Smartphone-based measurements of Scots pine trunk diameters in Kostroma region, Russia

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Abstract. In the study, the use of a smartphone equipped with a LiDAR sensor for forest stand inventory was analyzed. The accuracy of determining diameter at breast height (DBH), basal area, and stand volume was investigated by comparing the Arboreal Forest app with traditional forest inventory methods. Data from pure Scots pine stands across four temporary sample plots in the Kostroma region (Russia) were examined. Metrics such as *RMSE, MBE, MAE, MAPE*, and R^2 were determined based on statistical analysis and graphical evaluations. A high agreement between DBH and basal area values obtained via the Arboreal Forest app and manual caliper measurements was established, with mean DBH deviations not exceeding ±1.6%. The alignment of diameter class distributions, confirmed by the Kolmogorov-Smirnov test (p = 0.05), was validated across all plots. Permissible deviations in stand basal area and volume (±3.2%) were identified, meeting Russian forest inventory standards. Directions for improving mobile LiDAR-based technologies to enhance forest assessment efficiency were proposed. The potential for scaling this methodology to other forest types was substantiated. Overall, the results demonstrate smartphones' viability as rapid, accurate tools for forest inventory, maintaining compliance with regulatory precision requirements.

1 Introduction

The rapid advancement of technology facilitates the development of innovative, efficient tools for assessing both quantitative and qualitative characteristics of forest resources. Algorithms for forest inventory based on laser scanning can offer broad opportunities for application in the field of forestry research. In forestry research utilizing remote sensing methods, data collected via airborne LiDAR (Light Detection and Ranging) are widely employed. This optical system uses laser beams to generate three-dimensional spatial data models, enabling precise measurements and calculations. M. N. Bazezew et al. [1] argue that ground-based laser scanning provides the most accurate estimation of forest stand parameters. This method allows for highly precise determination of tree heights and trunk diameters [2–4]. D. Panagiotidis et al. [5] demonstrated that combining ground-based and

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airborne LiDAR yields more accurate tree trunk diameter measurements than traditional ground-based inventory methods alone.

Modern mobile devices equipped with LiDAR sensors enable laser scanning functionality to determine individual tree parameters and conduct ground-based forest inventory, as demonstrated by applications developed by foreign developers. According to D. Costantino et al. [6], the key advantages of LiDAR-equipped mobile devices include their lightweight design, compact size, intuitive operation, rapid data transfer capabilities, operational efficiency, real-time imaging, and object geolocation [7]. A. Sandim et al. [8] argue that integrating smartphones with forest inventory applications can significantly improve fieldwork efficiency and reduce implementation costs. This cost-effectiveness stems from the relatively low price of mobile devices, which can replace multiple specialized tools while maintaining data accuracy and quality. A. Sandim et al. [8] evaluated the quality of deriving forest inventory parameters for pine and eucalyptus stands in northern Portugal using Android and iOS-based devices, compared to traditional forest inventory methods. According to the study results, the Swedish Arboreal Forest application demonstrated the closest alignment with instrumental methods in estimating the number of trees per sample plot and their diameter-class distribution. In a related study, Noah A. Howie and Andrea De Stefano [9] compared trunk diameter measurements obtained via the Arboreal Forest app with those from a diameter tape, reporting strong overall agreement but identifying a slight tendency for the app to underestimate diameter values.

In Russia, research on determining forest inventory parameters using mobile devices has only recently begun to develop. A.V. Lebedev (2023) proposes smartphone applications as an effective alternative to traditional forest inventory methods. E.M. Mitrofanov et al. (2024) investigated the application of terrestrial laser scanning via mobile devices for measuring tree heights using three-dimensional terrain models. The authors validated the feasibility of their measurement system through positive assessments of repeatability, reproducibility, and the integration of graphical analysis tools. However, the potential of smartphones equipped with specialized software for determining forest inventory metrics—such as individual tree parameters and stand-level characteristics—during forest area assessments in Russia remains an open question.

The aim of the study is to evaluate the accuracy of determining forest inventory parameters such as trunk diameters at breast height (DBH), stand basal area, and stand volume of Scots pine stands in the Kostroma region - using a LiDAR-equipped smartphone with the Arboreal Forest application, compared to traditional forest inventory methods.

2 Materials and methods

2.1 Methods

The study was conducted in the Kologrivsky (58.820144° N, 44.349788° E) and Manturovsky (58.052989° N, 44.609449° E) districts of the Kostroma Region. The natural and climatic conditions of the study are typical for the central part of the East European Plain [10.]. Data collection was carried out in Scots pine (*Pinus sylvestris* L.) stands.

The diameter at breast height (DBH) of pine trunks was measured using two methods: a Haglöf Mantax Blue caliper, with measurements taken in two mutually perpendicular directions (accuracy: 0.1 cm), and the Arboreal Forest application (v3.50) installed on an Apple iPhone 14 Pro. The mobile application was operated according to the developer's guidelines. Prior to measurements, a ground reference point was established using the smartphone to calibrate tree distances [8]. A full inventory was then conducted within the forest subcompartment boundaries. For app-based measurements, the smartphone camera

was positioned 0,3–1,0 m from the trunk (distance adjusted based on tree size) and aligned at 1,3 m height. The application automatically detected trunk contours and recorded DBH values (accuracy: 0.1 cm). In manual mode, the following data were added as comments for each tree: tree species and caliper-measured DBH (0,1 cm accuracy). Geographic coordinates were auto-recorded by the app. Upon completing the inventory, the following data were exported as a JSON file: tree ID, DBH, number of trunks, measurement date, GPS coordinates (latitude, longitude) and positional accuracy, tree species, and surveyor's comments.

2.2 Data

Following the methodology described above, pine tree measurements were conducted within four sample plots in the forest subcompartment. Parameters for these plots were derived from a full tree inventory using calipers, adhering to generally accepted methods. Field data from Arboreal Forest reports were exported and organized into a Microsoft Excel spreadsheet for statistical analysis. Based on the collected diameter values, average diameters were calculated for each sample plot, and total basal area was computed. The analysis focused on identifying correlations and discrepancies between diameter and basal area values at breast height (1,3 m) obtained via the Arboreal Forest application and those measured using conventional methods.

2.3 Evaluation of the quality

The agreement between diameter-at-breast-height (DBH) values measured using conventional methods and those obtained via the Arboreal Forest application was assessed through graphical analysis and standard statistical metrics: root mean square error (*RMSE*), mean bias error (*MBE*), mean absolute error (*MAE*), mean absolute percentage error (*MAPE*), and the coefficient of determination (R^2).

The goodness-of-fit between the frequency distributions of 4-cm diameter classes (measured with a caliper) and those obtained via Arboreal Forest was assessed using the Kolmogorov-Smirnov test. The analysis was performed in the R computing environment (v4.4.2) at a significance level of $p < 0,05$. [11].

3 Results and discussion

3.1 Measurement results

Graphical visualizations of the relationships between diameter-at-breast-height (DBH, 1.3 m) and basal area values—measured with a caliper and via the Arboreal Forest application—demonstrate strong agreement. Most data points cluster closely around the trend lines, and the coefficients of determination (R^2 = 0,893–0,941 for DBH; R^2 = 0,879–0,925 for basal area) indicate high consistency between the datasets.

Analysis of deviations between diameter-at-breast-height and basal area values measured via Arboreal Forest and caliper methods indicates that the residuals are largely independent and clustered near zero. For DBH measurements on sample plots 1 and 2, a slight underestimation by Arboreal Forest compared to caliper measurements was observed, as evidenced by negative slope coefficients in the trend lines. The low coefficients of determination (R^2 = 0,022 and R^2 = 0,001) suggest no statistically significant relationship

between these deviations. A similar trend for basal area was noted only in sample plot 1, though the R^2 value (0,021) remains negligible.

Analysis of the correspondence metrics for diameter-at-breast-height (DBH, 1,3 m) and total basal area values – measured with a caliper and the Arboreal Forest application across four sample plots (Table 1) – reveals that RMSE values range from 1,157 to 2,677 cm for DBH and from 0,003 to 0,015 m² for basal area. MAE values for DBH fall between 0,805 and 2,038 cm, while basal area *MAE* spans 0,002 to 0,011 m². The *MBE* metric indicates a slight systematic underestimation of DBH and basal area values by Arboreal Forest compared to caliper measurements. The mean absolute percentage error (*MAPE*) for DBH measurements does not exceed 6,437%, whereas basal area MAPE remains below 12,739%. Strong agreement between caliper – and Arboreal Forest-derived values is supported by high coefficients of determination (R^2), ranging from 0,893 to 0,941 for DBH and 0,879 to 1,000 for basal area.

Table 1. Metrics assessing the correspondence between diameter-at-breast-height (DBH) and stand basal area values measured with a caliper versus the Arboreal Forest app.

№ sample plot	***RMSE***	***MBE***	***MAE***	***MAPE***	**R^2**
DBH					
1	1,157	0,235	0,805	5,782	0,941
2	2,677	0,411	2,038	6,437	0,893
3	2,214	-0,273	1,478	5,103	0,913
4	1,745	0,464	1,197	4,506	0,909
Stand basal area					
1	0,003	0,001	0,002	11,438	1,000
2	0,015	0,002	0,011	12,739	0,879
3	0,012	-0,002	0,007	10,416	0,898
4	0,007	0,002	0,005	8,709	0,918

Figure 1 shows the correspondence between diameter classes measured using a caliper and those derived from the Arboreal Forest application. Analysis of the figure reveals no significant deviations in the distribution of trees across diameter classes when comparing caliper measurements with Arboreal Forest results in all sample plots. The Kolmogorov-Smirnov test results confirm that the null hypothesis stating that the diameter class distributions obtained via caliper and Arboreal Forest are identical cannot be rejected at the 0,05-significance level for any sample plot.

Thus, the use of Arboreal Forest during full tree inventories produced diameter-at-breast-height and stand basal area measurements comparable to those derived from caliper-based methods.

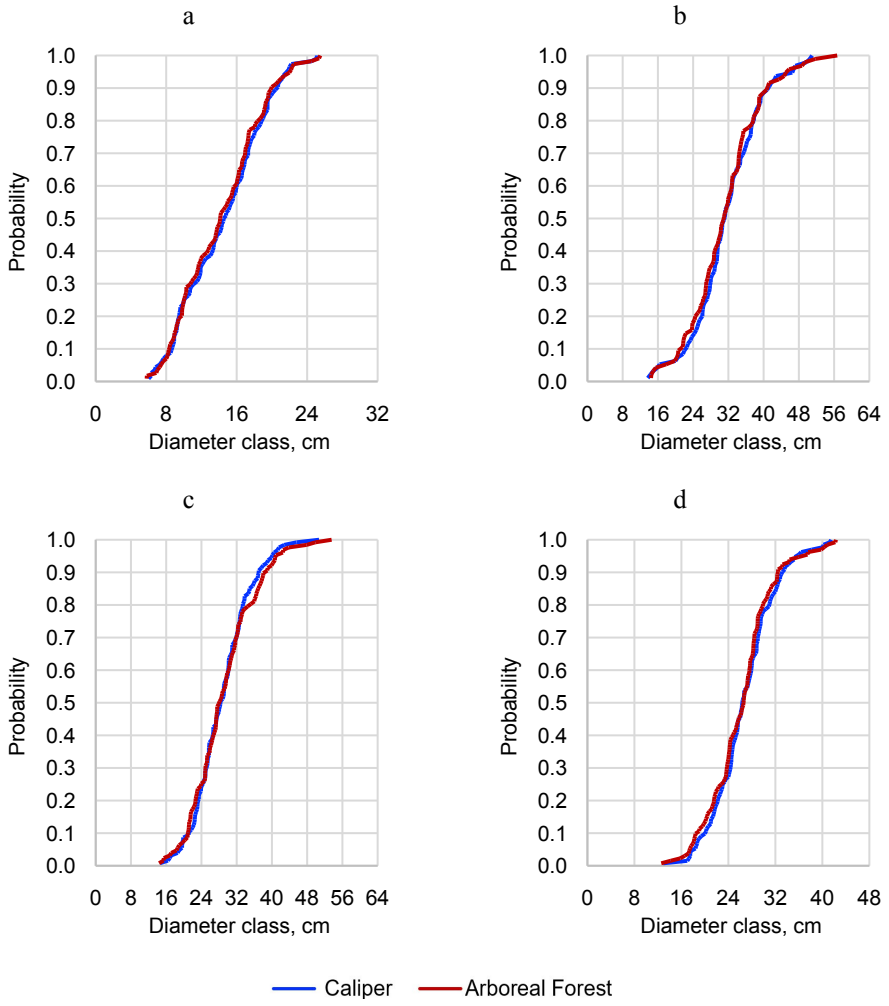

Fig. 1. Correspondence between diameter class established using a caliper and Arboreal Forest: a) sample plot 1 (*KS* = 0,053; *p* = 1,00); b) sample plot 2 (*KS* = 0,074; *p* = 0,96); c) sample plot 3 (*KS* = 0,063; *p* = 0,96); d) sample plot 4 (*KS* = 0,091; *p* = 0,65)

3.2 Discussion

The deviation of the mean diameter calculated via Arboreal Forest from caliper measurements ranged from -0,5 cm (-1,6%) to +0,4 cm (+1,5%), which is within the permissible random error threshold (±10%) for visual-measuring forest inventory methods, as stipulated by Order of the Ministry of Natural Resources of Russia dated March 29, 2018 № 122 (as amended on May 12, 2020) on approval of the Forest Inventory Instructions.

For stand basal area, values derived from Arboreal Forest deviated from caliper-based measurements by -0.2 m^2 (-2,9%) to 0,3 m^2 (3,2%).

The volume of wood is determined using the values of the stand basal areas (*G*), the average height (*H*) and the average form factor (*F*) according to the formula (1):

$$M = G \times H \times F \quad (1)$$

Thus, given consistent values of mean stand height and mean form factor, the accuracy of forest stand volume estimation depends on the total basal area. When determining this parameter using Arboreal Forest for Scots pine stands in the Kostroma region, deviations in volume compared to caliper measurements do not exceed 3,2%, which is within the permissible random error (±15%) for visual-measuring forest inventory methods.

The findings of this study align with domestic and international practices for acquiring forest inventory parameters via laser scanning. The use of LiDAR-equipped smartphones enables accurate measurement of tree trunk metrics (DBH, basal area, volume), achieving precision comparable to traditional instrumental methods, thus proving effective for forest stand inventories [12]. Radtke (2006) reported a pine trunk diameter measurement error of ±1 cm using terrestrial laser scanning. Similarly, G. Liu et al. (2018) achieved an accuracy of ±1,28 cm for DBH measurements of dominant tree species in northwest Yunnan, China, using ground-based LiDAR. S.V. Shaitura et al. (2024) reconstructed 3D sample plot scenes via mobile laser scanning, achieving diameter classification accuracy. A. Holcomb et al. [13] developed a custom mobile app, reporting a DBH error of ±3,7 cm. S.A. Borz et al. [14] attribute measurement discrepancies to inherent LiDAR sensor limitations. Sandim A. et al. [8] emphasize that Arboreal Forest significantly reduces measurement time compared to manual methods while meeting accuracy requirements for DBH determination.

The impact of habitat conditions on the accuracy of smartphone-based forest inventory remains underexplored in global literature [12]. Significant challenges arise when using mobile devices to measure tree heights due to dense undergrowth, canopy closure, insufficient lighting, and device-specific limitations. In Russia, research on the effectiveness of mobile devices for forest inventory remains limited.

A potential solution lies in developing regionalized forest inventory algorithms for mobile devices, incorporating stem taper functions and local growth-dependent height-diameter models validated against regional datasets.

4 Conclusions

The accuracy of determining diameter-at-breast-height (DBH) and basal area values for Scots pine (Pinus sylvestris) trunks using the Arboreal Forest mobile application (Apple iPhone 14 Pro) was analyzed during full tree inventories on sample plots. Graphical analysis and statistical metrics (*RMSE, MAE, R^2*) demonstrated strong agreement between Arboreal Forest and caliper-derived DBH and basal area measurements. The Kolmogorov-Smirnov test confirmed consistency in the distribution of diameter classes obtained via both methods. For Scots pine stands in the Kostroma region, deviations in mean DBH values measured by Arboreal Forest versus calipers did not exceed 1,6%, while total basal area and stand volume deviations remained within 3,2%. These results align with acceptable accuracy thresholds for visual-measuring forest inventory methods. Further research should focus on refining forest inventory protocols using LiDAR-equipped smartphones to enhance operational efficiency while maintaining measurement precision.

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