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Development of mobile application for tree height measurement using geometric principle: Establishing global database of tree height and data

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ABSTRACT

Accurate measurement of tree height is essential for ecological research, forest management, and carbon sequestration assessments. Traditional tools such as clinometers often face limitations due to terrain complexity, tree species variability, and operator dependency, while advanced technologies like LiDAR and UAVs, though precise, remain costly and less accessible. In this study, we developed a photographic tree height measurement method and integrated it into an Android application, referred to as M-Tree. The app allows users to capture tree images and calculate height using pixel-based markers, with the results synced to a global database containing tree height and associated data. To validate accuracy, M-Tree's measurements were compared to those obtained using a Suunto clinometer across 85 samples of trees and non-tree objects. Validation through Pearson correlation and Bland-Altman analyses demonstrated strong agreement, with root mean squared errors (RMSE) of 0.187 m for the clinometer and 0.192 m for M-Tree, alongside near-perfect correlations of 0.996 and 0.998, respectively. These results confirmed the M-Tree's effectiveness for tree height estimation, with a potential of broadening the geographic scope and accessibility of tree measurement data.

1. Introduction

Accurate measurement of tree height and diameter at breast height (DBH) is essential for understanding forest structure, estimating biomass using allometric equations [50] and assessing carbon sequestration potential, all of which are critical for ecological research and forest management [7,11,39,46]. Traditionally, tree measurements have relied on trigonometric and geometric principles using tools like clinometers and rangefinders [23,29]. However, their accuracy is often influenced by factors such as tree species, terrain slope, and the experience of the observer which can lead to significant over or underestimation, especially for tall or multi-layered tree stands [37]. As a result, there is increasing interest in developing more innovative and accessible approaches to measuring tree height that ensure accuracy and scalability across different environments.

Recent technological advancements have transformed the way tree

measurements are collected. LiDAR (Light Detection and Ranging), UAVs (Unmanned Aerial Vehicles), and terrestrial laser scanning have revolutionized tree height, canopy structure, and biomass measurement, providing highly accurate 3D structural data across multiple scales [10, 41,49]. LiDAR, in particular, has enabled researchers to generate detailed models of tree height and above-ground biomass, covering both individual trees and entire landscapes [35]. UAV-based LiDAR and photogrammetry have further increased accessibility, allowing monitoring of remote and difficult-to-reach forest areas [28]. Additionally, satellite technologies like NASA's Global Ecosystem Dynamics Investigation (GEDI) provide canopy height data at global scale. However, despite the precision and scale of these methods, they are often expensive, technically demanding, and may lack the granularity needed for individual tree measurements, particularly for isolated trees or trees in non-forested areas.

To address these limitations, smartphone applications equipped with

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advanced sensors, GPS, and image processing algorithms have emerged as cost-effective alternatives for measuring tree height and other key metrics. They offer a practical and accessible solution for researchers, foresters, and citizen scientists, enabling them to collect tree data with reasonable accuracy in a wide variety of environments [24]. The use of mobile phones in forest management has garnered significant attention in recent years confirming their roles in streamlining various operations, such as tree height measurement, species identification, and tree positioning [2,18,38].

In this study, we developed a photographic approach for measuring tree height using geometry incorporated into an Android-based mobile application, referred to as M-Tree. This app will allow researchers, forestry professionals, and even casual users to measure tree height efficiently without the need for any expensive or complex equipment (See [9,29]). Tree height and DBH are vital for constructing allometric equations to estimate biomass and carbon storage [1,16,27,33]. Despite the critical nature of these parameters, a publicly accessible global database of tree height and DBH of individual tree measurements remains limited especially for developing countries. While regional efforts like Aussenac et al. [3] focus on European data, a global-scale database could significantly advance ecological research and forest management. To fill this gap, we proposed a global database that would provide tree height and DBH measurements from various parts of the world using the M-Tree app. In this paper, we present the methodology behind the photographic approach and the M-Tree app, validated the accuracy of its measurements compared to clinometer, and discuss the potential of the proposed global database as a foundational resource for advancing forest research.

2. Methodology

The principle of the tree height measurement in the M-Tree app is geometry, modeled after the Christen height meter [14]. The similarity of triangles is a fundamental geometric concept stating that two triangles are similar if their corresponding angles are congruent and their corresponding sides are proportional (Birkhof & Beatley, 2024). In this research, the methodology leverages this principle to estimate tree heights using the following geometric relationships:

1. The tree and its shadow or projection form a larger triangle, and a reference marker and its corresponding projection form a smaller triangle.
2. Since both triangles share the same perspective and maintain consistent angles due to the camera's alignment, they are similar by the Angle-Angle (AA) criterion of triangle similarity (see Fig. 1).

2.1. Technical Details of the application

In the model (Fig. 1), tree height (H) is derived through the relationship of corresponding sides of similar triangles such that $\triangle ABD$ is

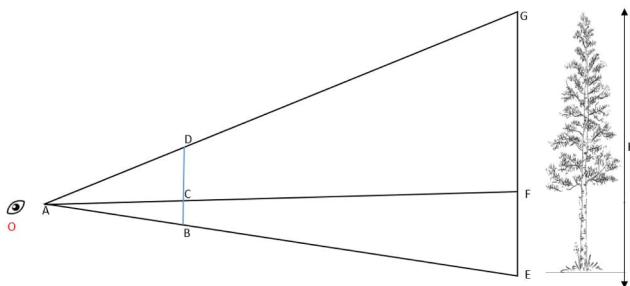


Fig. 1. The principle of similar triangle on which tree height estimation in this paper is based.

similar to $\triangle AEG$; $\triangle ABC$ is similar to $\triangle AEF$ and $\triangle ACD$ is similar to $\triangle AFG$. Therefore (Fig. 2):

$$\frac{CB}{DB} = \frac{FE}{GE} \tag{1}$$

To solve for GE, which represents the total height of the tree (H), Eq. (1) is rearranged to:

$$CB \times GE = DB \times FE \tag{2}$$

Thus:

$$GE = \frac{DB \times FE}{CB} \tag{3}$$

In practical terms, if the length DB is replaced with a known reference point (e.g., a ruler) and FE is set as a fixed height (typically breast height, 1.3 m), then GE, the total height of the tree, can be calculated using Eq. (3). In the app, line DB is represented by a virtual centimeter scale (see Fig. 3). A default value of 1.3 m is automatically set in the app as the reference height for FE, eliminating the need for users to manually input it during calculations.

2.2. The M-Tree application layout

The M-Tree app runs on Android devices (version 4.0 or higher) and operates offline. The landing page provides two options for measuring tree height: (1) importing a tree photo from the phone gallery or (2) capturing a live measurement using the phone's camera. The app allows users to add project details (project title, sampling methodology, user name, email address of the project leader, institution, country, tree species and tree DBH) and automatically logs the location, date, and the calculated tree height. Users can export data in Excel format, and all data is uploaded to a global database for public access. In the measurement interface, a centimeter scale with two movable pointers is displayed to mark reference points on the tree image. The app captures pixel distances between the reference and top of the tree using these pointers, which are dynamically adjustable by the user (see Fig. 3 for detailed illustration).

2.3. Tree height calculation

The tree height is computed by the app using the "getHeight" method. After importing the tree image, the app identifies two parameters: firstValue and secondValue, representing pixel distances between a reference point on the tree stem and top of the tree. Users interact with draggable markers (markerBase for the reference, and markerTip for the top). These positions are dynamically updated using onTouchListener events. The app then divides firstValue by secondValue to compute a scaling ratio that accounts for perspective distortion. This ratio is multiplied by a constant reference value of 1.3 m (breast height),

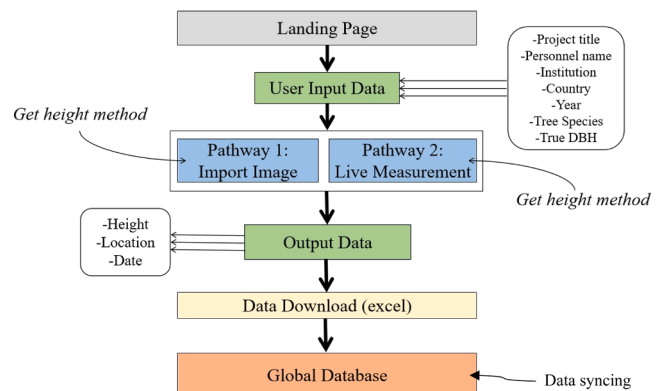


Fig. 2. The M-Tree application layout.

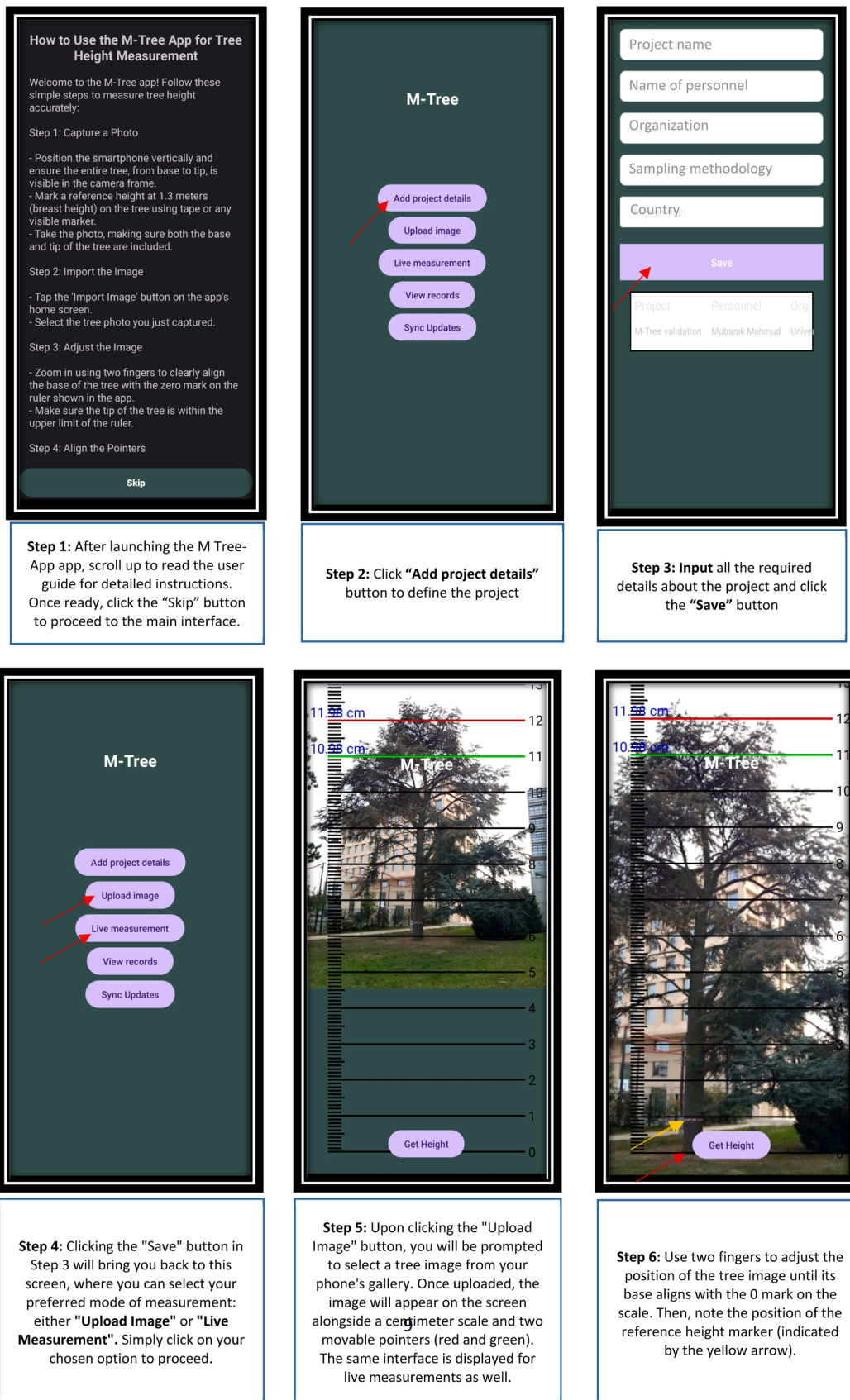
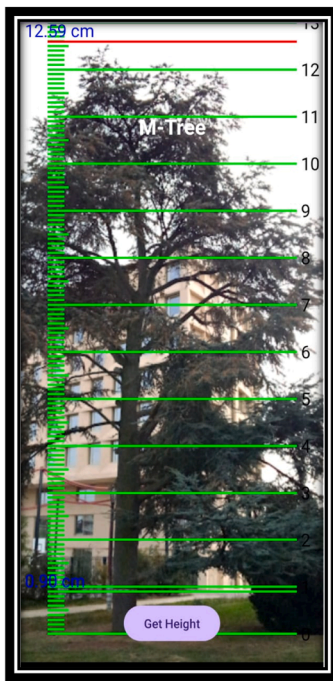
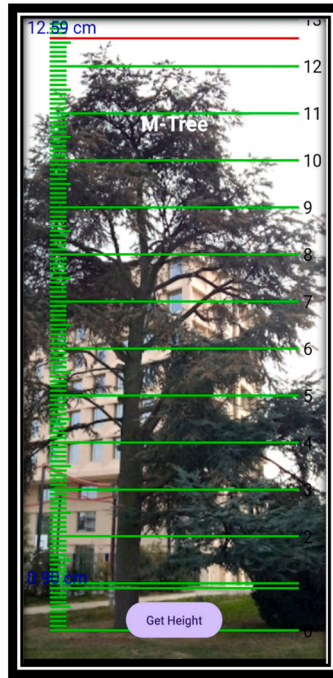


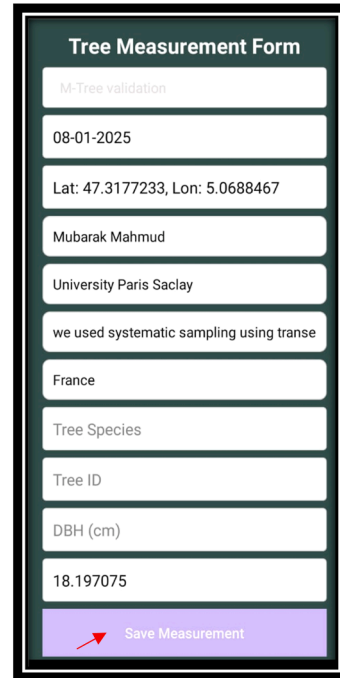
Fig. 3. Screenshot of the M-Tree app interfaces describing the tree height measurement steps.



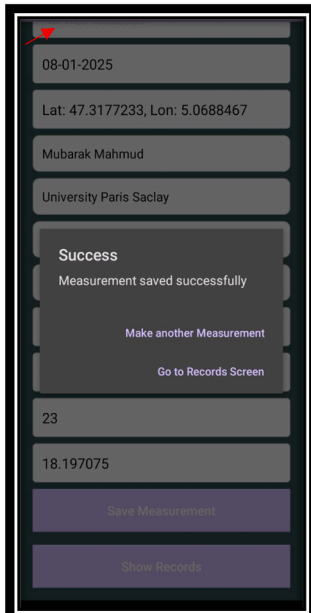
Step 7: Move one of the movable pointers using a single finger to align it with the reference height marker (green arrow). Adjust the other pointer to align with the highest point of the tree (red arrow).



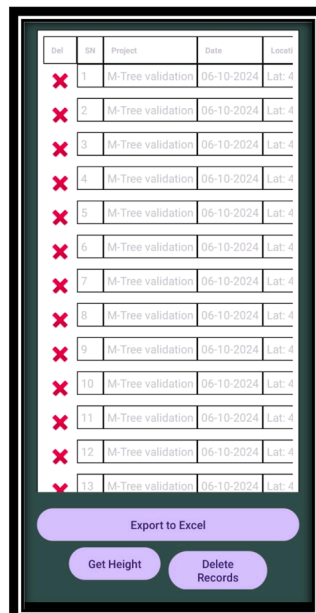
Step 8: Click the “Get Height” button to obtain the tree height in meters



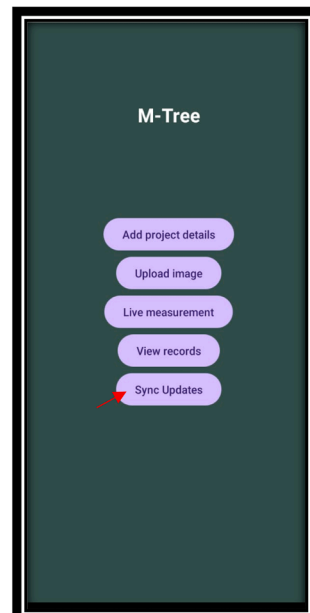
Step 9: Enter the required details about the tree (species, ID, and DBH (Diameter at Breast Height)), then click the “Save Measurement” button to record the data.



Step 10: You can record additional measurements by clicking the “Make Another Measurement” button. Note that each new measurement will use the same project details entered in Step 2 unless a new project is created. To select a saved project from multiple options, click the field indicated by the red arrow.



Step 11: This is the record screen, accessible by clicking the “Go to Records Screen” button in 10. Export measurements to an Excel spreadsheet with “Export to Excel” button. Delete individual records using the red X mark or delete all records at once using the “Delete Records” button. To take a new measurement, click “Get Height”



Step 12: To sync updates after taking measurements or if the measurements were conducted offline, click the “Sync Updates” button. Some project details (title, country and email address of the project lead) might appear on specific site for potential data requests.

Fig. 3. (continued).

yielding the tree’s estimated height. The calculated height, along with other data, is then displayed in the app and passed to subsequent modules using an Intent for further processing or export.

2.4. The M-Tree accuracy validation

To assess the accuracy of the M-Tree app, a comparative study was conducted using both the app and a Suunto clinometer across a total of 85 samples which included 75 trees and 10 non-tree objects (poles and buildings). The tree samples were selected to represent a diverse range of species and environmental conditions (isolated trees, mixed forest stands, flat terrains, hilly landscapes as well as poles and buildings of known height).

Systematic sampling was employed for tree samples selection in two locations: France (30 trees) and Nigeria (45 trees). Transects of 500 m were established, and along each transect, every 5th tree encountered was selected for measurement. For each tree, height measurements were taken independently using both the M-Tree app and the Suunto clinometer. The 10 non-tree objects included in the study, had their heights measured directly using a tape measure (in France). These objects served as control points to benchmark the app’s precision against direct measurement methods.

2.5. Steps for measuring tree height using M-Tree app

Tree height measurements were captured using smartphones (Infinix Hot-5 and Xiaomi Mi 10-Lite), using the procedure as follows. A fixed reference height of 1.3 m (breast height) was marked on each tree or object using cordon tape or masking paper to establish a reference point. Photos were then taken from a sufficient distance to ensure the entire tree, from base to tip, and the reference height were visible within the frame. Precise distance measurements were not required, as the app only needed the tree and reference point to be in view. The smartphone was held vertically to minimize perspective distortion, ensuring that the tree’s base and tip were aligned within the frame, while the camera sensor was carefully aligned parallel to the tree stem to avoid measurement bias. Where the tree base was obscured, a marker was placed to ensure its clear identification in the image.

To initiate the measurement process in the M-Tree app, a new project was created by clicking the ‘Add Project Details’ button on the landing page (Fig. 3). Initial details which are project name, personnel name, organization, sampling methodology, and country, were added. These

details were only entered once per project. After the project setup, the captured image was imported into the app via the “Import Image” button. The image was then zoomed using a two-finger gesture to ensure that the base of the tree in the photo coincided with the zero mark of the ruler displayed in the app and that the tip of the tree was within the ruler’s upper limit. The user then used one finger to move the first movable pointer to align with the reference height (cordon tape or masking paper) on the tree photo, and a similar one-finger gesture was used to move the second movable pointer to align with the tip of the tree (see Fig. 4 for the alignment procedure). After the alignment, the “Get Height” button was clicked, and the app instantly generated the estimated tree height. Finally, the measurement was saved by clicking the “Save Measurement” button.

2.6. Clinometer measurement procedure

Using the Suunto clinometer available at ESE laboratory of University Paris Saclay, the height of each sample was measured by targeting both the top and base of the tree. The angles of elevation (α for the top, β for the base) were recorded. The horizontal distance (d) from the observer to the tree was measured using a measuring tape [47].

The tree’s height was calculated as:

$$H = (\tan\alpha + \tan\beta) \times d \tag{4}$$

For trees on hilly terrain, the slope distance (s) and slope angle (θ) were measured. The horizontal distance (d) was then computed using:

$$D = s \times \cos(\theta) \tag{5}$$

2.7. Statistical analysis

To evaluate the correlation between the tree height measurements obtained using the M-Tree and the clinometer, Pearson correlation analysis was performed. The Bland-Altman test was used to assess agreement between the two methods. Additionally, the Root Mean Squared Error (RMSE) was calculated to quantify the level of error between the predicted (M-Tree app) and observed (clinometer) tree heights.

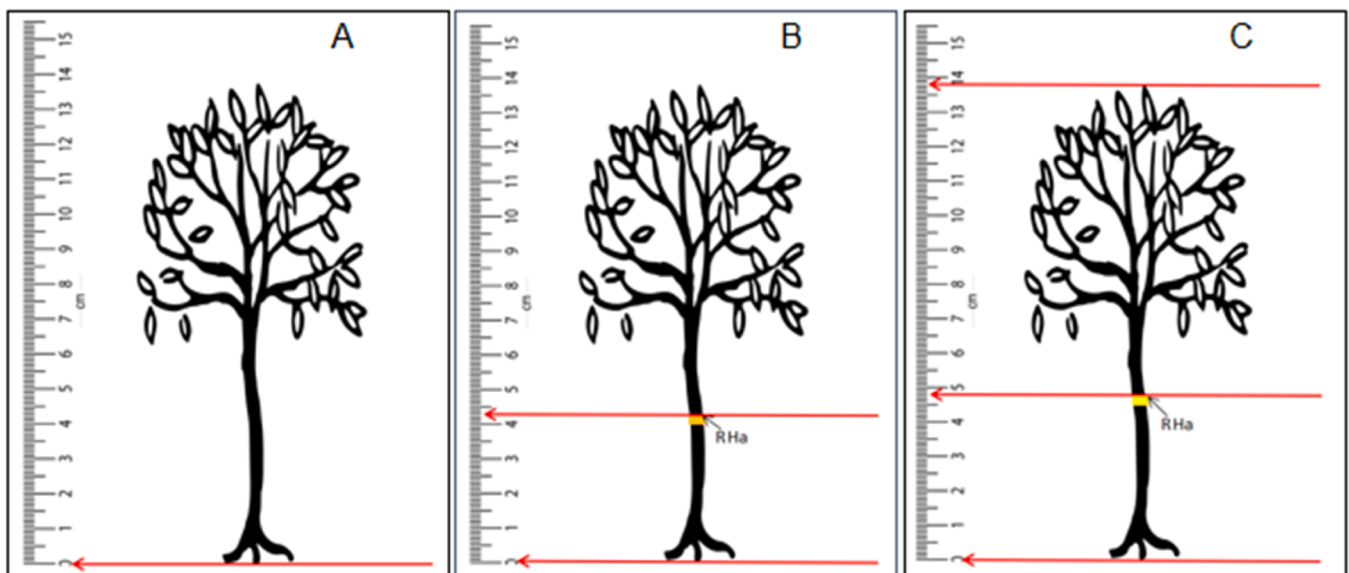


Fig. 4. Alignment procedure showing (A) Aligning the base of the tree, the reference height of the tree (B), and the tip of the tree (C).

3. Results

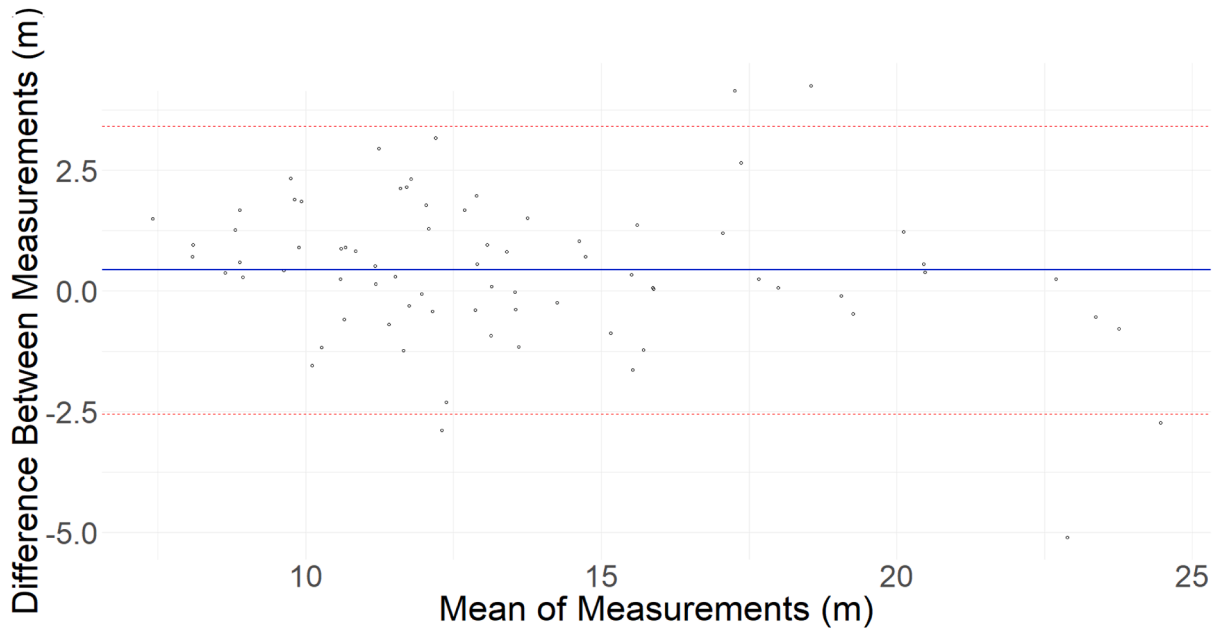
3.1. The M-Tree app and database access

The original version of the M-Tree app can be safely downloaded and installed from this link: <https://drive.google.com/file/d/1aRJb29UNjUzQGMHXpaSgxMeCLCDqAdzB/view?usp=sharing>. The M-Tree app is available on Google Play Store as "M-Tree" and will be getting updated with new features. The M-Tree database can be accessed via m-tress.net

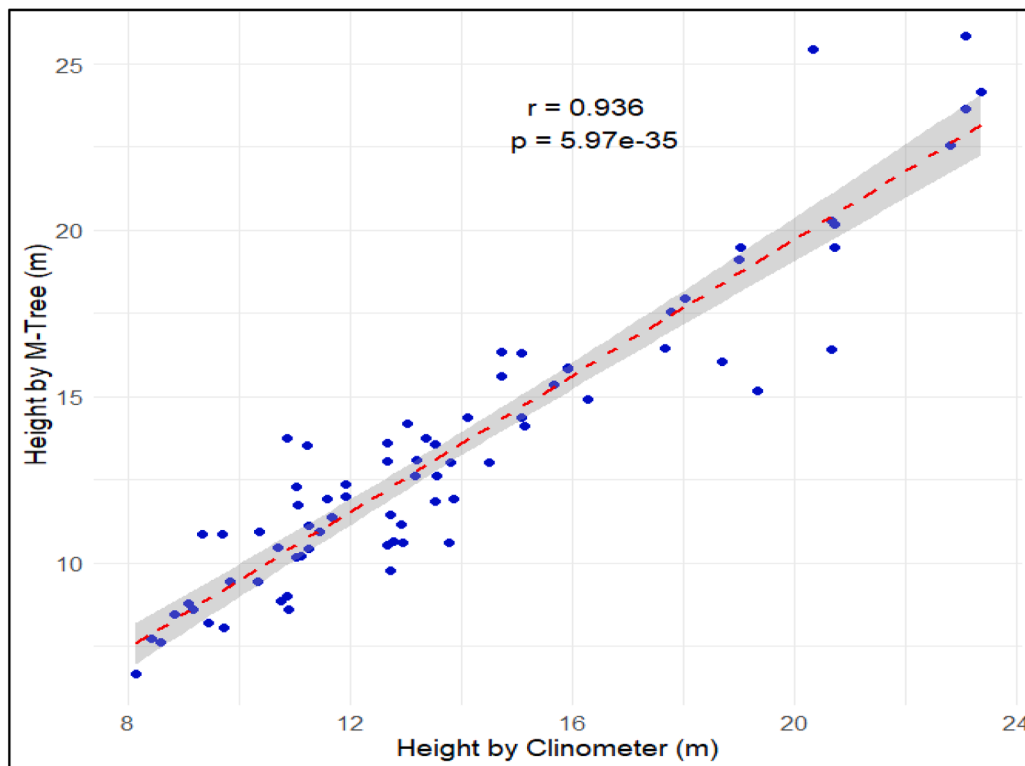
or temporarily via <https://t.ly/AEu99>. The heights of 75 tree samples, along with their corresponding photos (in a hyperlink associated with their respective IDs), are presented in Table Ap (in the Appendix).

3.2. Methods validation

The comparison of height estimation by the clinometer and the M-Tree revealed a general trend of close agreement. While there were instances where the estimates showed variations, the overall pattern



A



B

Fig. 5. A Bland-Altman Plot showing the agreement between Clinometer and M-TREE for tree height measurement (A). Correlation analysis of height measurement by clinometer and by M-TREE methods (B). Number of measurements = 75.

suggested that both methods provided reasonably consistent height estimations. As shown in Fig. 5A, most of the data points clustered around the centerline of the plot, which represented the mean difference between the methods suggesting a systematic agreement, indicating that, on average, they provided fairly similar measurements. The horizontal dashed lines in the Fig. 5A, commonly known as the 'limits of agreement,' were situated at an equal distance above and below the centerline. These lines helped define a range within which the differences between the methods are expected to fall for approximately 95 % of the data. We found that most data points indeed fall within these limits, suggesting reasonable agreement.

At 95 % confidence interval, the results of the Pearson product-moment correlation analysis revealed a strong and highly significant positive correlation between the two method ($r^2 = 0.93$ for tree measurements and $r^2 = 0.996$ and 0.998 for clinometer and M-Tree respectively for non-tree objects with known heights) (Fig. 5B and Table 1). The t-value, which was 72.714, indicated a high level of significance suggesting a strong relationship. The results of error analysis for non-tree object (Table 1) indicated that both the clinometer and M-TREE delivered height estimates that were, for the most part, in close proximity to the actual tree heights (RMSE of 0.187m and 0.192m for clinometer and M-Tree respectively). An RMSE of 1.572m was obtained for 75 trees measured using the clinometer as the reference relative to the M-Tree (see Table Ap in the appendix).

4. Discussion

The strong positive correlation ($r = 0.93$) between the clinometer and M-Tree methods and the r-values of 0.996 and 0.998 for clinometer and M-Tree respectively (Fig. 5C) suggested that both methods were consistent in measuring tree height. However, the RMSE of 1.572 m observed for the 75 measured trees indicated some variability in height estimates that could be attributed to factors such as measurement technique differences, operator-dependent errors (as two different persons conducted the measurements in two different countries), or the M-Tree's algorithmic processing of height data compared to the manual clinometer. As the error analysis for non-tree objects shows close agreement with actual heights (RMSE of 0.187 and 0.192 for clinometer and M-Tree, respectively), we therefore demonstrated the importance of considering both correlation strength and error analysis when assessing the reliability and applicability of two methods in field settings.

4.1. Addressing gaps in existing databases with the M-Tree's data and database

Smartphone applications have been increasingly employed in various ecological and forestry studies, including the measurement of tree heights and showed high accuracy [5,18,24,30,32,34,48]. As demonstrated in our study, the M-Tree app effectively estimates tree

Table 1
Comparison of Non-Tree Objects Height Measurements by Clinometer and M-TREE with Actual Heights. RMSE is the Root Mean Squared Error.

IDs	actual height (m)	height by clinometer (m)	height by M-Tree (m)
1	10	10	9.92
2	5.9	6.15	5.76
3	10	10.01	9.91
4	6	5.94	5.94
5	4	4.00	3.91
6	2.82	2.91	2.94
7	7.61	7.65	7.51
8	7.5	7.49	6.98
9	3.53	3.33	3.60
10	3.1	3.26	3.18
RMSE		0.187	0.192
r^2		0.996	0.998

heights within the accuracy range reported in several other studies that utilized smartphone applications for height measurement (such as [5,18,24]). Traditional clinometers also offer comparable accuracy, typically ranging between 0.10 m and 0.80 m [22,25,47]. In recent years, the collection and availability of global tree measurement data, including tree height and DBH, have improved significantly. Several large-scale databases have been developed. The Global Forest Biodiversity Initiative (GFBI), aggregates data from over 1.2 million forest plots [20,21], and the TRY Plant Trait Database, provides species-specific trait information, including height and DBH for various plants [17]. The Biomass and Allometry Database (BAAD), which focuses on tropical and temperate species [44], and the Global Forest Canopy Height Database, derived from satellite lidar data [40], also offer resources for tree height information. In addition, national and regional efforts such as the Norwegian National Forest Inventory (NFI) and the European Forest Institute (EFI) provide detailed forest inventories that include tree measurements [6,45].

Despite these advancements, many of these existing databases face limitations in geographic coverage, species-level specificity, and measurement consistency [20]. For example, remote sensing-derived datasets, such as NASA's GEDI, provide detailed canopy height data, but lack individual tree-level information such as DBH or species identification [26,31]. Similarly, many national inventories are not globally harmonized, and regional databases like the Tropical Tree Database may lack the coverage needed to study global forest trends [36]. While these databases are instrumental in furthering ecological research, they are often constrained by inconsistent data collection methods, incomplete geographic coverage, and an underrepresentation of certain regions, such as urban areas and developing countries [4,8,15].

In this context, the M-Tree app would enable users to collect precise measurements of tree height, DBH, species, and location, with data information synced to the global database. Researchers would be able to request these data directly from project leaders. This could potentially address several of the limitations seen in existing databases.

Thomas et al. [43] studied the important role of Trees Outside Forests (TOF), particularly in countries with low forest cover, and highlighted the challenges of integrating these critical resources into national forest inventories. Their research illustrated how remote sensing techniques, including Sentinel-1 and Sentinel-2 satellite imagery and TanDEM-X Digital Elevation Models, can be utilized to map TOF extent and estimate canopy height at a national scale. However, the study also revealed limitations in existing data collection methods, especially in terms of spatial resolution and accessibility, which often lead to the underestimation of TOF and their exclusion from comprehensive forest assessments. In this context, M-Tree database can address some of the limitations highlighted by Thomas et al. [43]. Satellite-derived maps offer large-scale data, but they often miss smaller tree stands or isolated trees in urban and rural areas due to resolution constraints. M-Tree's ability to measure individual trees directly fills this gap by providing on-the-ground measurements at a much finer scale which can be used to validate and enhance remote sensing data, thereby improving the accuracy of TOF extent and structure estimates. This will allow for more precise mapping of fragmented tree resources and better assessments of biomass, carbon storage, and ecosystem services provided by TOF.

4.2. Strengths and weaknesses of the M-Tree app

The app offers several advantages. It allows for precise selection of the tip and base positions on trees, addressing a challenge often encountered with clinometers. Furthermore, it enables the storage of tree photos for future reference, facilitating further analysis and assessment, which is not possible with clinometers. M-TREE also provide accurate measurements regardless of the terrain or distance from the tree. With minimal equipment requirements, primarily a smartphone with a camera, it is cost-effective and accessible to a wider range of

users. This aspect holds particular significance in regions such as sub-Saharan Africa, which confront challenges in forestry research and institutional reform due to funding limitations to purchase research equipments [12,13,19,42]. The app has a user-friendly interface, which ensures that both professionals and casual users can navigate the app's features with ease. This is an essential feature, especially for individuals who may not be highly tech-savvy but still need access to the application's resources. Another strength of the application is the potential for offline access. If users can use the app without needing an internet connection, this would greatly enhance its utility, especially for researchers working in remote areas with limited connectivity. Data export and sharing are another asset, allowing users to collect and share information easily.

However, the application also presents some weaknesses. The app is only available on Android, it restricts its accessibility to iOS and desktop users, which could reduce its potential audience. The app might also lack advanced features, such as tools for data analysis, mapping, or integration with other research softwares. Additionally, wide-angle lenses or improper focal lengths may introduce perspective distortion, especially when measuring tall trees. This might affect the proportionality of the triangles.

5. Conclusion

The M-Tree app offers great potential as a practical alternative for tree height estimation, especially for Trees Outside Forests (TOF) and in regions where access to expensive or complex equipment is limited. The app's validation demonstrated strong agreement with Suunto clinometer, with a Pearson correlation coefficient of 0.93 for tree measurements and near-perfect correlations of 0.996 and 0.998 for non-tree objects. The Root Mean Squared Error (RMSE) values of 0.187 m for the clinometer and 0.192 m for the M-Tree further confirmed the app's accuracy. However, the RMSE of 1.572 m for tree measurements suggested some variability, which may be attributed to factors such as operator-dependent errors, measurement techniques, or algorithmic processing. As a result, the M-Tree method may require calibration & refinement in future studies. Additionally, expanding the app's availability to iOS and desktop platforms would increase accessibility and broaden its user base. Also, integrating advanced features such as data analysis, mapping, and compatibility with research tools like GIS software and ecological databases would enhance the app's utility for professional researchers. Further development to include other important metrics such as biomass, carbon stock estimation, and tree volume would transform the app into a more comprehensive tool for forest monitoring and environmental management.

Appendix

Table Ap
Comparison of tree height measurements using Clinometer and M-Tree.

IDs	Height by clinometer (m)	Height by M-Tree (m)
ID1	15.1	16.32
ID2	15.09	14.38
ID3	13.18	12.63
ID4	14.13	14.37
ID5	19.02	19.5
ID6	10.71	10.46
ID7	17.79	17.55
ID8	15.91	15.84
ID9	17.66	16.46
ID10	15.91	15.87
ID11	11.26	10.44
ID12	22.82	22.57

(continued on next page)

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Ethical statement

All authors of this manuscript affirm that the research described herein adheres to the ethical standards outlined in Elsevier's Publishing Ethics Policy. This work has not been previously published elsewhere.

The manuscript is not currently under consideration for publication in any other journal. All authors have reviewed and approved the submission. If the article is accepted, it will not be published elsewhere in any form.

CRedit authorship contribution statement

Mubarak Mahmud: Writing – review & editing, Writing – original draft, Validation, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jianhong Lin:** Writing – review & editing, Project administration, Investigation. **Mojtaba Houballah:** Writing – review & editing, Validation, Supervision. **Ibrahim Garba Buba:** Writing – review & editing, Supervision, Formal analysis, Data curation. **Laure Barthes:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Mubarak Mahmud reports financial support was provided by Climate and Land Convergence Institute (CLAND) and Kano State Government of Nigeria. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table Ap (continued)

IDs	Height by clinometer (m)	Height by M-Tree (m)
ID13	20.73	20.18
ID14	20.67	20.28
ID15	11.67	11.37
ID16	23.1	23.64
ID17	18.02	17.96
ID18	12.67	13.07
ID19	12.93	11.15
ID20	23.36	24.15
ID21	9.69	10.86
ID22	11.6	11.91
ID23	11.04	12.28
ID24	15.14	14.11
ID25	13.81	13
ID26	15.68	15.34
ID27	9.08	8.79
ID28	19.01	19.11
ID29	12.94	10.62
ID30	13.55	12.6
ID31	11.26	11.12
ID32	16.29	14.92
ID33	20.73	19.5
ID34	20.67	16.42
ID35	14.72	16.35
ID36	23.10	25.83
ID37	20.34	25.44
ID38	12.67	10.54
ID39	11.93	12.36
ID40	18.69	16.04
ID41	11.44	10.92
ID42	10.86	13.75
ID43	10.36	10.95
ID44	13.78	10.61
ID45	14.72	15.6
ID46	19.33	15.18
ID47	13.53	11.85
ID48	10.86	9
ID49	11.93	12
ID50	9.34	10.88
ID51	11.12	10.22
ID52	10.91	8.58
ID53	10.76	8.86
ID54	8.44	7.73
ID55	11.04	10.16
ID56	8.16	6.67
ID57	13.53	13.55
ID58	10.34	9.44
ID59	8.58	7.62
ID60	9.84	9.42
ID61	13.88	11.91
ID62	9.73	8.05
ID63	12.78	10.63
ID64	9.44	8.18
ID65	13.19	13.1
ID66	14.51	13
ID67	12.72	9.77
ID68	12.67	13.6
ID69	13.03	14.19
ID70	9.18	8.58
ID71	12.73	11.44
ID72	11.06	11.75
ID73	8.83	8.45
ID74	13.36	13.75
ID75	11.23	13.54
RMSE	1.576	

Data availability

Data will be made available on request.

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