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ORIGINAL PAPER

# Precision forestry: an open-source IoT digital caliper and app to simplify tree diameter measurements

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**Abstract** Forest planning involves estimating the biomass of species present in the area. Two fundamental parameters are diameter and height through which it is possible to indirectly estimate of biomass present. Digitalisation of forestry operations, such as forest planning, is crucial and should be affordable and easy-to-use digital applications and open-source devices. A digital progressive web application (PWA) was designed to record measurements. The app was connected via bluetoot to an open-source IoT digital forestry caliper prototyped by modifying a commercial tree caliper. An economic analysis was carried out considering all costs necessary for the development and operation of the app on smartphones and the preparation of electronic means for creation of the digital caliper. A comparison was made between costs of detecting tree diameters through application of the technology developed compared to costs calculated by applying the use of a dendrometric caliper (three technological levels were considered: *L1*, *L2* and *L3*). The PWA allowed for easy data entry and viewing, maps and tree densities. The open-source digital caliper showed accuracy and precision comparable with similar commercial devices (1.5% ± 0.9% and 0.0% ± 0.9%, respectively). Total time per operator was lower using the digital caliper. From an economic perspective, application of the digital technology was more sustainable than the traditional system. Use of the digital caliper in combination with the web application optimizes detection time of a single tree, and therefore decreases overall cost.

**Keywords** Digital forestry · Forestry planning · Dendrometric instruments · Bluetooth · Progressive web application · Economic analysis

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## Introduction

Precision forestry (PF), considered a branch of precision agriculture, is defined as "the discipline that uses computer devices to improve forest management through measurements and data collection in order to obtain a decision support system" (Lubello and Cavalli 2006). It may be applied in different forest sectors, from planning to traceability in the wood supply chain (Corona et al. 2017). PF is an area that deals with the use of modern information and communication technologies (ICT) for the sustainable management of all forestry activities. The term "precision" refers to the use of computers, sensing technologies and other ICT devices to coordinate and control spatial processes and to manage temporal variability. The term "forestry" is understood in a broad sense and includes monitoring, planning, and management activities and the use of forest resources (Kovácsová and Antalová 2010). The concept of PF refers to the use of methods and technologies to obtain detailed information about forest systems in order to improve decision-making and ensure the achievement of sustainable forest management objectives. In a modern vision, PF also extends to the classification, testing and initial processing of wood and the marketing and certification of both forest products and those of ecosystemic utility (Corona et al. 2022). PF was created because, in recent years, even in forest management, there has been a growing use of tools that allow the collection and analysis of data through sensors, drones, and also using artificial intelligence (AI) algorithms (Gabrys 2020). Digital technologies used in forestry include airborne laser scanning (ALS). This technique has increased measurement efficiency in inventories by improving forest planning (Goodbody et al. 2019).

In forest planning, another aspect to consider is the utilization of high mechanization. Some dendrometric surveys can be carried out starting from machines used for felling and producing timber assortments. In fact, most modern timber harvesters have a felling head that integrates sensors capable of measuring the diameter of the stems and their length and transferring this data to the forwarder who will load the logs. Measurement, however, takes place a posteriori at the time of harvesting the tree. It, therefore, loses its usefulness with regards to the decision-making aspect of the quantity of wood being removed which is fundamental, however, in the management planning phase, i.e., the phase in which the forest survey, a priori, constitutes a fundamental variable for the orientation of choices. Sensors mounted on the arms of the harvester head are able to measure the length of the logs and, consequently, the volume of the commercial assortment and not the volume of the whole tree. This leads to underestimating the overall biomass produced as the part of branches eliminated by the knives during the sliding of the trunk on the header is not counted. The choice of roller size is essential to avoid errors in length measurements (Strubergs et al. 2018). In addition, generally for smaller trees, the harvester underestimates the volumes (Brewer et al. 2018).

Unlike traditional instruments, digital tools allow for more precise measurements, especially diameters or the distance between the trees. There are optical sensors that use lasers to count trees and measure their diameter; other techniques, through the detection of illuminated line segments, can determine diameters. LiDAR technology also allows diameters to be measured, although this is often overestimated due to bark irregularities (Weaver 2014). Tree marking can also be performed by tablet marking, which involves marking of groups of trees by GIS or LiDAR (Rainey 2021). Keresztfalvi and Pásztory (2020) proposed an app to measure tree diameters, namely "MobileForester". This, unlike a traditional dendrometric caliper, can perform the task even at a distance of 50 m. First, the distance from the tree is measured by zooming in on the tree and then, thanks to an algorithm provided, the correct measurement is made. If this is not considered correct, it can be repeated or modified. This technology prevents the need to measure the diameter manually. Yuan et al. (2021) proposed an intelligent electronic device (IED) of accurately and efficiently measure diameters and heights using an algorithm and sensors. Both metrics are not transcribed manually by the operator but loaded through a software installed in a personal computer and downloaded from it. One method for measuring diameter is to use passive (a smartphone) and active (a laser ranger) optical sensors. The sensor measures the horizontal distance from the operator to the tree trunk, and the image is captured via a smartphone. Next, an automatic detection algorithm is used to identify the trunk within the image, and the diameter is measured by combining the horizontal distance using photogrammetry (Shao et al. 2022). Li et al. (2023) developed an intelligent device to digitally measure tree diameters. The instrument uses a classic caliper. If the trunk is irregular, the diameter is calculated several times, and finally provides an average. The instrument is connected to a computer and the data can be uploaded into the PC software to perform statistics and analysis.

Another modern technique for measuring diameters involves the combination of AI and photogrammetry. AI extracts the contour of the trunk and then, through the image of the tree and the pixel coordinates and the coordinates of the space, the diameter is obtained. In a study by Wu et al. (2019), this technique had the absolute error is $< 0.24$ cm and the relative error is less than 1.27%.

The technologies indicated represent an overview of the digital tools currently available on the market and in the world of research (prototypes). They are certainly tools that simplify the action of operators in the forest but do not predict results in real time. In fact, the data must be processed using complex software or downloaded from the software onto a PC. For this reason, the aim of this study is to present a digital tool that can be effective in the phase of log marking operations and that can give results and analysis in real time. This tool is a prototype of a digital forest dendrometric caliper that measures diameters using a classic dendrometric caliper as a basis. However, it is connected via Bluetooth to an app that digitally records the diameters, avoiding human errors in manually reporting. It is an open-source and low-cost tool. In addition to the presentation of the prototype, an analysis was carried out to verify the economic sustainability of this digital tool in the field.

Some studies have reported the use of smartphone apps for forest management. Specifically, Ferster et al. (2013) used a smartphone app to collect data on forest fuels, fires, and the forest communities. Kangas et al. (2015) also developed a smartphone application to collect site-specific views of recreational and aesthetic characteristics of forests and forest management. The use of apps makes it possible to increase forest activities and reduce errors due to manual writing (Corona et al. 2022).

The aim of this study was to evaluate the technical and economic sustainability of using an innovative dendrometric tool for detecting forest tree diameters. The tool consists of a digital caliper connected to a smartphone app that records diameters through the caliper, reducing both measurement times and human errors related to field manual recording and office digital data transcription. The prototype caliper design is open-source and its production will be less expensive compared with similar products on the market. The open-source device, to accomplish the low production cost, is equipped with a laser sensor that estimates range diameters with an accuracy of 1 cm as tested in laboratory and field tests.

## Materials and methods

### Experiment description

A dedicated web-app for mobile devices was developed to collect tree data and to record dendrometric statistics directly in the field. The web-app is also capable of graph and map data visualization and can upload data on to the cloud on a user repository, also visible by a browser. Relatedly, an open-source digital caliper was designed and developed starting from a traditional one. The digital caliper measures the diameter through a laser sensor and associates it to a user selected species. All caliper data are sent automatically to the web-application via Bluetooth. An experimental survey data collection in a coniferous stand has been designed and recorded to verify the timing and economic advantages of using the new digital caliper in conjunction with the web-app versus the traditional caliper and paper data collection.

### Web-app

The web-app allows for the integration of different levels of information with digital systems based on radiofrequency or QR code for traceability of wood along the supply chain. The web-app provides search functions and reconstruction of the supply chain of a product. The progressive web application (PWA) is combined with an electronic caliper for reading diameters and is designed for data entry via voice dictation, recording and transmission via Bluetooth connection. PWA development is based on the Ionic framework, a toolkit for developing multiplatform web, iOS and Android apps in JavaScript. The system can make the PWA interact at low levels with the smartphone's Bluetooth sensors and GNSS positioning interfaces, offering the possibility of using the PWA without data connection by configuring an off-line mode. The Ionic framework will also allow in the future to deliver the same PWA as an installable app from the Android and the iOS app store.

The user can manage more operations of log marking, called generically reliefs, and in each, they can insert a list of trees specifying their main characteristics such as species and diameter. The user is facilitated in their operation through various automatisms:

(1) The position of each tree, with low precision derived from a single fix smartphone GNSS, is automatically stored and used for subsequent GIS (geographical information system) processing;

(2) The user can enter the tree data with a virtual numeric keypad which is facilitated by the voice recognition of the dictation of the species (Ortenzi et al. 2021);

(3) The user can insert diameters through an automatic reading of the electronic caliper connected via Bluetooth;

(4) The relevant characteristics of the inserted trees are automatically calculated in real time due to defining models for each species to estimate height and volume based on the diameter;

(5) The collected data are automatically transmitted and stored in a space reserved for the user on an internet cloud platform and can be read and downloaded from other devices, for example, an office desktop computer.

To communicate with the mobile app, the electronic caliper uses a Generic Attribute Profile (GATT) via Bluetooth Low Energy (BLE), through which the measurements and other attributes necessary for dialogue between the caliper and the smartphone are exchanged.

### Open-source digital forestry stand hardware-software prototype IoT

A prototype of IoT open-source digital forest caliper (Fig. 1) was developed by modifying a commercial forest caliper


**Fig. 1** A prototype of IoT open-source digital forest caliper: **A** PCB and electronics design exposed; **B** placement of the time-of-flight sensor; **C** buttons placement and overall shape

(range 0–80 cm). The sliding portion of the caliper was modified by integrating a custom PCB board (Open-Hardware Laboratory of CREA-IT Monterotondo, Rome, Italy) with a laser distance metre sensor with time-of-flight (ToF) technology, a microcontroller to interface sensor ToF, a Bluetooth low energy (BLE) module for sending data and an OLED display. The following information is displayed on the OLED display:

(1) Last measurement;

(2) Percentage of battery;

(3) Confirmation of sending the data.

The circuit includes six buttons:

(1) Ergonomically positioned side button for measurement;

(2) For quick selection of three favourite species (identifiable by the connect-ed app);

(3) To scroll between other species potentially present (identifiable by the connected app).

The frame of the mobile part of the caliper was custom made using 3D modelling and printing methods at the Open-Hardware Laboratory of CREA-IT Monterotondo. The software is in C language and provides the following features: correction of the acquired data by calibration equation obtained empirically using a fitting polynomial model (second degree) based on approximately 1000 measurements; data temporary recorder until sending to the dedicated app; Bluetooth BLE with the generic attribute profile (GATT), which is a general specification for sending and receiving short pieces of data known as "attributes" over a BLE link. Hardware and software were completed in February 2022 (Fig. 2).

The forestry electronic caliper uses the measuring principle through a 940 nm ToF laser sensor. The control electronics consists of Arduino BLE 33 sense which is equipped with BLE and various sensors, including a 3-axis accelerometer is used as a level to help, where necessary, to improve the measurement of the diameter. The device is equipped with a display for the control of the measurement and technological level.

### Description of the experiment

The analysis was aimed at evaluating, from a technical and economic point of view, the application of digital technology in dendrometric surveys. To this end, experimental tests aimed at analyzing the times required to detect the tree diameters. The study area was located within the Ovile farm of the CREA-FL Research Centre in Rome, in central Italy (41°54′28.68" N; 12°21′33.92" E). Two plots of 15 trees each were selected, the first a monospecific stand (MS), with only *Pinus eldarica* Medw.; for the second polyspecific stand (PS), there were three species (*P. eldarica* Medw., *Cedrus atlantica* Man. and *Cedrus libani* A. Rich.). The experiment used instruments of increasing technological level in diameter detection: the low-tech level (*L1*) used the traditional dendrometric caliper; the medium-tech level (*L2*) used the dendrometric caliper and APP application on smartphone; and, the high-tech level (*L3*) used a self-assembling digital electronic caliper and APP on smartphone. For the *L1*

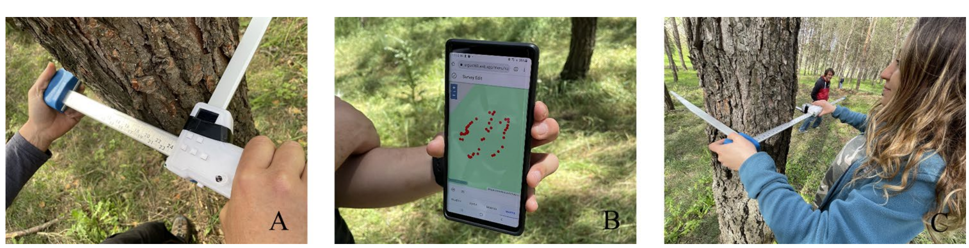


**Fig. 2** Hardware and software use-case; **A** detail of the complete prototype; **B** Detail of the web-app, GPS tagging section; **C** Operator testing the tool

level, the survey was carried out by two operators, one who measured with a caliper and a second who recorded in a notebook. For the *L2* level, two operators were employed, the first for the direct measurement, the second for annotating the data on the smartphone via the APP application. The *L3* level involved the use of a single operator with an electronic-digital caliper and automatic recording on the APP, directly via the caliper buttons. In the MF plot, diameter measurements were carried out by three forestry operators with different levels of experience: *O1*, highly experienced; *O2*, medium experience; *O3*, little experience. For each technological level, three repetitions were carried out for each operator. In the PF plot, only the *O1* and *O2* operators were employed, with two repetitions for each.

### Time study and experimental dataset

The time study was to determine the operating detection time (*DT*) for diameter at breast height (DBH) for each tree in a sample plot. It was divided into moving time (*MT*), i.e., the time required to move from one tree to another, and reading time (*RT*), i.e., the time needed for the operator to place the caliper against the tree and speak the measurement. The data transcription time (*TT*) has been added to these direct times and represents the average time required for an operator to order and transcribe the data on digital support. This time was estimated at around 25% of *DT* for *L1* (data transfer from notebook to digital support), while it was around 2% of *DT* for *L2* and *L3* as the use of the APP automatically prepared the data on digital support, for which the digitization time is extremely short. The overall gross time (*GT*) was then obtained with the following formula (1):

$$GT = MT + RT + TT \tag{1}$$

where all the times were expressed in seconds ind$^{-1}$.

The acquisition of the times was carried out by making videos in the woods for each survey and subsequently re-examining them in the laboratory by extracting the times with a still image. A total of 315 observations were made in MF and 90 in *PF*.

### Statistical analysis

To measure the accuracy and precision of the dendrometric digital caliper, 50 replications (manual and digital) were acquired on a fixed 49-cm diameter trunk. Accuracy and precision of the instrument were calculated according to the formulas (2) and (3):

$$Accuracy = \frac{Measuredvalue - truevalue}{\text{true value}} \times 100 \tag{2}$$

$$Precision = \frac{Measured\ value - Medium\ value}{Medium\ value} \times 100 \tag{3}$$

Statistical analysis was developed based on the two datasets of 315 and 90 records, referring respectively, to surveys in monospecific and polyspecific stands. Each observation included the following variables: DBH, moving time (*MT*), reading time (*RT*), operating detection time (*DT*), data transcription time (*TT*), total time (*GT*), cost per tree (*Ct*), and cost per hectare (*Cha*). The latter was calculated considering an average stand density of 500 trees per hectare.

Statistical analyses were performed on both the measurements taken to extract the diameters and the time taken to perform the measurement. For both, differences between the three levels, *L1*, *L2* and *L3*, and the *O1*, *O2* and *O3* operators were analysed. A two-way ANOVA test was applied to estimate how the mean of a quantitative variable changes, based on the levels of two categorical variables. Two-way ANOVA is used to understand how two independent variables, in combination, affect a dependent variable (Kim 2017). All variables were tested for normality and homogeneity of variance of the distributions using the Shapiro–Wilk test and the Levene test, respectively. ANOVA and Tuckey's post hoc test highlighted the significant differences between the means of the groups and their classification in homogeneous groups with a level of significance of $p < 0.05$. The non-parametric Kruskal Wallis test was performed for variables with non-normal distributions. This test was performed using the free PAST software (2.17c, Øyvind Hammer, Museum of Natural History, University of Oslo, Oslo, Norway).

### Economic analysis

This considered all necessary costs for the development and management of the APP on smartphones, and for the preparation and purchase of electronic supports for the electronic-digital caliper, and the cost for surveying in the woods by applying the technology developed. These costs were compared with those of a traditional survey system using a traditional dendrometric caliper. The calculation includes the depreciation rates of the tools and the hourly rate attributed to the technicians for the construction of the tools and the field survey. As regards to the calculation of amortization rates of the instruments, 10 years was considered with 100 h a$^{-1}$ of effective use of the traditional dendrometric caliper, and 5 years and 100 h a$^{-1}$ for the APP and the electronic-digital caliper. Table 1 shows both the main elements considered for the calculation and the related hourly costs for each technological level considered.

Hourly costs of the survey, divided by the technological level of the tools, was calculated using formulas (4), (5) and (6):

**Table 1** Technical-economic elements for the economic analysis and relative hourly costs, distinguished by technological level used in surveying

| Description | | Basic cost of the dendrometric caliper (€) | Depreciation period of dendrometric caliper (years) | Cost of making APP on Smartphone (€) | Initial cost of making electronic circuits (€) | Depreciation period of the APP and electronic devices (years) | Working times to implemented electronic boards (h) | Gross rate for forestry operators (€/h) |
|---|---|---|---|---|---|---|---|---|
| Technological level of the diameter detection tool | *L1*–Traditional caliper | 115 | 10 | – | – | – | – | 34.65 |
| | *L2*–Traditional caliper with APP on Smartphone | 115 | 10 | 1500 | – | 5 | – | 34.65 |
| | *L3*–Electronic-digital caliper with APP on Smartphone | 115 | 10 | 1500 | 4851 | 5 | 140 | 34.65 |

| Description | | Cost of purchase of materials for the digital caliper (€) | Annual cost of digital device updates (€/a) | Engaged forestry operators (N.) | Data transcription time (% of detection time) | Total hourly cost of the survey (€/h) | Total cost of the survey (€/s) | Data transcription cost (€/s) |
|---|---|---|---|---|---|---|---|---|
| Technological level of the diameter detection tool | *L1*–Traditional caliper | – | – | 2 | 25 | 69.42 | 0.019 | 0.01 |
| | *L2*–Traditional caliper with APP on Smartphone | – | – | 2 | 2 | 72.42 | 0.02 | 0.01 |
| | *L3*–Electronic-digital caliper with APP on Smartphone | 180 | 120 | 1 | 2 | 49.03 | 0.014 | 0.01 |

$$CL1 = \frac{Ccal}{(Yt \times Ht)} + Top \times N1 \quad (4)$$

$$CL2 = \frac{Ccal}{(Yt \times Ht)} + \frac{Capp}{(Yd \times Hd)} + Top \times N2 \quad (5)$$

$$CL3 = \frac{Ccal}{(Yt \times Ht)} + \frac{Capp + Ccir + Cmat}{(Yd \times Hd)} + Top \times N3 \quad (6)$$

where: *CL1*, *CL2* and *CL3* are the hourly costs for the survey applying the technological level *L1*, *L2* and *L3*, respectively; *Ccal* is the cost of the traditional dendrometric caliper; *Top* is the hourly rate of forestry operators; *N1*, *N2* and *N3* are the number of forestry operators involved in relation to the technological level applied (2 operators for *L1* and *L2*, and 1 operator for *L3*); *Capp* is the cost of the APP implementation; *Ccir* is the cost of electronic circuits; *Cmat* is the cost of electronic materials; *Yt* and *Yd* are the years of depreciation of traditional and digital devices; *Ht* and *Hd* are the hours of annual use of traditional and digital devices.

## Results

### Performance of technologies and statistical analysis

The accuracy and precision of the instrument used on 50 repeated measurements of a 50- cm trunk showed values of 1.5% ± 0.9% and 0.0% ± 0.9% respectively.

With regards the detection times of diameters for each tree, those carried out with a digital electronic caliper were longer. They increased on average when moving from a monospecific stand to a polyspecific one and as the detector's experience decreased. A comparison of the results was considered based on the grouping factors represented by the level of applied technology and the experience of the operators. Figure 3 shows the differences between DBH and the different time variables as a function of the three technological levels in the two stand types, considering all the surveys carried out without accounting for the difference in operator experience. The Shapiro–Wilk normality test and the Levene homoskedasticity (i.e., homogeneity of variance) test were performed on all data, rejecting the null hypotheses (i.e., data non-normally distributed and heteroskedastic) ($p < 0.05$). In Fig. 3, the Kruskal–Wallis non-parametric ANOVA test evaluated the median differences among the three technological *L1*, *L2*, *L3* levels within each time variables (*MT*, *RT*, *DT*, *TT*, *GT*) and diameter, to highlight the statistical differences between the variables. No statistical difference was found in the measurement of the diameters with reference to the application of the three technological levels ($p > 0.05$). Statistical differences were found for both stand types only with regards to the reading time (*RT*; $p < 0.05$) and detection time (*DT*; $p < 0.05$), which are both greater for *L3*, while the data transcription time (*TT*; $p < 0.05$) is greater for *L1*, then *L3* a finally *L2*.

In Fig. 4, times are examined according to the grouping factor represented by the level of experience of the operators for the two stands. There were no significant differences (Kruskal–Wallis test; $p > 0.05$) found in diameter measurements with reference to the forestry operators, while statistical differences were found for both stand types for all the times recorded (*MT*, *RT*, *DT* and *CT*), with the exception of the transcription time (*TT*). The less experienced operator *O3* scored the longest times. Considering the different operator working gross time (*GT*), there is a clear statistical difference between the more experienced one (*O1*), who recorded shorter detection times compared to the less experienced one in the monospecific stand. In polyspecific stand, the most expert operator had statistically shorter detection times than the average operator.

The results of the two-way ANOVA on both measurements and times datasets are shown in Tables 2 and 3. The interaction between the technological level and the forestry operator showed no significant difference in diameter measurement (Table 2). The technological level did not show a significant difference ($p < 0.05$); this indicates that the technological level does not quantitatively influence the measurements. The forestry operator showed a significant difference ($p < 0.05$), confirming, in some way, the subjectivity of the manual measurement (*L1*, *L2*).

Table 3 shows the results of the two-way ANOVAs on the different time variables for measurements for monospecific and polyspecific stands. The results show highly significant differences ($p < 0.001$) for reading time (*RT*) between forestry operator and technological level for the polyspecific stand. Also, for the monospecific stand, the higher F value has been shown to be the time for reading (*RT*; F = 22.89; $p < 0.001$).

## Economic analysis

Figure 5 compares the average values of cost per tree and per hectare, grouped respectively by technological level and experience of the forestry operators. It also shows the

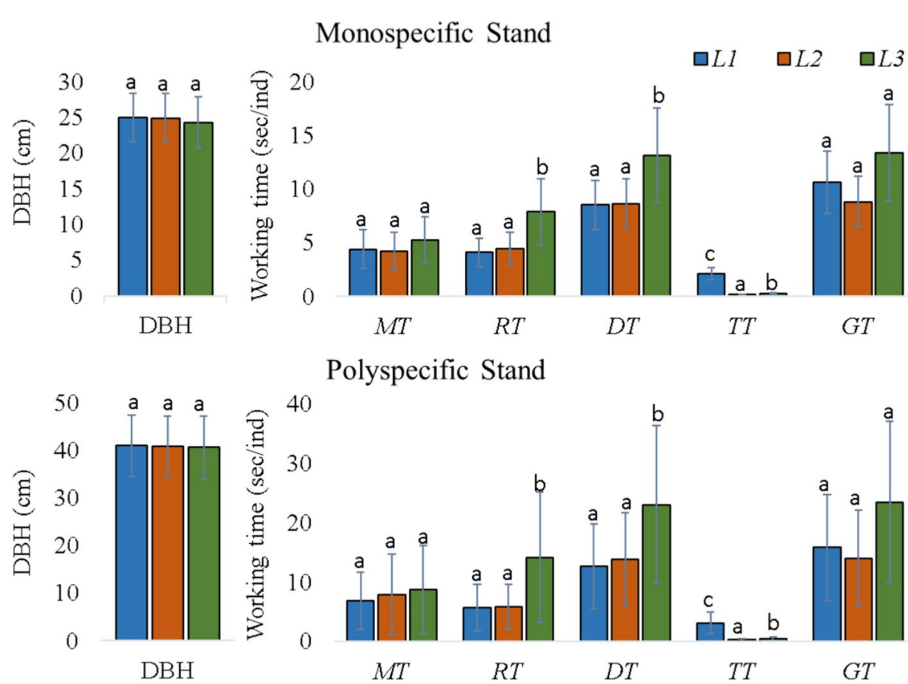


**Fig. 3** Average DBH values (cm) and working times (sec/ind) distinguished according to the technological level (*L1*, low; *L2*, medium; *L3*, high) in the two stands; working time divided into: *MT*, moving time; *RT*, reading time; *DT*, detection time; *TT*, transcription data time; *GT*, total gross time; letters indicate a statistically significant difference ($p < 0.05$)

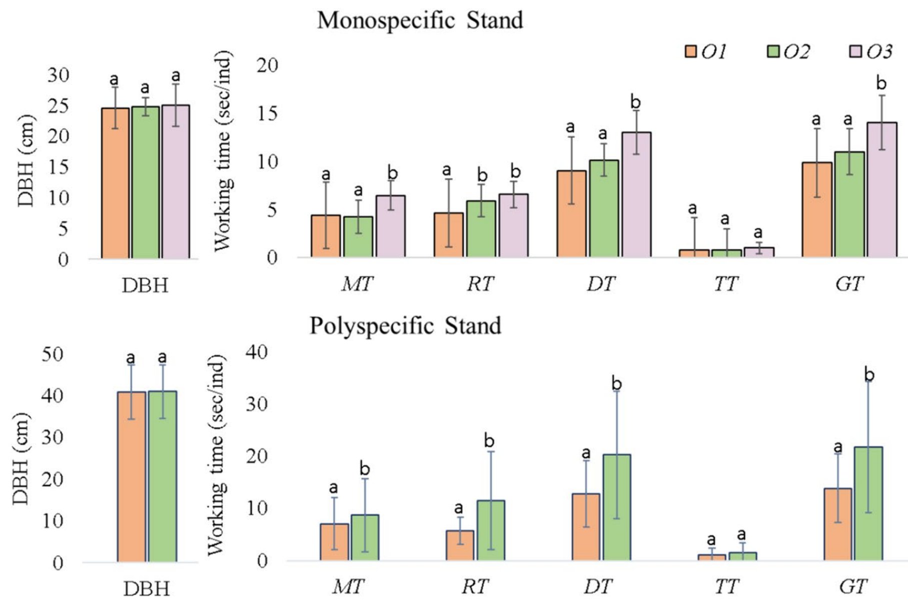


**Fig. 4** Average values of DBH (cm) and working times (in sec/ind) based on the degree of experience of the technician (*O1*, high; *O2*, medium; *O3*, low) in the two stands; working time divided into: *MT*, moving time; *RT*, reading time; *DT*, detection time; *TT*, transcription data time; *GT*, total gross time. Different letters indicate a statistically significant difference ($p < 0.05$)

**Table 2** Two-way ANOVA based on diameter measurements for the monospecific and polyspecific datasets

| Parameters | Sumsqrs | df | Meansqr | F | *p* |
|---|---|---|---|---|---|
| Forestry operator | 8.10E+04 | 2 | 4.05E+04 | 5.863 | 0.00407 |
| Technological Level | 29.25 | 2 | 14.62 | 0.002541 | 0.9975 |
| Interaction | 16.59 | 4 | 4.147 | −0.00061 | 1 |
| AxSub | 6.08E+05 | 88 | 6906 | | |
| BxSub | 5.06E+05 | 88 | 5755 | | |
| AxBxSub | −1.19E+06 | 176 | −6753 | | |

detection productivity values (*DP*) for operator and the three technological levels. This highlights the differences between the three technological levels. The *DP* values, in fact, always increased with the increase in the technological level and with the increase of operator experience. For the more experienced operator (*O1*), the highest productivity was always recorded using the digital caliper (*L3*) with values ranging from 325 ind $h^{-1}$ in the monospecific stand to 236 ind $h^{-1}$ in the polyspecific stand. The less experienced operator however, had a productivity of 198 and 146 ind $h^{-1}$ respectively. The increase in productivity in the monospecific stand was 38% compared to the polyspecific one while, with respect to the experience of the operators, the increase in productivity of the more experienced rose to 64% in the monospecific stand and 62% in the polyspecific one.

Figure 5 shows that, in general, a higher detection productivity was achieved for the more experienced operator (*O1*), and consequently, also lower costs per tree and per hectare compared to the least experienced operator. Compared to the level of technology, the more expert forestry operator reduced costs more by applying high technology (*L3*) compared to surveys with traditional technology (*L1*).

**Table 3** F values of the two-way ANOVAs based on the different time variables for measurements for monospecific and polyspecific stands

| Two-way ANOVAs | Parameters | Moving time *MT* (s) | Reading time *RT* (s) | Detection time *DT* (s/team) | Transcription time *TT* (s) | Gross time *GT* (s) | Detection productivity *DP* (ind $h^{-1}$ $op^{-1}$) |
|---|---|---|---|---|---|---|---|
| Monospecific stand | Forestry operator | 27.61*** | 27.65*** | 36.23*** | 6.446** | 34.37*** | 26.39*** |
| | Technological level | 9.984*** | 144.7*** | 98.77*** | 1169*** | 65.01*** | 80.91*** |
| | Interaction | 0.6596 | 22.89*** | 12.72*** | 2.074 | 10.87*** | 6.33*** |
| Polyspecific stand | Forestry operator | 1.583 | 26.49*** | 17.58*** | 4.083* | 16.98*** | 24.82*** |
| | Technological level | 0.7523 | 24.14*** | 13.52*** | 75*** | 9.04*** | 3.659* |
| | Interaction | 0.1759 | 5.484** | 2.29 | 1.361 | 1.78 | 1.771 |

*$p < 0.05$, **$p < 0.01$, *** $p < 0.001$

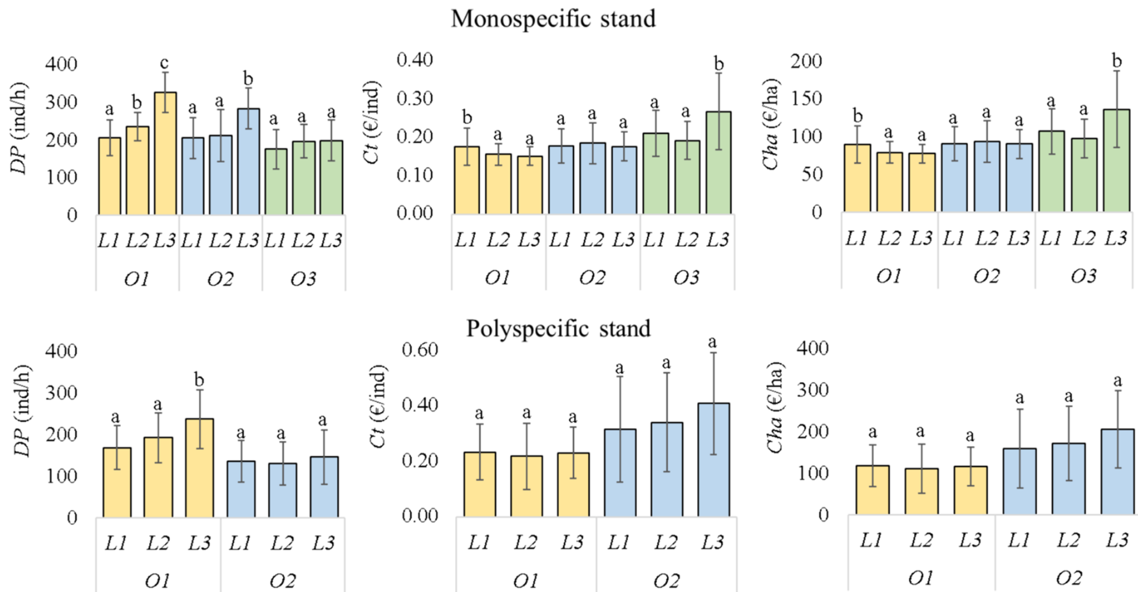


**Fig. 5** Detection productivity (*DP*, ind $h^{-1}$ per operator), cost per tree (*Ct*, € $ind^{-1}$) and cost per hectare (*Cha*, € $ha^{-1}$) according to technological level (*L1*, *L2* and *L3*) and expertise of the forestry operator (*O1*, *O2* and *O3*) in the monospecific (*MF*) and the polyspecific stands (*PF*). Different letters indicate a statistically significant difference (Kruskal–Wallis's test; $p < 0.05$)

Conversely, these costs of the *L3* level, compared to the *L1* level, tended to increase with less experienced operators.

From an economic consideration, the application of digital technology was more sustainable than that conducted with the traditional system.

In the monospecific stand, costs per tree with level *L3* vary from 0.15 € $ind^{-1}$ to 0.27 € $ind^{-1}$, passing from the most experienced to the least experienced. In the polyspecific stand, these rose to 0.23 and 0.41 € $ind^{-1}$ respectively. The cost per hectare of the L3 technology was 77 € for expert operators and 136 € $ha^{-1}$ for those less experienced in the monospecific stand, while in the polyspecific one, the costs were 116 and 204 € $ha^{-1}$ respectively. Compared to traditional technology, digital technology applied by experts allowed for savings of about 16% in the monospecific stand and just over 1% in the polyspecific one.

The results of the two-way ANOVA analysis on costs in monospecific and polyspecific stands are shown in Table 4. Considering the monospecific stand, for all three variables (*Ct*, *Cha*, Time), the interactions between operators and technological levels were significant. Considering the polyspecific stand, significant differences were observed only for the factor forestry operator.

## Discussion

According to García Morote et al. (2021), forests are complex systems from a structural and functional point of view. They provide products and energy, but also enable the reduction of greenhouse gas emissions by carbon dioxide sequestration. Precisely because of the important role that forest ecosystems play, there is a need for their sustainable management using technologies such as sensors, automation systems, IoT and AI systems that enable optimization of field operations while decreasing costs and time (Chirico and Bonavolonia 2020). In this sense, precision forestry plays a key role as it allows the application of non-destructive

**Table 4** F values of the two-way ANOVA based on costs for measuring for monospecific and polyspecific stands

| Two-way ANOVAs | Parameters | *Ct* (€/ind) | *Cha* (€/ha) | Time (h/ha/op) |
|---|---|---|---|---|
| Monospecific Stand | Forestry operator | 30.31*** | 30*** | 24.5*** |
| | Technological level | 1.761 | 0.9724 | 47.73*** |
| | Interaction | 6.878*** | 6.862*** | 3.848** |
| Polyspecific Stand | Forestry operator | 16*** | 16.06*** | 14.3*** |
| | Technological level | 0.8121 | 0.8107 | 1.138 |
| | Interaction | 0.7691 | 0.7736 | 0.2271 |

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

techniques, for example, forest inventorying (Singh et al. 2022). IoT allows real-time monitoring of forests (Singh et al. 2022). An important parameter to measure for better planning of forestry activities is diameter which, measured with the traditional dendrometric caliper, requires high cost and manpower. It involves manual recording, which is not only time-consuming but is also subject to human error (Li et al. 2023). However, to overcome these problems, new dendrometric instruments are available that allow automatic data storage. The digital caliper records diameters, possibly with other characteristics of each tree, which are then transmitted to a personal computer directly in the field via Bluetooth® and/or infrared ports or via a USB connection. Laser or ultrasonic hypsometers can measure heights and transmit the information directly to the electronic caliper (Corona et al. 2022).

The benefits of the use of this technological open-source caliper are the use of microelectronics combined with 3D printing techniques. In fact, the increasing use of embedded chips and sensors opens the way for new engineering scenarios for increasingly low-cost devices. This offers the opportunity to transform an analogue into a digital one, with all the current innovations, giving the possibility of upgrading instrumentation and optimizing work time. The main innovation concerns the use of wireless technologies such as Bluetooth to make the device "smart" in combination with a specific app (Corona et al. 2022).

Digitalization of field operations contribute to cut survey costs, both during data collection and office data processing. First, the automatization of digital data storing on a smart device and the automatic data validation provided by the web application reduces the cost of personnel dedicated to field data logging activities. As shown by the survey time measurements in this study, the digital caliper connected to the web application efficiently eliminates the necessity of a personnel unit dedicated to log data. Even in small survey teams, where a decrease of workers is not possible for safety reasons, cost reduction could be obtained by dedicating all the surveyors to data collection on their own devices without the necessity of a logging unit.

The digitalization of data acquisition also improves survey operations, enabling the possibility to automatically elaborate data statistics in real time directly in field on the device. In the web application presented in this study, the continuous updating after each tree insertion is noted of average diameter, average basal area and, thanks to species volumetric models set in the application, the volume of each tree and the total per hectare. This allows, during the succession of tree insertions in the web application, to obtain useful information to calibrate the survey operation. The developed web application could also aggregate data using histograms or a volume density map, owing to the geolocation of each inserted tree.

The complete survey data digitalisation provided by the digital caliper, the functionalities to elaborate, validate and Cloud upload of the survey results offered by the web-app, considerably reduces the post-processing time spent after a classical paper-based survey. The cost of office data elaborations is not high as field operations, but are crucial for data validation. Data validation from office post-processing to field operations, using the web-app, minimizes the need for an additional survey to repeat or integrate the data collected, that due to costs, frequently imply the acceptance of the error.

The results of field tests and analysis indicate that the use of digital callipers in combination with the web application, even with an increase in single tree detection time, reduces of total cost. The timing differences between the various technologies are in the order of a few seconds, and the missing industrial-level optimization of the experimental digital caliper and the limited familiarity of the operators with its use should be considered as it possibly required them to frequently add time to check the automatic measurements.

In addition, to lower overall costs of a digital survey, the web-app automatically provide functions to produce data analysis of the main statistics (e.g., basimetric area per hectare—G/ha, wood volume per hectare—V/ha), graphics of data distribution by species, and geographical raster maps of volume and diameter distribution. These continuously updated statistics and graphs allow to easily check the achievement of predetermined survey targets and, eventually, to correct the evolution of the field operations.

The immediate benefit of survey digitization is to no longer use paper datasheets and transcribe and elaborate data in a dedicated office activity. This benefit eliminates transcription errors and drastically reduces subsequent data processing times. The automatic acquisition of the geographic position of each tree allows the georeferencing of related data and the production of thematic maps that can be used in the subsequent phases of the work. For example, during the field survey, the web app generates raster maps of volume and diameter distribution that could be used to precisely determine the location of a timber extraction cable crane. Sharing data and maps in the Cloud could also be used as a valid support for forest management operations. Finally, the georeferencing of data on individual trees can be fundamental for implementing a certification and traceability process for wood products, particularly for rare or valuable species.

Another aspect in dendrometric digitization, in addition to the accuracy and precision of the measurements, the electronic instrument allows for the reduction of errors during the data collection and transcription phase compared to the traditional system, highlighting their usefulness and practicality as noted by Pereira et al. (2019).

With regards to the application of technologies used in dendrometric surveys, it was found that the survey time by the team of forestry operators was longer for the *L3* level. However, if the time per operator is calculated, the minimum time is always recorded with reference to the *L3* level in both forest stands. These reductions in work time were 30% and 18% in monospecific and polyspecific stands, respectively. These results confirm those reported by Binot et al. (1995). The digital instrument was an electronic tree-measuring fork instead of a digital caliper, resulting in time savings of 35%–45%. The level of experience of the operator applying the technology was also key, with the most experienced operator saving 26% and 35% of time in monospecific and polyspecific stands, respectively. The implementation of digital technology within the Research Centre also made it possible to verify its sustainability. In fact, although the economic results show statistically significant differences only with the most experienced operator (*O1*) between the costs of the traditional detection system (costs higher) compared to the other levels *L2* and *L3* (costs lower) in the monospecific stand, the digital system has the advantage of simplifying detection operations and reducing times for transcription and processing of data.

## Conclusion

Forest ecosystems are essential components of biodiversity conservation, as global carbon storage reservoirs but also as a renewable resource partially replacing fossil fuels in energy production. Aboveground biomass estimates are a key aspect and are based on tree size measurements of diameter and height, through which it is possible to estimate of biomass in a specific area. The diffusion of technological tools, sensors, digital devices, provides alternative, non-destructive approaches to derive biomass estimates.

This study compares the application of a digital electronic device for measuring tree diameters with the application of a dedicated web app to verify technical–economic sustainability. The application of digital technology for measurement, combined with the data management web-app, makes it possible to simplify survey inventories and the management of the data acquired on digital support. The economic sustainability of the application of digital technology, compared to the traditional detection system, has been demonstrated. In fact, although only the more experienced operator is able to make the most of this technology, allowing a substantial reduction in investigation costs, the advantage of simplifying detection operations in forestry operations and of reducing times for data transcription and processing compensates for the monetary investment of the digital technology.

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