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# New Technologies for Expedited Forest Inventory Using Smartphone Applications

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**Abstract:** The forest inventory plays a crucial role in forest management planning, and it is the first step in planning actions for forest production. However, conducting an inventory can be expensive and complex. Forest inventory applications on smartphones have emerged as an alternative to traditional methods and they aim to make field data collection more accessible to non-professionals while ensuring accuracy in determining the volume of wood in a given area. This study evaluates the effectiveness of the Katam, Arboreal, and Trestima applications compared to traditional data collection methods. The study focuses on assessing the stand density and diameter of sampled trees—two key variables that are assessed in forest inventories. Two species, maritime pine (*Pinus pinaster* Aiton) and *Eucalyptus* spp. (mainly *Eucalyptus globulus* and *Eucalyptus nitens*), were used to evaluate the performance of the methods, with assessments performed in the stands of diverse dendrometric characteristics, specifically those regarding the tree age, stand density, and topographic conditions (flat or sloping terrain). For the purpose of comparison, goodness-of-fit statistics ($R^2$, RMSE, and BIAS) were calculated, and an analysis of the diameter distribution and comparison of the mean diameter, number of trees per hectare, and basal area were performed. In general, the applications were accurate, and the average basal area did not differ significantly from the traditional method. The diameter measurements showed good accuracy. The accuracy of the applications varied depending on the terrain and forest characteristics, with the applications performing better in areas with flat terrain, as well as with older forests that were regular and had low under-cover density. In contrast, the applications performed worse in younger, irregular forests with sloping terrain, high tree density, and those with a great deal of understory vegetation. The applications still need to evolve in evaluating other important variables (such as tree height or volume) as they are currently estimated from auxiliary variables through mathematical equations.

**Keywords:** forest management; dendrometric evaluations; maritime pine; eucalyptus



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## 1. Introduction

For the efficient management of forest areas, all interventions must be preceded by knowledge regarding the qualitative and quantitative characteristics of the forest space. The characterization of the structure of the forests takes place through the forest inventory, which consists of providing information on quantitative aspects (such as the number of trees per area, as well as the volume of wood and biomass), and also qualitative elements (such as tree species, health condition, mortality, and the characteristics of morphology of tree trunks, among others). Collecting data in a forest inventory can be demanding due to economic, logistical, and technical limitations [1].

There are many techniques and equipment that are used in the measurement of dendrometric data, such as the diameter and height of trees; currently, the technology already allows the execution of such tasks with the use of applications on smartphones as an alternative to traditional methods. However, because they are relatively recent technologies, it is necessary to assess their reliability compared to the conventional methods that are already fully mastered by their users.

The reliability check happens whenever new methods appear, and it is not a recent technique. Robbies and Young (1968) [2] compared three instruments for measuring the diameter of trees in the 1960s, and they concluded that the measurements taken by the diametric tape, caliper, and relascope did not differ statistically. Freitas and Wickert (1998) [3] compared the results found when measuring the diameter and height of *Pinus* sp. and *Eucalyptus* sp. from the measurements obtained via the electronic device "Criterion 400", which is usually applied in topography with the results of the measurements of known instruments for the purpose of measuring height (such as the Suunto and the Blume-Leiss) and diameter evaluations (such as the tape measure and the caliper). They concluded that, in addition to the weight of the equipment, the significant differences between the measurements did not qualify the device for forestry use. Clark et al. [4] elaborated a ranking with 15 dendrometers that took into account the indicators of accuracy, measurement speed, price, availability, and restrictions.

With the advent of forest inventory applications, forestry research began to focus on comparing the results between known inventory methods and those that are indicated by such applications. Villasante (2014) [5] compared the measurement of tree heights obtained by the "Smart Tool version 1.5.0" application on two mobile phones (the Samsung Galaxy Note GT N 7000 and the HTC Desire Bravo) with the measurements of two devices that are frequently used in forest inventories (the Vertex IV Haglof and Blume-Leiss BL 8) and concluded that—after correcting the angle used by the application and by calibrating the curve of points indicated by the mobile phones—there was no significant difference in the measurements made by the devices.

Technologies for forest inventory based on software used on smartphones have stood out for being portable, simple, and intuitive, as well as for allowing their use by users without deep technical knowledge regarding the measurement of forests. Three applications (hereafter abbreviated as apps) that are available on the market, with potentials for widespread user adoption due to their ease of use and potential suitability for forest inventory in diverse forest types, are the Trestima, Katam, and Arboreal apps.

The Trestima app, developed by Trestima Oy in Finland, uses sample images taken by a smartphone camera at various points in the forest. These images are sent to the Trestima cloud where they are stored and analyzed to determine variables such as diameter, height, basal area, and the number of trees per hectare. The results are provided to the user in reports in either excel or xml format [6].

The Katam app, which originates from Sweden, is compatible with Android smartphones and provides dendrometric data by analyzing short videos captured within forests using smartphones. Additionally, it can integrate drone-collected images to estimate tree height and can capture video footage within forests. The application identifies trees and utilizes an algorithm to generate a digital model for analyzing specific areas [7].

Arboreal is a Swedish app that only works on IOS devices. With this app, users can select a specific center within a predetermined area and create a digital boundary. The app requires the user to gather images of every tree inside the boundary. The user is prompted by the app to input the height of a specified tree. Once the data are collected, the app processes them and generates a report with all the relevant information [8].

The Trestima app provides information on basal area, number of trees per hectare, volume per hectare, diameter at breast height, and average height. It has been found to produce statistical results comparable to traditional forest inventory methods for basal area in terms of the BIAS and RMSE indicators. In the case of *Pinus* trees, there is a tendency to overestimate the diameter and height at breast variables, but the results do not differ significantly when compared with the traditional method. However, the app tends to underestimate total tree height, and there is a significant difference in this regard when compared to traditional methods.

The results for basal area and tree density from the Trestima app were compared with those from the MOTI app developed by "Haute école des sciences agronomiques, forestières et al.imentaires (HAFL)" [9]. The analysis showed a significant difference in the results, although one that was not too broad. However, the study did not compare the app's performance with traditional methods, so no conclusion can be drawn about its accuracy.

Pitkanen et al. (2022) [10] verified a reduction in the variances of the results and, consequently, an improvement in the accuracy of the outputs of the Trestima application, specifically when data collection in the field was preceded by planning for forest sampling based on previous information such as inventory data and images of the forest. This procedure allowed for creating more homogeneous stands of the forest compared with the results generated by simple random sampling.

The Katam app was tested for accuracy in both production forests and conservation areas in Sweden. These areas are dominated by spruce, beech, and adult oaks ranging from 23 to 130 years old. The app presented satisfactory results in production forests, but struggled in conservation forests with denser undergrowth and less uniform trees. Specifically, the app tended to underestimate the diameter of very thin or very thick trees, and often missed recognizing trees with tortuosity. Additionally, trees with multiple stems tended not to be recognized, and those with two stems were frequently merged into one with a larger diameter [11].

A study conducted in central Italy demonstrated that the measurements of height, as well as the height on the basis of the canopy of urban trees, with the Arboreal app on an iPhone 12 Pro were shown to be strongly related with the measurements that were performed with the Vertex IV device, which was utilized with a reduced cost and training time [12]. Thicker diameters tend to be underestimated by the Arboreal app, and its height measurement accuracy increases with the improved visibility of a tree. The application is accurate when compared to traditional methods and the variation in brightness or visibility, as long as it is above 10 lux, does not affect its accuracy [13].

Inventory applications for smartphones have the potential to revolutionize forest inventory practices and can benefit all those involved in the forestry sector. By reducing costs and increasing efficiency, these apps add significant value. However, their effectiveness depends on providing accurate results that reflect the reality of the studied forest.

This investigation aimed to assess the precision of smartphone applications in evaluating the variable diameter at breast height (DBH). DBH, along with the number of trees per area, is a critical variable in forest inventory. The analysis involved the three different smartphone applications available on the market earlier mentioned: Arboreal, Katam, and Trestima. These apps allow for the direct measurement of DBH through image analysis. The evaluation did not focus on the tree height variable because this is a variable whose value is obtained indirectly with these apps, either by using equations based on diameter/basal area or is complemented with other technology. To evaluate the effectiveness of the apps, we compared the results obtained from these apps with those derived from traditional forest inventory methods. The working hypotheses were as follows: (i) there will be no significant difference in the precision of DBH measurements between the three smartphone applications; (ii) the measurements obtained from the smartphone applications will show a high level of consistency with the results derived from traditional forest inventory methods. These hypotheses guided the study and helped to evaluate the effectiveness of the smartphone applications in assessing the DBH. They also aided with considering the applications' accuracy, their consistency with traditional methods, and the potential differences between them.

The assessment was made in Portugal, on forests of maritime pine (*Pinus pinaster*) and eucalyptus (*Eucalyptus* sp.), two of the most represented species in the country, under the replant project. Table 1 summarizes the characteristics of the three applications.

**Table 1.** Summary of the Arboreal, Trestima, and Katam application characteristics.

| App | Operating System | Data Collection Methodology | Diameter Determination | Height Determination | Interface with Other Technologies | Outputs | Accuracy Reported by the Company |
|---|---|---|---|---|---|---|---|
| **Arboreal** | iOS | Individual tree image capture | Trunk recognition algorithm | Measurement of total height with the app on a representative tree identified by the app | Possibility of using Lidar on smartphones with this technology | - Diameter distribution<br>- Average diameter<br>- Average height<br>- Basal area per hectare<br>- Volume per hectare<br>- Number of trees per hectare | - Number of trees/ha— 2%;<br>- Average diameter—3%;<br>- Individual diameter— 7.5%; Height—2%;<br>- Basal Area—7%. (RMSE) (www.arboreal.se—accessed on 24 March 2023) |
| **Trestima** | Android | Capture multiple still images (Photography) | Trunk recognition algorithm | Estimation by a height–diameter model | Planning on the web platform | - Diameter distribution<br>- Average diameter<br>- Average height<br>- Basal area per hectare<br>- Volume per hectare<br>- Number of trees per hectare | Basal area standard error less than 5% (www.trestima.com—accessed on 24 March 2023) |
| **Katam** | Android | Dynamic image capture (Video) | Trunk recognition algorithm | Estimation by a height–diameter model | Possibility of collecting diameters and heights with unmanned aerial vehicle (drone) and processing data on the WEB | - Diameter distribution<br>- Average diameter<br>- Average height<br>- Basal area per hectare<br>- Volume per hectare<br>- Number of trees per hectare | Not indicated |

## 2. Materials and Methods

### 2.1. Study Area

This research was conducted in the northern part of Portugal. According to Koeppen, the region has a predominantly rainy winter, as well as a dry and slightly hot summer (Csb) climate [14]. Their study covered eight counties and included forests of maritime pine and eucalyptus, as is depicted in Figure 1.

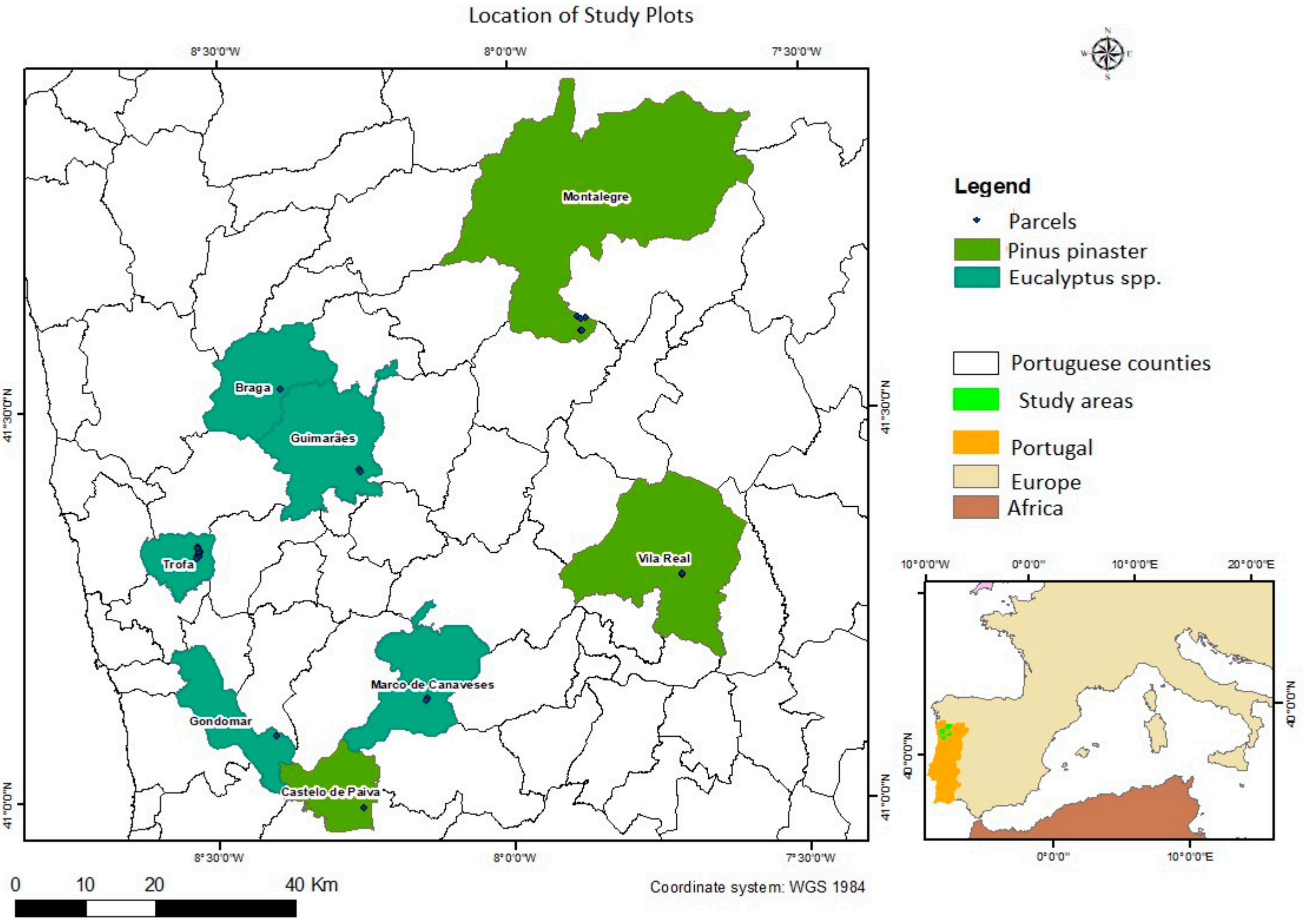


**Figure 1.** Map indicating the study sites in the northern region of Portugal.

In the study areas, 12 different types of forests were identified that varied in species, terrain slope, the age of the trees, the degree of cover for the non-woody vegetation in the under-cover areas, management regime (coppice or high-forest for eucalyptus), and the density of trees per hectare. Data on *Eucalyptus* forests were collected from the properties owned by Navigator Company (in Trofa, Braga, Gondomar, and Guimarães) and Altri Florestal (in Marco de Canaveses). Data on pine forests were collected from private properties (in Castelo de Paiva and Vila Real counties) and community lands in Montalegre county, the latter of which is managed by the Cooperativa Agrícola do Barroso (CoopBarroso). Data were collected in 36 plots across 12 typologies for the eucalyptus (Figure 2) and pine trees (Figure 3).


**Figure 2.** Typologies of the eucalyptus stands for data collection and the number of plots executed.


**Figure 3.** Typologies of the pine stands for data collection and the number of plots executed.

### *2.2. Data Collection*

Data collection took place during the period of August 2021 to July 2022, with at least two people involved in the study activities who had undergone prior training in the use of the apps. Circular plots were established in the corresponding areas of the predetermined typologies in which the center was allocated into representative portions for the surrounding forest. We sought to opt for areas where there were no clearings and where the elements that characterized the typology were evident throughout the entire extension of the plot.

The circular plot had an area of 400 $m^2$ and a radius of 11.28 m. This measure corresponds to one of the standard sizes used in Portuguese forest inventories and the Arboreal application; furthermore, the size also works with fixed-sized plots. The radius of the plot was adjusted on sloping ground.

After determining the location of the plot, the circumference determined by the plot was delimited and the dendrometric data of the diameter chest height (DBH) and total height of the trees were collected as described in Sections 2.2.1–2.2.4.

### 2.2.1. Traditional Method

In traditional data collection, each tree within the boundaries of the plot is assigned a number on a card and its diameter and height are measured. In this study, the breast height diameter (DBH) was measured with a calliper (with a precision of 1 mm) that was two perpendicular measurements of 1.30 m above ground level. The hypsometer Vertex III (precision of 0.1 m) was used to collect the height data, and the diameter and height data were recorded on field cards.

### 2.2.2. Data Collection with the Arboreal App

The data collection procedure with the Arboreal application took place according to the protocol presented by the developer, and the device used was an Iphone 12 PRO. The first step was to link up the cell phone device with the camera facing the ground; then, the center of the screen was made to match the center of the plot and the application button was pressed. After completing this, the application defined a virtual limit, one that was also visible on the screen. At the bottom of the screen, the application indicated the distance from the center of the plot, which decreases as the operator approaches the boundary. The number 0 m will appear when the operator reaches the boundary, thus helping to determine if the trees within that area should be included in the sample. Trees that were more than 11.28 m away from the center were not included in the sample, but they were indicated in the field form.

After delimiting the plot, the measurements were carried out. The procedure for measuring the diameters consisted of bringing the mobile phone approximately 1.30 m from the ground and around 30 cm away from each trunk, as shown in Figure 4. The application automatically recognized and captured the diameter. The operator can manually capture the diameter when the capture is not automatic.

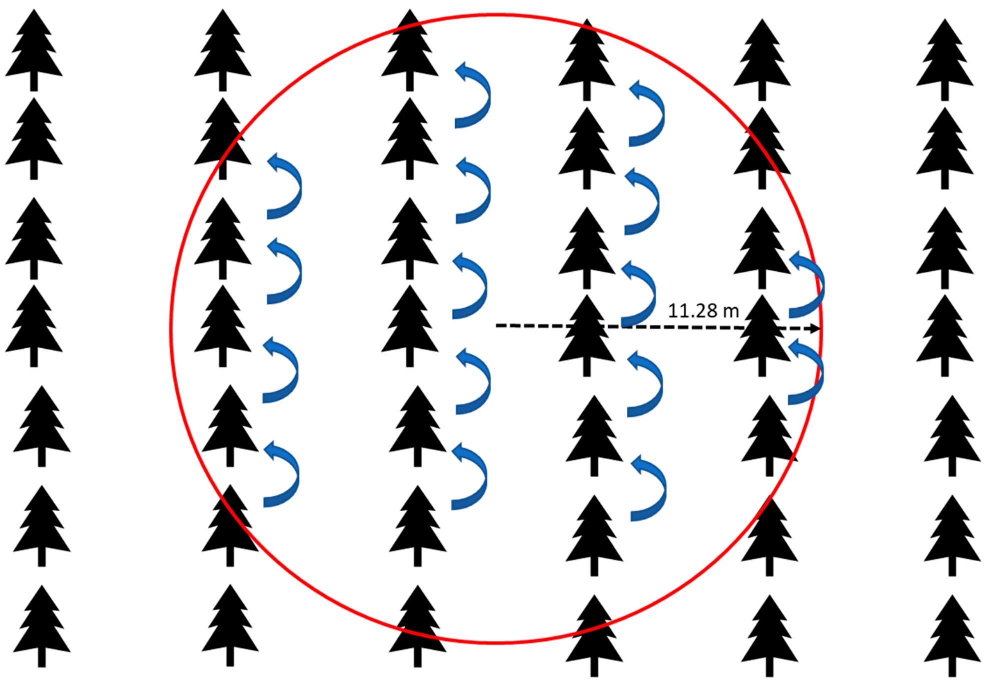


**Figure 4.** Measurement scheme with the Arboreal application.

After traversing all the trees in the plot according to the order of the cards, the next procedure was to take the height measurements. For this, the operator must visualize the plot from the center until finding a tree that is "marked" with a red circle, which means that the app has chosen that tree for collecting a height measurement. Next, the operator must approach the tree, point their mobile phone at it and then press the central button to reference it digitally. The operator should then move 10 m away from the tree and use the "Central crosshairs" on the screen to mark the base and tip of the tree. The application will then complete the measurement of the plot and provide the user with information about the sampled forest area, including the number of trees per hectare (N), volume per hectare ($m^3$), and the basal area ($m^2$/ha).

### 2.2.3. Data Collection with the Katam Application

The Katam application collects data from a dynamic image (video) of the sampled area, and the device used was the smartphone Huawei ELE-L29. The recording was made along transects with variable distance, in which—due to the operator's movement—they obligatorily crossed the interior of the previously determined plot and were taken in such a way that the number plates of the trees were captured in the videos. Multiple videos can be taken to ensure all trees are included.

In the recordings, the mobile phone should be in a horizontal position and approximately 1.30 m above the ground. The duration of the videos was around 1 min, and the length of the transect covered by the operator's displacement was large enough to cross the plot. After capturing each video (as depicted in Figure 5) and on the completion of its processing by the application, if executed, the digital video show "grids" in the captured trees that, when paused, allows the operator to press on the marked tree and to open a frame with the diameter and height of that tree.

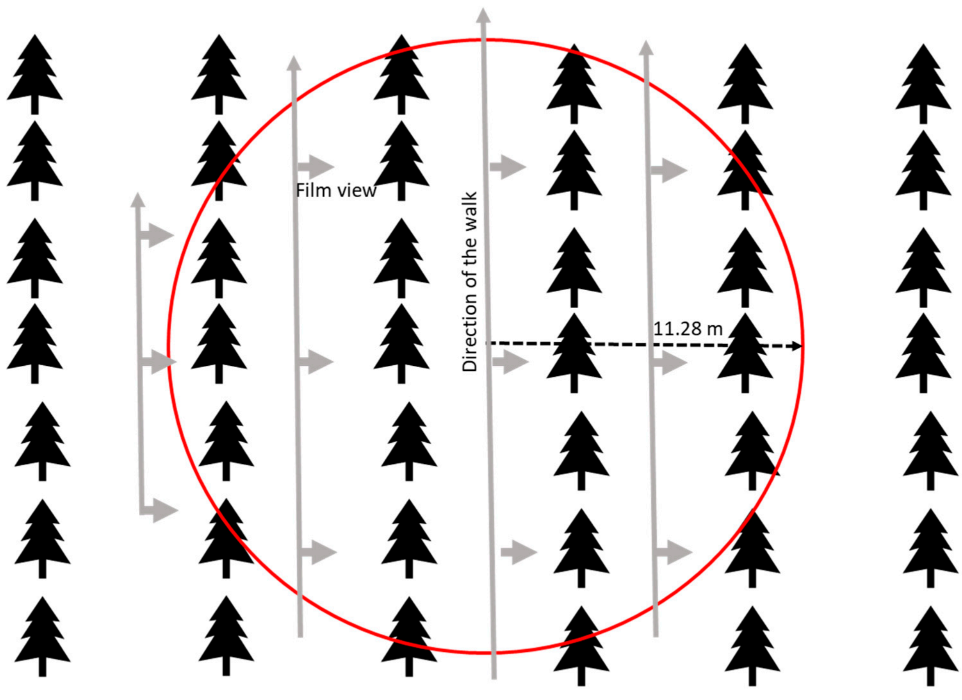


**Figure 5.** Measurement scheme with the Katam application.

Such verification is carried out in all the videos until the diameter of all the captured numbered trees are obtained. The app also stores the number of trees per hectare, volume per hectare ($m^3$), and the basal area ($m^2$/ha) of each video.

### 2.2.4. Data Collection with the Trestima App

The Trestima app's algorithm analyzes static images that are captured by the phone's camera, and the device used was the smartphone One Plus 6T. This application requires that virtual polygons be created in the study areas before going to the field. These polygons should cover the entire sampled area and can be drawn on the application platform before the field work. In the field, after the operator activates the application and ensures that the study plot is inside the polygon, they circle the study plot (as shown in Figure 6) and collect the data.

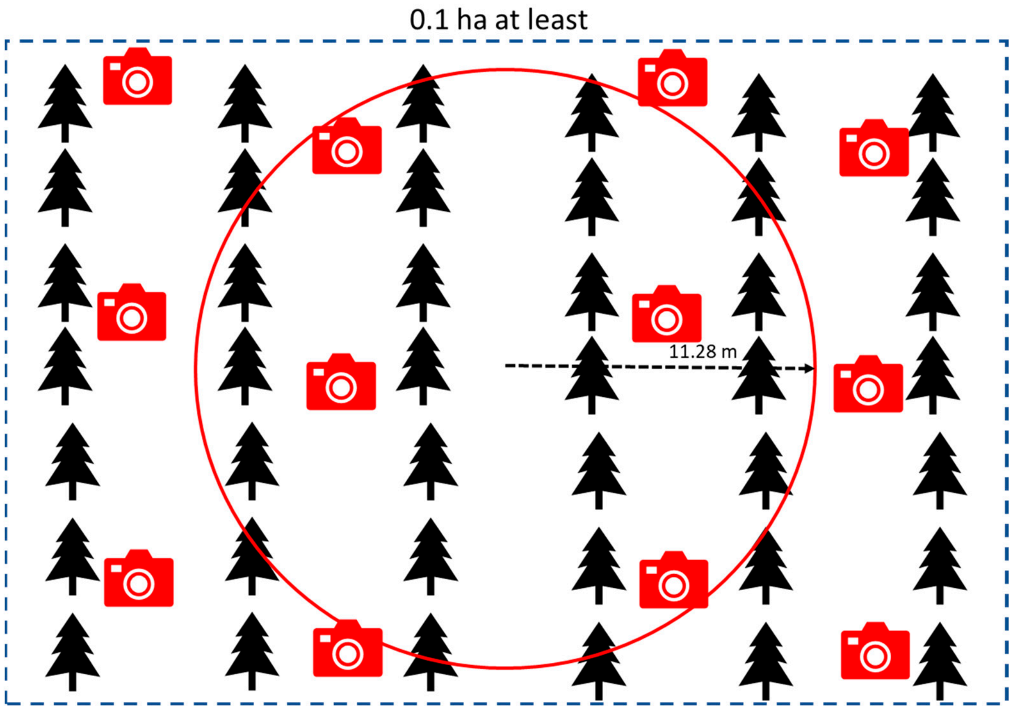


**Figure 6.** Scheme of measuring with the Trestima application.

According to the developer of the application, sample areas that are greater than 0.1 hectares guarantee a greater accuracy in the results, so the samples of this study always had areas higher than this value. While moving around the plot, 10 images were captured in random directions indicated by the application along the area. After the image is captured, the application processes the data and indicates the volume per hectare ($m^3$), basal area ($m^2$/ha), number of trees per hectare, the diameter, and average height.

*2.3. Data Processing*

Data from the field and app reports were organized in Excel tables by plot. The plot of the trees were then transferred to the JMP 5.0.1 ®statistical software (www.jmp.com, accessed on 24 June 2023) to perform the statistical data analysis.

In the data analysis, the diameter values obtained from the apps were compared to those measured by a calliper with the traditional method. The evaluation also examined factors such as stand density and time spent with the evaluations.

2.3.1. Statistical Treatment

To evaluate the similarities and differences in the diameter values between the methods, the authors calculated various metrics and used graphical data representation analysis and statistical tests.

The analysis focused on the individual diameter values that comprised the evaluation of the fit, precision, and bias statistics, as well as the comparison of the means and the study of the distribution of the diameters after grouping the values into classes. The former were evaluated through the metric coefficient of determination ($R^2$), the root mean squared error

(RMSE) of the fitted line (Equations (1) and (2)), and the BIAS (Equation (3)). Efficiency ($f$) was calculated as the product of the root mean squared error (RMSE) and the BIAS.

$$R^2 = \frac{\sum_{i=1}^{n}\left(d_i - \overline{d_i}\right)^2}{\sum_{i=1}^{n}\left(d_{ref\ i} - \overline{d_i}\right)^2} \quad (1)$$

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{\left(d_i - d_{ref\ i}\right)^2}{n}} \quad (2)$$

$$\mathrm{Bias} = \sum_{i=1}^{n} \frac{\left(d_i - d_{ref\ i}\right)}{n} \quad (3)$$

where $d_i$: the individual tree diameter measured by the app [cm]; $d_{ref\,i}$: the individual tree diameter measured at a 1.30 m height above ground level by the traditional inventory method [m]; and $n$: the number of trees with at least one diameter measurement.

Wilcoxon and Tukey–Kramer tests were applied (α = 0.05%) to verify the statistical significance of the difference in the mean diameters of the plots of each typology, thus defining whether the mean diameters at breast height that were indicated in the applications were similar to those collected by the traditional method. Likewise, the test was applied to the number of trees per hectare (N) and basal area per hectare ($G$) variables.

For the analysis based on the diameter distribution, the samples were organized into diameter classes that were 5 cm wide and were set according to the standard adopted in Portugal.

Differences were analyzed based on the calculation of the Error Index ($EI$) metric [15].

To calculate the $EI$ (Equation (4)), we grouped the diameters of each plot into classes that were 5 cm wide. From there, the basal area for each class was calculated by using the average diameter of each class and multiplying it by the number of trees in that class. We then subtracted the corresponding value estimated by the app to determine the error index of each class. The sum of the error indexes for all classes resulted in the error index for the portion or typology of each method.

$$EI = \sum_{j=1}^{M} |Gj - \hat{G}j| = \sum_{j=1}^{M} |\frac{\pi x^2}{4}\ (\hat{f}(x) - f_e(x))dx| \quad (4)$$

In Equation (4), $M$ refers to the number of diameter classes, $Gj$ indicates the basal area observed by the traditional method in class $j$, and $\hat{G}j$ indicates the basal area estimated by the apps (and whose diameters belong to class $j$). $\hat{f}(x)$ and $f(x)$ represent the frequency or the number of trees in the observed and estimated class $x$, while $d(x)$ represents the average diameter of class $x$.

The error index, when using the basal area as the weight, allows for a comparison between the distributions. Moreover, it is based on two variables that are directly collected by the applications ($d$ and N), which is unlike the height and volume or biomass that are dependent on hypsometric or volumetric equations [15].

An expedited survey was also carried out, where the time taken to collect data in the traditional method and in each of the applications was noted. For this survey, 6 plots in the pine forest and 5 plots in the eucalyptus forests were allocated and drawn.

Finally, a matrix was created to portrait the results and classify the applications based on their efficiency and accuracy. The matrix contained the results of the following parameters, which were calculated by a method in each typology: BIAS, RMSE, $R^2$, Efficiency $f$ (RMSE × BIAS), Similarity of N, Similarity of $d$, Execution time, Similarity of $G$, and the Error Index ($G$). For the parameters BIAS, RMSE, $R^2$, Error Index, Efficiency Index ($f$), and the execution time, we adopted the criterion of assigning a score of 2 to the application with the best result in each parameter, 1 to second place, and 0 to third. For the N similarity parameter, the methods received 1 point if the estimated N was statistically similar to the observed N and 0 points if this condition was not verified. In the similarity parameter d, the mean comparison test was applied for all typologies in each method. Then, the percentage of typologies where the observed average diameter was statistically similar to the estimated one was calculated. The application with the highest percentage received a grade 2, the second placed received a grade 1, and the third grade 0.

In order to assign greater importance to the most representative parameters, multipliers were considered in order to assign a greater weight to the most relevant parameters. The BIAS, RMSE, and $R^2$ parameters were assigned a weight of 0.5. For the parameters Efficiency, N Similarity, Runtime Similarity, a weight of 1 was assigned, and for G Similarity and Error Index, a weight of 2.

## 3. Results

### *3.1. Comparison of Diameter Distributions through Graphical Analysis and Compliance Metrics*

To facilitate the graphical analysis of the dispersion of the diameter data, the typologies were separated by species (*Eucalyptus* and *Pinus*) and by age (young versus adult). The results are shown in Figures 7–11 for the Katam and Arboreal apps.

When analyzing the types of adult pine stands (Figure 11), the Arboreal application displayed more effective dispersion patterns. Typologies T11 and T12 had an under-cover vegetation that could potentially affect the accuracy of the Katam application.

The Katam app failed to carry out a reading in the field during data collection in typology 7. Additionally, in typology 8, the trees were not individually identified, resulting in basic information being missing. As a result, the authors could not conduct any analysis for these typologies in regard to the Katam app. It has been previously stated that the Trestima app only provides tree diameter information in the form of ranges rather than specifics for individual trees. Therefore, due to the lack of detail, the Trestima app was not included in the assessments that required detailed data on tree diameters.

A straight line was superimposed in the plots along with the fitted line's coefficient of determination ($R^2$ statistic). It is important to note that an $R^2$ value of 1 does not always mean there is a perfect match between the diameter observations obtained through traditional measurement methods and those provided by the app. This is because some bias may occur. However, higher $R^2$ values indicate similar patterns in both distributions, whereas lower values indicate a lower adherence among the values or a greater variability.

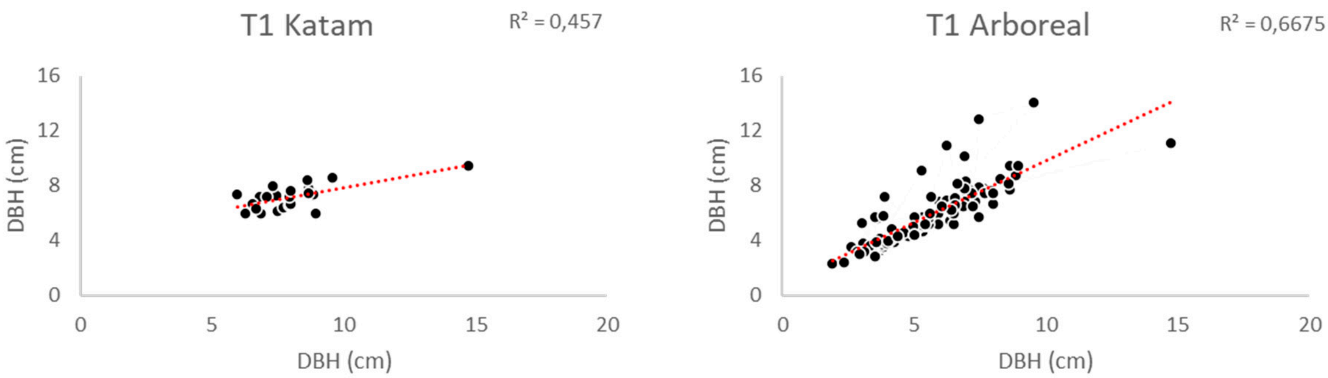


**Figure 7.** Scatter plot of the diameter values evaluated by the traditional method (X axis) and by the Katam and Arboreal applications for the T1 typology (young high-forest eucalyptus plantations up to 2 m high).

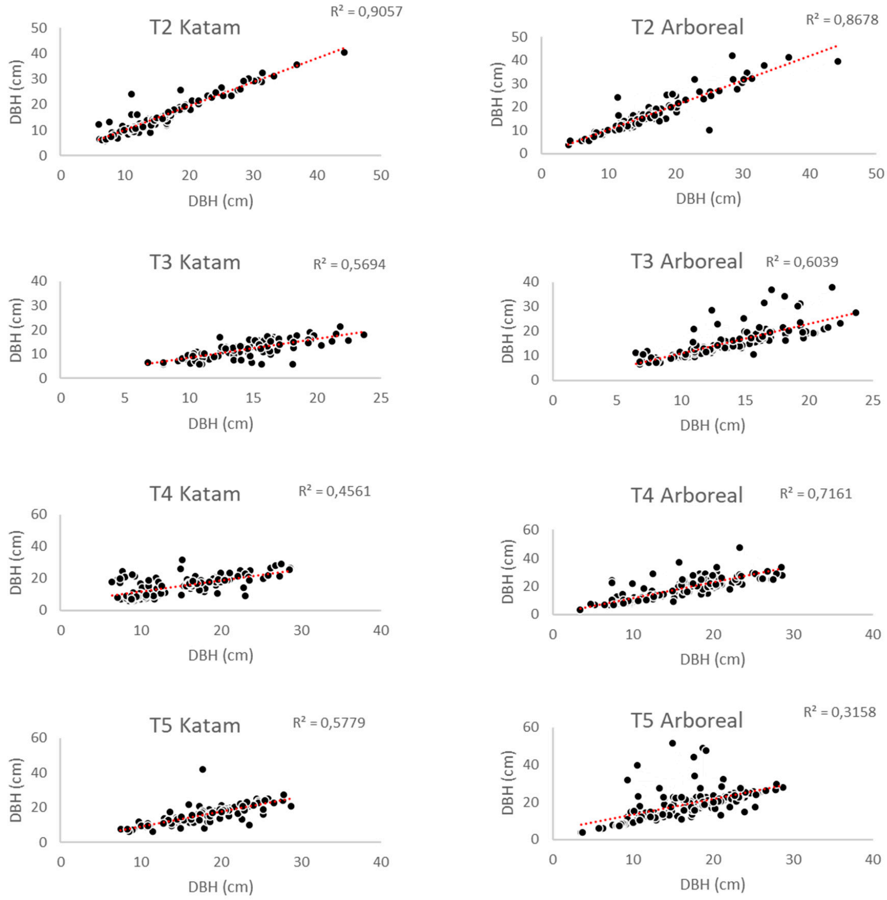


**Figure 8.** Scatter plot of the diameter values evaluated by the traditional method (XX axis) and by the Katam and Arboreal apps for typologies T2, T3, T4, and T5 (adult eucalyptus plantations with approximately 20 m in height with variation in the slope of the land and in the density of the under-cover vegetation).

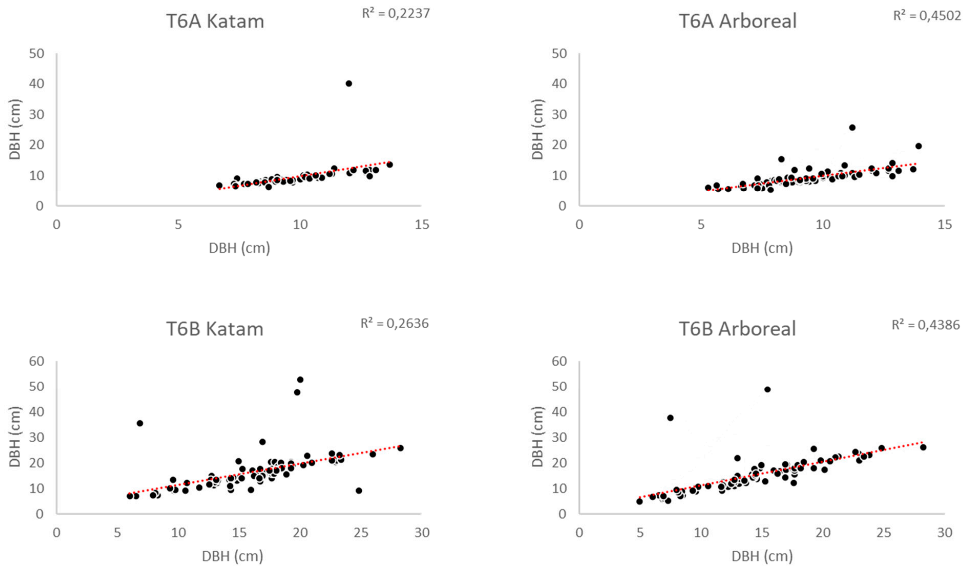


**Figure 9.** Scatter plot of the diameter values evaluated by the traditional method (XX axis) and by the Katam and Arboreal apps for typologies T6A and T6B (eucalyptus plantation in coppice with at least two stems per tree).

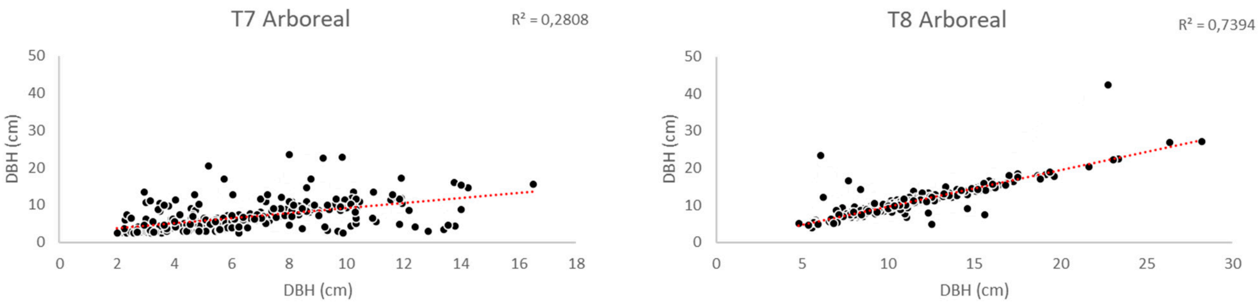


**Figure 10.** Scatter plot of the diameter values evaluated by the traditional method (XX axis) by the Arboreal app in typologies T7 and T8 (naturally regenerating young pine with variation in age and number of trees per hectare).

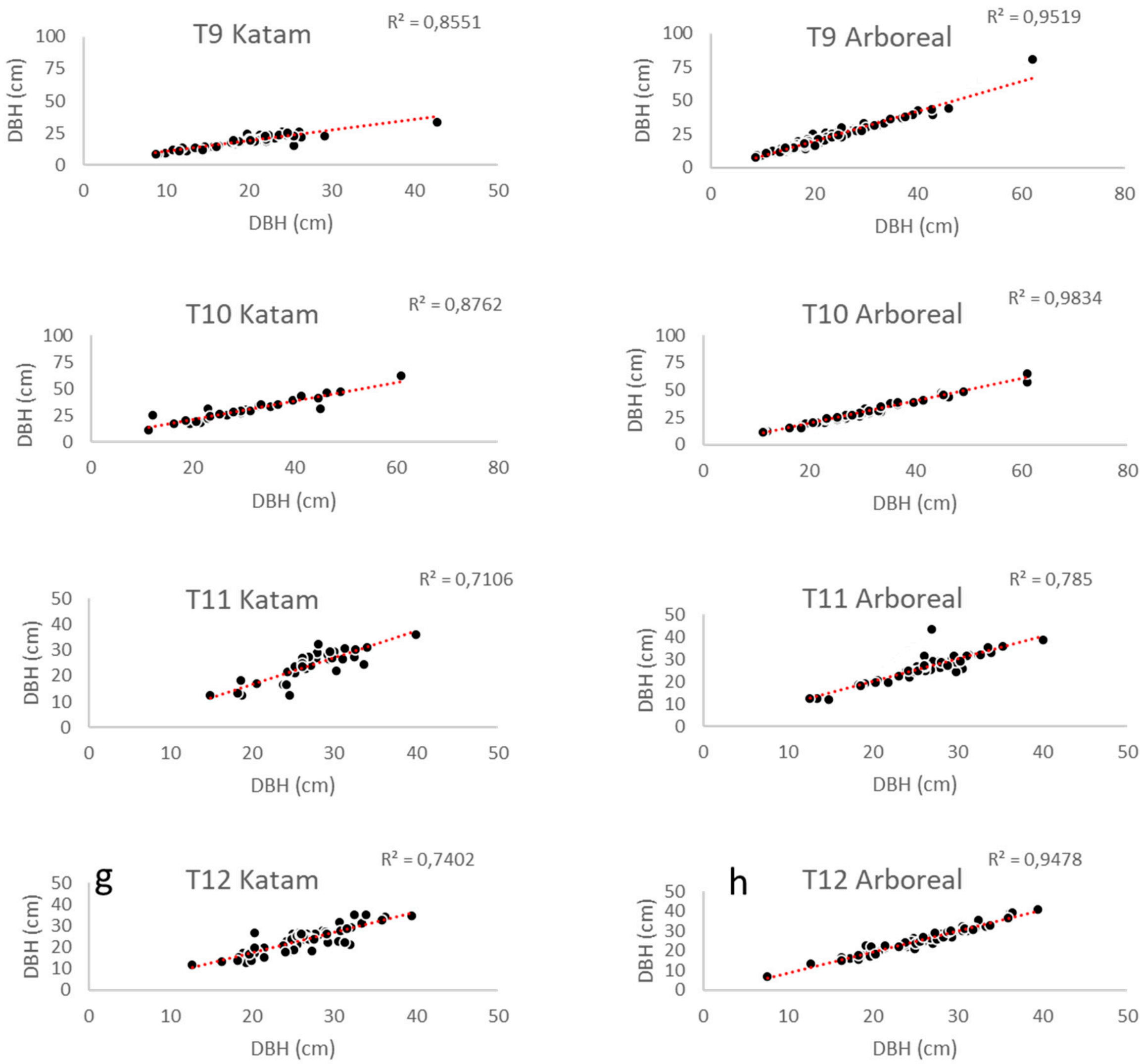


**Figure 11.** Scatter plot of the diameter values evaluated by the traditional method (XX axis) and by the Katam and Arboreal apps for typologies T9, T10, T11, and T12 (adult planted pine forest with variation in their under-cover vegetation density and slope).

### 3.1.1. *Eucalyptus* Stands

In Figure 7, the Katam app had the least amount of points because it identified fewer trees in the area. The Arboreal application showed a relatively even distribution of points overall, with a few exceptions ("outliers").

In the adult stands of eucalyptus (Figure 8), the factors of under-cover vegetation density and terrain slope seemed to influence the accuracy of the results presented by the applications. In typology 2, where there is no under-cover vegetation and the terrain is flat, both applications showed a greater homogeneity in the point cloud and a greater proximity to the adjusted regression line than in the other typologies. It is worth noting that there are apparent patterns of bias for certain typologies, which can be seen through differences in the axis scales. This is particularly noticeable when using the Arboreal app.

Both applications showed a few outliers in the eucalyptus coppice regime, with the estimated values being much higher than the measured ones (Figure 9)—probably due to the fusion of poles (trunks) when the images were generated.

### 3.1.2. Pinus Stands

For typologies T7 and T8, graphics were not generated for the Katam application since the application did not carry out the reading in the field. The Arboreal application had the worst performance in typology T7, probably due to the difficulty in recognizing the trees in the field by the algorithm given their density and low diameters. In typology T8, despite the appearance of some outliers, the pattern of cloud dispersion was more homogeneous. However, the different scales of the axes pointed to a bias (Figure 10).

The statistical parameters RMSE, BIAS, $R^2$, and Efficiency ($f$) were calculated for the Arboreal and Katam applications and can be seen in Table 2. Also listed are the $R^2$ values depicted in the graphs of Figures 7–11. The Trestima application was not considered in this analysis as it only provides access to the diametric distribution by classes and not individual diameters in its reports.

**Table 2.** The statistical parameters $R^2$, RMSE, BIAS, and Efficiency in the tree diameter evaluation conducted when using the Katam and Arboreal applications vs. the traditional inventory method.

| | $R^2$ | | RMSE (cm) | | BIAS (cm) | | Efficiency | |
|---|---|---|---|---|---|---|---|---|
| **Typology** | **Katam** | **Arboreal** | **Katam** | **Arboreal** | **Katam** | **Arboreal** | **Katam** | **Arboreal** |
| T1 | 0.457 | 0.668 | 1.55 | 1.26 | −0.82 | 0.28 | −1.266 | 0.356 |
| T2 | 0.906 | 0.868 | 2.15 | 2.96 | −0.43 | 0.53 | −0.918 | 1.577 |
| T3 | 0.569 | 0.604 | 3.58 | 4.48 | −2.49 | 1.95 | −8.931 | 8.724 |
| T4 | 0.456 | 0.716 | 4.52 | 4.62 | 0.27 | 1.93 | 1.224 | 8.921 |
| T5 | 0.578 | 0.316 | 4.18 | 6.87 | −2.12 | 2.04 | −8.858 | 14.012 |
| T6A | 0.224 | 0.450 | 4.02 | 2.20 | −0.14 | 0.02 | −0.584 | 0.037 |
| T6B | 0.264 | 0.439 | 6.44 | 4.70 | 0.53 | 0.28 | 3.403 | 1.326 |
| T7 | | 0.281 | | 3.26 | | 0.41 | | 1.347 |
| T8 | | 0.739 | | 2.26 | | −0.40 | | −0.911 |
| T9 | 0.855 | 0.952 | 2.40 | 2.30 | −0.95 | −0.13 | −2.290 | −0.297 |
| T10 | 0.876 | 0.983 | 4.02 | 1.51 | −0.16 | −0.43 | −0.641 | −0.644 |
| T11 | 0.711 | 0.785 | 4.27 | 2.80 | −2.86 | 0.08 | −12.200 | 0.232 |
| T12 | 0.740 | 0.948 | 4.20 | 1.22 | −2.93 | −0.22 | −12.307 | −0.275 |

Overall, the $R^2$ statistic was higher with the Arboreal than with the Katam application, thus reflecting a stronger relationship in the diameter values that were estimated with Arboreal compared with those measured by the traditional method and contrasted with Katam. According to the $R^2$ statistic, the Katam app had a lower performance in typology T6A—the eucalyptus conducted by coppice with approximately 5 years after selection and elimination of the stems with two or more remaining poles ($R^2$ = 0.224). The Katam app showed a better performance in typology T2—the eucalyptus in a high-forest regime without under-cover regions and without slope ($R^2$ = 0.906). The Arboreal app had a lower performance in typology T7—young pine forest before any intervention ($R^2$ = 0.281). Whereas it had its best performance in typology T9—adult pine forest without under-cover regions and without slope ($R^2$ = 0.952). When the analysis was made by species, Arboreal performed better overall in both eucalyptus and in pine compared to Katam, which outperformed just in 2 out of 11 cases.

The RMSE was the second statistical parameter analyzed. Both apps provided low values of RMSE values in Typology T1—young eucalyptus in a high-forest regime with approximately 2 m height. For the Arboreal app, the lowest RMSE value was determined in Typology T12—adult pine with under-cover regions and with slope (RMSE = 1.222 cm). The highest values for this metric were found with Katam in Typology T6B—eucalyptus conducted in a coppice regime in pre-cut conditions (RMSE = 6.440 cm), and with Arboreal in Typology T5—adult eucalyptus conducted in a high-forest regime with under-cover regions in sloping terrain (RMSE = 6.875 cm). The Katam app performed slightly better in eucalyptus typologies compared to Arboreal, which outperformed Katam in pine typologies.

When examining the BIAS metric, we could assess both the magnitude of differences as well as the degree of the over- or underestimation of values. The Arboreal application outperformed Katam in this regard, with an average BIAS of 0.488 cm compared to −1.101 cm. It should be noted that Arboreal tended to slightly overestimate diameter values while Katam had a tendency to underestimate them. The lowest BIAS values were −0.145 for Katam and 0.017 for Arboreal, both in Typology T6A—eucalyptus conducted by coppice approximately 5 years after selection and with an elimination of stems that had two or more remaining poles. The highest values of BIAS were verified with Katam in T12—adult pine with under-cover regions and with slope (2.931), as well as in T5 with Arboreal—adult *Eucalyptus* conducted in a tall-bore system with under-cover regions and with slope (2.038). Katam showed a pattern of better performance in eucalyptus typologies when compared to the Arboreal app. In pine typologies, Arboreal had a lower average BIAS in comparison to Katam.

The efficiency indicator $f$ conjugates RMSE and BIAS. The best results for these were found to be with Katam ($f$ = 0.584) and Arboreal ($f$ = 0.037) in Typology T6A—eucalyptus managed by coppice approximately 5 years after selection and with a removal of stems that had two or more remaining poles. Whereas the worst for these values were verified in T12 with Katam—adult pine with under-cover regions and with slope ($f$ = −12.307), and in T5 with Arboreal—adult *Eucalyptus* conducted in a high-forest regime with under-cover regions and with slope ($f$ = 14.012). Katam tends to perform better in eucalyptus typologies when compared to the Arboreal app. In pine typologies, the Arboreal app overall outperforms the Katam app.

### *3.2. Comparison of the Diameter Distributions and Stand Density Variables Means via Statistical Tests*

For a comparison of the difference in the mean diameters per typology, the data of all plots of a same typology were grouped and tests were carried out in JMP. Statistical tests indicated that, for the Katam application, 75% of the plots did not present normal distribution for the variable diameter, while for the Arboreal application this number was 72%. A normality test was not carried out for Trestima, as the reports of this application only present the distribution in diameter classes and do not allow access to the individual diameters of the trees. Given the results, it was decided that the Wilcoxon non-parametric test would be used to verify the similarity of the means.

In the comparison of the means, when there are equal letters, it means that there is no statistical difference between the means at the $p$ = 0.05 level. Therefore, considering that the control is the traditional method, the applications to be considered must provide similar diameter values in order to have the same letter.

#### 3.2.1. Diameter Distribution Means

Comparison of the means was performed between applications in each of the sample plots via the Tukey–Kramer test, and this was conducted after verifying the significant differences indicated by the Wilcoxon test. For the Trestima application, the average of the diameters was used based on the diametric distribution by classes, where the diameter of the trees corresponded to the diameter of the center of each class. Therefore, the results obtained for this application must be viewed with great caution.

The Trestima application was not able to recognize trees in the T1P2 (Typology 1 parcel 2) and T4P4 (Typology 4 parcel 4) plots, and no data were collected from T5P4 (Typology 5 parcel 4) and T5P5 (Typology 5 parcel 5). For the Katam application, there was no recognition of the trees in the T1P2 plot. The Arboreal app recognized trees in all plots, so it stood out in this parameter. The graphs represented in Figure 12 show the global percentages of the different means by species (eucalyptus and pine).

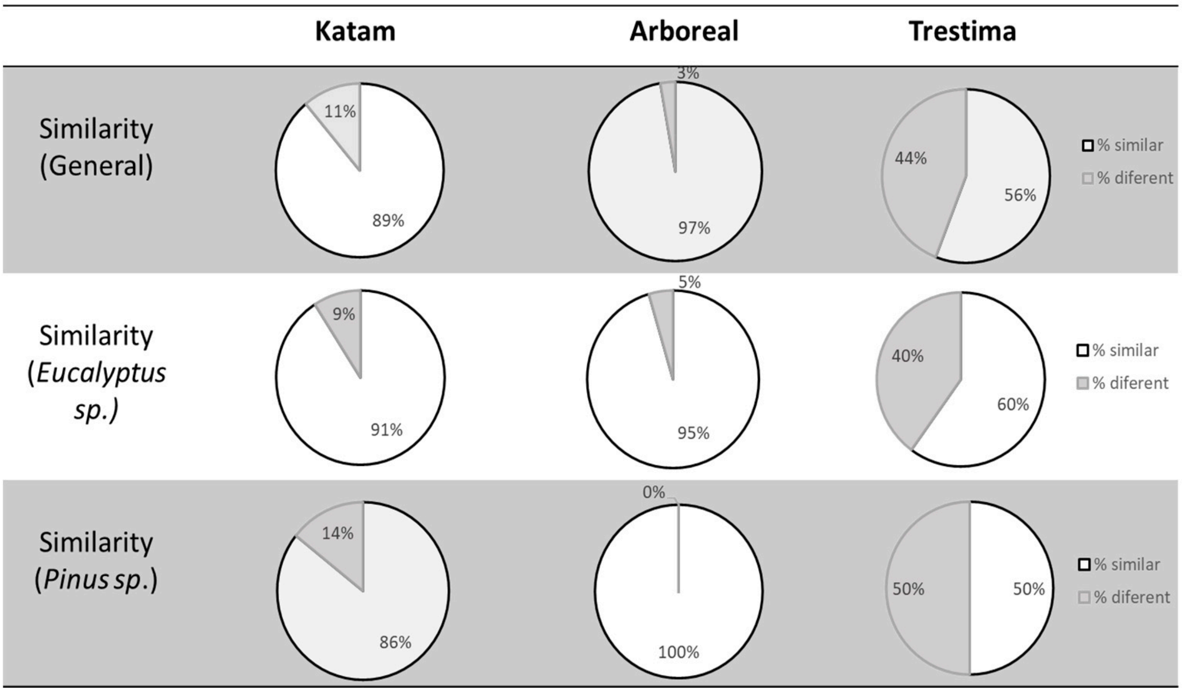


**Figure 12.** Percentage of the similarity between the average plot diameters as evaluated by the traditional method with the corresponding values when determined with the Katam, Arboreal, and Trestima applications.

In general, the Arboreal application had the lowest number of plots with significant differences with regard to the mean diameters between applications. Whereas Trestima showed the highest number of discrepant cases.

In eucalyptus, the Arboreal application performed better, with 95% of plots with averages that did not statistically differ from the ones determined with the traditional method. The worst performance was by the Trestima application with a 60% similarity. In the pine stands, the Arboreal application again stood out with a 100% similarity.

Table 3 shows the results for the different typologies. The analysis considers the average of the individual diameters in each typology, and these are based on the grouping of the data of the sampled plot of that typology in order to compare the results of the applications with the traditional method.

The information provided by Figure 12 is indicative of the proportion between the traditional method and each application that is statistically similar. The results may help users decide which technology to adopt in combination with other analyses; however, on their own, they do not conclusively determine the outcome of this study.

The Trestima application was the one with the greatest number of averages that were different from the traditional method when compared to the other two applications; it produced 7 different averages out of 13, and this was followed by Arboreal with 3 different averages, whereas Katam presented only 2 very different averages out of 13.

**Table 3.** Comparison of the average diameters measured between the typologies by application. The gray cells indicate that there was a statistically significant difference between the means. The means not connected by the same letter (a, b or c) are significantly different.

| | Traditional | | Katam | | Arboreal | | Trestima | |
|---|---|---|---|---|---|---|---|---|
| **Typology** | **Mean** | **Std** | **Mean** | **Std** | **Mean** | **Std** | **Mean** | **Std** |
| T1 | 5.705 c | 1.91610 | 7.181 b | 0.91685 | 5.954 bc | 2.12214 | 9.608 a | 3.10043 |
| T2 | 16.086 a | 6.97629 | 15.992 a | 6.75000 | 16.371 a | 7.96881 | 14.169 a | 5.72490 |
| T3 | 13.719 b | 4.03365 | 12.203 b | 3.76691 | 15.778 a | 6.30084 | 17.463 a | 5.73067 |
| T4 | 14.025 b | 5.83449 | 15.438 ab | 5.70857 | 15.917 a | 7.79753 | 14.714 ab | 6.35660 |
| T5 | 16.987 b | 5.49094 | 16.412 b | 5.47002 | 19.077 a | 7.88532 | 15.898 b | 6.89873 |
| T6A | 9.364 b | 1.94250 | 9.694 b | 4.57692 | 9.423 bc | 2.98755 | 12.555 a | 3.66517 |
| T6B | 14.964 a | 4.96652 | 16.597 a | 7.46641 | 15.850 a | 6.53727 | 15.058 a | 6.71233 |
| T7 | 6.442 c | 2.99048 | 9.233 b | 8.33888 | 6.796 c | 3.64509 | 11.505 a | 3.93149 |
| T8 | 11.386 a | 3.80811 | 12.785 a | 5.86721 | 10.999 a | 4.37026 | 12.008 a | 4.59613 |
| T9 | 23.323 a | 8.98368 | 22.213 a | 8.69248 | 22.468 a | 9.58425 | 22.700 a | 8.95050 |
| T10 | 29.759 a | 11.4986 | 29.858 a | 9.2892 | 29.311 ab | 1.3748 | 24.592 b | 7.2516 |
| T11 | 26.177 a | 5.36562 | 24.259 a | 5.96222 | 26.260 a | 6.08111 | 19.607 b | 7.33529 |
| T12 | 25.671 a | 5.58304 | 23.340 a | 5.91143 | 25.369 a | 6.44228 | 20.371 b | 6.56334 |

#### 3.2.2. Number of Trees and the Basal Area Means

Table 4 shows the comparison of the averages for the number of trees quantified by the applications and the traditional method by typology. Table 5 shows the comparison of the averages for basal area (G) by the applications and the traditional method by typology.

The mean comparison test disregarded the distribution of diameters through the classes and considered only the number of trees per hectare that were indicated by each method. Results show no significant difference between the number of trees identified with the traditional method and the Arboreal application in all typologies.

**Table 4.** Comparison of the average number of trees per hectare (N, trees/ha) estimated with the applications against the traditional method per typology. The means not connected by the same letter (a, b or c) are significantly different and are marked with gray color.

| Mean Comparison of N | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Traditional | | Katam | | Arboreal | | Trestima | |
| **Typology** | **Mean** | **Std** | **Mean** | **Std** | **Mean** | **Std** | **Mean** | **Std** |
| T1 | 1362.5 a | 53.0 | 45.5 c | 64.3 | 1313.4 a | 17.7 | 583.0 b | - |
| T2 | 1075.0 a | 175 | 834.0 a | 135.6 | 1025.7 a | 173.3 | 994.0 a | 391.3 |
| T3 | 1058.3 a | 118.1 | 609.3 b | 184.3 | 1000.6 ab | 86.6 | 533.0 b | 87.4 |
| T4 | 1156.2 a | 196.2 | 697.2 b | 237.3 | 1119.5 ab | 227.8 | 789.3 ab | 92.4 |
| T5 | 820.0 a | 119.1 | 541.4 c | 96.3 | 760.5 a | 101.0 | 587.3 bc | 106.6 |
| T6A | 2162.5 a | 1184.4 | 1091.5 a | 597.5 | 2101.4 a | 1132.1 | 899.0 a | 280.0 |
| T6B | 975.0 a | 90.1 | 628.6 a | 107.3 | 925.6 a | 86.6 | 877.3 a | 267.4 |
| T7 | 3800.0 a | 671.7 | 499.0 b | 104.6 | 3652.4 a | 530.7 | 1260.0 b | 39.6 |
| T8 | 3175.0 a | 671.7 | 2022.0 a | 231.9 | 3027.0 a | 742.9 | 3004.0 a | 0.0 |
| T9 | 1000.0 a | 519.6 | 873.0 a | 601.9 | 942.0 a | 573.9 | 670.6 a | 112.8 |
| T10 | 800.0 a | 0 | 871.5 a | 10.6 | 738.0 a | 123.9 | 794.5 a | 299.1 |
| T11 | 687.5 a | 17.7 | 435.0 a | 26.8 | 688.0 a | 17.7 | 687.0 a | 153.4 |
| T12 | 641.6 a | 166.4 | 372.0 a | 145.4 | 558.7 a | 101.1 | 589.6 a | 79.5 |

**Table 5.** Comparison of the average of the basal area (G, $m^2/ha$) estimated with the applications against the traditional method per typology. The means not connected by the same letter (a, b) are significantly different.

| Mean Comparison of G | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Traditional | | Katam | | Arboreal | | Trestima | |
| **Typology** | **Mean** | **Std** | **Mean** | **Std** | **Mean** | **Std** | **Mean** | **Std** |
| T1 | 1.6 a | 1.3 | 0.7 a | 0.7 | 1.5 a | 1.4 | 1.5 a | 1.0 |
| T2 | 4.9 a | 4.6 | 4.3 a | 4.3 | 4.5 a | 4.0 | 3.9 a | 2.7 |
| T3 | 3.8 a | 3.1 | 2.5 a | 2.2 | 3.6 a | 2.6 | 3.1 a | 2.0 |
| T4 | 4.5 a | 4.4 | 3.7 a | 3.1 | 4.3 a | 3.3 | 2.5 a | 1.8 |
| T5 | 4.6 a | 4.3 | 3.1 a | 3.1 | 4.1 a | 3.7 | 2.4 a | 1.6 |
| T6A | 2.6 a | 2.8 | 1.8 a | 2.2 | 2.0 a | 2.6 | 3.1 a | 3.1 |
| T6B | 4.1 a | 3.0 | 3.2 a | 2.1 | 3.7 a | 2.8 | 3.1 a | 2.1 |
| T7 | 4.0 a | 3.5 | 1.4 a | 2.2 | 3.6 a | 2.8 | 2.9 a | 3.1 |
| T8 | 6.5 ab | 6.1 | 1.7 b | 1.7 | 6.0 ab | 6.0 | 7.6 a | 4.5 |
| T9 | 6.7 a | 5.1 | 7.2 a | 5.9 | 6.3 a | 4.8 | 4.2 a | 2.6 |
| T10 | 6.4 a | 4.1 | 7.1 a | 5.4 | 6.1 a | 3.5 | 5.4 a | 4.2 |
| T11 | 7.1 a | 6.0 | 4.0 a | 4.0 | 7.1 a | 6.0 | 4.0 a | 3.1 |
| T12 | 6.1 a | 5.6 | 4.1 a | 3.6 | 4.7 a | 4.0 | 3.7 a | 2.7 |

The Katam application showed a different number of trees, with a significant difference in the typologies of T1, T3, T4, T5 (eucalyptus), and T7 (pinus). It was in the eucalyptus typologies where Katam performed the worse in estimating the variable N; these typologies referred to trees in coppice and high-stem regimes with the presence of bushes (dense vegetation under cover) and/or sloping terrain. The Trestima application presented differences in the same typologies as the Katam application, except for typology T4.

The assessment of differences in the individual diameters and the number of trees per hectare (N) were both critical. However, a central variable that helps to asseverate the precision of the application is the variable stand basal area ($G$), which also combines information on the number and tree size.

The comparison test of the means of the basal area by typology indicated that all the estimates of the basal areas per typology were similar, except for the $G$ value that was indicated by the Katam application for the T8 typology.

### *3.3. Comparison Considering the Diameter Data Grouped in Classes*

#### 3.3.1. Graphical Representation and Visual Analysis

To facilitate the graphical analysis of the diametric distribution in classes, the typologies were separated by species (eucalyptus and pine) and by age (young and adult). Figures 13–17 show the diameter distributions for the various typologies, and these consider the diameter classes with a range of 5 cm.

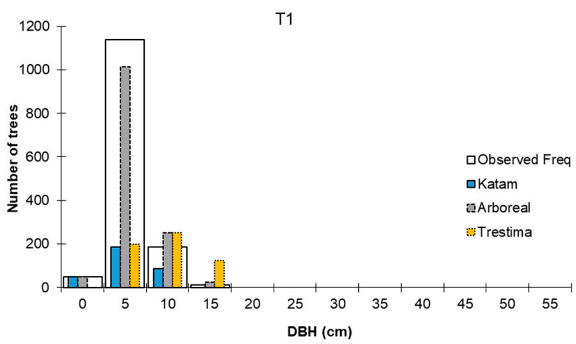


**Figure 13.** Diameter distributions for the T1 typology composed of young high-forest eucalyptus plantations up to 2 m high.

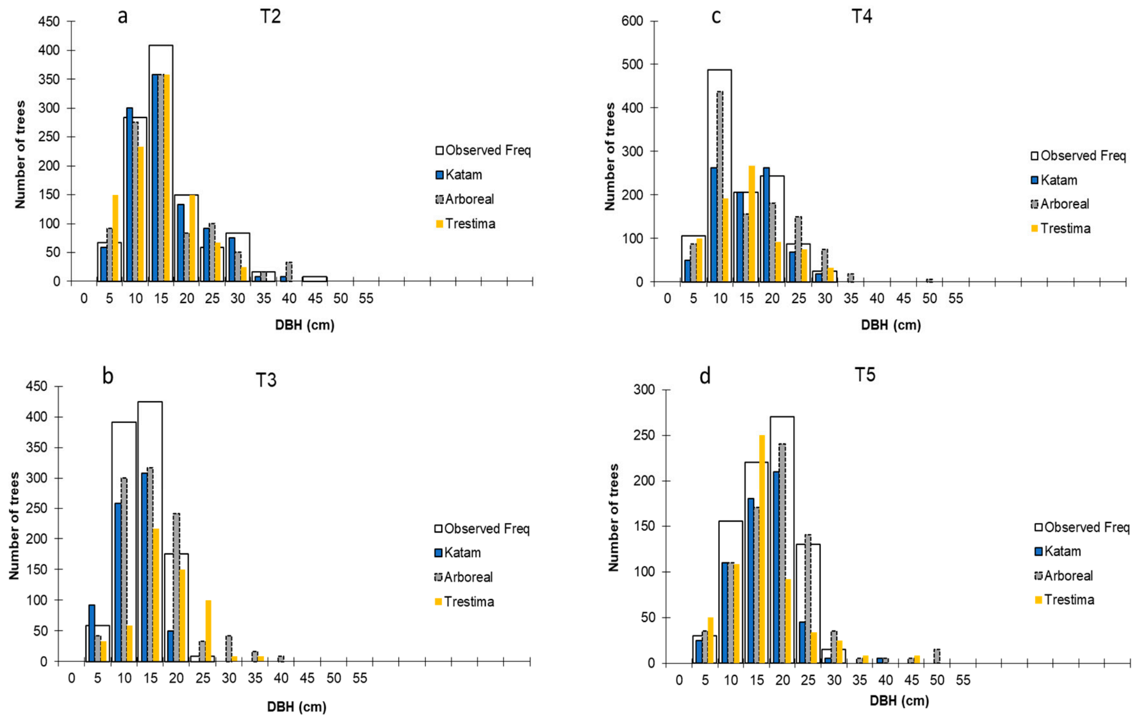


**Figure 14.** Diameter distributions for types T2 (**a**), T3 (**b**), T4 (**c**), and T5 (**d**) concerning the adult Eucalyptus plantations with approximately 20 m in height with variations in the slope of the terrain and in the density of the under-cover vegetation.

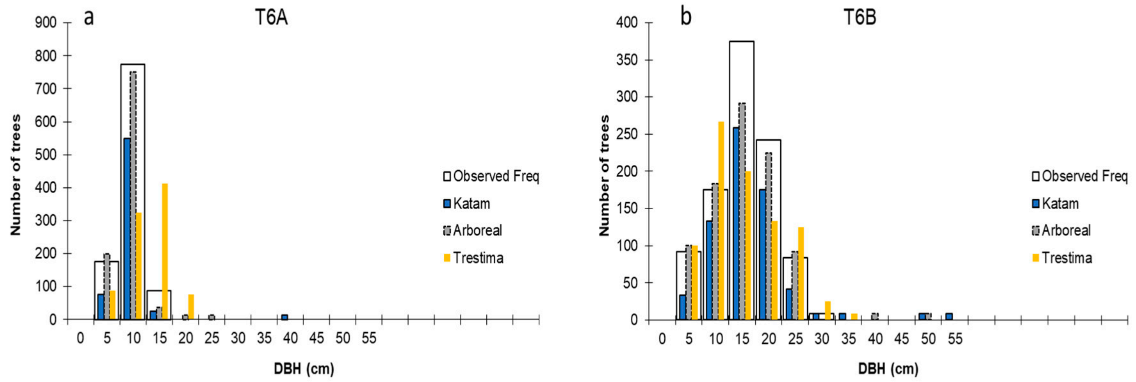


**Figure 15.** Diameter distributions for types T6A (**a**) and T6B (**b**) concerning the Eucalyptus plantation in coppice with at least two poles per tree.

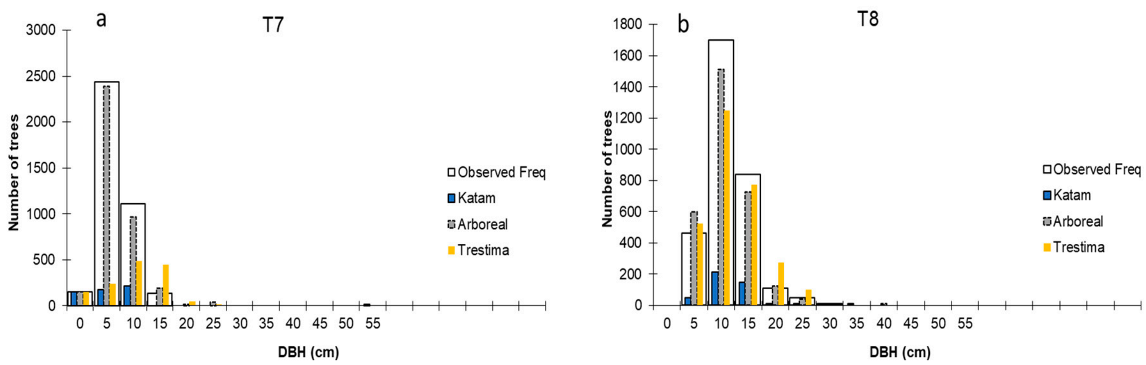


**Figure 16.** Diameter distributions for typologies T7 (**a**) and T8 (**b**) for the naturally regenerating young pine with age and density variation.

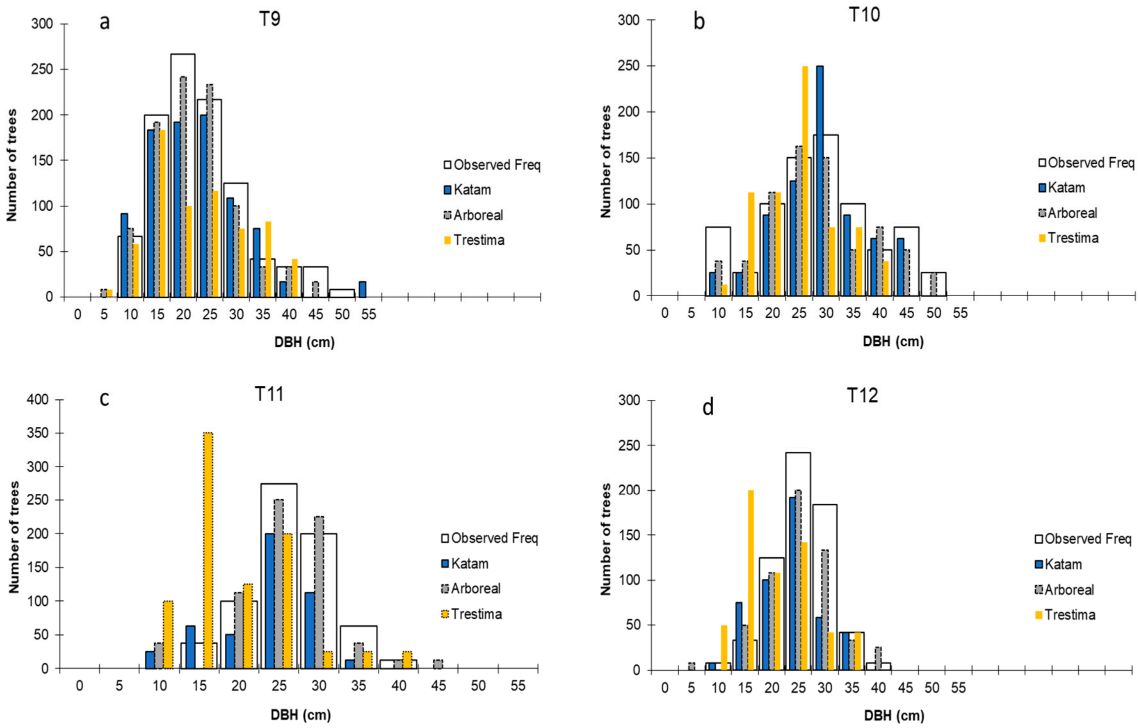


**Figure 17.** Diametric frequency by class for types T9 (**a**), T10 (**b**), T11 (**c**), and T12 (**d**) regarding the adult planted pine with variation in under-cover vegetation density and slope.

The Arboreal app's diameter distribution by class in the T1 typology closely matches the distribution obtained through the traditional method. However, it should be noted that the Trestima application overestimated the number of trees in the 15 cm class.

For typologies T2, T3, T4, and T5, the distribution of the diameter estimated with the applications generally followed the traditional method's pattern, but sometimes there were underestimated tree numbers in the most representative classes. The T3 typology had an underestimation of the trees, and the Trestima application overestimated the number of trees in class 25. Notably, the changes in the number of trees in the larger diameter classes had a more significant impact on the basal area per hectare due to their size and height.

In typologies T6A and T6B, the diameter distribution estimated with the apps followed the same pattern, with a slight underestimation tendency in the more numerous classes of the traditional method. The Trestima application overestimated the frequency of the trees in the 15 and 20 cm classes in typology T6A, as well as by 25 and 30 cm in typology T6B.

In the T7 typology, the Arboreal application quite accurately followed the distribution of the traditional method, while the distribution of the Trestima application underestimated the number of trees in the smaller diameter classes (0, 5, and 10 cm) and overestimated in the larger diameter classes (15 and 20 cm). The Katam application underestimated the number of trees in all classes. In the T8 typology, the applications showed a tendency similar to the traditional method, and again the Trestima application presented an overestimated number of trees in the 20 and 25 cm classes.

In typology T9, both the traditional methodology and the Arboreal application had a similar distribution. However, when it came to the 20 cm class, Arboreal underestimated the number of trees assigned to the 25 cm class while the Trestima application overestimated it. The Katam and Trestima applications underestimated the number of trees in the central class, but Trestima overestimated the number of trees in the 35 and 40 cm classes. Typology T10 also had a similar distribution between Arboreal and the traditional method. The Trestima application overestimated the number of trees in the 15, 20, and 25 cm classes.

In typology T11, Trestima estimated a significantly larger number of trees in the classes at the ends of the curve (10, 15, 20, and 40 cm) when compared to the traditional method.

The Trestima app estimates also exceeded the number of trees registered in the traditional method in typology T12.

3.3.2. Assessment of Differences Based on the Error Index

Figure 18 describes the behavior of the Error Index on a radar chart where the projection polygon eccentric represents the highest Error Index values.

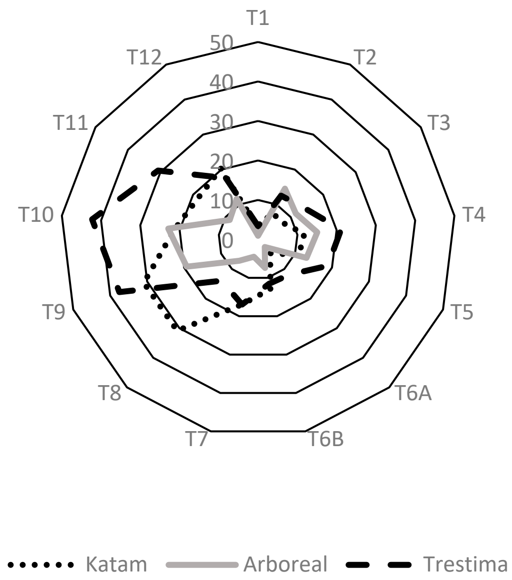


**Figure 18.** Representation of the Error Index ($m^2$/ha) by typology in a radar chart.

Figure 18 clearly displays a leftward shift in the error rate curves for certain typologies, namely those corresponding to pine plots. This indicates that these typologies had higher absolute error rates in the Trestima application, especially for typologies T9, T10, and T11. On the other hand, the eucalyptus typologies showed the worst result in typology T4, which corresponds to eucalyptus adults with a dense under-cover vegetation and no slope in the terrain.

The Katam application had higher absolute Error Index values in the typologies of pine in the natural regeneration T8 and stand adult T9 typologies. For the Arboreal application, the larger adult pine dimensions in typologies T9 and T10 had the highest Error Indexes. However, in general, the Arboreal application had lower Error Indexes, as indicated by its curve being closer to the center and by it being contained within the polygons of the other applications.

To eliminate the dimensional factor from the error rate analysis, where trees with larger dimensions tend to have a larger absolute Error Index than the smaller trees' dimensions, the absolute Error Index was converted to a relative Error Index (EI%). The values became more homogeneous and highlighted the peaks that indicated higher error index values for Trestima in the plots of typologies T5, T6A, and T6B, which are all of the eucalyptus stands. Katam, on the other hand, had higher error rates in typologies T7, T8, and T9, which are all pine trees. Finally, Arboreal had a peak error rate in typology T5, which is also a eucalyptus typology.

When considering the percentage values (Figure 19), it is clear that the Arboreal application has lower values compared to the other two applications. The polygon representing Arboreal was smaller, but with larger error indices on the right side for eucalyptus typologies. The Katam application still has the highest error rates for pine typologies, but the difference between pine and eucalyptus was not so evident. Trestima displayed the largest polygon area, with more extreme error rates that shifted toward Eucalyptus typologies.

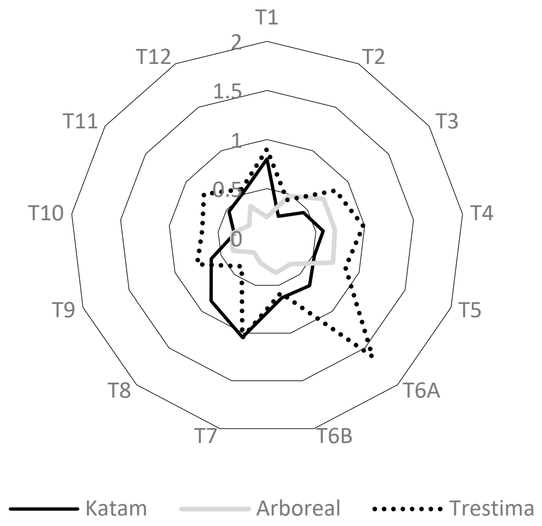


**Figure 19.** Representation of the Error Index in percentage by typology in a radar chart.

Figure 20 provides a comparison of the percentage error rates for each application and species.

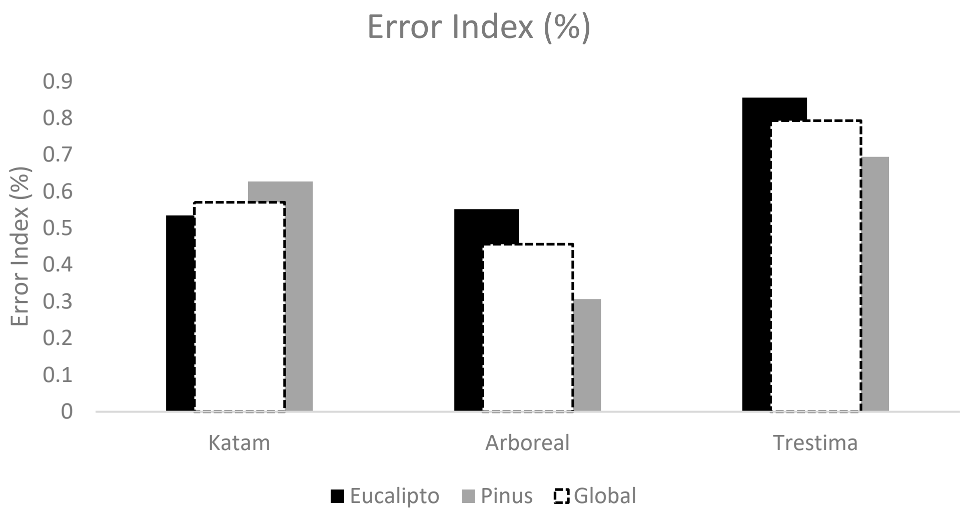


**Figure 20.** The Error Index in percentage by species in each application.

Figure 20 indicates that the overall percent Error Index values were lowest in the pine typologies for the Arboreal application, and the lowest Error Index values in the eucalyptus typologies were seen for the Katam application. The Trestima application had the highest error rates.

### *3.4. Average Time Required for Data Collection in the Field*

The average times taken in the collection of data, by portion, of each of the methods (application) are represented in the Figure 21 graph.

When evaluating efficiency, it is important to consider the amount of time spent measuring plots in the field. This can require significant resources, whether for large corporations or for small forest owners. By using a check measurement time, it was found in all cases that using these kinds of applications can significantly reduce the measurement time compared to traditional methods. Katam had a measurement time that was approximately four times lesser than traditional methods, taking only 7.1 min. Trestima took an average of 8.5 min, while the Arboreal application took the longest at 11.7 min; however, this is still significantly shorter than the traditional method, which takes—on average—28.7 min per plot.

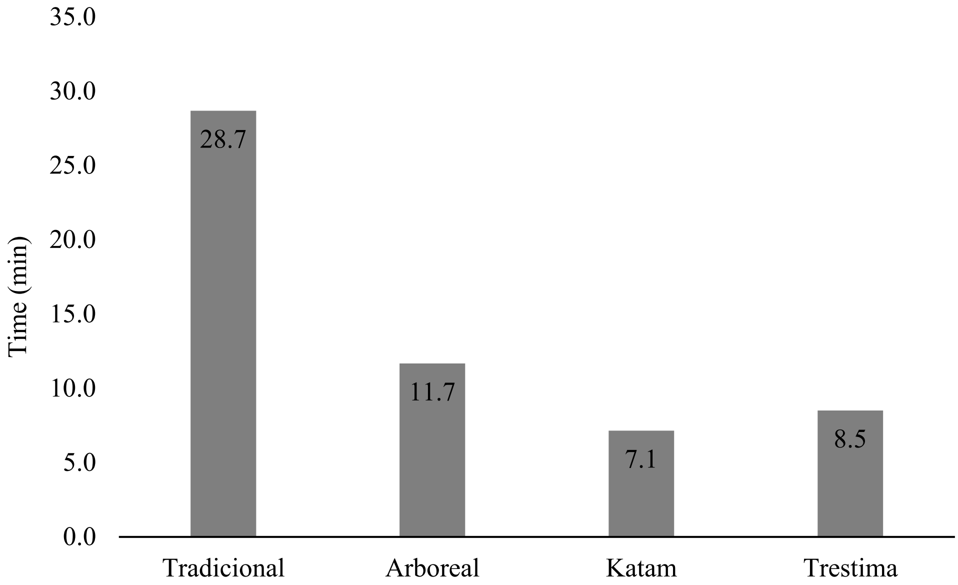


**Figure 21.** Average time in minutes elapsed in the collection of field data by method.

### 3.5. Ranking the Apps: An Assessment Approach

The matrix that indicates the score of each application based on the parameters evaluated as described in Section 2.3.1. is found in Table 6. The Arboreal application obtained the maximum score of 15.5 points, followed by Katam with 12 points, and finally Trestima with 6 points.

**Table 6.** Application evaluation parameter score matrix.

| Criterion | Classification | | | | Final Score | | |
|---|---|---|---|---|---|---|---|
| | Weight | Katam | Arboreal | Trestima | Katam | Arboreal | Trestima |
| BIAS | 0.5 | 1 | 2 | 0 | 0.5 | 1 | 0 |
| RMSE | 0.5 | 1 | 2 | 0 | 0.5 | 1 | 0 |
| $R^2$ | 0.5 | 2 | 1 | 0 | 1 | 0.5 | 0 |
| Efficiency (RMSE × BIAS) | 1 | 1 | 2 | 0 | 1 | 2 | 0 |
| Similarity N | 1 | 0 | 2 | 1 | 0 | 1 | 1 |
| Similarity d | 1 | 1 | 2 | 0 | 1 | 2 | 0 |
| Runtime | 1 | 2 | 0 | 1 | 2 | 0 | 1 |
| Similarity G | 2 | 2 | 2 | 2 | 4 | 4 | 4 |
| Error Index G | 2 | 1 | 2 | 0 | 2 | 4 | 0 |
| | | | | **Total** | **12** | **15.5** | **6** |

## 4. Discussion

In general, the apps provided results with varying accuracy. Some were comparable to the traditional method and incurred a considerably lesser measurement time. The preparation of a ranking to score the applications as a function of accuracy was only a way in which to group all the results of the parameters evaluated in a single space, but the choice to use one of the applications should be based more on the suitability of the characteristics of the application to the user and to the typology of forest where it is expected to be used.

Although all the applications presented the volume per hectare as the main result of the inventory, we chose to analyze the diameter of trees and the basal area since the calculation of the volume is influenced by the hypsometric equation used, by the characteristics of the smartphone used, and by the operator of the application [16]. Height is defined as a variable whose values are obtained indirectly, and it was assumed that if the equation was applied on accurate diameter data, then it is suitable for measuring forests and the volume will also be accurate. On the contrary, however, if the equation is inadequate—even for accurate diameters—then the volume may not be accurate.

It is important to consider that the Trestima application, unlike the others analyzed, does not allow access to a report with the individual diameters as it is restricted only to a diametric distribution report. The diametric distribution given by Trestima includes 2 cm classes, which, for the analyses, were converted to 5 cm classes. In addition, the individual diameter data presented by Arboreal and Katam were likewise framed in 5 cm classes so that a single standard for analysis was established. However, the lack of knowledge of the individual diameters certainly becomes a factor of uncertainty in the analysis of the Trestima results, so there should be some caution about the conclusions that can be drawn.

One of the elements to be considered is the topography of the terrain. The Katam application requires a recording to be taken, so the user needs to walk on the terrain and must have part of their attention focused on the inclination, height, and stability of the cell phone, which may contribute to stumbles and falls for the user and the occurrence of accidents in very rough or rocky terrain. Therefore, in this case, the use of Trestima or Arboreal may be more appropriate; in particular, Trestima would serve well as the image collection is guided and the user does it statically on the ground, thus running without the risk of accidents.

The accuracy factor is also important, and the highest for this was observed based on the error rate of Katam in *Pinus* and Arboreal in Eucalyptus. The results based on the Error Index show differences in the performance of the applications, with lower overall error values obtained with Arboreal (Figures 17–20). It should be noted, however, that the analysis by species and typologies shows a comparable or superior performance in the Katam app in specific situations, so the type of forest or the conditions in which it is located may be important aspects to consider when choosing the most appropriate app.

Regarding the number of trees per hectare (N), the Arboreal app presented the best results, and it was very close to the value recorded for N with the traditional method. However, the Trestima and Katam methods generated different numbers than anticipated, generally underestimating the value. In particular, Katam showed a significant statistical difference when compared to the traditional method, which was also confirmed by Werner and Dallacorte in a similar study conducted in Brazil [17]. It is possible that the difference is compensated by the distribution of diameters within the classes as the values of G ($m^2$/ha) did not differ. Regarding the N variable, although only Katam shows different statistics compared to the traditional method, the absolute figures of Katam and Trestima were appreciably lower than those found in the traditional method, a fact that indicates that the user should be very cautious when relying on these data for operations where the N variable is important, such as in thinning operations.

The evaluation performed points out that the forests with "ideal" characteristics for measurements with the tested applications are adult forests with low density, with small variations in its diameters, spatial organization (i.e., a distribution system where the trees are on the ground), flat terrain, and being without dense understory vegetation. Factors such as forest density, the presence of dense under-cover vegetation, slope, and age seem to affect the accuracy of the applications since the algorithm requires one clear image and that the trees are distinguishable from their trunks in order to obtain an accurate "tree" pattern recognition. During data collection, it was also observed, in an expeditious way, that the luminosity and the contrast defined by the light affected different components of the area studied, and that these also seemed to constitute a limiting of the factors regarding the precision of the applications.

Tests performed with the Arboreal application in Sweden also used the RMSE parameter for comparison with the traditional measurement methodology. Those results corroborated those verified in this study, which indicate accuracy in the measurements of N, G, and d, thus indicating a reduction in the measurement time [13].

## 5. Conclusions

Considering the results, the Arboreal application showed a lower percent in the Error Index values for pine forests, while the Katam application pointed to more accurate results in eucalyptus forests. The Trestima application, on average, showed less accurate results than the Katam and Arboreal applications, but it was the only one that allowed field measurements in the shortest time.

Although no statistically significant differences were found between the basal areas presented by the compared applications for the traditional method, in practice, the absolute values found can be quite significant when observed in larger scale measurements. The present study considered several typologies; however, it would be worthwhile to develop a study that isolates each of the forest variables in which the correlation of factors such as slope, presence of understory, species/genus, age, and the distribution pattern of trees in the stand could be verified.

It is relevant to consider that smartphone application technology, computer languages, artificial intelligence, and machine learning tools evolve very quickly. Furthermore, even during the period in which the applications were evaluated for this study, the course of this process may have created different conditions in image capture, tree recognition algorithm, and inventory calculations, so it is important to emphasize once again that the evaluation covers a defined time interval and that it gains or loses due to the evolution of technology. As such, there is a need to continue this study further.

The present results should be interpreted as preliminary. The evolution of this study, guided by what has been exposed here with a greater sample amplitude, may generate more concrete and definitive conclusions.

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