interpreting the results and highlight areas requiring attention in future research and development of AR climate services. The case studies should be seen as pilot studies demonstrating the potential of AR as a medium in this field, rather than as complete climate service products.

Future Research

This dissertation opens several promising avenues for future research in AR-based climate services, spanning technological developments, application contexts, and impact assessment methodologies.

Future research should explore the application of AR climate services across further environmental contexts and challenges. While this research demonstrated success in urban tree measurement and agricultural planning, with promising initial results from the Brazil case study, other environmental measurements and climate service applications could benefit from AR implementation. The Brazil study particularly highlights the potential for deeper integration with advanced crop modeling data, such as EPIC model projections, and the importance of iterative development based on stakeholder feedback. In addition to the expansion of the Brazil study, the already planned scaling to Harburg, Germany, can provide valuable insights into the adaptation requirements for different agricultural contexts, suggesting both opportunities and challenges in expanding AR climate services across diverse farming systems. Additionally, investigation of other extended reality technologies could provide valuable comparisons and insights into the most effective approaches for different use cases. The demonstrated success of both in-situ and table-top AR approaches suggests that various AR visualization and interaction methods deserve exploration in climate service contexts.

While AR glasses and advanced wearables represent exciting future possibilities, near-term research should focus on maximizing the potential of smartphone-based handheld AR, given its widespread availability and established user base. Particular attention should be paid to leveraging improved sensor capabilities in smartphones as they become available. The expanding availability of LiDAR sensors in mobile devices and increases in their range could enable more accurate environmental measurements, more sophisticated data collection and more advanced environment-based visualizations. Research should investigate how these advancing capabilities can enhance both the accuracy of measurements and the engagement of visualizations while maintaining accessibility for non-expert users.

The success of AR climate services in both developed urban and developing rural contexts suggests significant potential for expansion to other regions and cultural contexts. Future research should systematically evaluate the adaptation requirements and effectiveness of AR climate services across different geographical and cultural settings. For the tree measurement methodology specifically, this would include adapting and validating the machine vision system for tropical and other tree species, ensuring reliability across diverse forest ecosystems.

Building on the tree measurement capabilities, it is planned to expand TreeCarbonAR's functionality to incorporate predictive carbon sequestration modeling. By integrating climate risk maps and various management scenarios, the application could enable users to visualize future carbon sequestration potential under different climate scenarios. This enhancement would transform the tool from a current-state measurement system into a dynamic decision-support tool for forest management and climate adaptation planning. Research should investigate effective methods for visualizing these complex temporal projections while maintaining user engagement and comprehension.

Given AR's demonstrated effectiveness with non-expert users, future research should explore its potential to democratize access to climate information and environmental decision-making tools. This could include investigating how AR can bridge knowledge gaps and empower local communities in various environmental management contexts. Research should examine how AR can be optimized to serve users with different levels of technical literacy while maintaining scientific accuracy and usefulness.

A critical area for future research is developing robust methodologies for assessing the long-term impacts of AR climate services on user decision-making and behaviour change. This could involve longitudinal studies tracking how exposure to AR climate services influences environmental awareness, decision-making processes, and concrete actions over time. Research might explore combinations of quantitative metrics and qualitative assessments to capture both measurable outcomes and deeper insights into how AR tools influence user perspectives and choices.

Future research should investigate how AR climate services can be effectively integrated with existing environmental monitoring and decision-support systems. This includes exploring potential synergies between AR applications and traditional climate services, as well as examining how AR can complement and enhance existing environmental management practices.

Continuing technical research should focus on improving measurement accuracy across different conditions, developing more sophisticated data visualization approaches, and enhancing the user interface based on accumulated user feedback. This includes developing more robust methods for handling varied lighting conditions and complex environmental scenarios.

These research directions would contribute to establishing AR as a mainstream medium for climate services while expanding its accessibility and effectiveness across different contexts and user groups.