UAV LiDAR Survey for Forest Structure Metrics Estimation in Planning Scenario. A Case Study on a Laricio Pine Forest in the Sila Mountains (Southern Italy)

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Abstract. LiDAR (light detection and ranging) sensors, mounted on UAVs (unmanned aerial vehicles), are a consolidated technology for the remote sensing of the urban and/or natural structural parameters. This study investigates a practical aspect of the advantages of drone UAV LiDAR systems in estimating the main dendrometric parameters in a Calabrian laricio pine forest. In particular, the criteria of hypsometric dendrometry were applied, in which, unlike the classic criteria based on field surveys only, the variable to be determined is the diameter of the individual trees rather than the height. In fact, this last variable is definitely more available for more shafts than the diameter, thanks to LiDAR surveys. Dendrometric variables, such as trees' density, diameter and height, were measured adopting classic field-based methods for all the trees within some survey sample areas (SSAs), and other mean parameters were then obtained (e.g., mean basal area, mean diameter, mean Lorey's height, above ground trees' volume). The same parameters, retrieved by integrating hypsometric dendrometry and LiDAR data, were thus compared, and the degree of correlation/error was calculated. The error degree, obtained by comparing the field-measured diameters with the respective ones predicted using the LiDAR-based hypsometric model ($R^2 = 0.62$; $RMSE = 11.30$ cm; $Bias = 0.48$ cm), confirmed the reliability of LiDAR systems for their practical application in the professional forestry sector.

Keywords: airborne laser scanning (ALS) · forest management · above-ground biomass (AGB) · dendrometry · remote sensing · drone · image processing

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1 Introduction

1.1 A Subsection Sample

The well-known hypsometric models, adopted in the forestry planning common practice, are based on the principles of diametric dendrometry, as defined by Abramo et al. [1], for which the unknown structural variable to be predicted is constituted by the height of the individual trees. In fact, the forestry volumetric models use two specific dendrometric variables for the estimation of the volume of the above-ground structural parts of the single trees (trunk and great branches): the diameter at breast height (D) of the trunk and the tree's height from the ground to the highest point (H). During field survey campaigns, both variables are measured for a sample part of individual trees, grouped in sample survey areas (SSAs) to represent the entire forest. Although the simplification, D is still easier to retrieve than H of all the trees in the SSAs. Consequently, tree heights must be estimated using a hypsometric relationship.

With the introduction of remote sensing (RS) and light detection and ranging (LiDAR) sensors mounted on board an unmanned aerial vehicle (UAV) in forest structure parameters survey [2–8], the height of individual trees became more easily obtainable than D. In fact, in a single flight survey, the UAV LiDAR system can detect a very larger amount of the heights.

This reversal perspective has allowed the introduction of hypsometric dendrometry principles [1]. These are based on the inverting of hypsometric models, assuming that the H variable can be used as the known independent variable while D would be set as the variable to be determined.

Although new airborne laser scanning (ALS) systems have been introduced in the commercial market, reducing their costs, as well as more efficient software has been developed for easier processing of LiDAR data, the professional sector still seems to be wary of their full adoption as support in forestry surveys.

The purpose of the present study was to adopt and evaluate the criteria of hypsometric dendrometry for estimating the main dendrometric parameters, within a *laricio* pine monoplane forest, through the integration and comparison of structural trees variables measured by field and UAV LiDAR surveys. A hypsometric relationship was constructed between LiDAR-based trees' height and field-measured trees' diameters falling in the SSAs. This relationship was subsequently employed to predict the diameter values of all the trees located outside the SSAs in the study area. Integrating these two structural variables, different dendrometric parameters were estimated, including the trees' above-ground volume by applying two different volumetric models, and compared to those retrieved by field surveys only.

2 Study Site

The study area was located on the Sila (Southern Italy) mountain territory (39° 21'N; 16° 54'E), in the valley of Ampollino Lake, between 1250 and 1640 m a.s.l. In particular, the study area occupied 4.60 ha (Fig. 1), characterized by an average slope of 22%, involving a monoplane forest of *laricio* pine (*Pinus nigra* Arn. Spp *laricio* Poiret var. *Calabrica* Delamare), interspersed with small and young sparse groups of beech (*Fagus sylvatica* L.).

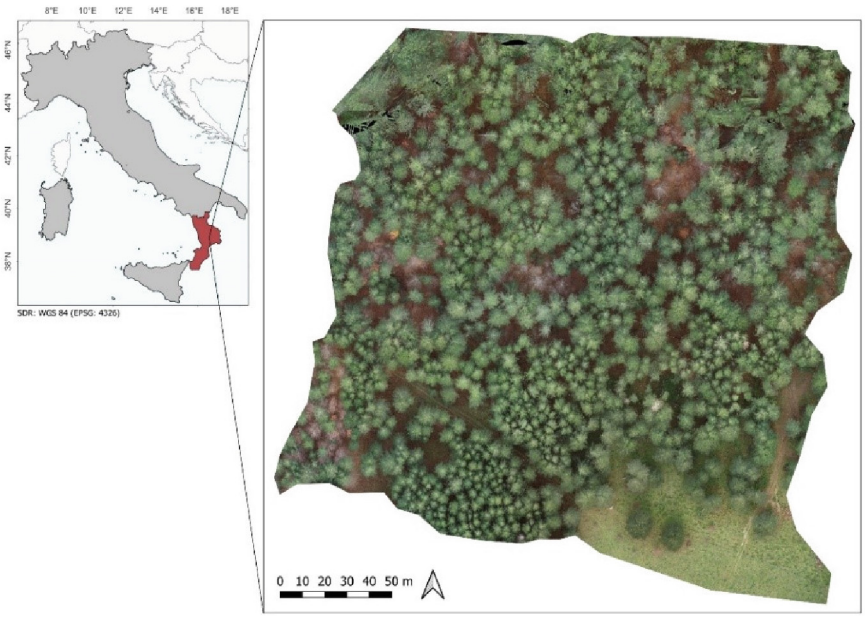


Fig. 1. Study area: location within the national territory (on the left); overview of the study area represented by the RGB orthophoto processed from the images acquired during the UAV survey.

3 Materials and Methods

3.1 Surveys and Datasets

Field Dendrometric Measurements

The dendrometric variables were measured during a site-survey campaign conducted in seven circular SSAs ($r = 10$ m or 20 m), randomly distributed and representative of the entire study site. In each SSA, D was measured for all the alive-standing trees. H was also measured using a Vertex IV hypsometer for the same trees. Only the trees having $D \geq 12.5$ cm were considered for the subsequent analyses.

On the basis of the acquired data, and for each SSA, various dendrometric parameters were calculated, such as the number of plants (N), the total basal area (G; Eq. 1), the average basal area (g; Eq. 2), the mean diameter of mean basal area (d_g; Eq. 3); and the mean Lorey's height (Eq. 4), defined as the mean height of the trees weighted by their basal area (H_{Lorey}):

$$G = \frac{\pi}{4} \cdot \sum_{(i=1)}^{N} D_i^2 \tag{1}$$

$$g = \frac{G}{N} \tag{2}$$

$$d_g = \sqrt{\frac{4 \cdot g}{\pi}} \tag{3}$$

$$H_{Lorey} = \frac{\sum_{i=1}^{N} \frac{\pi}{4} \cdot D_i^2 H_i}{\sum_{i=1}^{N} \frac{\pi}{4} \cdot D_i^2} \tag{4}$$

where *i* represents the single generic tree.

The volume of the single trees was estimated by the use of two different volumetric models: the first one is represented by a local single-entry (*D*) volumetric model (V_{PEBSP}; Eq. 5); the second one, was developed by the *Istituto Sperimentale per l'Assestamento Forestale e per l'Alpicoltura* (ISAFA) during the Italian national forest inventory (IFNI) [9] (V_{IFNI}; Eq. 6):

$$V_{PEBSP} = 0.000000000122989 \cdot D^6 - 0.000000038608516 \cdot D^5 + 0.000004839988707 \cdot D^4 - 0.000314196719082 \cdot D^3 + 0.012222419503339 \cdot D^2 - 0.197600010896784 \cdot D + 1.219706133402030) \tag{5}$$

$$V_{IFNI} = 0.000457023 + 0.0000380346 \cdot D^2 \cdot H - 0.0000423133 \cdot D + 0.00160308 \cdot H - 0.000112508 \cdot D \cdot H + 0.0000210093 \cdot D^2 + 0.0000132827 \cdot H^2 + 0.00000000337571 \cdot D^2 \cdot H^2 - 0.000000177836 \cdot D^3 - 0.000000000491192 \cdot D^3 \cdot H^2 \tag{6}$$

In order to relate the dendrometric parameters of each tree detected within the SSAs to the remotely sensed digital information, all the plants were progressively numbered, and the corresponding geographical coordinates detected by in-field visual inspection, supported by the use of the RGB orthophoto provided by the UAV survey. The semi-thick canopy cover prevented the use of GNSS receivers.

UAV Survey and Pre-processing of LiDAR Data

The drone surveys were performed using the Zenmuse L1 multi-sensor module mounted on a DJI Matrice 300 RTK drone. Specifically, the L1 module is formed by 3 different sensors: i) a Livox LiDAR sensor with a class 1 laser and a field of view (FOV) of 70.4° x 77.2° (horizontal x vertical), 480,000 points emitted per second up to a maximum distance of 450 m; ii) a 1-inch 20 megapixel CMOS sensor RGB camera, synchronized to LiDAR capture; and iii) a high precision inertial measurement unit (IMU) able to constantly monitor the flight parameters (pitch, roll, and yaw). The use of the high-precision GNSS D-RTK mobile station guaranteed the correct georeferencing of the data. In order to obtain the RGB-colored point clouds, the raw data have been processed using the proprietary software DJI Terra because no other alternative software solution is available [10]. The point cloud returned by the survey had an average density of 379 points/m^2.

A fundamental step in the LiDAR data pre-processing workflow is correctly identifying what in the point-clouds represents the ground and what represents the above-ground forest structure [11]. The cloud points were classified using the automatic *point cloud classification* algorithm implemented in eCognition Developer 10.3 software [12] (Fig. 2).

Once classified, the point clouds were used to construct the digital surface -models (DSM) and the digital terrain model (DTM). After having set the *Z* parameter value

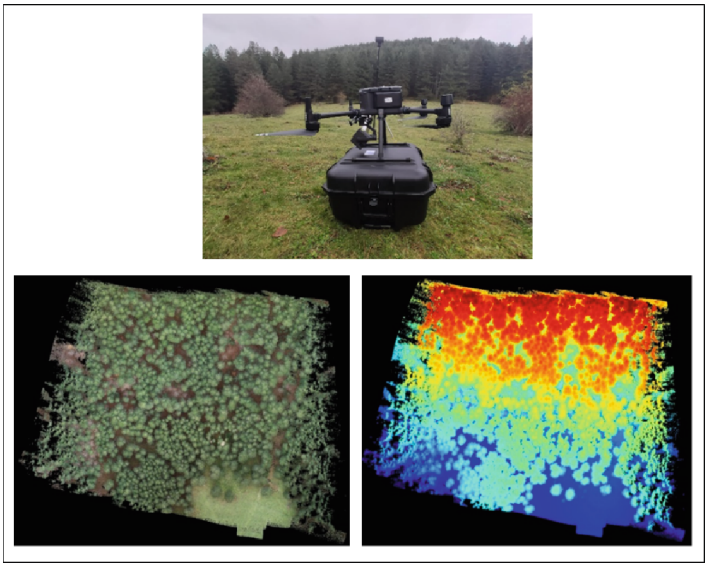


Fig. 2. DJI Matrice 300 RTK drone with DJI L1 module mounted (top); At the bottom, the RGB orthophoto (left) and the LiDAR point clouds (right).

(elevation) of each output pixel as the maximum value of the points falling in and the interpolation kernel size equal to 3 for empty pixels filling, the *rasterize point cloud* algorithm was separately applied to the points classified as ground and as above ground objects to retrieve the DTM and the DSM, respectively. The spatial resolution of the final output was 0.1 m × 0.1 m. Finally, the canopy height model (CHM) was calculated by subtracting the DTM from the DSM.

3.2 Hypsometric Model Construction

As a first step, the relationship between field-measured H values (reference) and the respective LiDAR-based tree heights (H_L), directly retrieved from the CHM, was investigated. The coefficient R^2 (Eq. 7), root mean squared error (*RMSE*) (Eq. 8), and the *Bias* (Eq. 9) were calculated as indicators of the degree of correlation and error:

$$R2 = 1 - \sum_{j=1}^{n} \frac{(H_{Li_j} - H_j)^2}{(H_j - \mu_H)^2} \tag{7}$$

$$RMSE = \sqrt{\frac{\sum_{j=1}^{n} (H_{Li_j} - H_j)^2}{n}} \tag{8}$$

$$Bias = \frac{\sum_{i=1}^{n} (H_{Li_j} - H_j)}{n} \tag{9}$$

where H_{Lij} represents the height of tree j measured by LiDAR; Hj represents the field-measured reference height of the tree j; μH represents the average of all the reference

heights measured for the comparison; n represents the number of trees used in the comparison.

A part (66%) of the individual dendrometric variables (H_L and D) measured within the SSAs were used for the calibration of the hypsometric model (Eq. 10). Inversely from what commonly happens in diametric dendrometry, the variable to be determined (y) is represented by the tree's diameter (D_L), while the known variable (x) is the respective H_L:

$$y(D_L) = a \cdot e^{x \cdot b} \tag{10}$$

Having available both the D_L and the H_L values, these were employed to calculate the dendrometric parameters G, g and dg in each SSAs, and, apply the two volumetric models to estimate the volume of standing trees.

The accuracy of the model was assessed by comparing the remaining part (34%) of field-measured D values to the corresponding values predicted with the exponential equation in Eq. 10. The R^2, *RMSE* and *Bias* metrics were used as analytical accuracy descriptors.

3.3 Estimation and Mapping of Dendrometric Parameters on the Entire Study Area

In order to calculate the main dendrometric parameters for each individual pine tree in the entire study area and map their spatial distribution, the hypsometric relationship expressed by Eq. 10 was initially applied to each pixel of the CHM image to obtain the distribution map of D_L (diameter map). In turn, having both the H_L (CHM) and DL values in raster format, these were involved in implementing Eqs. 5 and 6 to obtain the respective volume maps. After that, the unique value of the respective dendrometric parameter for the specific canopy, reported on each map described above, was finally obtained by calculating the *majority* zonal statistic for each group of pixels belonging to a single canopy. Subsequently, the fundamental dendrometric parameters N, G, g, d_g and V were calculated for all the trees in the study area.

4 Results and Discussions

4.1 Field-Measured Dendrometric Parameters

The dendrometric parameters obtained from the seven SSAs, occupying a compressive area of 4089.20 m^2, are shown in Table 1.

It is noticeable as the mean diameter (d_g) mainly falls into two "diametric classes": around 40 cm (SSAs 1,2 and 4) and around 52 cm (SSAs 3,5 and 7), with the only exception represented by the SSA 6, which is slightly over 56 cm. Consequently, the mean basal area (g) remains constant between 0.12–0.13 m^2 and 0.21–0.25 m^2. The mean Lorey's height (H_{Lorey}) is similar in all SSAs, between 28.2 m and 32.8 m. This was predictable, considering the monoplane structure of the analyzed pine forest. The above-ground structure volume calculated from the two different volumetric models was co-consistent, with the V_{PEBSP} returning slightly lower values (never exceeding 12%).

Table 1. Field-measured dendrometric parameters for each of the seven survey sample areas (SSA), referred both to one hectare (ha) and to the entire study area (4.60 ha).

	r [m]	N [n]	G [m^2]	g [m^2]	d_g [cm]	H_{Lorey} [m]	V_{PEBSP} [m^3]	V_{INFI} [m^3]
SSA 1	10	22	2.74	0.12	39.09	30.00	36.87	38.05
SSA 2	10	27	3.48	0.13	40.68	29.80	47.00	48.13
SSA 3	20	45	10.04	0.22	52.93	32.30	137.12	155.31
SSA4	10	24	3.20	0.13	40.68	30.50	45.35	46.95
SSA 5	10	15	3.18	0.21	51.71	28.20	43.52	46.16
SSA 6	10	13	3.23	0.25	56.42	32.80	44.03	48.66
SSA 7	20	53	11.74	0.22	52.93	33.00	161.65	178.42
ha		487	92.09	0.19	49.18	31.70	1255.82	1373.54
TOT study site		2240	423.06				5799.38	6318.28

4.2 LiDAR-Vertex Height Correlation

Figure 3 shows the scatter plot in which the linear relationship between field-measured H values and LiDAR-based H_L is reported. Observing the R^2 value (0.61), the correlation between the two data is relatively good, with a higher degree of linearity observable between 28 m and 38 m (considering H). However, some outliers are visibly present, significantly below 28 m (H), bringing the *RMSE* and *Bias* values to 2.16 m and 1.11 m, respectively.

Neglecting the intrinsic error to which the LiDAR sensor may be subject, the most sensitive error step comprises the estimation phases by interpolating the DTM and DSM. Future studies will aim to optimize this step, trying to understand and reduce the source of the errors.

4.3 Hypsometric Model and Its Validation

Observing Fig. 4, the relationship between H_L and D appears to be exponential. The model allowed the estimation of the diameters D_L of the individual pine trees falling within the entire study area. This was possible thanks to the availability of a datum such as the CHM. A single drone flight mission, in fact, allows the rapid survey of a greater number of tree heights than could be done by field surveys. The SSAs were used to have comparative information between traditional and Lidar-based data, besides a group of data for training and validating the hypsometric model.

The accuracy assessment of the model revealed that the R^2, *RMSE* and *Bias* reached values equal to 0.62, 11.30 cm and 0.48 cm. Considering the preliminary nature of these experiments, a good result aimed at optimizing the process for more substantial future applications. This is further confirmed by comparing the LiDAR-based dendrometric parameters shown in Table 2 with those field-measured presented in Table 1.

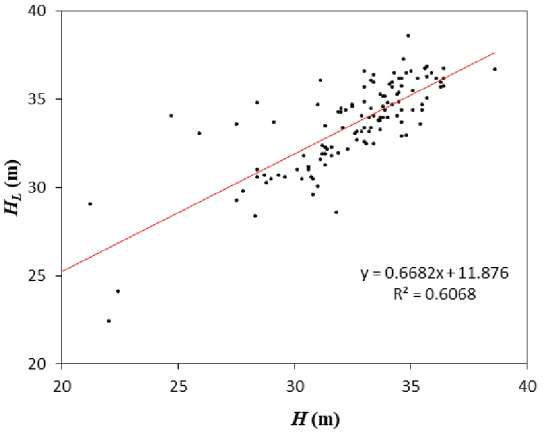


Fig. 3. Scatterplot showing the linear correlation between the field-measured trees height values (H) and the corresponding reference values measured by the LiDAR (H_L).

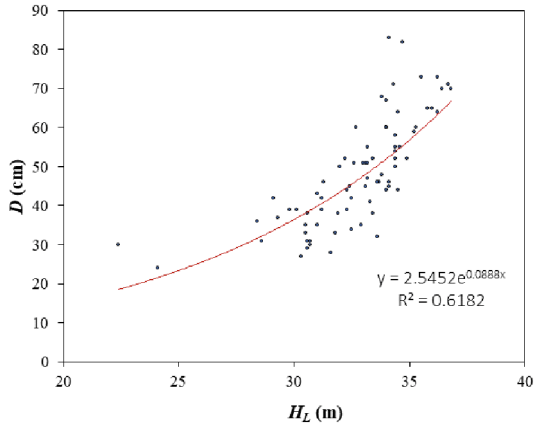


Fig. 4. Ipso-diametric relationship, from which the exponential trend curve (red line) was interpolated between the heights extracted from the CHM obtained from the LiDAR survey and the diameters measured on the ground.

4.4 Estimation and Mapping of Dendrometric Parameters on the Entire Study Area

In Fig. 5, the maps report the spatial distribution of the main dendrometric parameters obtained directly (CHM) or indirectly (diameters and volumes maps) from the LiDAR surveys.

Comparing the dendrometric parameters (Table 3) retrieved starting from the maps mentioned above for the entire study area and comparing them with those of Table 2 calculated for the SSAs, the only noticeable difference is the number of plants: 256 N/ha, against the 487 N/ha estimated through SSAs. This is due to the heterogeneity of habitats and natural systems that the SSAs-based surveys fail to catch: the density of the trees

Table 2. Dendrometric parameters based on the HL and DL parameters obtained from LiDAR surveys for each of the seven survey sample areas (SSA), referred to as hectare (ha) and for the entire study area (4.60 ha).

	r [m]	**N** [n]	**G** [m^2]	**g** [m^2]	**d_g** [cm]	**H_{Lorey}** [m]	**V_{PEBSP}** [m^3]	**V_{INFI}** [m^3]
SSA 1	10	22	3.04	0.14	42.22	31.90	35.90	38.97
SSA 2	10	27	4.09	0.15	43.70	32.50	49.23	53.85
SSA 3	20	45	8.64	0.19	49.18	34.10	114.66	131.01
SSA4	10	24	3.58	0.15	43.70	32.30	45.31	49.34
SSA 5	10	15	3.10	0.21	51.70	34.40	35.25	40.42
SSA 6	10	13	3.32	0.26	57.54	35.40	44.30	51.78
SSA 7	20	53	11.77	0.22	52.93	35.00	155.53	180.96
ha		487	91.97	0.19	49.18	34.00	1174.26	1336.03
TOT study site		2240	423.06				5401.60	6145.74

varies unpredictably along the study area. However, the remaining dendrometric parameters remain consistent. Even the volume can be considered proportionally consistent. This demonstrated, on the one hand, the reliability of the method. On the other hand, the problem of the SSAs remains mainly the exact population density estimate.

Table 3. Dendrometric parameters obtained from dendrometric parameter maps (CHM, diameter map and volume maps), referred to hectare (ha) and for the entire study area (4.60 ha).

	N [n]	**G** [m^2]	**g** [m^2]	**dg** [cm]	**H_{Lorey}** [m]	**V_{PEBSP}** [m^3]	**V_{INFI}** [m^3]
ha	256	49.16	0.19	49.18	34.00	672.80	775.03
TOT study site	1176	226.13				3094.90	3565.16

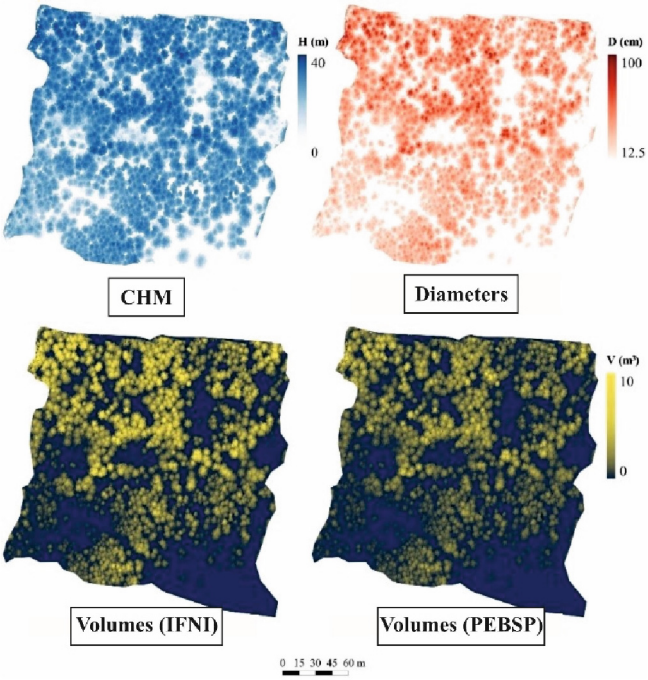


Fig. 5. Maps reporting the spatial distribution of Lidar-based heights (CHM), diameters (diameters map), and volumes (volumes map). The latter is represented by those calculated with the VIFNI and the V_{PEBSP}.

5 Conclusions

The present study showed the reliability of LiDAR for measuring fundamental dendrometric and forest structure parameters in a monoplane conifer forest. The remote measurement of tree heights, on a larger scale and in a short time, allows the reduction of the time-onerous amount of forest field surveys and the increase of detected territory portions. Consider that the increasing availability of open-source, user-friendly applications based on artificial intelligence might significantly help improve the reliability of these processes and practical applications.

A limit to the present approach could be modeling the trees belonging to the secondary vertical forest planes. In future analyses, it will be necessary to evaluate the capability of the DJI L1 module for measuring the heights of those trees in more heterogeneous forest environments.

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