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ORIGINAL ARTICLE

# Assessment of above-ground biomass of individual hazelnut trees by terrestrial laser scanning and MATLAB® analysis

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## Abstract

**Key message** The proposed methodology represents the first work to estimate the AGB of hazelnut trees by TLS and for representing the different woody structures. Potential application for carbon credit certification.

**Abstract** Accurate estimation of Aboveground Biomass (AGB) in tree orchards is essential for assessing productivity and carbon sequestration. The objective of this research was to develop a method for estimating the total AGB of hazelnut trees (*Corylus avellana* L.) of different ages, based on TLS technology integrated with the MATLAB TreeQSM algorithm combined with destructive measurements of coarse (Ø ≥ 4 mm) and fine (Ø ≤ 4 mm) structures in order to overcome the estimation limitations of the algorithm. This study, the first contribution on hazelnuts, proposed an integrated approach for estimating AGB, combining Laser Imaging Detection and Ranging (LiDAR) based on TLS, computational analysis in MATLAB®, and targeted destructive and manual measurements to derive key dendrometric parameters. Results revealed statistically significant differences in fine structure biomass between 15-year-old (22.56 ± 4.15 kg) and 20-year-old trees (34.69 ± 10.80 kg), confirming the use of TLS, combined with MATLAB processing and limited destructive measurements, as an appropriate technology for biomass estimation and for representing the different structures. TreeQSM algorithm was found to be highly reliable in estimating the length of branches with Ø ≤ 4 mm ($R^2 = 0.95$) and in estimating the volume of woody structures Ø ≥ 4 mm. The proposed methodology provides valuable support for AGB estimation in tree crops by integrating TLS-based modelling with empirical measurements. A key outcome of this study is the potential application of the proposed methodology for carbon credit certification. Future research should extend to the different stages of tree growth to consider the growth dynamics induced by agronomic management.

**Keywords** *Corylus avellana* · LiDAR-TLS · Allometric relationships · Carbon credits · Dendrometry

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## Introduction

### Importance of AGB estimation and limitations of traditional methods

Determining the biomass content of trees and their characteristics is essential for assessing productivity and carbon sequestration in both forests and orchards (Velázquez-Martí and Annevelink 2009; Velázquez-Martí and Fernandez-Gonzalez, 2010; Enquist and Niklas 2002). Traditionally, forestry studies have developed dendrometric equations to provide faster biomass estimates. However, the direct method, which involves cutting and weighing trees, is time-consuming and expensive (Attiwill and Ovington 1968; Disney et al. 2018). These equations facilitate the computation of biomass and make it possible to assess the contribution of trees to climate change mitigation by quantifying the $CO^2$ absorbed during photosynthesis (Cannell 2003; Joosten et al. 2004). A common indirect approach to estimate Aboveground Biomass (AGB) relies on relationships between structural parameters such as diameter at breast height (DBH) and tree height (Zeng and Tang 2011; Chave et al. 2014). While this method is effective on a large scale, it has limitations when applied to individual trees or small samples, where estimation errors can propagate and compromise accuracy (Chave et al. 2004; Molto et al. 2013). To overcome these issues, Laser Imaging Detection and Ranging (LiDAR) technology has emerged as the most accurate method for estimating tree biomass (Cao et al. 2019; Disney et al. 2018; Demol et al. 2022). Compared to traditional approaches, it enables the development of precise allometric relationships (Calders et al. 2015; Girardeau-Montaut 2020; Krok et al. 2020).

### TLS and QSM advantages

Point clouds generated from LiDAR scanning provide detailed information about trees, including structure, branch distribution and size, and canopy dimensions (Côté et al. 2009; Raumonen et al. 2013; Calders et al. 2015). The Terrestrial Laser Scanner (TLS), or terrestrial LiDAR, is an active remote sensing technique that measures the three-dimensional (3D) structure of trees with high accuracy by transmitting laser pulses and analyzing the reflected energy (Hackenberg et al. 2015; Wallace et al. 2017). When integrated with airborne laser scanning data, it provides an innovative approach to large-scale biomass estimation (Brede et al. 2019; Wang et al. 2023).

A geometric model known as the Quantitative Structural Model (QSM) enables the hierarchical representation of a tree and the extraction of specific features from point clouds (Raumonen et al. 2013). Using TLS data, QSM can directly determine tree volume, and by integrating wood density data, it can estimate AGB (Raumonen et al. 2012, 2015) although validation through destructive sampling is sometimes required (Calders et al. 2015).

An implementation of QSM, known as the TreeQSM (Raumonen et al. 2013), has been used in several studies to build 3D models and estimate canopy volume, tree's structure parameters such as branch and stem and AGB. This algorithm has been successfully applied to low and compact apple orchards, where it effectively extracted branch information with high precision when point clouds were sufficiently accurate (Zhang et al. 2020; Qiu et al. 2024), in peach trees (Knapp-Wilson et al. 2023), in walnut (Estornell et al. 2017), in olive trees (Chiappini et al. 2022). Instead, Schindler et al. (2023) in wild cherry have estimated carbon and nutrient content in addition to basic parameters. In addition, residual biomass using TLS has been estimated in olive (Fernández-Sarría et al. 2019), citrus species (Velázquez-Martí et al. 2013). In hazelnut, basic geometric parameters such as Projected Ground Area (PGA), the height of the canopy, the height of the tree and of the trunk and canopy volume were estimated by Unmanned Aerial Vehicle (UAV) based point cloud (Altieri et al. 2022; Vinci et al. 2023).

Despite these advances, the application of such innovative methods to nut crops, and particularly to hazelnut, remains scarcely investigated.

### Hazelnut context

Native to Europe and Western Asia, European hazelnut (*Corylus avellana* L.) is a shrubby understorey species found in deciduous forests, which prefers upland areas shaded by tall trees (Del Favero 2004; Gioia et al. 2021; Kull and Niinemets 1993; Kirchlechner 1900). In-shell hazelnut production has increased in recent decades, according to FAO data. In 1962, world production was 226,010 tons until 2023, with 1,125,220.69 tons, representing an average annual growth rate of 2.67%. In the last five years, from 2019 to 2023, the Asian continent is confirmed to be a top player in terms of quantity, with Turkey representing for 62.92%, followed by Italy with 9.33% of the global production (FAOSTAT 2023).

Hazelnut sequesters atmospheric carbon dioxide through the photosynthetic process, storing it in its biomass and soil organic matter, providing economic and environmental benefits (Granata et al. 2020; Pacchiarelli et al. 2022). Fireman (2019) highlighted the long-term carbon storage role of hazelnut compared to conventional crops. It is a crop that from late spring (May) to late fall (October) sequesters CO2 with the highest quantities in May (Granata et al. 2020). Agricultural practices in hazelnut management and the training system influence photosynthetic process and

thus inorganic carbon sequestration. Granata et al. (2020) reported the importance of hazelnut planting density and pruning practices for the interception of photosynthetically active radiation (PAR). They consider it appropriate a classic planting density of 400 plants/ha with bush training. Pruning, for the penetration of sunlight into the canopy, should consist of more energetic pruning every 2–3 years and a light one every year (Cristofori et al. 2009). Irrigation, integrated in orchard management, prevents hazelnuts from suffering drought stress by reducing carbon uptake (Chaves et al. 2002; Medrano et al. 2002; Granata et al. 2020). Tillage practices have also shown that soil carbon stocks decrease in the first few years after planting (Pacchiarelli et al. 2022).

In recent years, single stem hazel cultivation has become widespread (Ahmadov, 2024). However, bush-training systems showed higher levels of carbon sequestration (Granata et al. 2021).

From an ecological point of view, hazelnut cultivation provides protection against soil erosion due to its fibrous root surface structure, prevents surface sediment runoff and promotes soil and water conservation (Tshering et al. 2017). Considering the findings, hazelnut cultivation can be considered an important crop, not only economically for hazelnut production, but especially ecologically and environmentally, having a positive role as carbon sink in global climate change scenario.

Since hazel is a species native of forest understorey, it is important to distinguish the behavior of uncultivated trees from cultivated ones, due to competition for sunlight, to estimate different allometric equations and carbon storage (Pacchiarelli et al. 2022). Differences in tree architecture and wood density generate species-specific allometric equations (Alberti et al. 2005; Zianis et al. 2005). Alberti et al. (2008) and Škėma et al. (2018) estimated AGB through allometric equations of shrubs hazelnut in forest environment using density of wood and volume of the tree while Škėma et al. (2018) examined biomass relationships with morphometric parameters, including stem diameter (D) at 1.3 m and 0.3 m above the ground, stem height (H) and crown length and the complex index $D^2H$. Pisetta (2011) also used allometric equations and, in hazelnut orchard trained as multi-stemmed bush, estimated an average annual uptake of 3.15 kg C per year per plant considering the total of all branches, corresponding to an average uptake of 1.26 t/ha/year of carbon. Albert et al. (2014) developed biomass equations for several species in central German forests to predict total AGB, stem biomass and canopy biomass using regression analyses from typical inventory data (DBH, height). These species included common hazel (*Corylus avellana* L.) grown in coppice forests with a natural bushy habit. This study explained that 91%, and in some cases up to 99%, of the variance was explained by DBH as a predictor. Therefore, using DBH as the sole variable provided accurate estimates of total AGB and biomass of tree compartments in the coppice forest system. It appears unnecessary to include stem height and other independent variables, such as crown length or root collar diameter, in the equations. Stem diameter rather than stem height should be preferred to estimate the AGB of the underbrush species with natural bushy habit (Škėma et al. 2018), because the search for sunlight leads to longer and thinner structures, compared to trees not subjected to this type of competition (Pacchiarelli et al. 2022). Pacchiarelli et al. (2022) also proposed a new equation to estimate the dry weight of branches. This equation is based on the ratio between fresh and dry branch weights, branch length, and diameters measured at 0.3, 0.6, and 1.3 m from the soil surface for each branch.

In short, there are no traditional and LiDAR-based methods for estimating total AGB in trained single stem hazelnut trees. Moreover, traditional estimation methods refer to bush training systems and do not distinguish between coarse and fine woody structures.

### Study objective

The main objective of this research was to develop a method for estimating the total AGB of hazelnut trees (Corylus avellana L.) of different ages, based on TLS technology integrated with the MATLAB TreeQSM algorithm combined with destructive measurements of coarse ($Ø \geq 4$ mm) and fine ($Ø \leq 4$ mm) structures in order to overcome the estimation limitations of the algorithm.

## Materials and methods

### Study area

In January 2023, surveys were conducted in a non-irrigated commercial hazelnut orchard of 0.32 ha, located in Montoro (Avellino), southern Italy, at latitude 40°50'21.01 *N* −14°46'40.02 E, at 193 m a.s.l., a traditional area for hazelnut production.

Montoro area is characterized by volcanic origin soils, with a mild and breezy climate. The rainfall regime ranges from a maximum in November/December to a spring period of intermediate precipitation and a summer minimum in July/August. Soil was mapped using the EMP-400 GSSI Electro Magnetometer Profiler to measure the spatial variability of the soil. Very low spatial variability was found in the field.

The soil texture was classified as sandy-loam (78% sand, 14% loam and 8% clay) according to the FAO soil classification system (Bashour and Sayegh 2007), with a

**Table 1** Technical characteristics of trimble X7 3D-scanner used for TLS data acquisition in hazelnut trees. Units are provided as indicated by the manufacturer (https://fieldtech.trimble.com/resources/product-guides-brochures-datasheets/datasheet-trimble-x7-3d-laser-scanner)

| | |
|---|---|
| Weight | 5.8 kg |
| Dimensions | 178 × 353 × 170 mm |
| Laser wavelength | 1550 nm, invisible |
| Field of view | 360° × 282° |
| Scan duration | Fastest 2 min 34 s with images 1 min 34 s without |
| Scan speed | Up to 500 kHz |
| Range principle | High speed, digital time-of-flight distance of measurement |
| Range noise | < 2.5 @30 m |
| Range | 0.6–80 m |
| Range accuracy | 2 mm |
| Angular accuracy | 21” |
| Sensors | 3 coaxial, calibrated 10 MP cameras |
| Resolution | 3840 × 2746 pixels for each image |
| Raw image capture | Fast = 1 min − 15 images 158 MP; Quality = 2 min − 30 images 316 MP |
| Integrated calibration system | Full auto-calibration of range and angular system in 25 s |
| Angular calibration | Applies a correction to the collimation error |
| Range calibration | Applies a distances correction in the albedo and the distance measurement |

carbon-nitrogen ratio of 10.2. Orchard management included fertilization, pesticide application, and annual pruning. Fertilization is performed once a year, in early May, with 12-12-17 title at a dose of about 30 kg/ha. Pesticide application includes the active substances sulfur and lambda-cyhalothrin. Annual pruning is carried out to remove suckers. The cultivar under study was “Tonda di Giffoni”, trees were trained on single stem, although some of them were multi-stemmed, and planted 4 m between row and 4 m on the row, with a density of 625 trees $ha^{-1}$ in east-west row orientation.

The orchard was non-irrigated, and its soil texture was classified as sandy loam according the FAO soil classification system (Bashour and Sayegh 2007). The orchard was composed of three blocks with trees of different ages: 15, 20 and 25 years.

## Field data acquisition by terrestrial laser scanning

Fifteen individual hazelnut trees, without leaves, of different ages, selected from 30 trees using mean measured value of the projected ground area (Altieri et al. 2022), were scanned by TLS in January. Scanner acquisition was carried out on: five similar 15-year-old trees, five 20-year-old trees and five 25-year-old trees.et al. Studies with a similar number of selected trees were also conducted by Zhang et al. (2020).

To minimize external disturbances, the scanning procedure was conducted in an open field, in winter, under the most favourable conditions, to reduce occlusion effects from leaves and to ensure minimal atmospheric disturbance, such as wind or precipitation, which can lead to measurement errors (Krok et al. 2020), and avoiding interference from surrounding plant material, a common issue when representing trees (Heinzel & Huber 2016; Schneider et al. 2019; Wang et al. 2019).

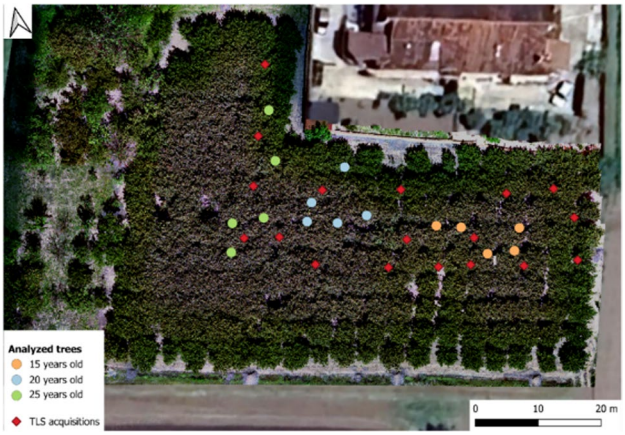


**Fig. 1** Aerial view of the field showing the spatial distribution of 15 hazelnut trees classified by age groups, marked with different colours: green for 25-year-old trees, blue for 20-year-old trees, and orange for 15-year-old trees. The red diamond-shaped markers indicate the positions of the terrestrial laser scanner (TLS) stations

The scanning was conducted by a Trimble X7 TLS equipped with LiDAR technology for 3D point cloud reconstruction. Technical characteristics of the device are summarized in Table 1 (further information is available on the manufacturer website).

High-resolution 3D models of individual trees were obtained through scans conducted at an average distance of 2.5 m. Multiple scans were taken from various positions surrounding the trees, following the recommendations of Raumonen et al. (2013), who suggest measurements from at least three different locations. Specifically, 18 scans were performed (Fig. 1). The individual scans were aligned and co-registered using Trimble Realworks© software, generating a single point cloud consisting of 3,725,680 points. From this unified point cloud, 15 individual trees were selected, each represented by a point cloud containing an average of 1,907,063 points per tree.

## Manual measurements

Trunks of the selected trees scanned with TLS were manually measured using a metric wheel. Specifically, trunk diameters were recorded at 30 cm and 60 cm above the ground, along with additional field measurements conducted following Qui et al. (2024) (Fig. 2). These measurements included *“Ht”* the total height from the ground to

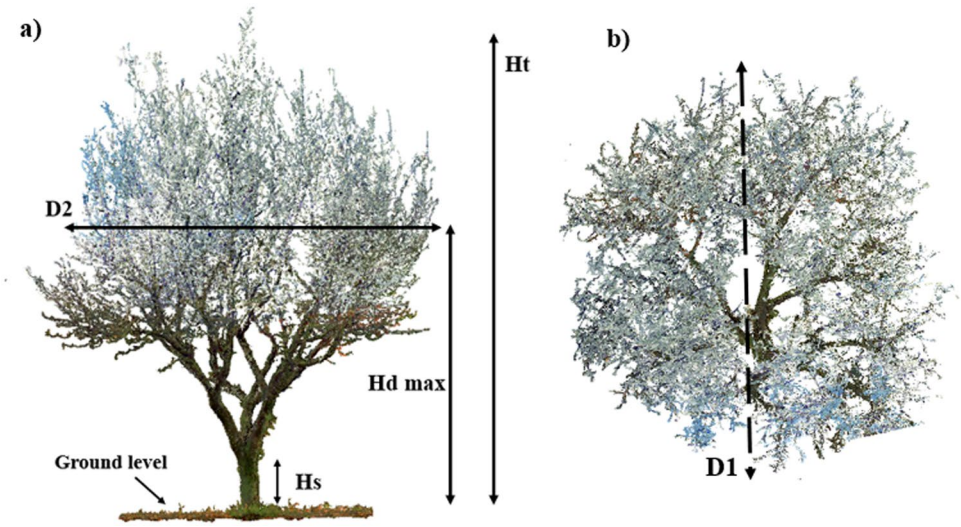


**Fig. 2** Schematic representation of tree manually measured structural parameters (**a**) front view: *Ht* = tree height from the ground to the top of the canopy (m); *Hd max* = height from the ground to the maximum canopy diameter (m); *Hs* = height from the ground to the insertion point with the branches (m); *D1* = canopy diameter along the north-south axis; (**b**) top view: *D2* = canopy diameter along the east-west axis



**Fig. 3** Example of a hazelnut branch segmented from TLS point cloud, flagged and removed for laboratory measurements

the top of the canopy (m); "*Hd max"*, the total height from the ground to the point of maximum canopy diameter (m), "*Hs*", the height from the ground to the first branch insertion point (m), "*D1*", the canopy along the north-south axis and "*D2*", the canopy diameter along the east-west axis.

Using these parameters, the canopy volume (V) and canopy surface area (A) were estimated to provide additional structural descriptors for each tree (Qi et al. 2021). The canopy area and volume were calculated using the following formulas:

$$A = \pi\, r^2$$

$$V = \left(\left(\frac{\pi\, r^2}{4}\right) \times \left(2\frac{Ht - Hdmax}{3}\right) + (Hdmax - Hs)\right)$$

where *r* represents canopy radius, calculated as half of the mean canopy diameter; *Ht* is the total tree height, measured from the ground to the top of the canopy; *Hdmax* is the height at the maximum canopy diameter, and Hs is the height of the first branch insertion.

A total of 27 branches were randomly selected from nine hazel trees (three branches per tree), marked with tape, and then pruned using shears. Each branch was assigned a unique identification number to ensure accurate tracking in CloudCompare, allowing clear differentiation from the surrounding tree canopy biomass within the point cloud.

In the laboratory, the 27 structures (Fig. 3) were first oven-dried at 65 °C for 48 h until constant weight was achieved. Afterwards, each sample was weighed using a technical balance (0.00 g). Length was measured with a metric wheel, diameter with a digital calliper, and volume was calculated using the cylindrical formula.

Each branch was then segmented into pieces of uniform diameter, a necessary step for further processing using the TreeQSM tool in MATLAB® software (Natick, Massachusetts-USA, MathWorks, v.2023a). This classification enabled the evaluation of potential relationships between the dry weight of the woody structures, their volume, and the length of the identified diameter classes. To ensure accurate segmentation, diameter measurements were conducted using a digital caliper, leading to the definition of the following diameter classes: Ø ≤ 1.5 mm, 1.5 mm < Ø ≤ 2.5 mm, 2.5 mm < Ø ≤ 4 mm, and 4≥mm. These classifications facilitated the calculation of length, volume, and biomass estimation.

## Point cloud processing

Point clouds from TLS acquisition were exported from the Trimble X7's integrated and dedicated Trimble Realworks© software and opened with the open-source CloudCompare software (version 2.12.4, Kyiv - www.cloudcompare.org). CloudCompare software enables various point

cloud processing and analysis operations. The point clouds obtained from the laser scanner acquisition were cleaned of "ghost spots" and noise using Statistical Outlier Removal (SOR) filteraccording to the methodology proposed by Zhang et al. (2020).

The processed point clouds were exported to MATLAB® software. In addition to the pre-processing step, the TreeQSM algorithm applies its own internal filtering routines (Hackenberg et al. 2015), which rely on statistical k-nearest neighbour distance and point density criteria to discard small clusters or isolated components not belonging to the woody structure.

The aim was to split fine structural components with diameter≤4 mm from coarse structures, thus with diameter≥4 mm. This separation was necessary due to the tendency of the TreeQSM algorithm, later employed in MATLAB® for volume processing, to miscalculate the volume of structures with a diameter less than 5 mm. This overestimation is primarily attributed to factors such as beam divergence, occlusion, wind effects, and coregistration errors, particularly in the diameter class between 2.5 and 5 mm (Demol et al. 2022; Hackenberg et al. 2015; Morales and MacFarlane 2024).

One of the most relevant features of the point cloud was the homogeneity and intensity of all points. To perform accurate discrimination, the intensity scale was converted to the RGB color system. This approach allowed a subdivision of the points according to the values of red, green and blue wavelength, which was here an efficient method to separate the thin structures from the larger ones. After careful analysis, it was determined that values lower than 100 of red component, identified coarse structures while thin structures had values greater than 100. Figure 4 shows the discrimination of the point clouds into fine and coarse structures.

## Evaluation of biomass estimation for coarse and fine structures: TreeQSM algorithm in MATLAB® software and allometric approach

Figure 5 shows the flowchart of the applied methodology to estimate total AGB through the sum of fine and coarse structures. A distinctive methodology was adopted for the evaluation of fine and coarse structures of hazelnut trees.

The biomass assessment of coarse structures of hazel trees was carried out using TreeQSM, a quantitative structural model (QSM) tool developed by Raumonen et al. (2013) and implemented in MATLAB®. This tool provides a comprehensive description of tree properties based on point cloud data. The methodology followed the guidelines outlined by Raumonen (2022) and the open-source manual available at https://github.com/InverseTampere/TreeQSM/blob/master/Manual. The TreeQSM algorithm requires several input parameters that can be adjusted to match the specific characteristics of the trees under analysis.

In this study, the following TreeQSM parameters were customised to optimise model performance and reconstruction accuracy:

- **PatchDiam2Max**: adjusted individually for each tree according to the measured trunk diameter at the base (e.g. 0.15–0.18 m for a trunk of 17 cm diameter).
- **PatchDiam1** and **PatchDiam2Min**: set slightly lower than PatchDiam2Max, following TreeQSM recommendations, to progressively increase detail in the reconstruction of finer branches.

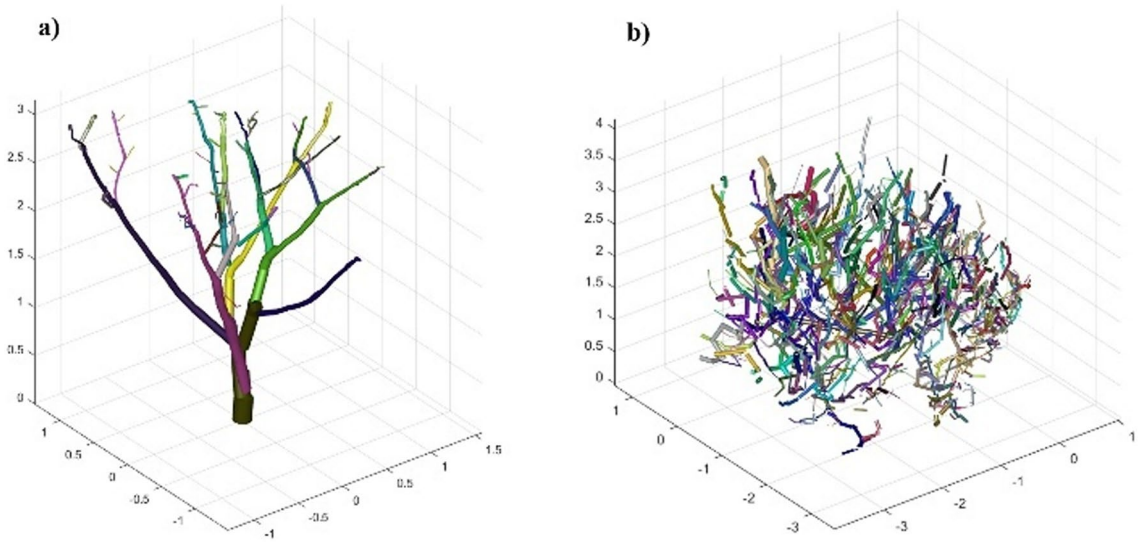


**Fig. 4** Visualization of TreeQSM output showing the distinction between coarse (**a**) and fine (**b**) structures based on cylinder diameters, as computed in CloudCompare and visualized in MATLAB®

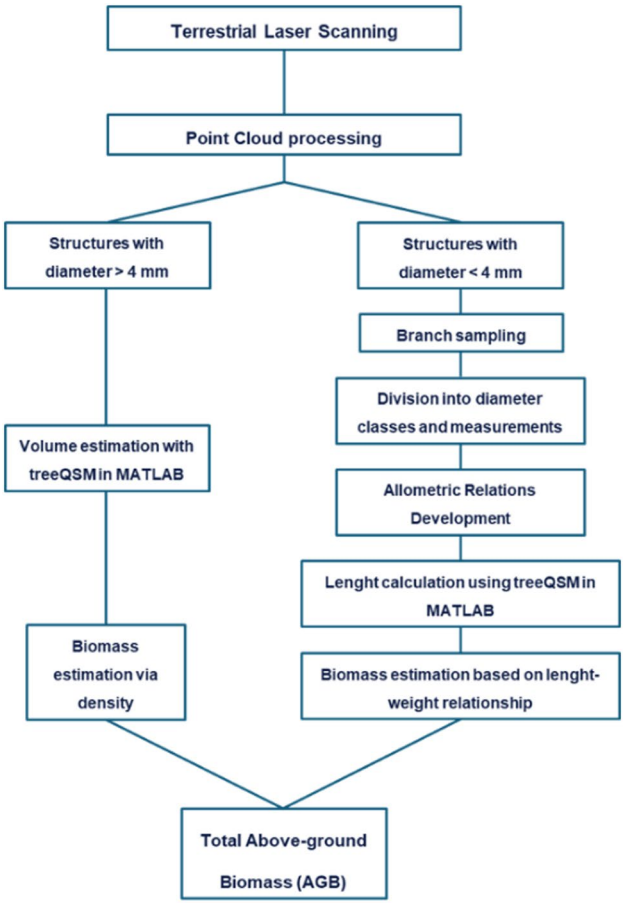


**Fig. 5** Flow chart of the applied methodology for Aboveground Biomass (AGB) estimation in hazelnut trees, combining Terrestrial Laser Scanner (TLS) based point cloud acquisition, TreeQSM modelling, and allometric relationships

- **MinCylRad**: fixed at 2.5 mm (corresponding to a 5 mm diameter) to prevent overestimation artefacts in the modelling of very small structures, as highlighted in previous studies.

The software output consists of a matrix of 1 × 8 dimensions, divided into six main components: cylinder, branch, tree data, run data, pm distance and triangulation. Among these, the tree data component is particularly relevant as it provides numerical descriptors of tree properties, including volumes, areas, lengths, and other structural attributes.

### Methodology of biomass estimation for fine structures

As mentioned above, the TreeQSM algorithm in MATLAB® overestimates the volume of structures below a specific diameter, than, we explored the possibility of using the relationship between length and dry weight of fine structures.

Firstly, we assessed the accuracy of the TreeQSM algorithm in estimating structures length. Manual measurements of the length of 19 random sampled structures random selected branches were evaluated by TreeQSM. A linear regression model, constrained to pass through the origin, was applied, and the coefficient of determination ($R^2$) was calculated to evaluate the correlation between predicted and actual measurements.

The linear significative relation (linear regression) obtained was used to correct TreeQSM data ensuring a more reliable length estimation. Subsequently, the relationship between estimates length and weight for different diameter classes was analyzed to establish a length-to-weight model.

### Methodology for biomass estimation for coarse structures

Regarding coarse structures (Ø ≥ 4 mm), which are not subject to miscalculation, TreeQSM algorithm was used to obtain the total volume value. The total volume value was multiplied by mean value of hazelnut wood density derived by literature. Density of hazelnut wood, 610 kg $m^{-3}$ oven dry mass/fresh volume, was averaged from five density values reported in the literature for *Corylus avellana* L., (Zanne et al. 2009; Slater and Ennos 2015; Gençer and Özgül 2016; Özden et al. 2017; Slater 2021).

### Total AGB carbon sequestered

The total amount of sequestered carbon was calculated by multiplying the AGB by a factor of 0.45, based on the carbon content reported for hazelnut trees by Picchi et al. (2018). The carbon mass was converted to total $CO_2$ equivalents using stoichiometric coefficient of 3.67 ($CO_2$/C). Finally, $CO_2$ sequestered per hectare was calculated to multiplying tree CO2 equivalent content to tree density of 400 trees/ha.

## Statistical analysis

The experimental data were statistically analyzed by JMP (Pro 18, SAS Institute Inc., Cary, NC, 1989–2023) software and Excel for descriptive statistics. Homogeneity of variance and normality were tested by Bartlett and Shapiro-Wilk tests, respectively, ($P = 0.05$). For all other variables, a one-way ANOVA ($P < 0.05$) was performed, followed by Tukey's post hoc test to identify significant differences between treatments ($P < 0.05$). Additionally, a multiple regression analysis was conducted to examine the relationship between measured tree parameters and estimated total AGB. All analyses were based on 15 trees, which represents a sample size comparable to that adopted in previous TLS-based orchard studies.

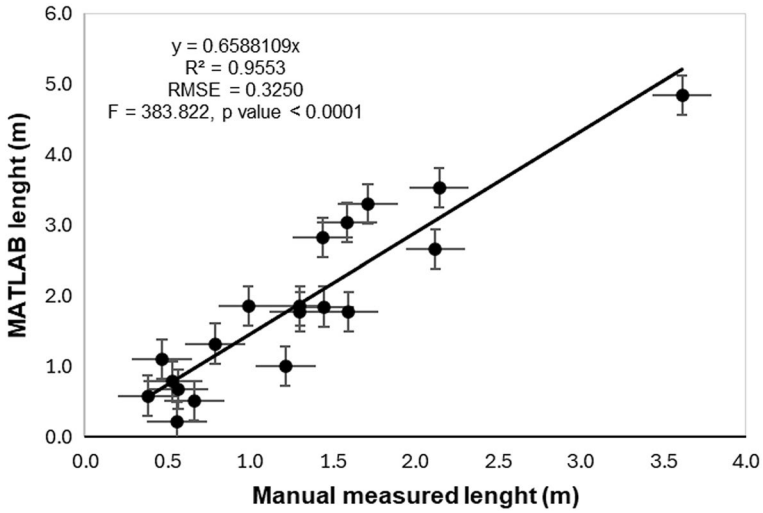


**Fig. 6** Correlation between destructive and MATLAB®-estimated branch length measurements for 19 hazelnut structures. Error bars indicate variability in manual and model-based measurements

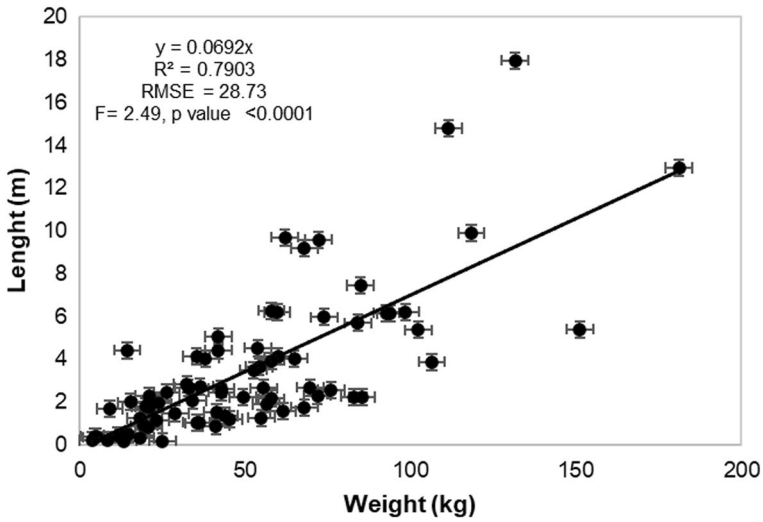


**Fig. 7** Allometric relationship between branch length (m) and weight (kg) for fine structures (Ø ≤ 4 mm) of hazelnut structures. Error bars represent variability within diameter classes

## Results

### Accuracy of TreeQSM algorithm in estimating branch length

Figure 6 illustrates the strong correlation between the branch lengths measured using the TreeQSM algorithm and those obtained through destructive sampling ($R^2$=0.95, RMSE=0.3250, F=383.8, $p$<0.001). This relationship is well described by a linear model, expressed as y=0.6588x, constrained to pass through the origin.

Since QSM algorithms tend to overestimate the volume of fine structures due to beam divergence, occlusion, wind effects and coregistration errors (Demol et al. 2022; Hackenberg et al. 2015; Morales and MacFarlane 2024), the fine structures length estimated with the treeQSM algorithm was approximated by multiplying the obtained value by 1.449. Thus, corrected branch length estimates can be obtained by multiplying this correction factor to the values generated by the algorithm, improving accuracy in length estimation. The strong correlation found confirms the reliability and accuracy of the MATLAB-implemented TreeQSM algorithm as a tool for branch length measurement.

### Allometric relationships between length and weight in fine structures

Allometric relationships between weight and length in fine structures, classified into diameter classes Ø ≤ 1.5 mm, 1.5 < Ø ≤ 2.5 mm, and 2.5 < Ø ≤ 4 mm, showed strong correlations with statistical significance in all classes analysed. The coefficient of determination ($R^2$=0.79, RMSE=28.73, F=2.49, $p$<0.001) indicates highly reliable relationships for biomass estimation (Fig. 7).

To improve the robustness of the biomass prediction model, data from all diameter classes were combined to develop a regression equation that allowed an overall estimate of weight based on branch length. This approach

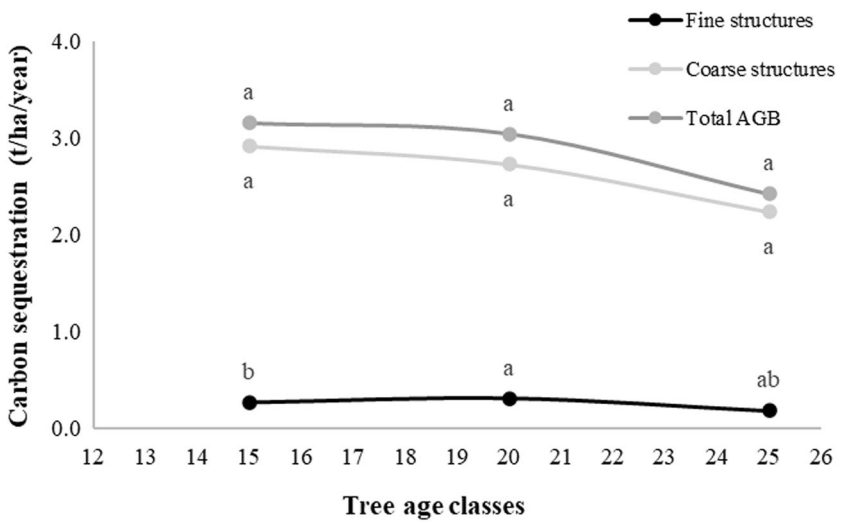


**Fig. 8** Annual carbon stock (t/ha/year) in fine structures, coarse structures and total aboveground biomass (AGB) *of* hazelnut trees at three age classes *(15,20 and 25 years).*Mean values associated with different letters are significantly different, according to Tukey's HSD test at $p<0.05$ ($n=5$)

**Table 2** Mean values of crown and trunk diameter, tree height and sequestered C by tree age classes (15, 20 and 25 years). The standard deviation is shown in italics.

| Tree age | | Crown diameter (m tree$^{-1}$) | | Trunk diameter (m tree$^{-1}$) | | Tree height (m tree$^{-1}$) | | Sequestered C (kg tree$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|
| **15** | mean | 4.52 | a | 0.155 | a | 5.17 | b | 119.48 | a |
| | ± σ | *0.47* | | *0.860* | | *0.1* | | *13.89* | |
| **20** | mean | 4.69 | a | 0.178 | a | 5.44 | ab | 152.04 | a |
| | ± σ | *0.42* | | *2.612* | | *0.38* | | *19.56* | |
| **25** | mean | 4.72 | a | 0.193 | a | 5.82 | a | 151.45 | a |
| | ± σ | *0.78* | | *2.833* | | *0.23* | | *27.93* | |

Mean values associated with different letters are significantly different, according to Tukey's HSD test at $p<0.05$ ($n=5$)

ensures a practical application of the model for fine structure biomass assessment, reducing potential biases associated with individual diameter class regressions. The total fine structure length, corrected by the previously derived coefficient, was then used as an input for the final biomass estimation. Specifically, the corrected length values were incorporated into the global regression equation $y=0.0692x$ ($R^2=0.79$). The length-weight correlation indicates strongly reliable relationships for estimating the biomass of fine structures.

## Biomass partitioning in fine and coarse structures and total AGB

The biomass partitioning values for branches of different ages are shown in Fig. 8. Coarse structures (CS) did not exhibit statistically significant differences between branches of different ages. In contrast, fine structures showed a significant difference between the branches of 20-year-old (34.69 kg ± 10.18) and 15-year-old (22.56 kg ± 4.15) trees, with the highest and lowest values, respectively, while 25-year-old plants were statistically equal to 15- and 20-year-old plants. This analysis shows that 25-year-old plants, compared to 20-year-old plants, have reached maturity by investing less in fine structures, while 15-year-old plants are still undergoing vegetative renewal. The typical behavior of tree is that, at the onset of senescence, the plant tries to compensate for the loss of vigor by increasing the emission of fine structures, which is an attempt at vegetative renewal (Grisafi et al. 2022). In this context, orchard management and biological processes, explained in the discussion section, also have an impact.

Overall AGB showed no significant differences between the different age groups, with a mean value of about 312.3 kg tree$^{-1}$. The distribution of biomass in terms of percentage showed that coarse structures represent about 90% of the total epigeal biomass.

## Insights into plant architecture from TreeQSM in MATLAB®

Table 2 shows mean values of crown and trunk diameter, tree height and sequestered C by tree age classes. Between plants of different age groups, no significant differences were observed in crown and trunk diameter, with mean values of 4.64 m tree$^{-1}$ and 0.175 m tree$^{-1}$, respectively. Tree height showed a statistically significant difference in 25-year-old plants with higher mean values of 5.82 m tree$^{-1}$ compared to lower values in 15-year-old plants of 5.17 m tree$^{-1}$. No differences were observed between the amount of

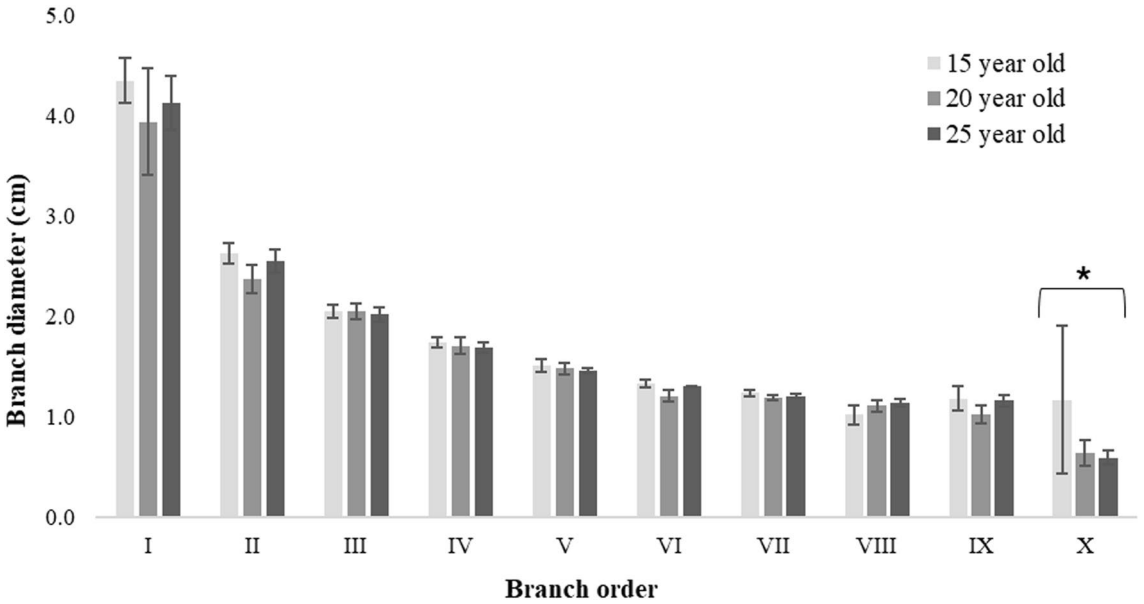


**Fig. 9** Mean values of branch diameter (cm) by branch order (I to X) in hazelnut trees of three age classes (15, 20 and 25 years). Error bars represent standard deviation. The asterisk indicates statistically significant difference among age classes within the 10th branch order, according to Tukey's HSD test $p<0.05$

C sequestered in the plants of the different age groups(mean value of about 140 kg tree$^{-1}$).

However, with an estimated sequestration capacity of approximately 140 kg of C per plant and considering a density of 400 plants per hectare, a hazelnut orchard can sequester up to 56 tons of C. Considering the age of the trees mean annual carbon sequestration value is 2.87 ± 0.39 t per hectare equivalent to 10.54 t ± 1.44 of $CO_2$.

This data, in line with the highest estimates observed in crop systems with high photosynthetic efficiency (Granata et al. 2021), highlights the potential role of hazelnuts as a crop capable of sequestering carbon.

The exploitation of these ecosystem benefits can translate into sustainable agricultural management strategies such as biomass maintenance, reduced tillage, and permanent soil cover and offer concrete access to carbon farming programs and voluntary carbon markets (VCM).

From this perspective, hazelnut orchard is not only a production system but also an environmental asset that can contribute to climate change mitigation and the generation of new sources of income through the ecosystem services they provide. Figure 9 shows a clear trend, indicating that first-order branches, located closer to the main stem, exhibit greater robustness and thickness, showing larger diameters compared to higher-order branches. As expected, this pattern revealed a decreasing distribution of branch sizes with increasing hierarchical order. This hierarchical organization of branch diameters plays a key role in determining the distribution of biomass within the plant, influencing the overall structure and efficiency of resource allocation. To further investigate the relationship between tree structural parameters and biomass, a multiple regression analysis was conducted, considering total height (Ht), first branch insertion height (Hs), canopy surface area, and canopy volume as predictors of total AGB. However, no highly significant relationships were found ($P>0.05$), suggesting that these variables alone do not sufficiently explain AGB variation.

## Discussions

### Accuracy of TreeQSM in estimating branch length

TreeQSM is widely used for extracting structural information from trees, demonstrating high accuracy in reconstructing branching architecture from LiDAR point clouds (Hackenberg et al. 2015; Du et al. 2019). However, its application to hazelnut trees, which have reduced height and complex sympodial branching (Grisafi et al. 2024), presents both challenges and opportunities in terms of model accuracy and external factor control.

The results confirm the high reliability of TreeQSM in estimating branch length, with an $R^2=0.95$, consistent with previous studies (Lau et al. 2018; Disney et al. 2018). Fernández-Sarría et al. (2019) showed that in residual biomass of olive trees, strong correlations existed between total height, crown diameter and crown volume observed in the field and estimated by TLS, with $R^2$ values of 0.85, 0.92 and 0.87, respectively. Similar results were reported by Moorthy

et al. (2011) for olive trees and walnut trees (Estornell et al. 2017).

Traditional allometric models, often developed from limited sample sets, tend to lack transferability across different varieties or environmental conditions, which can lead to significant estimation errors. These models typically rely on simplified geometric parameters, such as height and stem diameter, and thus fail to capture the full three-dimensional complexity of tree structure particularly in fruit crops characterized by irregular architectures or subjected to regular pruning. As a result, they frequently overestimate or underestimate aboveground biomass. In contrast, TLS-based approaches combined with quantitative structure modelling (e.g., TreeQSM) enable detailed three-dimensional reconstructions of individual trees, providing more realistic and spatially explicit volume estimates, even for pruned trees with irregular forms. TreeQSM is especially effective in modelling primary and secondary branches, which account for a large share of total biomass. However, its accuracy tends to decrease in the reconstruction of fine structures and smaller branches, where estimation errors are typically higher (Zhang et al. 2020; Lee et al. 2025; Bornand et al. 2023).

The use of multiple scanning positions around the trees and the short distance between the sensor and the trees enabled the acquisition of a high-density point cloud, highlighting how the use of TLS, for AGB estimation, provides better accuracy in reconstructing branch structure.

The findings of this study further validate TreeQSM as a reliable tool for branch length estimation in hazelnut trees, provided that data acquisition is conducted under optimal scanning conditions and with sufficient point cloud density.

## Allometric relationships between length and weight in fine structures

Allometric relationships are commonly used to estimate tree biomass from measurable structural parameters. In this study, the relationship between branch length and weight in fine structures (Ø ≤ 4 mm) was analyzed to develop a predictive biomass model. The results showed a strong correlation across all diameter classes, highlighting that branch length serves as a reliable predictor of fine structural biomass. Alberti et al. (2008) and Škėma et al. (2018) showed how allometric relationships applied in the forest context to estimate AGB allowed effective quantification of carbon accumulation over time.

## Biomass partitioning in fine and coarse structures and total AGB

Statistical analysis of coarse structures and total AGB did not reveal differences between trees of different ages. This may be explained by the fact that environmental conditions, pruning practices, or single stem formation contributed to the overall balance in biomass production, suggesting stability in the interaction between the trees and their environment. Fine structures showed significant differences between 20 and 15 year-old trees, where the first showed higher mean values in contrast to the coarse structures, which showed no differences.

Trees around 20 years of age show maximum fine branching activity, with a balance between vigor and productivity, resulting in a balanced architecture with good ability to renew productive branches (especially mixed and sylleptic), which declines in mature age (Grisafi 2023). This could be attributed to the fact that, under those conditions, growth rates in fine structures tend to stabilize after 20 years. As age increases, the hormone profile changes, reducing the potential for branching, with reference to cytokinin content, which reduces the ability to form new shoots (Andrés et al. 2002). Severe pruning affects endogenous polyamine levels in hazelnut plants. Young plants generally show an increase in endogenous polyamines after pruning, related to their increased capacity for growth and regeneration, with polyamine levels supporting the development of new tissues while adult plants show a less pronounced increase, due to a more stable metabolism or less physiological plasticity with age (Rey et al. 1994). Our study shows that coarse structures account for 89–92% of total AGB, highlighting their dominant contribution to overall biomass accumulation. In agreement with our study Bijak et al. (2013) highlight how with aging in forest woody species, total biomass shifts toward more robust structures.

It is clear from the reported literature that pruning is the agronomic practice that plays a crucial role in shaping biomass allocation, influencing the development and turnover of fine branches. Around the age of 20–30 years, the vegetative branching of one-year-old shoots drops significantly, confirming that mature plants have a reduced ability to renew fine structures. This justifies the need in older hazelnut orchards of strategic pruning (rejuvenation) to stimulate new vegetative shoots.

## Insights into plant architecture from TreeQSM in MATLAB®

The observed hierarchical organization of branch diameters, where first-order branches exhibit greater robustness, reflects a common biomass allocation strategy. Larger,

lower-order branches provide structural support, while higher-order branches contribute more to resource distribution and photosynthetic efficiency. Despite these clear structural patterns, multiple regression analysis did not reveal significant correlations between tree parameters (Ht, Hs, canopy area, and canopy volume) and total AGB ($P > 0.05$). This suggests that AGB is influenced by factors beyond overall tree dimensions, such as wood density, branching architecture, and management practices. The lack of a relationship between canopy volume and AGB further indicates that volume metrics alone are insufficient for biomass prediction, possibly due to variations in canopy density and structural composition. A distinguishing factor is mainly the training system, which strongly influences biomass relationships. The relationships between biomass and morphometric parameters of understory species are not comparable to those used for canopy trees because of differences in light availability and competition regimes (Škėma et al. 2018). These findings highlight the complexity of biomass allocation in hazelnut trees and suggest that future studies should incorporate wood density, detailed branch-level traits, and functional parameters to improve AGB estimations.

## Conclusions

This innovative approach combining terrestrial laser scanner, equipped with a LiDAR sensor, with MATLAB®-based computational processing for Above Ground Biomass estimation is the first contribution carried out on single-stem hazelnut trees raised in commercial orchards to apply TLS by implementing a Quantitative Structural Model (QSM), known as TreeQSM. The main objective of this research was to develop and apply a non-destructive methodology based on TLS and MATLAB® software to obtain reliable estimates of volume and Aboveground Biomass, differentiating between coarse and fine structures of individual hazel trees.

The used methodology, confirms the use of TLS, combined with MATLAB processing and limited destructive measurements, as an appropriate technology for biomass estimation and for representing the different structures with diameter Ø ≥ 4 mm that account for about 90% of the total epigeal biomass by highlighting the dominant contribution of structures and main stem to the overall biomass accumulation; significant differences in the biomass of fine structures related to age; TreeQSM algorithm was found to be highly reliable in estimating the length of branches with Ø ≤ 4 mm in hazel trees and in estimating the volume of woody structures Ø ≥ 4 mm; the allometric relationships between branch length and the weight of structures with Ø ≤ 4 mm were appropriate for developing predictive models of biomass in hazelnut.

The integration of TLS and TreeQSM represents an effective and operationally efficient approach for improving biomass estimation and monitoring in hazelnut orchard. Compared to traditional allometric methods, this methodology is more accurate, non-destructive, and well-suited to pruned trees or those with complex architectures. The ability to generate detailed and repeatable three-dimensional data makes it particularly suitable for carbon credit certification, offering greater transparency and verifiability. Moreover, the operational efficiency of TLS scanning significantly reduces time and labour requirements in the field, enabling large-scale monitoring. These features make this approach a promising tool to support sustainable management and carbon accounting in perennial fruit crops such as hazelnut. This highlights the importance of non-destructive approaches for both certification and the long-term monitoring of AGB dynamics. Nevertheless, a key consideration is the necessity to extend this methodology to different hazelnut cultivation systems, such as bush-trained and pot cultivation systems.

An important aspect for future research is the application of this method to hazelnut trees increasing the sample size, including different cultivars, and extending the evaluation of plants with different training systems. This would provide a deeper understanding of biomass distribution and plant architecture overtime, contributing to a more comprehensive assessment of the crop. Furthermore, additional research may be necessary to adapt the methodology for evergreen and other tree species, opening new opportunities for the application of this innovative technology in other agricultural and forestry contexts.

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**Data availability** Raw TLS point clouds, MATLAB scripts, and related datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Competing Interests** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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