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"Innovative surveying methodologies through Handheld Terrestrial LIDAR Scanner technologies for forest resource assessment"

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CONTENTS **Pag.**

ABSTRACT

Precision Forestry is an innovative sector that is currently of great importance for forest and spatial planning. It enables complex analyses of forest data to be carried out in a simple and economical way and facilitates collaboration between technicians, industry operators and stakeholders, thus ensuring transparency in forestry interventions (Corona *et al.*, 2017). The principles of "Precision Forestry" are to use modern tools and technologies with the aim to obtain as much real information as possible, to improve decision-making, and to ensure the current objectives of forest management. Thanks to the rapid technological developments in remote sensing during the last few decades, there have been remarkable improvements in measurement accuracy, and consequentially improvements in the quality of technical elaborations supporting planning decisions. During this period, several scientific publications have demonstrated the potential of the LIDAR system for measuring and mapping forests, geology, and topography in large-scale forest areas. The LIDAR scans obtained from the TLS and HLS systems provide detailed information about the internal characteristics of tree canopys, making them an essential tool for studying stem allometry, volume, light environments, photosynthesis, and production models. In light of these considerations, this thesis aims to expand the current knowledge on the terrestrial LIDAR system applications for monitoring forest ecosystems and dynamics by providing insight on the feasibility and effectiveness of these systems for forest planning. In particular, this study fills a gap in the literature regarding practical examples of the use of innovative technologies in forestry.

The main themes of this work are:

A) The strengths and weaknesses of the mobile LIDAR system for a forest company;

B) The applicability and versatility of the LIDAR HLS tool for sustainable forest management applications;

C) Single tree analysis from HLS LIDAR data.

To investigate these themes, we analyzed six cases studies:

1) An investigation of the feasibility and efficiency of LIDAR HLS scanning for an accurate estimation of forest structural attributes by comparing scans using the LIDAR HLS survey method (Handheld Mobile Laser Scanner) to traditional instruments;

2) An examination of walking scan path density's influence on single-tree attribute estimation by HMLS, taking into account the structural biodiversity of two forest ecosystems under examination, and an estimation of the cost-effectiveness of each type of laser survey based on the path scheme considered;

3) A study of how LIDAR HLS surveys can contribute to fire prevention interventions by providing a quantitative classification of fuels and a preliminary description of the structural and spatial development of the forest in question;

4) An application of a method for assessing and rating stem straightness in tree posture using LIDAR HLS surveys to quantify differences between stands of different log qualities;

5) The identification of features of a Mediterranean old-growth forest using LIDAR HLS surveys according to the criteria established in the literature;

6) The extrapolation of dimensional information for *Ficus macrophylla* subsp. *columnaris* to identify the monumental character of the tree by comparing the most appropriate LIDAR HLS point cloud processing methodologies and estimating the total volume of individual trees.

In conclusion, the results of these cases studies are useful to determine new research aspects within the system in the forest environment by applying recently published analysis methodologies and indications of relevant terrestrial LIDAR methodologies.

Keywords: Precision Forestry, 3D Remote Sensing Data, LIDAR applications, Terrestrial Laser Scanner, Handheld Mobile Laser Scanner, Point Cloud processing, Forestry, Forest structure, Forest Management, natural resources, Organizational efficiency.

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1. INTRODUCTION

European area contains 227 million hectares together with 27 million of forest land (35% of the total European surface area is covered by forests). European forests are made up of 46% of coniferous extensions and 37% of hardwood surface, the rest of mixed forests. Nowdays, a quarter of the European forest area is protected by laws and regulations with the main objective to preserve biodiversity, out of a total of 49.3 million hectares of forest areas and 4.1 million hectares of other forest areas.

In Europe, forests contribute to the society's wood supply (at least 75% of the forest area) and to the reduction of CO_2 emissions by sequestering carbon dioxide in their biomass that corresponds to one-tenth of CO_2 emitted each year by anthropological activities. Between 2010 and 2020, the average annual sequestration of carbon in forest biomass reached 155 million tons in the European region. In recent years, the health status of forests is strongly influenced by frequent and threatening events which determine severe droughts, widespread fires, a series of strong wind storms and infestations of new pests.

It is increasingly evident that the observed impacts have overcome the expectations of past impact projections, which calls into question sustainable forest management (SFM) in Europe and requires adaptation to climate change. Adaptation to climate change refers to the adjustments of ecological, social and economic systems in response to their effects (Raši *et al.*, 2020).

"*Sustainable forest management means the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems*" (Ministerial Conference on the Protection of Forests, Helsinki, 1993).

The pan-European concept of Sustainable Forest Management (SFM) has safeguarded a common front for dialogue, monitoring and policy-making on the protection of European forests. Europe stands in a state of balance between the components of the sustainable forest management sector. However, new pressures and challenges can lead to changes in this balance by requiring holistic and evidence-based decisions to be applied in order to achieve a new state of political-socioeconomic equilibrium. Forest operational planning is generally based on population, owners or the regional level as the primary treatment unit. A forest landscape is a spatial mosaic of arbitrary boundaries containing distinct functionally interacting areas. In recent years, therefore, interest has turned towards the use of smaller units of an area in such a way that the formation of treatment unity becomes part of the operational planning. There is a need for continuous updating of the inventory of forest resources at the company level by monitoring, for example, land use changes or structural and compositional changes in forest resources, necessary requirements for the key data collection phase in forest planning. This is forcing foresters to look for more cost-effective alternatives to field surveying and productivity in terms of costs and productivity (Suarez *et al.*,2005; Shiba *et al.*, 2006).

Forest communities need to understand the effects of climate change on forests and determine which adaptation actions could be taken now and, in the future, to respond to this threat. For example, among the effects reported by the FAO, there is a clear increase in foliage loss between 2010-2018 equal to 19% of parcels and repetition of climatic events such as continuous heat waves and a reduction of water availability which cause forest fires in the last 10 years in the European Mediterranean areas with a high level of vegetal and animal biodiversity. The monitoring of forests could support the proactive management of the risk of a disturbance if it is done through immediate mapping of damages following large-scale disturbances and continuous detection of facts that influence the risk of the disturbance. From the objectives indicated by the SFM, it will be essential to improve the collection of information on forest resources at the national level by involving experts and interested stakeholders (Raši *et al.* 2020).

Italian forest patrimony covers a total of almost 11 million hectares, corresponding to more than a third of the national surface. In Italy, there is a significant biological, landscape and cultural wealth in forest biodiversity that represents an essential resource for the green economy and its development towards the profitability of mountain and forest communities. The technological innovation developed in recent decades has allowed entrepreneurs, forest technicians and forest owners to favor integration with stakeholders and the social community, by guaranteeing transparency in complex forest management operations and carrying out data analysis of the forest heritage in a simple and economical way.

From the need to implement and integrate new information technologies and recognize them as considerable tools for the national forest production system, a new term, Precision Forestry, has been coined in recent decades following the First Precision Forestry Symposium organized in 2001 by the University of Washington in collaboration with the United States National Forest Service, In that context, was proposed the following definition: "*precision forestry uses high technology sensing and analytical tools to support site-specific, economic, environmental, and sustainable decision-making for the forestry sector supporting the forestry value chain from bareland to the customer buying a sheet of paper or board*" (Bare and Dean, 2001). Since the 2001 Symposium, precision forestry has found its place in the world economy through its applications for forest inventory conformation, especially in Europe and North America.

Precision forestry builds on the cornerstones of "Precision Agriculture" (Kovácsová and Antalová 2010). The substantial difference with precision agriculture is the wider Spatio-temporal domain covered by precision forestry ranging from the single tree to the global scale, on different temporal frequencies of observation (Corona *et al.*,2017). The principle of "Precision Forestry" is to use modern tools and technologies to obtain as much real information, improve decision-making, and ensure the current objectives of forest management.

A team of researchers, SE Taylor, TP McDonald, FW Corly (2002), define precision forestry as planning and carrying out site-specific forest management activities and interventions to improve the quality of woody products and use, reduce waste and increase profits and maintain environment quality.

Precision forestry is made up of two main categories:

1) use of information deriving from geospatial technologies (GPS, GIS, remote/proximal sensing, LIDAR) to assist forest management and planning,

2) specific silvicultural interventions including data on product growth and yield, product quality and environmental conditions according to place and time (Taylor *et al.*, 2002).

Holopainen *et al.* (2014) reported that in suitable conditions, the economic advantages attributable to Precision Forestry are between 15% and 20% of profitability increase, compared to traditional interventions. The integration of consolidated technologies and the analytical potential of data through Big Data opens up concrete prospects for enhancing the forest-wood supply chain, thus obtaining full availability of information and a smart characterization of forest resources (Holopainen *et al.*, 2014).

Precision forestry can be considered as an "*environmentally friendly system solution that optimizes product quality and quantity by minimizing costs, human impact and human intervention, and the variation caused by unpredictable nature*" (Joint Research Center of the European Commission, 2014).

"Strategic agenda for research and innovation for 2020" of the European Forest Institute highlighted the need to address societal challenges and improve industrial competitiveness in accordance with the European strategy. So far, precision forestry represents a cornerstone of technological development in the forestry sector (Fardusi *et al.*, 2017).

1.1 Literature review

1.1.1 The development of Forest and Woodland LIDAR remote/proximal sensing applications

The conservation of the ecosystem services provided by the forests themselves is one of the priorities of sustainable forest management which can be achieved in an efficient time thanks to the cutting edge of remote sensing technologies (Masek *et al.*, 2015). Forest system assessment for decision making in Forest Planning has been supported by computer technology developed over the last 30 years. Remote sensing is defined as the technology for measuring the characteristics of an object or surface at a long distance, more than 100 meters (Sabins and Floyd, 1978; Sofia *et al.*, 2022). In other words, the field of remote sensing applies different measurement and recording techniques in order to analyze multi-source data at high spatial and/or temporal resolution to allow management practices or to support scientific discovery (Kovacsova *et al.*,2010).

The most common technologies belong to two main categories:

- passive remote sensing technologies: optical (Photogrammetry) or thermal sensors that detect the energy received by the Earth due to reflection and re-emission of solar energy from the Earth's surface or from the atmosphere (wavelengths between visible and Near InfraRed);
- active remote sensing technologies: radar sensors (Radio Detection and Ranging) operating in the lower part of the spectrum (microwave) by sending energy to Earth and monitoring the energy received from the Earth's surface or atmosphere and LIDAR sensors (Light Detection and Ranging) that send laser pulses in the Near InfraRed range and calculate the spatial position of the affected targets, allowing the three-dimensional reconstruction of objects (Renslow *et al.*, 2000; Sofia *et al.*, 2022).

The Proximal sensing involves the use of sensors (LIDAR and/or photogrammetry) close proximity to the plants (<100 meters) using different platforms with an resolution considerably higher as compared to remote sensing.

The remote and proximal sensing systems can provide a multitude of information for forest applications, with the main objective being to map, monitor and model forest resources. Thanks to continuous technological progress, more mature techniques are ready to be applied to the management of forest resources (Talbot *et al.*, 2017).

LIDARThanks to continuous technological progress, more mature techniques are ready to be applied to the management of forest resources.

The latest technologies offer improvements to forest management such as:

- tighter control of operations with better data collection,
- increased selectivity of requirements according to site and needs,
- automation of forestry operations,
- optimization of decision-making with analytical tools (Suarez *et al.*, 2005; Kovacsova *et al.*, 2010).

Current remote sensing methods have exceeded the limits of traditional detection by providing a wide range of multi-temporal, multi-scale and multidimensional forest structure information relevant for inventory, forest monitoring for planning purposes (Wulder *et al.*, 2012; Fu *et al.*, 2021). It is testified by several publications that remote sensing techniques were cheaper and more efficient than field surveys in terms of cost and productivity for long-term and wide-ranging forest censuses (Renslow *et al.*, 2000).

LIDAR and UAV are among the leading technologies of remote sensing adopted globally for the forestry sector.

LIDAR sensors with different characteristics are currently available for ground-based, airborne, and satellite-based surveys. Depending on the sensor type, velocity, and distance from the object, point density may vary, resulting in greater or lesser accuracy in representing the object. LIDAR data does not require aerial triangulation and orthorectification, as each measurement is individually georeferenced (Suarez, 2005). In the case of forest surfaces, the laser scanner has particular advantages that make it suitable for the study of vegetation and related phenomena.

LIDAR can measure different parameters of the structure of forest environments, landscape scale results of considerable utility for research. The survey modalities and the correlation with forest characteristics differ depending on the type of sensor used and the density of points obtained (Dubayah and Drake, 2000). The estimated variables can be at the level of forest stand (Næsset, 2004), particle or even single tree (Barilotti *et al.* 2007; Reitberger *et al.*, 2009). From LIDAR data it is possible to extrapolate specific key information for the assessment of habitat quality in the case of protected forest areas and for their management such as tree coverage, density and continuity of foliage, spatial distribution of forest species, distribution of the size class of the trees investigated etc. Many researchers claim that the combination of multiple tools belonging to remote/proximal sensing can contribute to the study of carbon flow at the biosphere level, to the optimal fire management and forecasting, carbon sequestration monitoring and habitat distribution (Moskal *et al.*, 2009; Kobayashi *et al.* 2012, Antonarakis and Coutiño, 2017; Hasan *et al.*, 2019). Furthermore, a correct laser scanner can also give information on the surface of the ground under cover such as slope, curvature, the presence of roads. More accurate knowledge of land, water flows and forest inventory can help to optimize not only road construction (strategically positioned with low environmental impact and full satisfaction of logging plan) but also for the planning of mechanization operations in the forest (Choudhry and O'Kelly, 2018).

Remote/proximal sensing technologies have enabled more accurate and accurate forest surveys to be carried out, as required by global initiatives such as the United Nations Programme on Reducing Emissions from Deforestation and Forest Degradation (REDD), the Global Forest Resource Monitoring (FAO - Global Forest Resource Monitoring) and European (Forest Europe - Interministerial Conference on the Protection of Forests in Europe) (Chirici, 2020).

From these advantages obtained by the technological revolution of remote/proximal sensing it is possible to predict a future full of competence and understanding of natural resources and for the development of an economic sector that meets the needs of the public and the environment (Fardusi *et al.*, 2018). Professionals still have more and more sophisticated information for decision-making (University of Washington, 2003). However, LIDAR systems are now recognized in the market as expensive equipment for many public and private companies, and LIDAR data sharing is limited to many industry professionals. Also, open source softwares developed in recent years show rather complex procedures that need in the processing team professionals who have a high level of preparation compared to the standards. So, it is necessary to establish new interdisciplinary collaborations between professionals and researchers to maximize the benefits of the technologies present in the research and identify new application protocols instrumental for forest planning (Beland *et al.*, 2019).

1.1.2 The forest Surveying and LIDAR data Collection methods

In the past, traditional dendrometric measurements such as hypsometers and easels were performed in the field to collect a reasonable quantity of sample data for forecasting future forestry interventions in line with the objectives of sustainable forest planning. However, the costs of traditional forest surveys in the revision of management plans were often unsustainable, yet essential to guarantee at least historical continuity such as the evolution of the mass, of the forest structure, of the use and increase, etc. (Abramo *et al.*, 2007). Moreover, past technologies were limited because they could not obtain complete dimensional measurements on individual trees (West *et al.*, 2009). Today, thanks to the rapid technological development of the last decades, there has been a remarkable improvement in measurement, leading to an increase in quality in the technical elaborations supporting planning choices.

In the field of LIDAR technologies, it is possible to identify four laser scan systems:

1) Airborne laser scanning (ALS) system supported from a manned aircraft or Unmanned Laser Scanning (ULS) supported from UAS/UAV platforms,

2) Terrestrial laser scanning system (TLS)

3) Hand held laser scanning system (HLS)

4) LIDARSatellite Laser Scanning (SLS) (Brede *et al.*, 2019).

Recently, there has been a demanding growth in the purchase of LIDAR by several private companies due to its versatility in various fields of research and application, which may represent an opportunity for public-private research projects and collaborations between different fields such as geology, agronomy, hydrogeological instability, architecture, cultural heritage, landscape, urban planning, archaeology, sculpture, etc. (Don and Chen, 2017; Brede *et al.*, 2019). Some researchers have produced several research papers on LIDAR efficacy, showing strengths and weaknesses in the field of research and the forest application for each LIDAR system.

In the context of the Airborne LIDAR scanner system (ALS) supported by the aircraft and UAV systems (ULS) the strengths are as follows:

- wide spatial coverage analyzed by the ALS,
- direct estimates of canopy roughness and fraction of forest cover,
- terrain elevation maps (Digital Terrain Model),
- monitoring of disturbances through repeated contiguous measurements.

The weaknesses are as follows:

- limited description of the internal canopy structure,

- data collection conducted by airborne LIDAR provided by services,

- LIDAR data collection period influenced by the meteorological conditions in the area,

- air data collection logistics influenced by flight regulations for UAV systems.

(Beland *et al.*, 2019).

In recent decades, the LIDAR ALS system are perfect for forest, geological and topographic measurement and mapping for large-scale forest areas. In fact, the ALS systems supported by helicopters or rotary-wing aircraft cover surfaces of 10-1000 km^2 following elevation profiles up to 3000 m a.s.l. The ULS systems are similar to the ALS in terms of components, but are more miniaturized and installed on board a UAV flying at low altitude of about 100 a.s.l.

Depending on the engine power of the UAV, ULS systems can cover areas of 0.02-10 km2 providing data of higher point density than ALS. Different data products can be derived from the ALS, such as digital elevation model grids, level curves, raw point data and intensity clouds.

LIDARCurrently, the ALS is one of the most promising and effective technologies for a wide range of forest applications, such as biomass estimation in large areas becoming operational in many regional and national forest inventories (Næsset, 2004; Wulder *et al.* 2012; Laurin *et al.* 2016; Nie *et al.* 2017). However, the standardization of point cloud processing, the comparability between different products generated by different resolution ALS data and the influence of LIDAR accuracy on topography, on land cover categories and canopy density are still critical issues for the operational use of ALS data (Scrinzi and Clementel, 2014; Fardusi *et al.*, 2017).

In the context of the Terrestrial Laser scanner system (TLS), belonging to the proximal sensing systems, the strengths are as follows:

- detailed information on the internal structure of the canopy,

- accurate LAI estimation and full 3D foliage distribution,

- accurate foliage distribution based on laser interception by wood and leaves.

- high information accuracy and accuracy at very fine (millimeter) spatial scales.

The weaknesses are as follows:

- limited spatial coverage (a few hundred metres),

- time-consuming LIDAR data collection with TLS system due to numerous scans for a complete digitisation of the forest area investigated;

- potential gaps in data in canopy and areas of dense undergrowth/canopy foliage,

- still complex methods in the multi-scan alignment phase,

- LIDAR TLS expensive equipment and not accessible for many small businesses.

Terrestrial Laser Scanner (TLS) is mainly used for detailed point clouds of nearby targets (< 100 m). The TLS instrument is generally stationary and fixed to a detection tripod, and scans from multiple locations can be combined to increase coverage and minimize occlusions (Duanmu and Yanqiu, 2020).

Forest surveys carried out by LIDAR with TLS system are useful for the evaluation of a sample number of forest sites for accurate planning of the investigated area. A single shaft can be modeled accurately by performing an accurate scan from different angles to estimate the volume of its epigee components (Pirotti *et al.* 2010).

The terrestrial laser scanner allows to obtain very accurate models on areas limited by the density of the forest and the number of stations scanned. It also allows an accurate estimation of individual volumes of wood through the application of some data processing methods such as structure modeling (QSM) obtaining accurate measurements and possible time series analysis (Raumonen *et al.*, 2013; Hackenberg *et al.*, 2015).

In recent years there have been records that testify to the efficiency of LIDAR TLS instrumentation for tree mapping (Pueschel *et al.* 2013), for tree height estimation (Olofsson *et al.* 2014; Srinivasan *et al.* 2015; Woods *et al.* 2018) for the estimation of structural canopy parameters (Zhao *et al.* 2012, Zheng *et al.* 2013, Cifuentes *et al.* 2014, Atkins *et al.* 2018) and for the calculation of forest biomass (Srinivasan *et al.* 2014, Greaves *et al.* 2015, Vicari *et al.*, 2019). Despite these improvements, LIDAR TLS instrumentation is still limited due to its high cost and complexity of extrapolating parameters from LIDAR data, requiring the need for well-trained operators in the team. Moreover, the accuracy of the LIDAR TLS data depends strongly on the operator (from the acquisition phase to the processing of the "Point Cloud") and the characteristics of the survey plot (canopy coverage, tree density, phenological period) affect the replicability of the product (Fardusi *et al.*, 2017; Beland *et al.*, 2019).The latest technological innovations of proximal sensing have made available LIDAR systems, considered versatile and efficient compared to LIDAR TLS systems, easily managing data in the case of standardized forest inventories.

In the context of the system Hand-heldLaser Scanning System two types of systems are classified: the first type of system is placed in a backpack or vehicle while the operator walks or the vehicle moves inside the forest (HLS), the second type of system called Portable Canopy LIDAR (PCL), which emits lasers only in the upward direction, while the operator carries the LIDAR system while walking along a transept (Duanmu and Yanqiu, 2020; Gough *et al.* 2022).

In the context of the Hand-held laser scanning system (HLS), the strengths are as follows:
- detailed information on the internal structure of the canopy,
- accuracy of information not high but acceptable for planning with precision at very fine (centimeter) spatial scales;
- reduced time required for LIDAR data collection with HLS in the field;
- efficient georeferencing of LIDAR HLS system data due to embedded SLAM technology.

The weaknesses are as follows:
- limited spatial coverage (some fifty metres or more),
- potential data gaps in canopy and dense undergrowth areas/canopy foliage,
- still complex methods in the phase of extrapolation of dendrometric parameters from "Point Clouds",
- LIDAR HLS equipment expensive and not accessible for many small businesses.

The LIDAR scans obtained from the TLS and HLS systems provide enormous details on the internal characteristics of the canopy and are an essential choice for studies of stem allometry and biomass, simulation of light environments, photosynthesis tests and production models. They can also calibrate/validate products from aircraft or satellite systems.

For example, Shao *et al.* 2020 shows a high reliability data dendro-auxometric results from the use of LIDAR TLS and HLS systems in a forest survey highlighting the benefits obtained for both systems (reduction of dendrometric survey times in the forest with LIDAR instruments compared to traditional dendrometric surveys) and differences in performance in both LIDAR systems. In particular, it has established how HLS is able to improve absolute positioning accuracy in odometry (estimating the movement of each cloud of HLS points in the frame compared to single-scan TLS data) and global optimization of the LIDAR relief (simultaneous optimization of all LIDAR point clouds poses) (Shao *et al.*, 2020).

In a business context, however, they are always considered expensive tools for small businesses. One of the alternative solutions is to unite several public and private companies, large or small, through different research projects, focusing on the same common objective, namely the determination of data on the same survey area. This is possible through a complete sharing of skills and knowledge for the acquisition of forest data to be able to develop innovative forest survey methodologies following the needs of the companies involved.

In a forest research context one of the solutions exposed in many research concerns the use of different tools belonging to remote sensing for a complete observation and extrapolation of dendro - auxometric data of the forest area involved.

For example, a positive response has been demonstrated in the article by Brede et. al 2019, in the survey performed through the use of the laser scanner supported by the UAV platform and the use of the laser scanner supported by the stable terrestrial platform (TLS). In this article the LIDAR scan obtained from the TLS system shows a high potential for direct volumetric tree estimates showing a good reliability index of the results, while the output data obtained from the LIDAR survey from the UAV-system ALS results with a high density that demonstrate the complete digital representation of the canopy top area, a difficult area for a TLS system (Brede et. al, 2019).

1.1.3 The Hand-held LIDARLaser Scanner Systems (HLS)

It is essential to know the structure of the forest because it forms the basis of appropriate intervention choices to make appropriate choices and take actions to be carried out for its growth and sustainability.

The forest structure is analyzed by considering the distribution of the plant in space, the vertical distribution of canopys and branching, and the distribution of species. Moreover, the forest inventory is strongly related to the arboreal biomass, the total volume of a tree and many other ecological traits as ecological biodiversity indices (Zianis *et al.*, 2005).

In recent years, emerging terrestrial LIDAR technology known as Hand-held Laser Scanner (HLS) has shown a good potential to get this information thanks to its ability to extrapolate dendrometric parameters compared to manual methods, its speed of field acquisition and relevant spatial coverage.

In particular, the progress of experimental technological research has allowed the evolution of the structure and data acquisition capabilities of LIDARHLS systems. In fact, the first HLS prototypes were characterized by excessive volume and weight together with GNSS navigation systems resulting in a forest environment (Hyyppä *et al.* 2013, Liang *et al.* 2014, Kukko *et al.* 2017).

Nowadays, the market has lightweight and structured miniaturized instruments HLS with complete GNSS signal replacement from simultaneous location (SLAM). SLAM ALGORITHM (Simultaneous Localization and Mapping) arises from the results of research advancements in the field of robotics in recent years. SLAM makes it possible to simultaneously record scatter clouds taking into account the concept of the homologous object that is present in each scan performed by the same instrument and obtaining spatial information of the investigation area without having to resort to the spatial localization given by GNSS. This technology allows performing LIDAR surveys in under-canopy forest environments where the GNSS signal is often degraded. It also exceeds the utility in the field of the terrestrial laser scanner system (TLS) through the technological innovation of mobile systems such as Handheld terrestrial LIDAR to get dendrometric information of the forest in question (Beland *et al.*, 2019, Del perugia *et al.*, 2019). Notably, the main problem of TLS systems is the formation of occluded areas present in a single scan that are not deleted but only reduced if several multiple scans are performed. Multiple TLS scans performed in the forest field would represent an extension of data acquisition time and more work in the data processing phase. However, TLS systems are still innovative and essential in other fields of research such as the mapping of cultural heritage sites and the risk management of cavity collapse for the enhancement of the territory and its landscape forest protection (Chen *et al.*, 2019).

In the last decades, HLS and TLS systems have been recognized in the market sector of LIDAR technologies of Precision Forestry. Fig. n. 1 shows an analysis of the relationship between the two LIDAR Terrestrial systems (HLS and TLS) referring to the market prices and their level of accuracy according to brands and models available in the market.

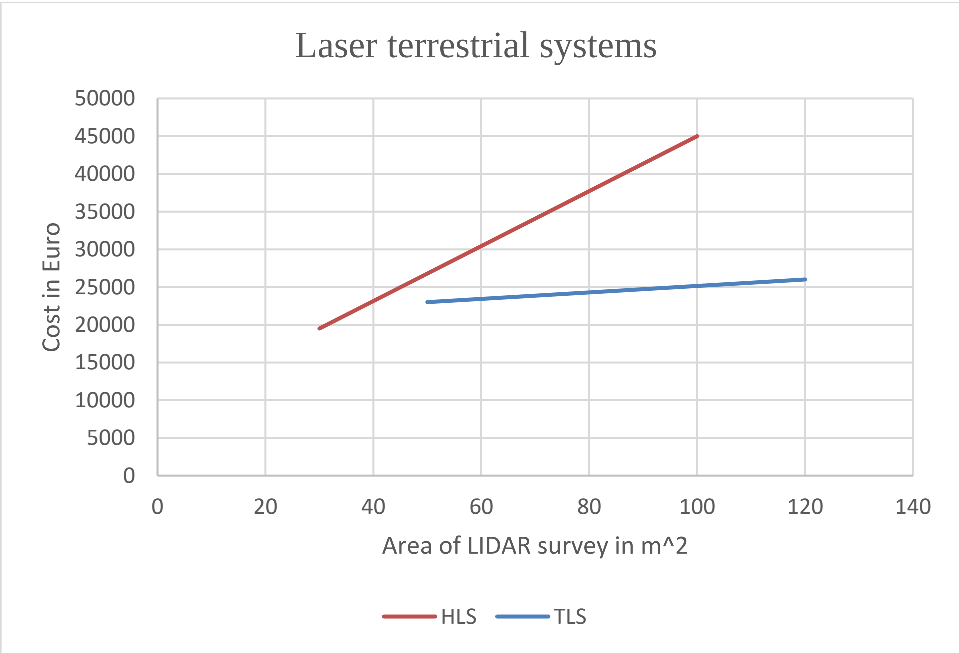


Figure n. 1 - Illustration of the relationship between the two LIDAR terrestrial systems (TLS, HLS) in terms of cost vs area coverage.

Information relating to costs was obtained directly from manufacturers.

Many researchers acknowledge that the HLS system makes it possible to implement the estimation of dendrometric parameters at the individual level in more complex forest conditions and with satisfactory accuracy and efficiency. Indeed, many recently published papers related to trees mapping show over 90% spatial localization (95% in Giannetti *et al.* (2018), 74% in Oveland *et al.* (2018), 93% in Chen *et al.* (2019), 96% in Gollob *et al.* (2020) (Giannetti *et al.*, 2018, Oveland *et al.*, 2018, Chen *et al.*, 2019, Gollob *et al.*, 2020).

These results represent a step forward in the field of HLS applications overcoming the performance of multiple TLS scans in forest conditions with 30% complex structure.

Regarding the estimation of DBH and H parameters, an in-depth bibliographic analysis of research results from the last 10 years in the field of Hand-held Laser scanner systems' application in forest and green urban environments has been conducted. It has been possible to identify and compare the RMSE (%) and bias (%) values of DBH and H to exploit the potential of the instrument investigated by researchers in their experiments. The survey shows an accuracy value of DBH ranging from 0 to 30% RMSE (%) (with mean absolute values of RMSE between 1-3 cm), while the accuracy value for H ranges from 0 to 50% RMSE % (with mean absolute values of RMSE between 3-5 m) and has a range of values from -10 to 35% bias (%), (Figure n. 2). The quality of HLS data depends on LIDAR instrumental precision and the accuracy of all components' synchronization (Bauwens *et al.*, 2016).

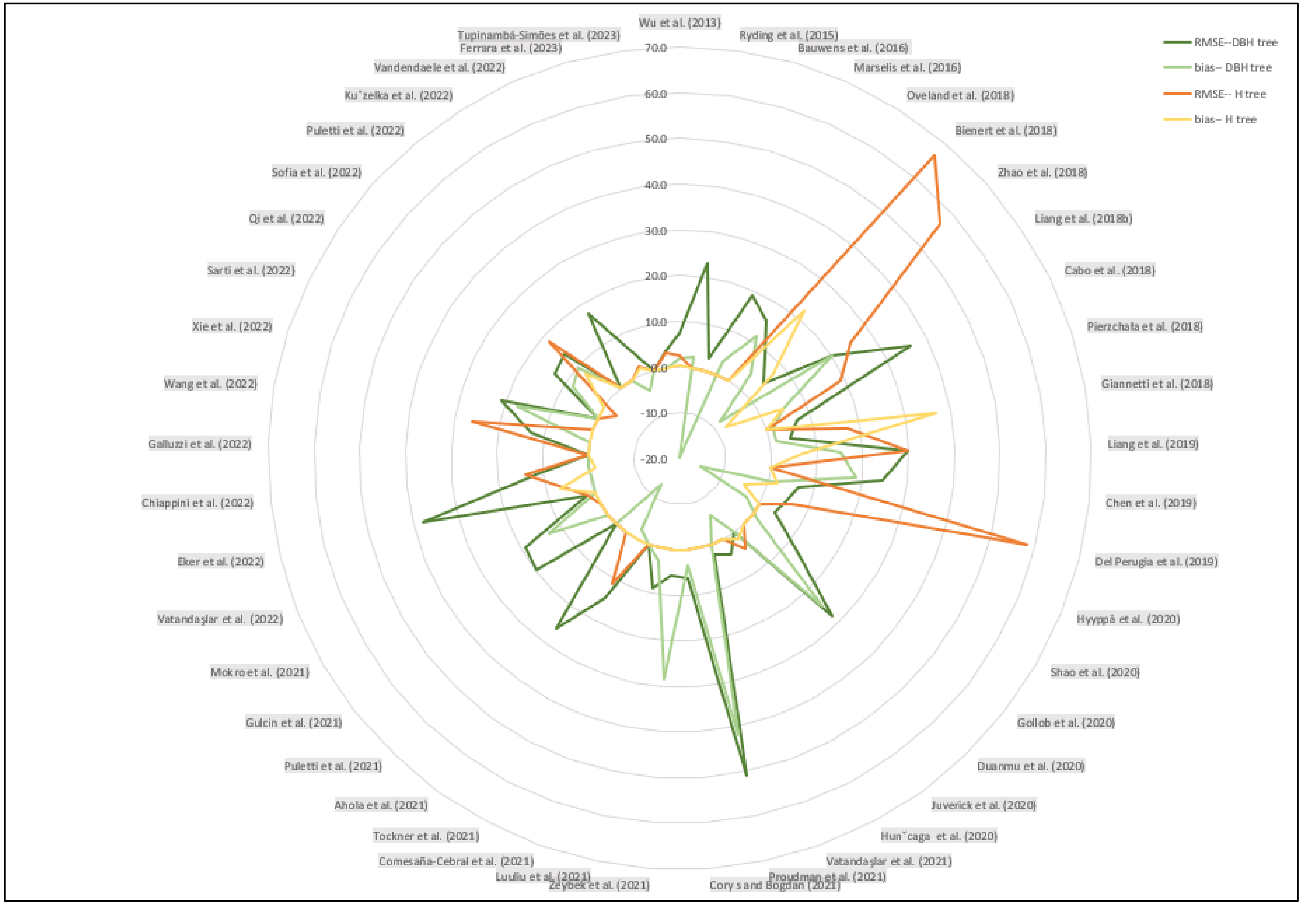


Figure n. 2 - Spider plot on the qualities of results from experimental applications performed in the forest environment with LIDAR data derived from the HLS instrument.

HLS instruments have accuracy values lower than the values of TLS scans (Chen *et al.*, 2019). However, the results present in the bibliographical analysis show HLS potentiality in the forest inventory, providing optimal accuracy results for forest planning (Balenović *et al.* 2021). In order to exploit the research revolution of Precision Forestry in the application of HLS system, a worldwide spatial distribution of LIDAR HLS note places (Figure n. 3) and a survey of the main topics addressed in the cited articles of the last 10 years (Figure n. 4) has been realized.

The distinctive trait of the bibliographic survey is related to the greater concentration of applied research in European forest areas (26 papers in Europe) compared to other international areas (19 papers in the rest of the world). In the worldwide contest, research has been carried out on artificial forest sites (Duanmu *et al.*, 2020; Cory and Bogdan, 2021) or of greater structural complexity (Xie *et al.* 2022). In the European contest, the research has been carried out in highly valuable forest sites from the biological point of view (high % of biodiversity) or areas where there was a need to collect dendrometric information for future drafting of forest management plans (Vatandaşlar and Zeybek, 2021). In particular in the Italian territory the areas examined by the researchers in the application of the Hand-held Laser Scanner system, are represented by forests characterized by Mediterranean forest species with very complex structures and with high species composition or that have a productive role for the local territory (Giannetti *et al.* 2018; Puletti *et al.* 2021; Sofia *et al.* 2022).

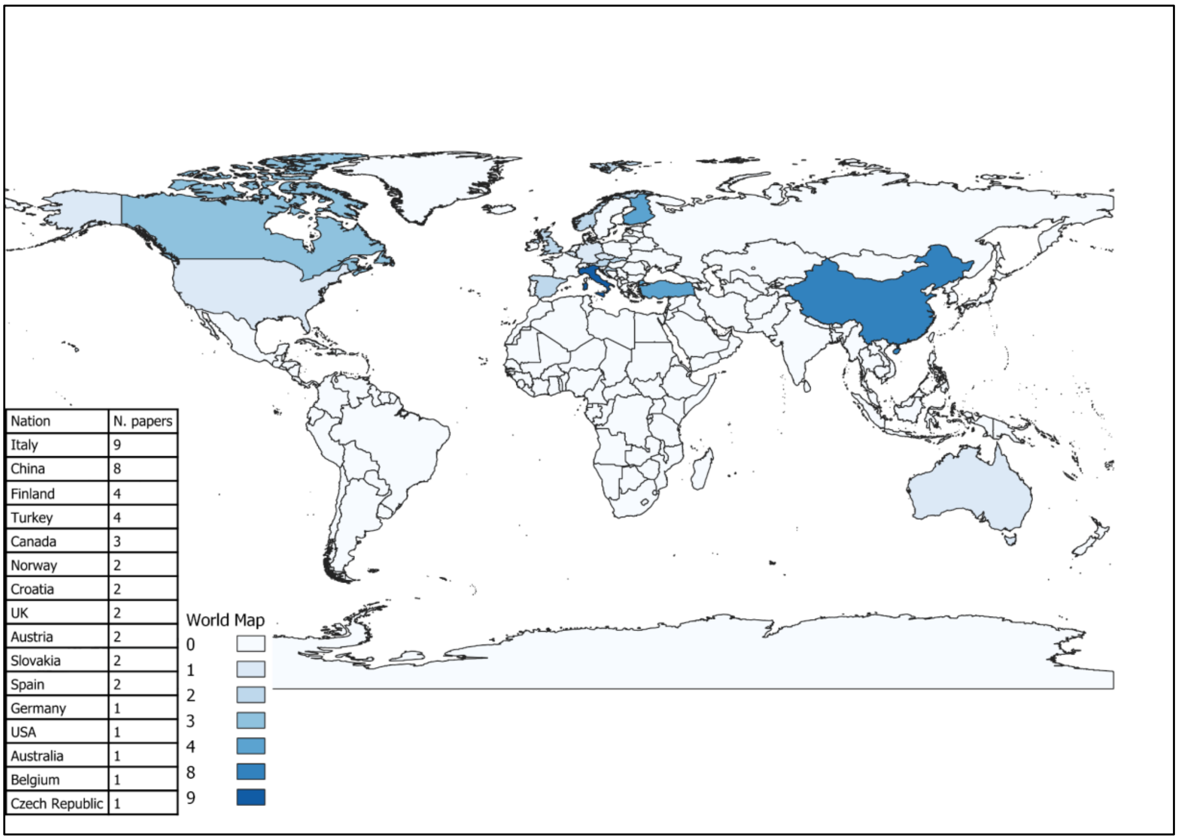


Figure n. 3 - Global spatial distribution on the intensity of papers devoted to testing LIDAR surveys derived from the HLS instrument in the forest environment.

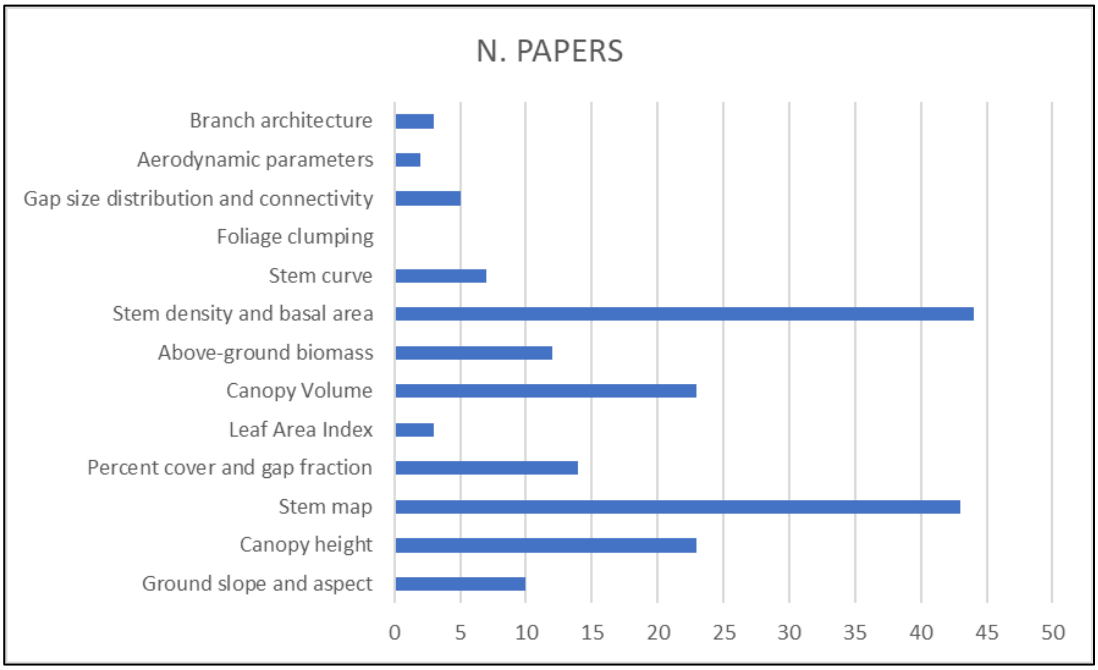


Figure n. 4 - Column plot on the number of current and potential products derived from the application of the LIDAR HLS system in the forest environment.

Observations of research carried out in recent years highlight the possibility of obtaining benefits from the application of these LIDAR instruments in the forest field.

A specific research work (Bettella *et al.*, 2018) has compared and evaluated the advantages and disadvantages of the traditional survey and the survey with a mobile land platform LIDAR system for the characterization of forest protection from falling boulders.

The main benefit of the technique of survey with a mobile LIDAR emphasized by the paper is that it drastically reduces the time spent in the wood, thus improving the safety conditions of the staff and reducing the risks due to its handling (Bettella *et al.*, 2018). HLS (Hand Held Mobile Laser Scanner) is one of the simplest tools to use with excellent results of reliability that can be applied in different fields of study in the production of surveys on the field and among the innovative instruments of the market.

A specific study conducted in 2017 by Giannetti *et al.* highlighted the effectiveness of using LIDAR HLS instruments for quantifying forest soil damage and generating high-precision digital topographic models (Gianetti *et al.*, 2017). Several other studies (Bawens *et al.*, 2016; Liang *et al.*, 2018; Chen *et al.*, 2019; Zhou *et al.*, 2019; Balenović *et al.*, 2021) have also emphasized the compactness, lightness, and ease of use of these instruments in forest environments, allowing for multiple scans of the forest's vertical structure to obtain a comprehensive view of the forest. Figures 5(a), 5(b) and 5(c) shows the results of a field trial where a LIDAR HLS instrument was raised to different heights on the same study area, using a machine UAV support to reach the treetops. Through a complex process of scanning automatic alignment during the processing phase, a complete structural profile of the forest was obtained. This information is valuable for foresters in assessing the straightness and abundance of individual trees and shrubs, which can be used to create a protection plan for forest fire prevention and determine appropriate forestry interventions for improving the wood technologies of the analyzed forest area.

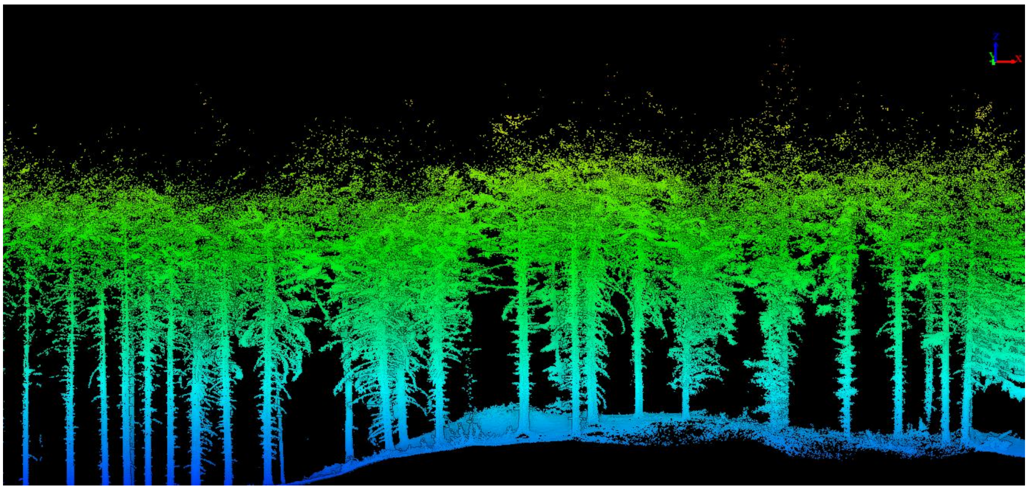


Figure n. 5(a) - Representation of the forest profile from the same HLS system at 1.30 m height above the ground.

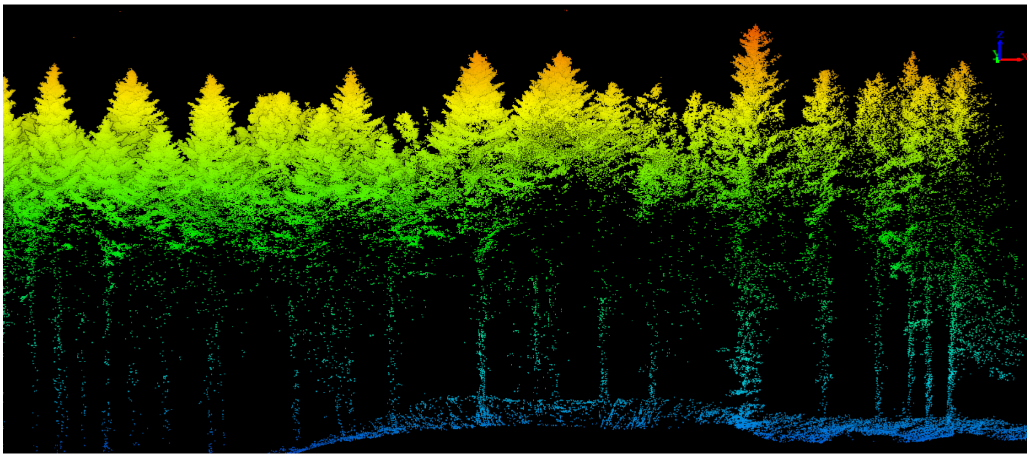


Figure n. 5 (b) - Representation of the forest profile from the same HLS system at 35 m height above the ground.

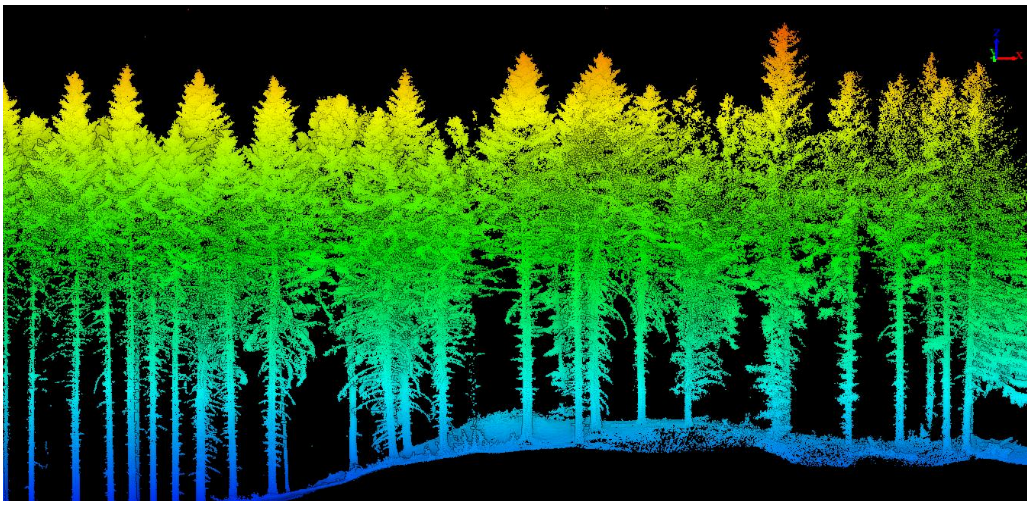


Figure n. 5 (c) - Representation of the forest profile from the same HLS system at two different values of heights of the survey, obtained from the point cloud alignment results.

1.1.4 The Softwares 3D applied on Precision Forestry.

The success of a technological and innovative survey lies not only in the use of the best LIDAR technology in the field but also in the skill of the operator in using complex software for editing and extracting key information from the raw data (point cloud). Processing tools are critical for harnessing the benefits of LIDAR data for forest sciences. The operator is faced with an infinite number of increasingly complex softwares made by several international researchers who are determined to find solutions suitable for every type of research and application.

The processing tools have evolved in recent years thanks to the continuous identification of the algorithm or manipulation code given the LIDAR ideal in the forestry sector.

It is possible to identify in table n. 1 the essential information of the LIDAR data processing codes and softwares for forest purposes shown in the papers.

Here are the OpenSource software that are efficient for their LIDAR data extraction functionality in the papers of recent years:

"Treeseg" (Burt *et al.*, 2018), "SimpleForest" tool on "Computree" (Hackenberg *et al.*, 2015; Hackenberg *et al.*, 2021), "TreeLS-rLIDAR-lidr" R packages (Tockner *et al.,* 2021, Chiappini *et al.,* 2022), "ForestFIT" (Teimouri *et al.*, 2020), "3D Forest" (Trochta *et al.*, 2017) "TreeQSM" MatLab package (Raumonen *et al.,* 2013; Disney *et al.* 2018), "3D-tools, Forestutils" (Su *et al.*, 2020) and "ForestR" R package (Atkins *et al.,* 2018).

The softwares recognized in the economic market for a good level of productivity in the extrapolation of dendrometric data from the LIDAR data are: LIDAR360 software (Xie *et al.* 2022, Chen *et al.*, 2019) and FINT software (Dorren *et al.*, 2017).

From the bibliographical survey were reported the first experimental analysis of efficiency and accuracy of some codes and software of LIDAR data processing for forestry purposes, carried out in 2022 by the research team of the Polytechnic University of Marche.

The forest plots involved a plantation of Black Pine, of simple structure, extended for 0.5 ha where 50 individuals of better dendrometric representation were taken as the reference data. The experimentation consisted of comparing three platforms such as "3D Forest", "VoxR" (R code package) and "TreeLS-lidr-rLIDAR" (R code package) considering the values of diameter, height and volume of the reference trees.

Considering only the most basic and essential dendrometric parameter (DBH), the article reported the lowest RMSE value (%) from the R code package "TreeLS-lidr-rLIDAR" resulting in a value of 10 % accompanied by a bias 0 %. Otherwise, the higher RMSE (%) value from the DBH extrapolation from the 3D forest software (16.3% with a 3.8% bias) is

considered a more than acceptable value for forest planning (Chiappini *et al.*, 2022).
From the technological innovation present in the market and from the continuous search for perfection within a single computer algorithm, still today has not been born a real profession of forestry doctor who really deals with the processing of data terrestrial LIDAR in Italian territory. On the other hand, it is internationally recognized as one of the essential figures in the field of Precision Forestry.
Therefore, it is necessary to encourage the development of research, the distribution of technologies in the market (with affordable prices for more demanding companies) and the dissemination of knowledge in the scientific community towards those entrepreneurial forest realities where it is still developing ensuring the stability of Precision Forestry in the local territory.

Table n. 1- Basic information of software 3D and computer codes to process LIDAR data cited in the bibliography.

Platform Names	**Treeseg**	**"Simple Forest" tool on Computree**	**R (TreeLS-rLIDAR-lidr package)**	**R (ForestFit package)**	**R (rLIDAR package)**	**R (Forest Tools package)**	**3D forest**	**Matlab (TreeQSM)**	**3D-tools**	**Dendrocloud**	**R (VoxR)**	**LIDAR 360**	**Geo-Plus VisionLIDAR**	**FINT**	**Envi LIDAR from ENVI**
commercial / open source platform	open source	open source	open source	open source	open source	open source	open source	open source	open source	open source	open source	commercial	commercial	commercial	commercial
Instrument of the LIDAR source data supported from platform (ALS, TLS, MLS)	ALS, TLS e HLS	ALS, TLS,	TLS	ALS, TLS e HLS	ALS	ALS	TLS/UAV	TLS e HLS	TLS, HLS	ALS, TLS, HLS	TLS, HLS	ALS, UAV, HLS	ALS, UAV, HLS	LIDAR, ALS, TLS IMMAGINI RASTER	ALS
launching date	2018	2015	2017	2020	2017	2018	2020	2013	2016	2017	2022	2020/21	2020	2006	2012

Name algorithm or tool of packages or model or processing 3D data methods cited	methods for the near-automatic extraction (Nearest neighbour distance, Downsampling, Euclidean clustering), random consensus model fitting (RANSAC)	Stem Filter by RANSAC, Segmentation Euclidean Clustering, QSM methods (Point to Cylinder distance,Point to Model distance, Cloud to Model distance)	reconstruction of the geometrical primitive,Voxel space neighborhoods,Stem modelling,RANSAC circle fit algorithm	gamma mixture model	FindTrees CHM algorithm, LIDAR Canopy Height Model, chullLIDAR2D algorithm,	Variable window filter tool, Grey-level co-occurrence matrices (GLCMs) Marker segmentation tool, Summarize forest information tool	LSR method,RHT method,Computing DBH tool (with Least squares regression algorithm), The circle fitting with the Gauss-Newton method, QSM model	QSM reconstruction model	A point-cloud-based individual tree segmentation algorithm	DBH estimation to maximum distance method, circle-fitting methods	voxelization algorithm, analyses of temporal changes, distance based clustering tool, visualisation of 3D voxel clouds tools	//	//	//	//
Compatible computer system	Ubuntu 20.04	Windows, Linux	Windows, Mac, Linux	Windows, Mac, Linux	Windows, Mac, Linux	Windows, Mac, Linux	Windows, Mac, Linux	Windows, Mac, Linux (MatLab programme)	Windows, Mac, Linux (Python programme)	Windows	Windows, Mac, Linux	Windows	Windows	Windows, Mac, Linux	Windows
Producer/ Research institution	CAVElab - Computational & Applied Vegetation Ecology, Ghent University, Ghent, Belgium	University of Freiburg	University of Maryland	Gonbad Kavous University	University of Florida	Tesera Systems Inc. company	Department of Forest Ecology of The Silva Tarouca Research Institute of Czech Republic, Czechia	Tampere University,Finlandia	The Borevitz Lab, in the ARC Centre of Excellence in Plant Energy Biology. Australia	Technical University in Zvolen, Slovak Republic	Università del Quebec a Montreal	GreeenValley company	Geo-plus-Canada/USA company	Bern University of Applied Sciences - HAFL	L3Harris Geospatial company

Type of input format	PCD binary format	LAS format	ASCII format	ASCII format	ASCII format	RASTER (JPG format, GeoTIFF format) and LIDAR o photogrammetric point clouds (LAS format)	ASCII format	LAS format	PLY format	LAS format	.txt format	TIF, LAS/LAZ, TXT, PLY, ASC, NEU, XYZ, PTS, CSV format	.DXF format , shapefile format., .TXT format	.txt,.csv format	Orthophoto images (JPG format, GeoTIFF format)
Type of output format	ASCII format	Csv file	Csv file	Csv file	Csv file	Csv file	.txt, .ply or .pcd format	PLY or DXF format	LAS format	Csv format	.txt format	.las, .laz, .e57, .pts or .csv format	.las, .laz, .e57, .pts or .csv format	ESRI ASCII Format or GeoTIFF format	.las, .laz, .e57, .pts or .csv format
References	Burt *et al.*, (2018)	Hackenberg *et al.*, (2015), Hackenberg *et al.* (2021), Othmani *et al.* (2013), Giannetti *et al.* (2018)	Tiago de Conto *et al.* (2017), Tockner *et al.* (2021), Chiappini *et al.* (2022)	Teomouri *et al.* (2020), Kerns *et al.* (2017), Zhang *et al.* (2008)	Silva *et al.* (2017)	Gülçin *et al.*, (2021), Tinkham *et al.* (2021)	Trochta *et al.* (2017), Krucek *et al.*(2020), Chiappini *et al.* (2022)	Raumonen *et al.* (2013), Disney *et al.* (2018).	Su *et al.* (2020)	Koreň *et al.* (2017), Hunčaga *et al.* (2020) Koreň *et al.* (2020)	Lecigne *et al.* (2018)	Shilin *et al.* (2019), Li *et al.* (2012), Chang *et al.*,(2011), Xie *et al.* (2022)	Zajiac 2019 (PhD thesis)	Menk *et al.* (2017); Dorren *et al.* (2017)	//

1.2 Gaps of research

Forest planning is essential for managing forest landscape resources because it combines the economic aspect with the need to ensure the dynamic conservation of the forest and landscape. It also ensures sustainability in the relationship between man and environment over time. However, planning faces high survey and maintenance costs in the forest. The realization times are long because of the complexity of the data collection in order to have the supporting data suitable for the drafting of the forest plan.

Remote sensing technologies have made progress expanding the availability of innovative instruments that provide strong support in extrapolating processes of dendrometric data, key information for forest planning. It was even possible to have even more complete results by performing several surveys in the countryside on the same forest area by coupling LIDAR systems or from instruments belonging to Aerial Photogrammetry (supported by SAPR) to have the complete availability of forest data for the inventory of the same forest resources (Corona *et al.*, 2017).

In the context of the application of LIDAR technologies within forest management and conservation, a potential major drawback to a greater spread of HLS in small businesses and research is represented by the instrumentation costs present in the market (Oveland *et al.*, 2017, Zhou *et al.*, 2019). Several studies suggest that manufacturers need to reduce the costs of their systems, or researchers need to develop more affordable HLS alternatives. HLS systems currently available on the market cost tens of thousands of euros only for the system and it would take additional subscription costs for the manufacturer's proprietary software, as reported by Shaw in his thesis (Shaw, 2022). Therefore, it is essential to investigate the real potential of LIDAR HLS instrumentation in order to make it part of the standard instrumentation within the forest community.

When prices become affordable for foresters, precision tools should become indispensable tools for foresters by obtaining less investment in time and labor compared to current operations (Fardusi *et al.*, 2017). LIDAR technology has now reached a very interesting level of accuracy, witnessed by several articles (Figure n. 2) that present a growing database available to the scientific community. These data could help to carry out the best professional work in the protection and enhancement of the local territory allowing for example to have an in-depth study on the structure of forest formations or on allowing landscape analysis well and also verify phenomena of instability. However, studies are lacking that identify optimal LIDAR relevant methodologies for field data acquisition by testing the performance of HLS instrumentation in different forest conditions in order to identify better standard planning protocols (Chen *et al.*, 2019; Del perugia *et al.* 2019).

Balenović *et al.*, 2020 highlights that the suitability of HLS systems for forest data collection as operational tools is influenced by the presence of external environmental factors. Even today, the presence of a density of vegetative undergrowth present or the slope of the highest terrain in the area contributes to the extension of the processing time in the phase of dendrometric data extrapolations from the LIDAR data in the office and to the complexity application of different LIDAR data processing algorithms influencing the accuracy of the result (Shaw, 2022). To date, there are no in-depth studies on environmental factors (Del Perugia *et al.*2019; Balenović *et al.*, 2020).

As mentioned in previous chapters, the validation of a standard protocol at the operational level within forest planning through an effective management of LIDAR instruments is an innovation in the professional world. However, it has been hindered by a lack of understanding among many forest operators regarding the potential of this technology. Therefore, it would be interesting to explore the potential of LIDAR HLS instrumentation within high-quality landscape forest contexts. By conducting an accurate dimensional analysis, it may be possible to identify important details such as the spatial distribution of the main branches of the canopy, the verticality of the stem, and the abundance of biomass on site. This information can be used to preserve and enhance forest individuals of high landscape value that express monumentality.

1.3 Research aims and objectives

Precision Forestry is today an innovative sector of great importance for forest and spatial planning because it allows to carry out complex analyses of forest data in a simple and economic way and facilitate integration between technicians, industry operators and stakeholders ensuring transparency in forestry interventions and decision-making in the forestry sector (Corona *et al.*, 2017). Therefore, the research applied to the field of precision forestry evolves towards a direction of control and safety of the collection in the countryside within the forest planning through the most innovative technologies of the 21st century, applying them in an integrated way in spatial planning and management processes. The research proposed within the European Industrial PhD project, outlined by the Department of Agricultural and Forestry Sciences of the University of Palermo and approved by the MIUR, addresses the definition of some fragile points of knowledge of terrestrial LIDAR technologies supported by Hand-held Laser Scanner (HLS).

Today, at the point where the research came, you can ask the following hypotheses:

H.1) HLS can improve the quality and efficiency of obtaining precise data in forestry by increasing the productivity of a forest company;

H.2) HLS can be influenced by some forest characters such as the structural complexity and species composition of a forest environment;

H.3) HLS can extract new information about a single tree and/or high quality forest environment.

The hypotheses submitted in this research give general indications that helped to shape and structure the research. Every hypothesis is associated with a well-researched topic in the field of Precision Forestry from the past decade's literature. Each theme has been outlined the main specific objectives that have been the goal in the research path. The main objective of the research is to provide concrete answers to previously written hypotheses, in order to identify new research aspects within the HLS system in the forest environment. This will be achieved by applying recently published analysis methodologies of terrestrial LIDAR that are relevant. To fulfill the objectives of this research, the following points were investigated:

Theme A) Strengths and weaknesses of the mobile LIDAR system in the forest company;

The present study compares the handheld laser scanner (HLS) scans with traditional survey method to study the efficiency of the technology HLS and its ability to produce an accurate structural forest attributes estimation with the least amount of time and effort (the case study I).

Theme B) The applicability/versatility of the LIDAR HLS tool for sustainable forest management applications as the detection of trees for forest inventory (B.1), the classification of fuels for drafting fire prevention interventions (B.2), the analysis of stem straightness to quantify differences between stands of different log quality (B.3).

In the case of B.1 theme, the present study investigates the influence of walking scan path density on single-tree attribute estimation by HMLS, considering three walking scan path schemes used in previous research, and taking into account the structural biodiversity of two forest ecosistems under examination. In addition, we also analyze the cost/benefit ratio of each type of laser survey according to the walking scheme considered, in order to evaluate the efficiency of field surveys (case study II). In the case of B.2 theme, it is carried out a innovative quantitative classification of fuels and the preliminary description of the structural and spatial development of the forest by LIDAR HLS surveys for the preparation of data for the purposes of drafting fire prevention interventions (case study III). In the case of B.3 theme, this study evaluates the application of a method for assessing and scoring stem straightness in tree standing by LIDAR HLS surveys to quantify differences between stands of different log quality (case study IV).

Theme C) Single tree analysis from HLS datas in an old-growth forest context (C.1) and in an urban context considering some large trees (C.2);

In the case of C.1 theme, this study examined the main characteristics of old-growth trees in a Mediterranean forest according to the criteria established by the bibliography through the HLS surveys, detecting the structural pecularities of the large trees (case study V). In the case of C.2 theme, the present study identifies the features of two singular large trees obtaining key informations on the expression of tree monumentality. The study offers also a comparison of the best methodologies of HLS point cloud processing to obtain the total volume of single trees through newly published code and processing tools and estimate their accuracy (case study VI).

Many companies and research institutes will be able to achieve these objectives by establishing guidelines to use LIDAR terrestrial technologies in order to support economic, environmental and sustainable decision-making in the forestry sector.

2. MATERIAL AND METHODS

2.1. Experimental set-up

The research was organized in four main steps common to all six individual cases studies described:

1- Identification of forest sampling areas;

2- Performance of the HLS survey (LIDAR scanning and storage of collected data);

3- Data processing (registration and conversion of the point cloud into LAS format, pre-processing of the collected data and processing of the corrected cloud for estimation of the dendrometric parameters);

4- Estimate of the error and level of precision of the estimation applying main dendrometric variables.

We present six case studies that highlight different peculiarities in the application of LIDAR technology, specifically in relation to two phases of the work: "Performance of the HLS survey" and "Data processing".

The case study I "Investigation of HLS LIDAR scanning efficiency in several plots of high forest (Alpe di Catenaia, Tuscany, Italy)", aimed to identify the strengths and weaknesses of the mobile LIDAR system in the forest company compared to traditional survey methods. We carried out HLS surveys using a star-shaped walinkg path in various forest areas with different ecological features and management practices, and we compared the results with those obtained using traditional survey methods.

In the case study II, titled "Benefit analysis of LIDAR HLS survey based on different types of walking paths (Camaldoli, Tuscany, Ficuzza, Sicily, Italy)", we tested three walking path schemes with the aim of investigating the applicability and versatility of the LIDAR HLS tool in forestry, in terms of time and efficiency. These routes have been deemed effective in recent literature, considering the structural biodiversity of the environment under examination, for detecting trees and estimating forest stand biometric parameters.

The case study III "The fine-scale combustible matter classification in the context of the Mediterranean forest from HLS LIDAR data (Bosco Niscemi, Sicily, Italy)", aimed to verify the versatility of the LIDAR HLS tool in forestry. We supported the classification of fuels through the data obtained from the HLS surveys of an area of high undercover density characterized by Mediterranean scrub. The HLS relief followed a serpentine walking path scheme for a better representation of the forest area in height. Finally, during the "Data Processing" phases, it was possible to make an accurate estimate of the vegetation density below the ground for different heights, following the forest profile, useful for estimating the risk of fire hazards in the investigated forest area.

In the case study IV, titled “Application of a method for assessing and scoring stem straightness in tree standing by LIDAR HLS surveys to quantify differences between stands of different log quality (Mt. Chortiatis, Macedonia, Greece, Camaldoli, Tuscany, Ficuzza, Sicily, Italy)”, we carried out a preliminary analysis on the development of stems of the forest types. We applied a methodology of evaluation of the straightness index through data obtained from the HLS surveys of four different forest types. The HLS survey followed a star path pattern. Finally, during data processing phases, a preliminary classification was performed according to a straightness index value thanks to a semi-automatic tool present in the bibliography.

In the case study V, “Characterization of Old-Growth Forest with an HLS LIDAR tool (Santa Maria del Bosco and Ficuzza, Sicily, Italy)”, we analyzed some sampling areas with large trees through HLS LIDAR data calculating the main dendrometric attributes to enhance two old growth forest contexts.

In the case study VI “Characterization of monumental single trees with a HLS LIDAR tool (*Ficus macrophylla* subsp. *columnaris*, Orto botanico di Palermo, Sicily, Italy)”, the total volume of two monumental *Ficus macrophylla* subsp. *columnaris* has been estimated to show singular features of two historic urban green areas. The methodological peculiarity of this last case study concerns the application of multiple LIDAR data processing software in order to identify that volume value closer to reality by applying different segmentation algorithms.

2.2. Study areas

Areas of investigation are located in both national and international territories, with forest sites most representative of biometric features that can show whole potential of the HLS tool in the context of forest planning.

Italian locations where the survey areas were selected are the following:

- Alpe di Catenaia (Tuscany, Italy),
- Camaldoli (Tuscany, Italy),
- Ficuzza- Bosco della Ramusa (Sicily, Italy),
- Ficuzza-Bosco del Fanuso (Sicily, Italy),
- Bosco Niscemi (Sicily, Italy),
- Santa Maria del Bosco-Bosco del Gurgo (Sicily, Italy),
- Palermo Botanical Garden and Garibaldi Garden (Palermo, Sicily, Italy).

The international location where the survey areas were selected is Mt. Chortiatis (Thessaloniki, Macedonia, Greece).

2.2.1 Alpe di Catenaia (Tuscany, Italy)

This study area is located in the Alpe di Catenaia (Est 1712318.06, Nord 4838745.53; Monte Mario/Gauss Boaga zona 1 EPSG:3003) a mountain range which belongs to the Tuscan Apennine in Italy (see Figure n. 6).

The Alpe di Catenaia complex covers an area of 2,341.95 hectares with a morphology of soil sweet and regular furrowed by deep incisions fluvial of numerous perennial torrents.

His skeleton is a turbidite formation of arenaceous deposits with facies flysch, with alternating psammitic and pelitic layers.

The average annual temperature of the Chiusi della Verna station, the thermo-pluviometric station near to the study area, is 9.2° C The hottest month is July, the coldest month is January, followed by December and February. As for the annual rainfall, the average annual precipitation is 1016.0 mm.

The monthly distribution of precipitation shows an autumn maximum in October (165.1 mm) and a summer minimum in July (28.0 mm). Rainfall remains relatively high from January to May (about 100 mm per month) and then decreases rapidly until the summer minimum (https://www.wunderground.com/forecast/it/chiusi-della-verna).

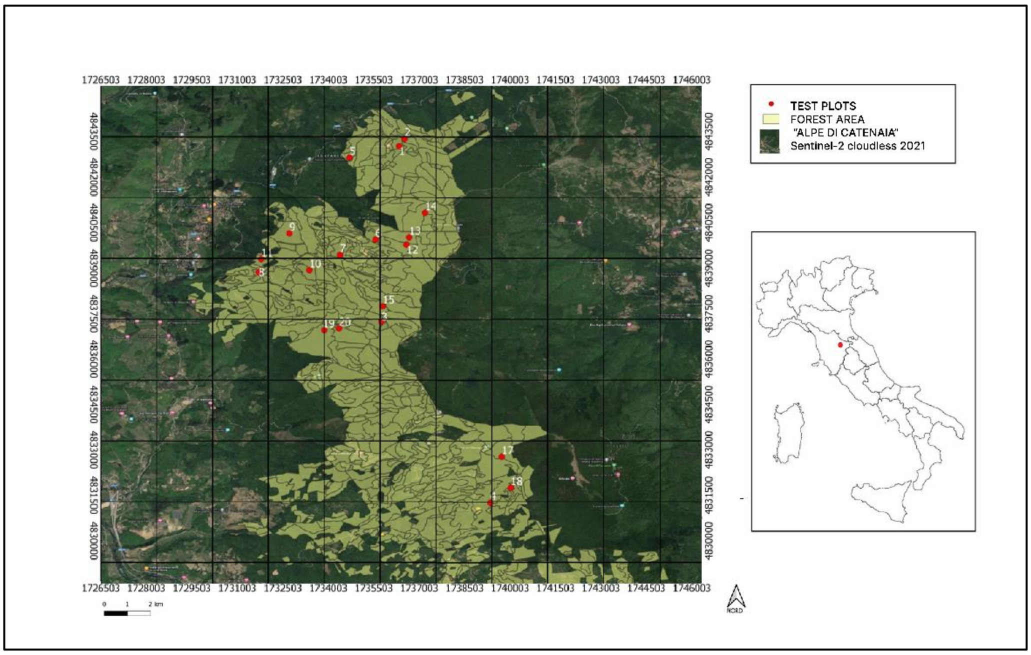


Figure n. 6 - Positions of plot centers in the study area Alpe di Catenaia (Tuscany, Italia).

The vegetation of Alpe di Catenaia can be distinguished in the following types: prairies, shrublands (es: *Cytisus scoparius*), beech woods, downy oaks woods, chestnut woods, mixed forests (*Quercus cerris*), artificial stands of conifer (*Abies alba and Pinus nigra*), and rocky vegetation formations.

According to the classification in vegetation belts described by Pignatti in 1979, we can identify:

- the sub-Atlantic belt, with beech forests, pastures, and shrublands;
- mid-European or sub-Mediterranean belt, composed by turkey oak, chestnut, oak, shrub, meadows, and other forms of anthropic alteration (Pignatti S.,1980).

The beech monospecific forests (*Fagus sylvatica*) are distributed from the lower altitudes up to the ridge. In addition to beech, chestnut (*Castanea sativa*), Turkey oak (*Quercus cerris*), silver fir (*Abies alba*), sweet cherry (*Prunus avium*) are randomly diffused.

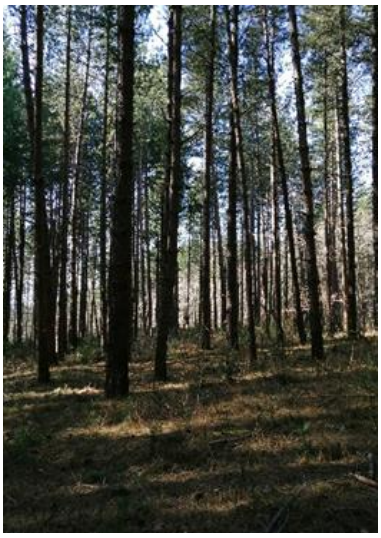
The chestnut woods (*Castanea sativa*) are managed as fruit woods, mature coppices and transitional forests on gentle morphological soils with absence of rockiness. In the upper level chestnut woods are diffused with Turkey oak (*Quercus cerris*), European plane tree (*Ostrya carpinifolia*), beech (*Fagus sylvatica*), downy oak (*Quercus pubescens*), sweet cherry (*Prunus avium*), sycamore maple *(Acer pseudoplatanus*). Mixed forests (Turkey oak - hop-hornbeam) are characterized by the mixture, in the upper floor, of Turkey oak (*Quercus cerris*), European hophornbeam (*Ostrya carpinifolia*), and locally chestnut woods (*Castanea sativa*). The prevailing species is the Turkey oak, located in northern exposures on poorly evolved soils and strongly disturbed (eroded and leached soil of nutrients) with high slopes. The main species are locally accompanied by Bosnian maple (*Acer opalus* subsp. *obtusatum*), flowering ash (*Fraxinus ornus*), and Turkey oak (*Quercus cerris*).

Oaks are present at the lowest altitudes of the forest complex on acid soils. In the upper level Downy oak (*Quercus pubescens*) dominates, with Turkey oak (*Quercus cerris*) and whitebeam (*Sorbus aria*). Artificial stands are composed of silver fir (*Abies alba*), Douglas fir (*Pseudotsuga menziesii*) and black pine (*Pinus nigra*) high forests. Silver fir (*Abies alba*) is naturally widespread in beech forests and, to a lesser extent, also in Turkey oak forests. In the silver fir mature stands there is an abundant and vital regeneration with the development of new fir stands. The Douglas fir forests (*Pseudotsuga menziesii*) originated from recent reforestations on former farmland. The plantations are distributed in strips on less deep soils and have high unevenness in development and vegetative vigor.

The black pine (*Pinus nigra)* stands on Mount Calvan were planted for protection purposes on extremely thin soils coming from calcareous rocks (Mondino and Bernetti, 1998; Blasi, 2010). Tables n. 2 and 3 report basic informations about the place of study area Alpe di Catenaia.

Table n. 2 - Main information of forest types classes investigated in the study area Alpe di Catenaia (Tuscany, Italia) (data from Sofia *et al.* 2021).

Forest types classes-conifers



Pinus nigra	***Abies alba***	***Pseudotsuga menziesii***
Slope: 5-15%	Slope: 15-30%	Slope: 15-30%
Regeneration class: 1	Regeneration class: 0	Regeneration class: 0
Stand class: 2	Stand class: 3	Stand class: 1
DBHm: 31.7 cm	DBHm: 37.46 cm	DBHm: 28.5 cm
Hm: 27.9 m	Hm: 26.02 m	Hm:33.04 m

Regeneration class: 0- no regeneration; 1- <1.3m coverage <33%;

Stand class: 1, DBH<22cm; 2, >50% DBH 22–37 cm; 3, >50% 37-52 cm.

DBHm: average value of DBH, Hm: average value of H.

Table n. 3 - Main information of forest types classes investigated in the study area Alpe di Catenaia (Tuscany, Italia), (data from Sofia *et al.* 2021).

Forest types classes-broadleaved	
	
Quercus cerris	***Fagus sylvatica***
Slope:15 - 30 %	Slope: 30-50%
Regeneration class: 4	Regeneration class: 1
Stand class: 2	Stand class: 2
DBHm : 28.7 cm	DBHm :29.2 cm
Hm: 24.5 m	Hm :23.2 m

Regeneration class: 1- <1.3m coverage <33%; 4->1.3 m coverage >66%.

Stand class: 2, >50% DBH 22–37 cm.

DBHm: average value of DBH, Hm: average value of H.

2.2.2 Camaldoli (Tuscany, Italy)

This study area is located in the Camaldoli (Est 1727803.39, Nord 4854853.55; Monte Mario/Gauss Boaga zona 1 EPSG:3003), in the Foreste Casentinesi, Monte Falterona and Campigna National Park, which belongs to the Tuscan Apennine in Italy from northwest to southeast on the hydrographic left of the Arno River (Figure n. 7).

Camadoli's area is of 682,9 hectares and is located at 1270 m. a.l.s. with a morphology characterized by relatively gentle shapes and rather high mountains.

The soils are predominantly brown podzolic generally characterized by a deep profile, good aggregation capacity (thanks to an elevated water retention capacity) and a good stability and very rare landslide with surface erosion phenomena (surface erosion/scarp erosion <5%).

The average annual temperature of the 'Camaldoli' station, the thermo-pluviometric station near to the sampling area, is 8.7 °C; the hottest month is July, while the coldest is January, followed by December and February. Average annual precipitation is 1641,6 mm, and the monthly distribution of rainfall shows an autumn maximum in October (179.0 mm) and a summer minimum in July (60.0 mm). Precipitation in the summer quarter is reduced by 75 mm, although there has been no real dry summer period on average.

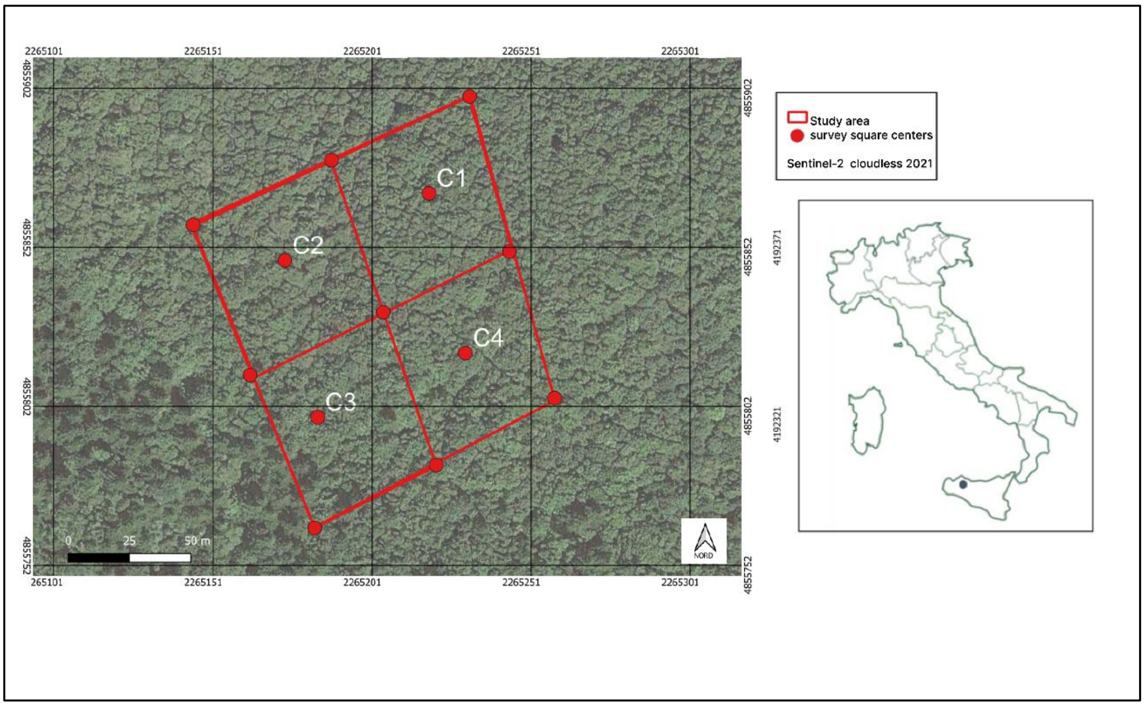


Figure n. 7 - Positions of plot centers in the study area Camaldoli (Tuscany, Italy).

The Camaldoli forest environment is characterized by Neutrophilous and beech-dominated woods of the Southern Alps and Apennines with mixed beech and silver fir woods, conifer reforestations, secondary meadows and shrublands. (Association: Asperulo-Fagetum). According to the Italian phytoclimatic classification of Pavari (1916), Camaldoli can be classified in the warm sub-zone of the Fagetum.

The beech woodland is a pure stand dominated by beech (*Fagus sylvatica*) with an high cover (95%). There are few tree species as sorbs (*Sorbus aucuparia*, *Sorbus aria*), sycamore maple (*Acer pseudoplatanus*), willow (*Salix caprea*) and silver fir (*Abies alba*) (Arrigoni P. V. *et al.*, 1998, Ubaldi D., 1988). The shrub layer remains absent or with little cover (5%). A distinctive feature of these beech forests is the presence of thermophilous herbaceous species (*Cyclamen*, *Galium odoratum*, *Hepatica nobilis*, fern, *daphne,* ivy).

According to the Italian classification by altitudinal planes the vegetation present belongs to the montane plan above 900 - 1000 ms of altitude, which is present with the lower montane horizon or of the broadleaf sciaphilous forests with beech forests, fir forests, forms of degradation and substitution. According to the classification in vegetation belts of Pignatti (1979) we can identify in the survey area the sub-Atlantic belt with beech, fir and alteration forms (Pignatti, 1980; Pignatti, 1982). Table n. 4 reports basic informations about the place of study area Camaldoli.

Table n. 4- Main forest information in the study area Camaldoli (Tuscany, Italia).

Forest type- *Fagus sylvatica*	
Structure: Pure Adult monoplane high forest Vigor: averagely vigorous Specific composition: *Fagus sylvatica* (>80%), *Acer pseudoplatanus* (>20%), *Abies alba* (>20%), *Salix caprea* (occasional) Shrub layer: absent Herb layer: *Cyclamen*, *Galium odoratum*, *Hepatica nobilis*, Fern, *Daphne*, Ivy Coverage: 95% Natural regeneration: insufficient DBH m: 31.2 cm H m: 22.44 m Number of trees: 664 n. tree/ha Volume: 557.9 m^3/ha	 
Basal area: 50.8 m^2/ha	Photos taken in Camaldoli

DBHm: average value of DBH, Hm: average value of H.

2.2.3 Ficuzza (Sicily, Italy)

These study areas are located in the Ficuzza forest, in Southern Italy, Sicily in the territory of Palermo, within the oriented nature reserve “Bosco della Ficuzza, Rocca Busambra, Bosco del Cappelliere and Gorgo del Drago”. The Natural Reserve covers an area of 7,400 hectares and it represents the largest protected area in Sicily (Figure n. 8-9).

The territory is characterized by an imposing carbonate massif called “Rocca Busambra” that extends to a height of 1613 m a.s.l. and separates three important hydrographic basins in western Sicily, relating to the Eleuterio, left Belice and, further east, San Leonardo rivers (Giunta and Liguori, 1975; Catalano, 2000).

The territory of Ficuzza falls within the Catena Apennine- Maghrebid chain, whose calcareous-dolomitic ridge emerges from a vast clay-arenaceous blanket, which is characterized by clayey-sandy-conglomeratic deposits.

The morphology is a coherent type with a lower erodibility of quartzarenites compared to the thin clayey levels (Cadoppi *et al.*, 2002; Polino *et al.*, 2002).

The average annual temperature at the the thermo-pluviometric station 'Ficuzza' (681 m a.s.l.), is 15.1° C; the hottest month is July (20.5°c), while the coldest is January (9.8°C). The average annual precipitation is 752 mm and the monthly rainfall distribution shows an autumn maximum in December (130 mm) and a summer minimum in July (4.8 mm) (http://www.astropa.inaf.it/).

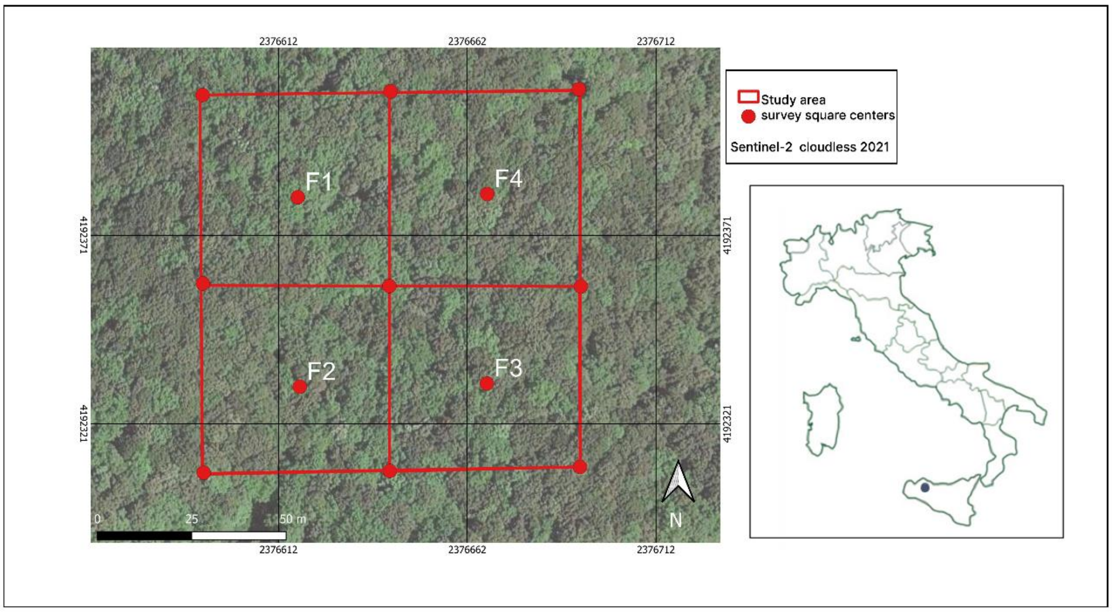


Figure n. 8 - Positions of plot centers in the study area Bosco della Ramusa-Ficuzza (Sicily, Italy).

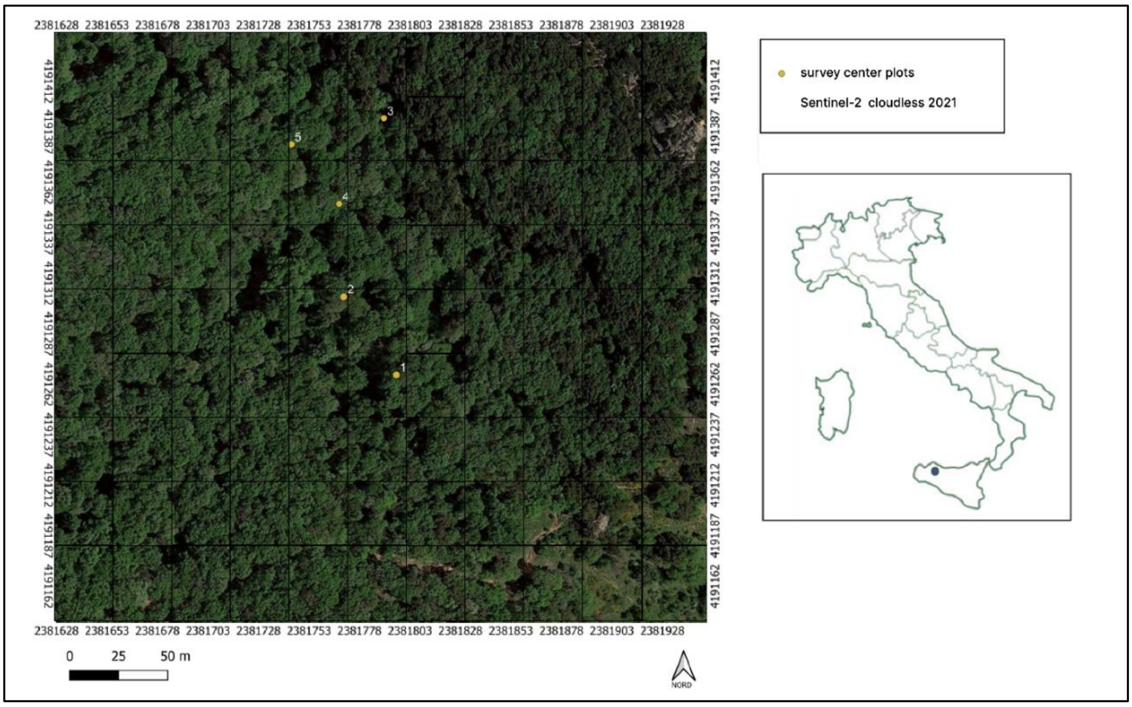


Figure n. 9 - Positions of plot centers in the study area Bosco del Fanuso - Ficuzza (Sicily, Italy).

The bioclimatic map of the Reserve (scale 1: 80,000) classified the survey area as belonging to the upper sub-humid meso-Mediterranean plane.

According to the phytoclimatic classification of Pavari (1916), the Ficuzza forest ecosystem can be classified in the warm sub-zone of the Lauretum of the 2nd type (with summer drought). The area is almost entirely subject to grazing activities.

2.2.3.1 Bosco della Ramusa-Ficuzza (Sicily, Italy)

The survey area called "Bosco della Ramusa"(Est 2378707 Nord 4193633; Monte Mario/Gauss Boaga zona 2 EPSG:3004), is characterized by a base of a continuously changing transitional Mediterranean forest with a predominance of holm oak (*Quercus ilex* 60%, *Quercus pubescens* 35%), with an covering of survey area 95%, accompanied by *Fraxinus ornur* and *Acer campestre* (20%) (alliance: *Fraxinus-Quercion ilicis*, association: *Aceri-Quercetum ilicis*) The shrub layer is very sporadic, with a covering of survey area <5%, consisting of hawthorn and bramble, while the herbaceous layer is <1/3 of the area characterized by the presence of broom, cyclamen, asparagus and daphne. It is possible to identify in table n. 5 main informations about the place of study area "Bosco della Ramusa" (Ficuzza).

Table n. 5 - Main forest information in the study area Bosco della Ramusa

Ficuzza forest - Sicily, Italy).

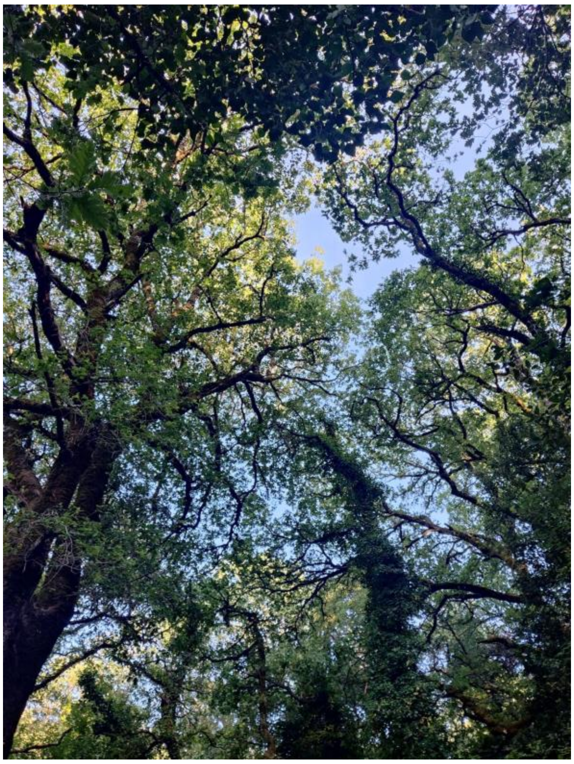
Forest type – *Quercus ilex*	
Structure: transitional Mediterranean old-growth forest with a predominance of holm oak	 
Vigor: averagely vigorous	
Specific composition: *Quercus ilex* (>60%), *Quercus pubescens* (>35%), *Fraxinus ornus* and *Acer campestre* (occasional).	
Shrub layer: *Crataegus monogyna* and *Rubus ulmifolius*	
Herb layer: *Calicotome spinosa*, *Cyclamen hederifolium*, *Asparagus acutifolius*, and *Daphne*	
Coverage: 95%	
Natural regeneration: sufficient	
DBH m: 29.7 cm	
H m: 14.2 m	
Number of trees: 502 n. trees/ha	
Volume: 265.8 m^3/ha	
Basal area: 34.9 m^2/ha	Photos taken in “Bosco della Ramusa”

DBHm: average value of DBH, Hm: average value of H.

2.2.3.2 Bosco del Fanuso - Ficuzza (Sicily, Italy)

The study area called "Bosco del Fanuso" is located in a small area of Ficuzza forest (Est 2381807, Nord 4191198 ; Monte Mario/Gauss Boaga zona 2 EPSG:3004), a thermo mesophilous forest stand dominated by downy oak (*Quercus pubescens Willd. s.l.*) with sporadic presence of *Fraxinus ornus L.* (manna ash), *Acer campestre L.* (Field maple), *Sorbus torminalis L. Crantz, Mespilus germanica L.* (common medlar), and *Malus sylvestris Mill* and uncommon woody species such as *Ostrya carpinifolia Scop*. and *Quercus trojana Webb* subsp. *Trojana*. Table n. 6 describes main features of the Fanuso Wood. Its undergrowth is very similar to that of the natural aspects of the natural deciduous forests of the surrounding areas. "Il bosco del Fanuso" falls within the habitat of Community interest 91AA* - Oriental woods of white oak. In some areas the forest cover is interrupted by several fallen trees (Pignatti, 1980; Pignatti, 1982; Gianguzzi and La Mantia, 2004; Badalamenti *et al.*, 2017).

Table n. 6 - Main forest information in the "Bosco del Fanuso" (Ficuzza forest - Sicily, Italy).

Forest type – *Quercus pubescens*	
Structure: Adult Mediterranean high forest with a predominance of downy oak Vigor: averagely vigorous Specific composition: *Quercus pubescens Willd. s.l.* (>60 %); *Fraxinus ornus L.* (manna ash), *Acer campestre L.* (field maple), *Pyrus spinosa*, *Ulmus minor* and *Malus sylvestris Mill* (>35%); Shrub layer: *Crataegus monogyna*, *Rosa sempervirens*. Herb layer: *Asparagus acutifolius*, *Geranium sanguineum*, *Epipactis helleborinae*, *Hedera helix*, *Smilax aspera* Coverage: 80% Natural regeneration: sufficient DBH m: 52.6 cm H m: 17.82 m	

Number of trees (with DBH>40cm): 248 n. trees/ha Volume: 370 m^3/ha	
Basal area: 34 m^2/ha	Photos taken in “Bosco del Fanuso”

DBHm: average value of DBH, Hm: average value of H.

2.2.4 Bosco Niscemi (Sicily, Italy)

This study area is located in the Bosco Niscemi, in southern Italy, Sicily. The Bosco Niscemi, extended 8,50 ha, is the only area of the “Parco della Favorita” included in zone A of the Nature Reserve "Monte Pellegrino" (East 2374361.3 1880124.60, North 4225068.6; Monte Mario/Gauss Boaga zone 2 EPSG:3004), which falls within the territory of the Municipality of Palermo, adjacent to the north of the city (Figure n. 10).

The natural reserve was established in 1799 by Ferdinand IV of Bourbon and today extends over an area of 1,050 hectares flanked by a carbonate chain called "Monte Pellegrino" that reaches 600 m in height. The reserve is characterized by Monte Pellegrino (zone A, strongly protected) and the area of La Favorita (zone B, moderately protected). Monte Pellegrino consists mainly of limestone rocks and thanks to karst phenomena is characterized by steep slopes with multiple exposures, valleys and plains. The rugged orography of the reserve favors the conformation of microclimates (presence of salinity in the east-north area, sunny plateau and in the reserve, there are some episodes of fog in winter). According to the Köppen classification the present climate is characterized by mild and humid winters and hot and dry summers. The average annual temperature at the 'Santa Rosalia' station (450 m a.s.l.), the thermo-pluviometric stations near to the sampling area, is 18.3C; the hottest month is August (45°c), while the coldest is February (9°C). The average annual precipitation is 754.5 mm and the monthly rainfall distribution shows an autumn maximum in December (123.7 mm) and a summer minimum in July (6.7 mm) (http://www.astropa.inaf.it/).

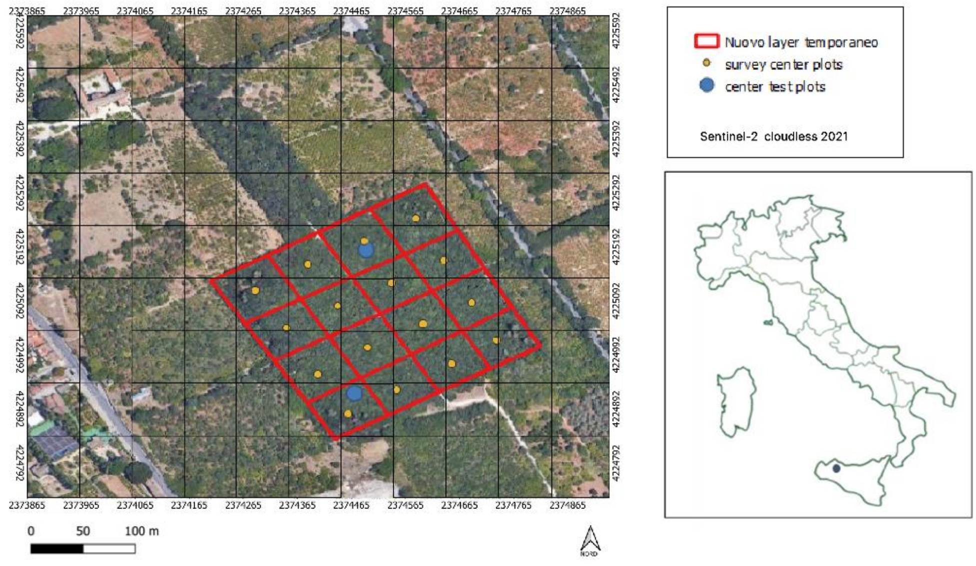


Figure n. 10 - Positions of plot centers in the “Bosco Niscemi” (Sicily, Italy).

From the bioclimatic point of view, the reserve falls within the thermo-Mediterranean bioclimate zone, lower with upper dry ombrotype in areas below 400 m. While in the highest areas (>400 m above sea level) conditions refer to the upper thermo-Mediterranean belt.

According to the classification in vegetation belts of Pignatti (1979) we can identify:

- the Dry Mediterranean Belt. (Pignatti S.,1980). In fact, the prevailing vegetation of the reserve is a shamanic forest-scrub oak and alaterno (association: *Rhamno alaterni - Quercetum ilicis*). In the lower portions and near the coast the forest-scrub is characterized by *Pistacio lentisci*, *Chamaeropetum humilis* while in the contexts of rock seeds the spot is dominated by *Rhamno alaterni-Euphorbietum dendroidis* (Brullo and Marcenò, 1985; Raimondo F.M., 2000).

The Wood Niscemi is an aged coppice consisting of holm oak (*Quercus ilex*), fillyrea (*Phillyrea latifolia*), arbutus (*Arbutus unedo*) in the tree layers and other species of the scrub such as terebinth (*Pistacia terebinthus)*, mastic (*Pistacia lentiscus*) and viburnum (*Viburnum tinus*) in the shrub layer. Among the sporadic tree species there are the bagolaro (*Celtis australis*), the orniello (*Fraxinus ornus*) and the Judas tree (*Cercis siliquastrum*). The Wood Niscemi is divided into sixteen squares, of extension 2 hectares each, which probably coincided with the sections of cutting the coppice for the production of firewood and coal (Di Martino and Raimondo, 1979; Venturella *et al.*, 1991) It is possible to identify in table n. 7 the basic information about the The Wood Niscemi.

Table n. 7 - Main forest information in the "Bosco Niscemi" (Sicily, Italy).

Forest type – *Quercus ilex*	
Structure: aged coppice forest with a predominance of holm oak Vigor: averagely vigorous Specific composition: *Quercus ilex, Phillyrea latifolia, Arbutus unedo* (>60 %); *Fraxinus ornus, Pistacia terebinthus, Pistacia lentiscus* (>35%); *Celtis australis, Fraxinus ornus, Cercis siliquastrum* (occasional). Shrub layer: *Viburnum tinus*, *Erica arborea*, *Ligustrum vulgare* Herb layer: *Rhamnus alaternus*, *Rubia peregrina*, *Smilax aspera*. Coverage: 70% Natural regeneration: sufficient DBHm: 16.9 cm Hm: 6.2 m Number of tree: 4880 n.trees/ha	 
	Photos taken in "Bosco Niscemi"

DBHm: average value of DBH, Hm: average value of H.

2.2.5 Il Bosco di Gurgo - Santa Maria del Bosco (Sicily, Italy)

This study area is located in the “Il Bosco di Gurgo” (Est 2359995.4, Nord 4173633.3; Monte Mario/Gauss Boaga zona 2 EPSG:3004), in southern Italy, Sicily, appartenente alla Riserva Naturale Orientata “Monte Genuardo e Santa Maria del Bosco”, nei pressi di Contessa Entellina e Giuliana (Palermo) (Figure n. 11). The reserve extends over 30 hectares of surface from 600 m of altitude up to 800 ms above sea level and is characterized by a carbonate substrate with deep soils.

The area is predominantly mountainous-hilly, with narrow alluvial valleys, characterized by a series of flyschioid outcrops, marl-spotted, clays, sands and conglomerates, with morphology also mainly on the slope, but with more contained acclivity.

The average annual temperature at the 'Contessa Entellina station (571 m a.s.l.), the thermo-pluviometric stations near to the sampling area, is 21 C; the hottest month is July (30.5°c), while the coldest is January (8°C). The average annual precipitation is 800-836,1 mm and the monthly rainfall distribution shows an autumn maximum in December (138 mm) and a summer minimum in July (3 mm) (http://www.astropa.inaf.it/).

According to the classification proposed by Rivas-Martinez, the forest community is located between the bioclimatic belts of the Mesomediterranean and the upper subhumid supra Mediterranean (Rivas-Martinez *et al.*, 2008).

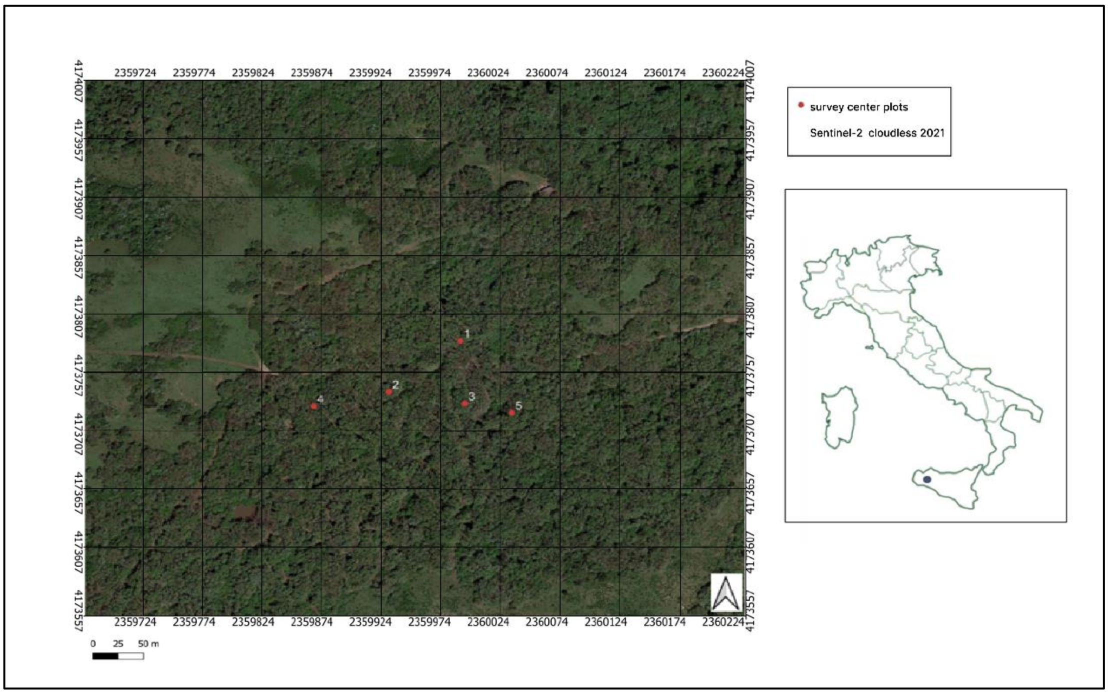


Figure n. 11 - Positions of plot centers in the “Il Bosco di Gurgo-Santa Maria del Bosco” (Sicily, Italy).

The vegetation of the reserve is characterized by mesophilic woods mixed with ornithine, chestnut oak and ciavardello (*Sorbo Torminali-Quercetum virgilianae*) and a vegetation of shrubs that acts as a mantle (*Pruno-Rubion ulmifolii*).

The forest area investigated is characterized by forest stands dominated by species belonging to the oak cycle (*Quercus pubescens Willd*. s.l.) such as *Quercus amplifolia Guss.* and *Quercus virgiliana*. Other characteristic species of particular phytogeographical interest are associated, such as *Sorbus torminalis*, *Physospermum verticillatum*, *Huetia cynapioides*, *Euphorbia meuselii*, *Daphne laureola* etc.

The Gurgo wood falls within the habitat of Community interest 91AA* - Oriental woods of white oak (Raimondo, 2000; Guzzardo, 2002; Incardona, 2005; Bazan *et al.*, 2007; Badalamenti *et al.*, 2022). It is possible to identify in table n. 8 the main forest information of the Wood Gurgo.

Table n. 8 - Main forest informations of the study area "Il Bosco di Gurgo-Santa Maria del Bosco" (Sicily, Italy).

Forest type – *Quercus amplifolia Guss.*	
Structure: Adult Mediterranean high forest with a predominance of white oak	
Vigor: averagely vigorous	
Specific composition: *Quercus amplifolia Guss. and Quercus virgiliana*, *Quercus ilex* (>60 %);	
Crataegus monogyna, *Malus sylvestris* (>35%),	
Sorbus torminalis, *Pyrus pyraster* (occasional)	
Shrub layer: *Asparagus acutifolius*, *Crataegus monogyna*	
Herb layer: *Huetia cynapioides*, *Euphorbia meuselii*, *Daphne laureola*, *Physospermum verticillatum*	
Coverage: 70%	
Natural regeneration: sufficient	
DBHm: 51.63 cm	

H m: 18.81 m

Number of trees (with DBH>40cm): 130 n. trees /ha

Volume: 390 m^3/ha

Basal area: 28.22 m^2/ha

Photos taken in
“Il Bosco di Gurgo-Santa Maria del Bosco”

DBHm: average value of DBH, Hm: average value of H.

2.2.6 Palermo Botanical Garden and Garibaldi Garden (Palermo, Sicily, Italy).

These study areas belong to the urban green area category called Palermo Botanical Garden (Est 2377527.9 Nord 4219394.5; Monte Mario/Gauss Boaga zona 2 EPSG:3004) and Garibaldi Garden (Est 2377078.0, Nord 4220076.4; Monte Mario/Gauss Boaga zona 2 EPSG:3004) because of the study of two tree of *Ficus Macrophylla* subsp. *columnaris* is located in Palermo's historic city center, in Sicily, south Italy (Figure n. 12-13).

Palermo lies in a basin, formed by the Papireto, Kemonia and Oreto rivers. The soils are platform and deep-sea carbonates of Triassic-Oligocene age from Oligo-Miocene terrigenous deposits. For the climatic framework, reference was made to the climatic data referred to the Palermo Astronomical Observatory station for the last twenty years. The average annual temperature is 18 °C; the hottest month is August (26.8 °C), while the coldest is February (12.2 °C). Average annual precipitation is 615 mm for the year, and the monthly distribution of precipitation shows an autumn maximum in December (95.0 mm) and a summer minimum in July (5.00 mm) (http://www.astropa.inaf.it/). Botanical garden of the city was founded by the University of Palermo in 1789 and opened to the public in 1795. It covers an area of just over 10 ha with a living collection of about 1,700 taxa and 12,000 different species (Speciale, 2018). The favorable climate of Palermo reproduces the natural habitat of most of the plants which allows for their natural growing and flowering. Large collections are represented by Mediterranean, tropical and subtropical plants, as well as numerous species of exotic plants (Viola and Speciale, 2021). These types of gardens still serve their initial purpose of study, contributing to the development of botanical science especially in medical and agricultural fields. Garibaldi Garden is a public garden in Palermo, built by the architect Giovan Battista Filippo Basile between 1861 and 1864 in Piazza Marina in Palermo. It is in the historic district of Kalsa and it was named after the national hero Giuseppe Garibaldi to celebrate the birth of the Italian nation. The garden has an irregularly quadrangular shape and it extends for just over 1 hectare. Main plants present in the garden are a species of Himalayan podocarpus (*Podocarpus neriifolius*), a very rare oak of Mexican origin (*Quercus polymorpha*), an imposing arboreal gardenia of South Africa (*Gardenia thunbergia*) and a majestic species of *Ficus Macrophylla* subsp. *columnaris*. In spring it is possible to watch the multicolored blooms of *Sophora secundiflora*, with purple flowers, alternating with the yellow inflorescences of *Roldana petasitis*, the orange ones of *Leonotis leonurus* and the white ones of *Sparmannia africana* (Bazan *et al.*, 2005; Barbera and Speciale, 2015; Schicchi and Speciale, 2020).

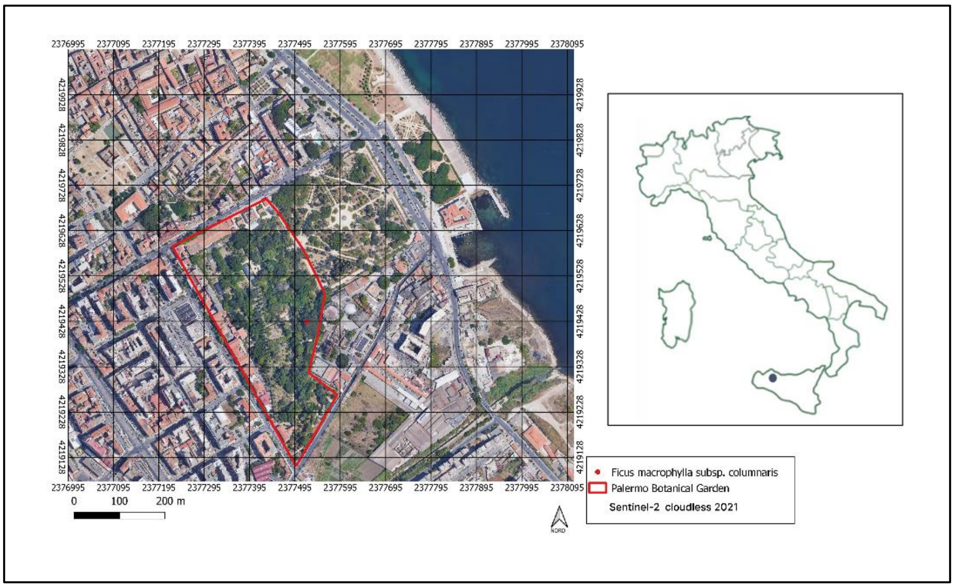


Figure n. 12 - Positions of the Palermo Botanical Garden (Palermo, Sicily, Italy).

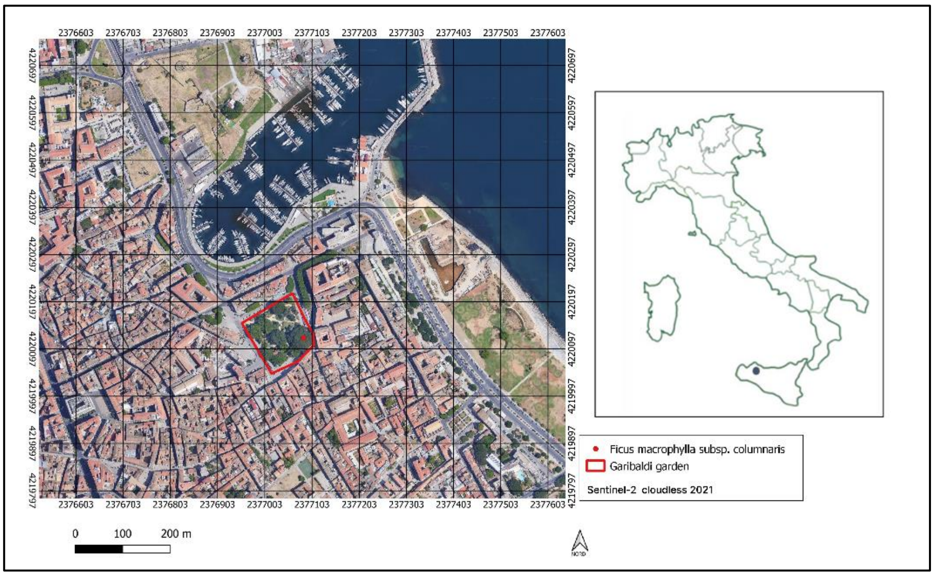


Figure n. 13 - Positions of the Garibaldi Garden (Palermo, Sicily, Italy).

Ficus macrophylla subsp. *columnaris* was imported from Norfolk Island (an Australian territory in the Pacific Ocean), in 1845 to the Palermo Botanical Garden and Garibaldi Garden. It is also native to the east coast of Australia and is known as Moreton Bay Ficus tree. Subsequently, it began its rapid and unstoppable spread in public and private parks and gardens on the Sicilian coast. In its native range, this singular tree generally arises as an epiphyte (that is, as a plant that grows on another but without being parasitic). It is now easy to see it in monumental tree examples, the growth of which has often profoundly altered the original architectural plantings. The plant's growth occurs in all directions of space: the vertically developing central body extends, in fact, laterally with the higher order branches; downwards with the columnar aerial roots that support the plant's branches; on the soil surface with the tabular roots. Numerous aerial roots begin to develop from the young stem and branching, which, as they touch the soil and branch out, will transform into supporting pseudo trunks, many of which weld together to form, together with the main trunk, a massive indistinct woody biomass. The aerial roots of its branches thicken into additional trunks when they touch the ground, which help support the weight of the canopy. In addition to these adventitious aerial roots, there are also large tabular roots, which support the main trunk and reach considerable lengths on the ground. The rather leathery and large leaves are dark green and glabrous on the upper page and slightly tomentose and rust-colored on the lower page. The axillary inflorescences (*syconia*), placed on the terminal zone of the branches, do not turn into infructescence due to the absence, in Italy, of the specific pollinating insects. Ficus tree of Palermo Botanical Garden is the tree with the largest canopy in Europe, the progenitor of the large ficus trees in the city of Palermo with a plant age of 173 years. The ficus tree in Garibaldi Garden is the tree with the largest trunk in Europe (a circumference of over 21 m) and a plant age of 146 years (Barbera and Speciale, 2015). Table n. 9 reports main informations about the *Ficus macrophylla* subsp. *columnaris* trees of Palermo Botanical Garden and Garibaldi Garden.

Table n. 9 - Main informations about the *Ficus macrophylla* subsp. *columnaris* trees to study areas "Palermo Botanical Garden and Garibaldi Garden" (Palermo, Sicily, Italy).

***Ficus macrophylla* subsp. *columnaris* to Garibaldi Garden**	***Ficus Macrophylla* subsp. *columnaris* to Palermo Botanical Garden**
	
DBH max: 225 cm	DBH max: 150 cm
H: 32 m	H: 29 m
Canopy surface: 1980 m^2 (0,198 ha)	Canopy surface: 2390 m^2 (0,239 ha)
Total structural elements (principal stem, prop roots, secondary stem, aerial roots): 234	Total structural elements (principal stem, prop roots, secondary stem, aerial roots): 144

2.2.7 Mt. Chortiatis (Thessaloniki, Macedonia, Greece).

International location of two survey areas is Mt. Chortiatis, Thessaloniki, Macedonia, Greece (Long: 667510 4490644, Lat: 688187 4505059, WGS 84/ UTM zone 34N EPSG:32364) (Figure n. 14). The Mount. Chortiatis complex covers an area of 1.350 hectares with the altitude varies a lot, from 590 to 1300 m, Kissos is its highest peak and it reaches 1.201 mt. The survey area belongs to the National Park of Lakes Koroneia - Volvi and Tempes Macedonian and its north-northeast part is part of the Special Protection Zone GR1220009 "Lake Koroneia - Volvi, Stena Rentina " (Municipality of Pylaia-Hortiati). The massif is of small extension and not particularly imposing. It is located at east of Thessaloniki, on the borders of Chalkidiki and the plain of Thessaloniki (Petaloudi *et al.*, 2022). Its morphology is smooth, poor in furrows and ridges. In the south-west slopes are poorly vegetated while the north-northeast slopes are covered with thick woods.

From a geological point of view, the areas investigated are characterized by two types of soil. The mountain areas where the chestnut trees are present are clay-sandy soils, more lightly belonging to the Magmatic series-Leucocratic albite sericite-microcline gneiss (green-schists, slightly acidic and poor nutrient soils) (Konstantinidis *et al.*, 2008). In the places where black pine (*Pinus nigra*) reforestation is located, the soil presents Dunites and peridotites mainly wherlites, partly iherzolite (olivine, diallage, bronzite), belonged to the schistose bodies, formation of antigoritic schists, talc and asbestos (shallow soils with an average soil depth) (Del Cerro *et al.*, 2009). The weather station of Hortiatis-Thessaloniki (570 m a.l.s.) near to the sampling area reports an average annual temperature of 14.59°C. The hottest month is July (30°c), the coldest month is January (6.4°C). As for the annual rainfall, the average annual precipitation is 649 mm. The monthly distribution of precipitation shows an autumn maximum in December (100 mm) and a summer minimum in August (19 mm). Rainfall remains relatively high in the months of January to May (about 100 mm per month) and then decreases rapidly until the summer minimum (http://www.hortiatis570.gr/weather/).

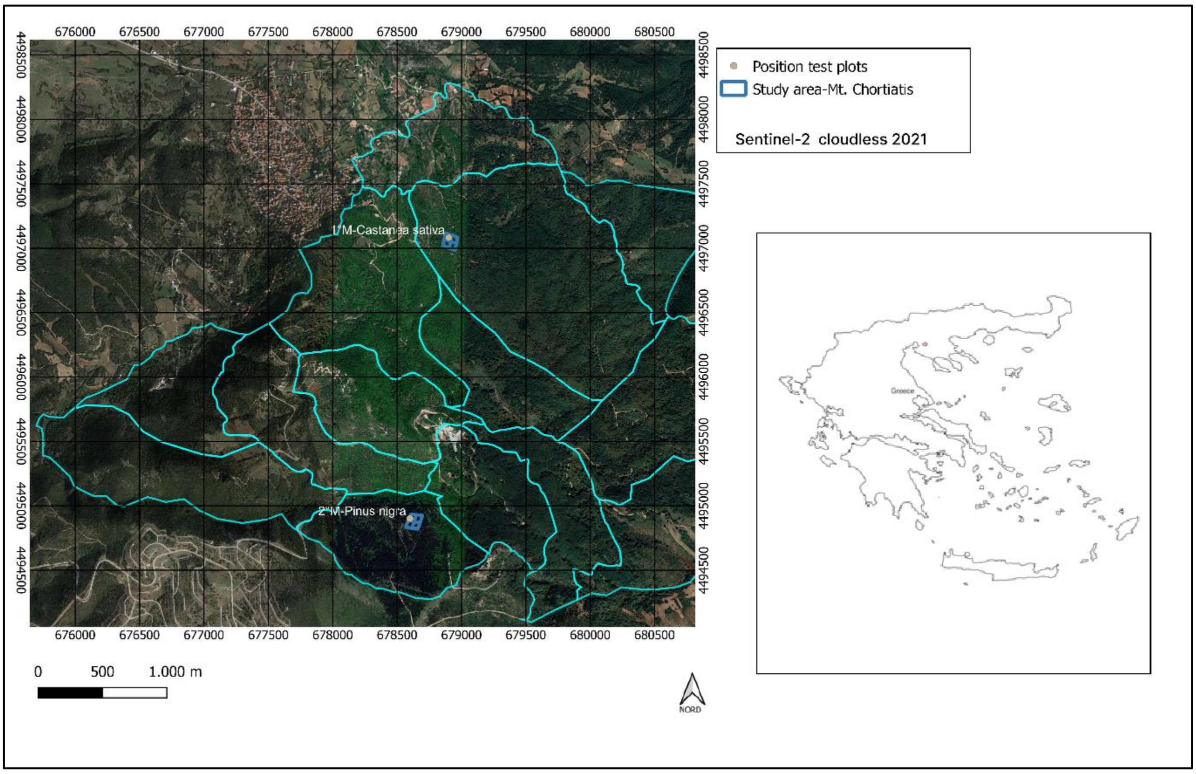


Figure n. 14 - Positions of Mt. Chortiatis plots (Thessaloniki, Macedonia, Greece).

Most of the forests of Mt. Chortiatis are predominantly deciduous. To the north-east there is a strong presence of the chestnut (*Castanea sativa*), while to the south-east the beech (*Fagus sylvatica*) is widespread. Beech forests appear dense, mainly between the peaks of Kissos and Kolosyrtis, the rest of the sites are dominated by oak forests, holly sites, mixed stands of oaks and chestnuts, evergreen oaks and hardwoods, but also limited areas of reforestation of black pine. There are many chestnut plantations (Santa Regina *et al.*, 2001; Konstantinidis *et al.*, 2008). There are three vegetation communities such as Ostryo-Carpinion orientalis (shrubs with *Quercus coccifera*) *Quercion confertae* (oak and chestnut forests), *Fagion moesiacae* (beech forests) belonging in the order *Querco-Fagetea* rare or threatened species: *Colchicum soboliferum*, *Colchicum tulakii* Th. Giannakis & al., which should be protected since their appearance in the area is geographically. The forest cover is continuous, except for the area of the settlement of Hortiatis, the few agricultural crops scattered. Holly, mallow, junipers, wild roses, Sparta, heathers, ferns, anemones, cyclamen, geraniums, crocuses, primroses, moss, bell-shaped, violets, colchica and orchids, complete the wealth of plants that the mountain hosts (Karagiannakidou and RausWilldenowia, 1996).

The two areas of investigation analyzed are characterized by chestnut old forest and *Pinus nigra* plantation. The monoplane high forest-old established plantations of Chestnut is averagely vigorous with a value of coverage as 70%. The dominant tree species in the chestnut forest are *Castanea sativa* (50% - 80%), *Quercus petraea*, *Sorbus torminalis, Tilia cordata* (50% - 20%), *Tilia tomentosa, Ostrya carpinifolia* (<20%). The composition of the Shrub layer consists of *Juniperus oxycedrusm, Rubus hirtus, R. sanctus, Erica arborea, Pteridium aquilinium, Cytisus scoparius, Vaccinium myrtillus*. Species belonging to grass layer are *Trifolium physodes, Polygonatum odoratum (Mill.) Druce, Helleborus foetidus, Luzula forsteri, Doronicum orientale, Lathyrus laxifluorus, Epilobium montanum, Rosa arvensis* and *Prunella vulgaris*. The "Nature 2000" Habitat code of chestnut forest is 9260 (Supra-Mediterranean and sub-Mediterranean *Castanea sativa* dominated forests and old established plantations with semi-natural undergrowth) (Santa Regina *et al.*, 2001; Konstantinidis *et al.*, 2008).

In the case of the *Pinus nigra* plantation, the forest is an averagely vigorous adult monoplane high forest with a cover value of 85%. The dominant tree species are *Pinus nigra* (50% - 80%), *Quercus daleschampii, Carpinus betulus* (50% - 20%), *Fraxinus ornus, Fagus sylvatica* (<20%).

The composition of shrub layer is characterized by *Arbutus unedo, Erica arborea, Carpinus orientalis, Clematis vitalba, Juniperus communis, J. oxycedrus, Rubus hirtus, Rosa genus.* Finally, the grass layer consists of *Pteridium aquilinum, Aremonia agromonoides, Hieracium bauhini, Pyrola chlorantha, Luzula forsteri, Brachypodium sylvaticum, Calamagrostis arundinacea, Hedera helix*. The "Nature 2000" Habitat code of *Pinus nigra* forest is 9530* (Sub-Mediterranean pine forests with endemic black pines) (Del Cerro *et al.*, 2009). It is possible to identify in table n. 10-11 the main information of the Mt. Chortiatis.

Table n. 10 – Main forest information about *Castanea sativa* old forest plot to “Mt. Chortiatis” (Thessaloniki, Macedonia, Greece).

Forest type – *Castanea sativa*

Structure: Monoplane high forest-old established plantations of *Castanea sativa*

Vigor: averagely vigorous

Specific composition:
Castanea sativa (50% - 80%),

Quercus petraea, *Sorbus torminalis*, *Tilia cordata* (50% - 20%),

Tilia tomentosa, *Ostrya carpinifolia* (<20%)

Shrub layer: *Juniperus oxycedrusm Rubus hirtus*, *R. sanctus*, *Erica arborea*, *Pteridium aquilinium*, *Cytisus scoparius*, *Vaccinium myrtillus*.

Herb layer: *Trifolium physodes*, *Polygonatum odoratum (Mill.) Druce*, *Helleborus foetidus*, *Luzula forsteri*, *Doronicum orientale*, *Lathyrus laxifluorus*, *Epilobium montanum*, *Rosa arvensis and Prunella vulgaris*.

Coverage: 70%

Natural regeneration: sufficient

DBHm: 20.47 cm

Hm: 10.75 m

Number of trees: 866 n. trees/ha

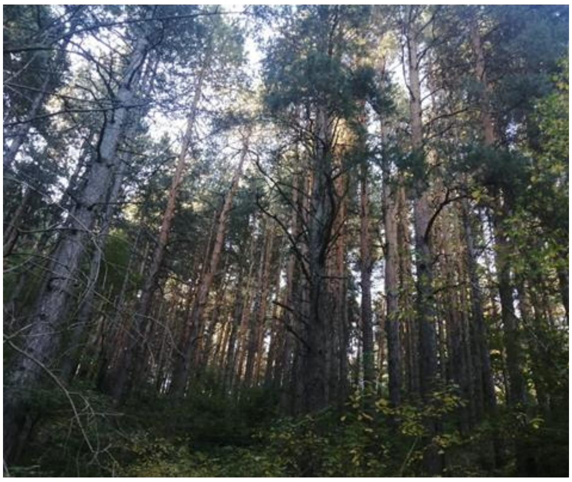
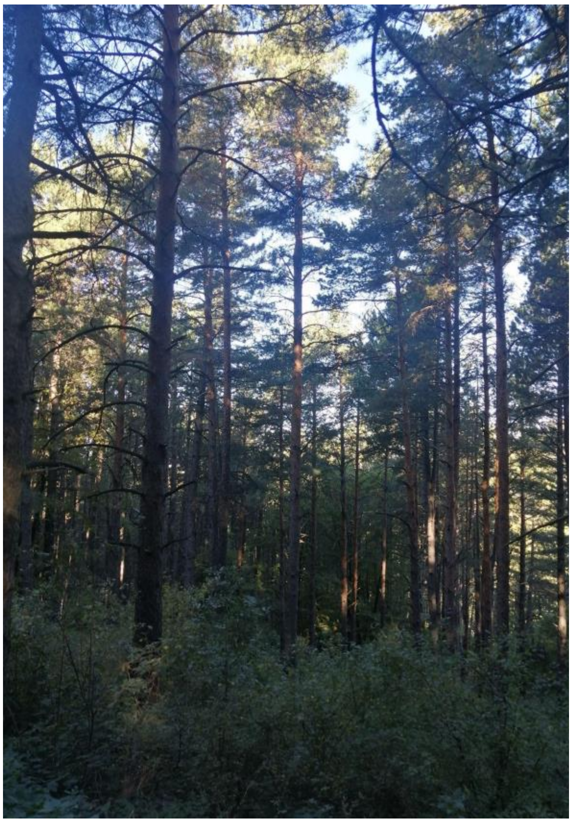
Volume: 220 m^3/ha

Basal area: 36 m^2/ha

Photos taken in “Mt. Chortiatis”

DBHm: average value of DBH, Hm: average value of H.

Table n. 11 - Main forest information about *Pinus nigra* plantation to “Mt. Chortiatis” (Thessaloniki, Macedonia, Greece).

Forest type - *Pinus nigra*	 
Structure: Adult monoplane high forest-established *Pinus nigra* plantation	
Vigor: averagely vigorous	
Specific composition: *Pinus nigra* (50% - 80%), *Quercus daleschampii*, *Carpinus betulus* (50% - 20%), *Fraxinus ornus*, *Fagus sylvatica* (<20%).	
Shrub layer: *Arbutus unedo*, *Erica arborea*, *Carpinus orientalis*, *Clematis vitalba*, *Juniperus communis*, *J. oxycedrus*, *Rubus hirtus*, *Rosa genus*.	
Herb layer: *Pteridium aquilinum*, *Aremonia agromonoides*, *Hieracium bauhini*, *Pyrola chlorantha*, *Luzula forsteri*, *Brachypodium sylvaticum*, *Calamagrostis arundinacea*, *Hedera helix*.	
Coverage: 85%	
Natural regeneration: sufficient	
DBH m: 28.1 cm	
H m: 18.33 m	
Number of tree: 692 n.trees/ha	
Volume: 405 m^3/ha	
Basal area: 45.7 m^2/ha	Photos taken in Mt. Chortiatis

DBHm: average value of DBH, Hm: average value of H.

2.3. Field Data

For sampling of the case study, I held in the study area Alpe di Catenaia (Tuscany, Italy) fifteen circular plots were identified, with a high productive vocation. They differ for forest type class (broadleaved, conifers, and mixed), dominant species, forest structure (one or two-layered), regeneration and stand class. The circular plots were constructed with a variable radius of 15, 20, 25 m, depending on the average height of the forest stand concerned (Figure n. 6 -Table n. 2-3).

To optimize sampling, plots shall be distributed over the total forest complexity according to the non-aligned systematic sampling scheme, or by random extraction of the location of a plot within a forest complex concerned. Terrestrial LIDAR data have been used to estimate the woody mass of the forest complex using recently published methodologies (Gollob *et al.* 2020; Sofia *et al.* 2021).

For the case study II, the research was carried out under the project “LIFE17 GIE/IT/000561” (LIFE GoProFor) in collaboration with the cooperative society "Dimensione Ricerca Ecologia Ambiente Italia" (D.R.E.Am. Italia), identifying two different forest environments. In this project the areas of study and the size of the plots derive from the research activity for the realization of "Martelloscopio", areas of simulation of indirect forestry interventions applied through the latest generation of computer support.

For the sampling, eight square areas of 2500 m^2 of surface were investigated, distinguished by forest type, slope, density and shrub cover. The first four areas (total area: 10,000 m^2) are part of the Camaldoli area. The topsoil is a single-layer fustaia, the same size, adult, of beech (*Fagus sylvatica*) medium vigorous with a coverage of 95% and absence of shrub vegetation (Figure n. 7, Table n. 4). The remaining four areas, equal for a total of 1 Ha, fall within the Nature Reserve "Bosco della Ficuzza", belonging to the study area "Bosco della Ramusa". The topsoil is a transitional stand of broad-leaved trees (*Quercus ilex, Quercus pubescens s.l., Acer campestre*) currently left to free evolution with a coverage of 95% and with a modest presence of shrub vegetation (*Ruscus aculeatus*) (Figure n. 8, Table n. 5).

As regards the case study III, it has been examined the whole area "Bosco Niscemi" present in the inserted Favorita Park, classified as zone A of the Nature Reserve "Monte Pellegrino", to provide a substantial forest sampling in the Mediterranean environment where there is a close contact with the city (Figure n. 10, Table n. 7). In particular, the forest area in question has been divided into 16 squares of 4000 m 2, delimited by paths on site, with a total of 6.4 hectares.

Finally, to verify the accuracy of the data obtained from the LIDAR survey, two circular plots were identified where a traditional dendrometric survey and a LIDAR survey could be carried out at the same time to compare the final results for each tree individually.

In the case study IV, four square areas of 2500 m^2 of different types of forest were selected in two European countries (Italy, Greece). In the sampled areas, there are noticeable variations in stem straightness, which led to the inclusion of a diverse range of trees with different levels of curvature and straightness in the experimental design, as opposed to the scoring system outlined by MacDonald in 2001. This approach aimed to increase the distinctiveness of individual forest stands. To achieve this, the sampled square areas were segregated into groups of forest trees with similar stem straightness characteristics.

In Italy the same areas investigated in the second case study were examined, and identified two different forest environments were identified: a single-layer stand of beech (*Fagus sylvatica*) and a transitional stand of broad-leaved trees (*Quercus ilex).*

In Greece (Thessaloniki, Macedonia) it was possible to carry out a sampling focused only in two areas belonging to particular habitats characteristic of the Mediterranean environment such as "9260: Chestnut Old Forest" and "9530*: Sub-Mediterranean pine forests" (Figure n. 14, Table n. 10-11). These areas were carried out as part of the project “LIFE21-NAT-IT-LIFE” (GOPROFOR MED) in collaboration with the cooperative society "Dimensione Ricerca Ecologia Ambiente Italia" (D.R.E.Am. Italia) and the international research centre "Greek Biotope/Wetland Centre" (EKBY, Thessaloniki, Greece).

In the case study V, it was carried out an in-depth analysis of two Mediterranean forest environments (dominated by species belonging to the oak, *Quercus pubescens Willd*. s.l.) in Sicily, identified and cited by the bibliography (Badalamenti *et al.*, 2017; Badalamenti, 2022). The objective of this study concerns the dimensional description of those individuals that showed potential sign of oldness, following the indications and identification criteria obtained from the bibliography (Testo Unico Forestale D.Lgs. 34/2018; Badalamenti *et al.*, 2018).

The first investigated study area for this case study was located within the Ficuzza Reserve ("Bosco del Fanuso") (Figure n. 9 Table n. 6). Instead, the second study area concerns "Bosco del Gurgo", located within the Santa Maria del Bosco Reserve (Figure n. 11, Table n. 8). For each study area, five circular plots of 20 m radius were spatially distributed at a distance of 4 m each within the forest environment. The individual plots were distinguished based on the number of trees with particular dimensional characteristics (n. of trees with DBH > 5 cm, n. trees with DBH > 40 cm), the percentage of necromass both standing on the ground, and the percentage of renewal present. In these study areas, it was possible to identify two circular plots in order to assess the level of accuracy of dendrometric data obtained from the LIDAR survey performed in those same areas through comparison with the results of traditional dendrometric surveys.

The areas of study and the size of the plots derive from the research activity for the forest monitoring of old oak forest stands present in Sicily and in habitats 91AA* (Oriental white oak woods) carried out under action A1.3 of the project LIFE16NAT/IT/000245 "LIFE4OAKFORESTS", in collaboration between the SAAF Department and the Management Authority for Parks and Biodiversity - Romagna.

In the case study VI, it was possible to investigate two trees that have characters of high singularity and monumentality, due to their conformation, size, age and historical value, located within some historic green areas of the city of Palermo. The trees investigated belong to the forest species present and characteristic of the urban area of Palermo, namely the *Ficus Macrophylla* subsp. *columnaris* and are located specifically inside the Botanical Garden of Palermo (Figure n. 12, Table n. 9) and inside the Garibaldi Garden (Figure n. 13, Table n. 9). They also belong to the list of Monumental Trees of Italy, national list pursuant to Law n. 10/2013 and Decree 23 October 2014 "Monumental Trees of Italy", because of their monumental feature for size and historical value. It is possible to identify in table n. 12 the main information of all study areas described.

Table n. 12 - Main characteristics of the the study areas.

Study area	Case study	Location	Forest type; Dominant tree species	Surveyed area
"Alpe di Catenaia"	I	Tuscany, Italy	The beech monospecific forests (*Fagus sylvatica).*	5 circular plots (r= 15-25m)
			The deciduous forests (*Quercus cerris*)	2 circular plots (r= 15-25m)
			Silver fir (*Abies alba*), Douglas fir (*Pseudotsuga menziesii*) and black pine (*Pinus nigra*) high forests	8 circular plots (r= 15-25m)
"Camaldoli"	II, IV	Tuscany, Italy	The pure beech woodland (*Fagus sylvatica*)	4 square plots (50*50m)
"Ficuzza- Bosco della Ramusa"	II, IV	Sicily, Italy	Transitional Mediterranean Forest of Holm Oak (*Quercus ilex*)	4 square plots (50*50m)
"Ficuzza-Bosco del Fanuso"	V	Sicily, Italy	Old-Growth Mediterranean Forest of Downy Oak (*Quercus pubescens*)	5 circular plots (r= 20m)
"Bosco Niscemi"	III	Sicily, Italy	Aged coppice forest of holm oak (*Quercus ilex*)	16 square plots (60*60m)
"Santa Maria del Bosco-Bosco del Gurgo"	V	Sicily, Italy	Old-Growth Mediterranean Forest of White Oak (*Quercus amplifolia Guss.*)	5 circular plots (r= 20m)
"Palermo Botanical Garden and Garibaldi Garden"	VI	Palermo city, Sicily, Italy	*Ficus macrophylla subsp. columnaris* large trees	2 sample trees
"Mt. Chortiatis"	IV	Thessaloniki, Macedonia, Greece	Monoplane high forest-old established plantations of chestnut (*Castanea sativa)*	4 square plots (50*50m)
			Adult monoplane high forest-established Black pine plantation (*Pinus nigra*)	4 square plots (50*50m)

2.1. HLS platform and LIDAR data collection

In the field, terrestrial Laser scanning was carried out using a lightweight HLS GEOSLAM ZEB HORIZON ™ (GEOSLAM ltd. (UK). This terrestrial laser scanner is a lightweight hand-held mobile laser scanner (weight: 3.5 kg) containing an eye-safe laser that provides 300,000 measurements per second qith an maximum scanning range of 100 m (Figure n. 15).

Figure n. 15 - GEOSLAM ZEB HORIZON™ Hand Held Mobile Laser Scanner (HLS)

This tool uses SLAM (Simultaneous Localization and Mapping) technology developed by the robotics and computer vision community to survey and scan the survey area, making it practical for outdoor surveys. In this way, the problem of no GNSS signal or poor signal under the forest canopy can be solved using this instrument (Ryding *et al.*, 2015; Gollob *et al.*, 2020; ZEB HORIZON ™ - GeoSLAM, 2020). The data acquisition with ZEB HORIZON starts with IMU initialization to establish the local coordinate reference system. The VLP-16[1] (0.83 kg) has 16 channels and uses time-of-flight Light Detection and Ranging (LIDAR) technology to measure the distance with a continuous wavelength of 903 nm and range accuracy of ±3 cm. The field of view of the VLP-16 is 360◦ × 30◦ with a horizontal angular resolution of 0.1◦–0.4◦ and a vertical angular resolution of 2◦. The combination of the internal and external rotation of VLP-16 attached to the ZEB HORIZON results in an angular field of view of 360◦ × 270◦. The size of the collection point data is 100–200 MB for a minute. The scanner is easy to handle during forest surveys thanks to its compact design (100 mm × 200 mm × 240 mm for the hand-held part) and the longevity of battery capacity (3.50 hours continued). Finally, it can be equipped with an optional Firefly 8si camera with 4k resolution to record different videos of the sampling area, useful for forest quality aspect inspection (Liang *et al.*, 2015; Ryding *et al.*, 2015; Gollob *et al.*, 2020; ZEB Horizon—GeoSLAM, 2020). In the HLS scan, the operator stands in the middle of the plot and he waits 15 seconds to find stability of the instrument. Then the operator handhelds the scanner and starts walking inside the sampling area, while the rotating head of the scanner captures the 3D data. During the optimal scanning time of 15-20 minutes with the HLS instrument, the operator stops for 15 seconds at least three positions in the survey area (Reference Points), marked first by the GNSS detector. At the end of the scanning time, the operator returns to the starting point and stops scanning. The coordinates taken for the three identified locations will be used in the office to georeference the "Point Cloud" LIDAR output data into a local reference system to obtain a better location of the site. The paths created with the HLS laser scanner have different shapes according to the cases studies.

For the case study I, it was decided to run a star-shaped path (Figure n. 16), the best representation of path according to the recent bibliography (Bauwens *et al.*2016; Del Perugia *et al.*2019; Gollob *et al.* 2020; Sofia *et al.* 2021). The initial and final point of the walking path was the test plot center. The mean time necessary for laser scanning in one circular test plot (area of 705 square m) was 10 minutes.

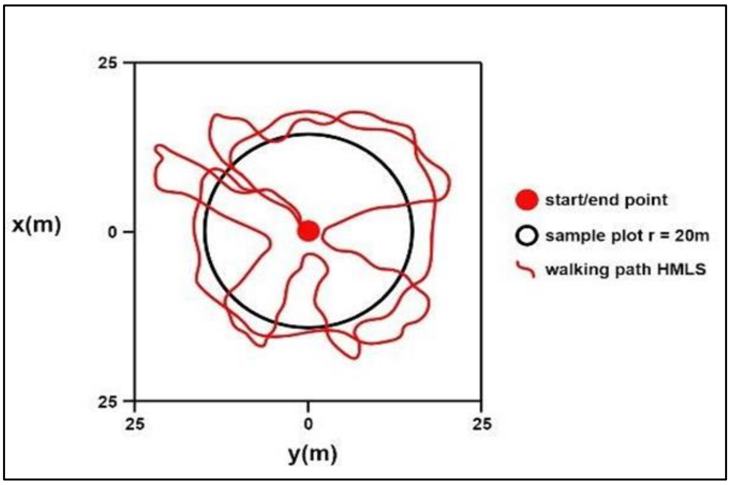


Figure n. 16 - Scheme of walking path during HLS scanning into the first case study (Sofia *et al.*, 2021)

As regards the case study II, a repetition of LIDAR scans was carried out on the same area of investigation by performing three types of walking path: a star shape, a serpentine shape and finally a square shape remaining at the border of the area investigated (Figure n. 17). The mean time necessary for laser scanning in one square test plot (area of 2500 square metres) was 15 minutes.

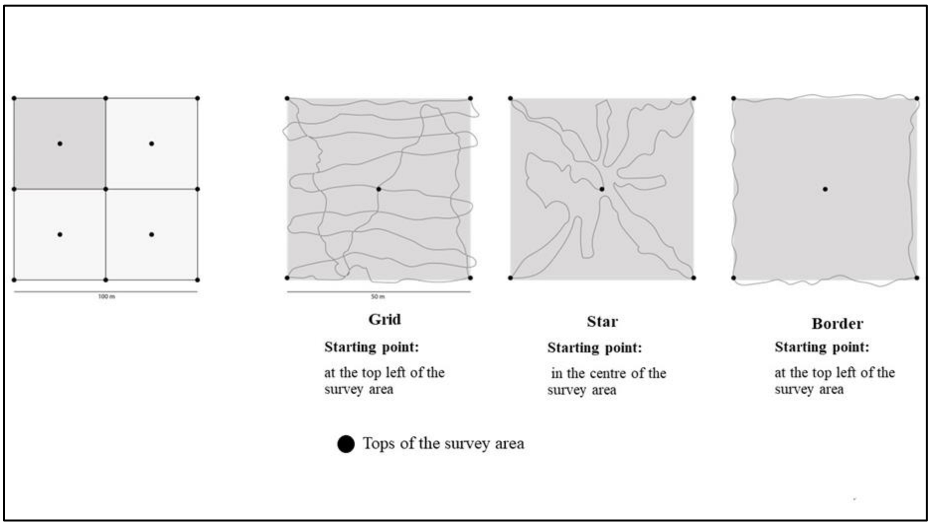


Figure n. 17 - Schemes of walking path during HLS scanning applied into the second case study.

The case study III has the objective of obtaining a better tree representation from the forest area represented by the dense Mediterranean scrub. For this case study, a narrow serpentine path was carried out inside each square area investigated (Figure n. 18). The mean time necessary for laser scanning in one square test plot (area of 4000 square metres) was 25 minutes.

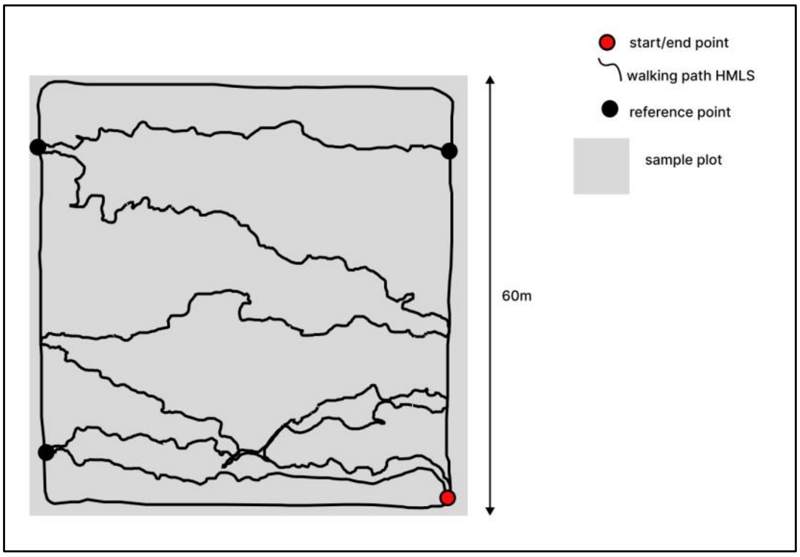


Figure n. 18 - Scheme of walking path during HLS applied into the third case study.

In the case study IV, it was decided to follow the best representation of walking path according to the recent bibliography that is star-shaped path (Figure n. 19) (Bauwens *et al.*2016; Del Perugia *et al.*2019; Gollob *et al.* 2020; Sofia *et al.* 2021).

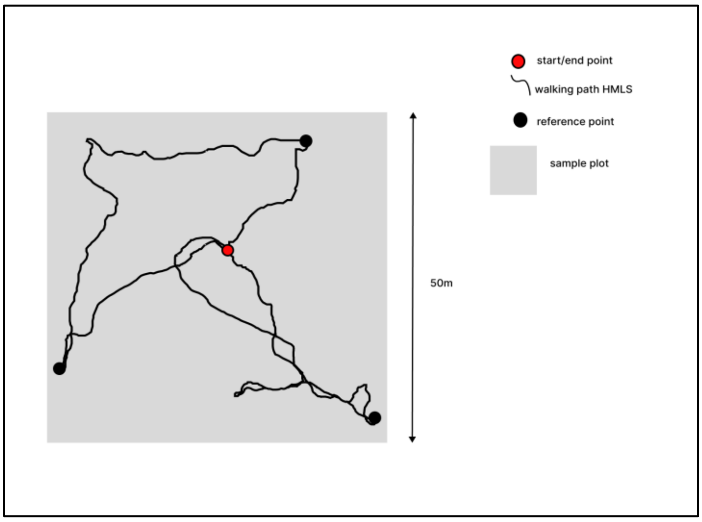


Figure n. 19 - Scheme of walking path during HLS applied into the fourth case study.

In the case study V, random walkways were simply carried out within the investigation area, stopping only at three strategic points, forming a triangle around the centre of the area under investigation (Figure n. 20). The mean time necessary for laser scanning in one test plot (area of 705 square metres) was 10 minutes.

Figure n. 20 - Scheme of walking path during HLS applied into the fifth case study.

In the case study VI, the walkway was performed with two concentric circles. The inner one provides a better representation of the under canopy, while the wider circle gives more information of the canopy following its maximum expansion (Figure n. 21-22). The mean time necessary for laser scanning in one test tree plot was 7 minutes.

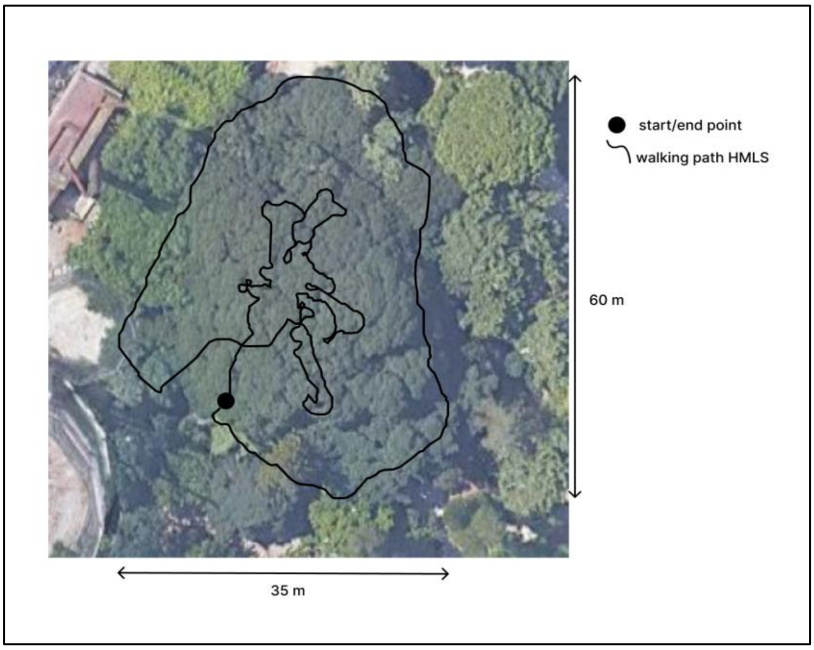


Figure n. 21- Scheme of walking path during HLS applied into the sixth case study around the Palermo Botanical Garden’s *Ficus macrophylla* subsp. *Columnaris* tree.

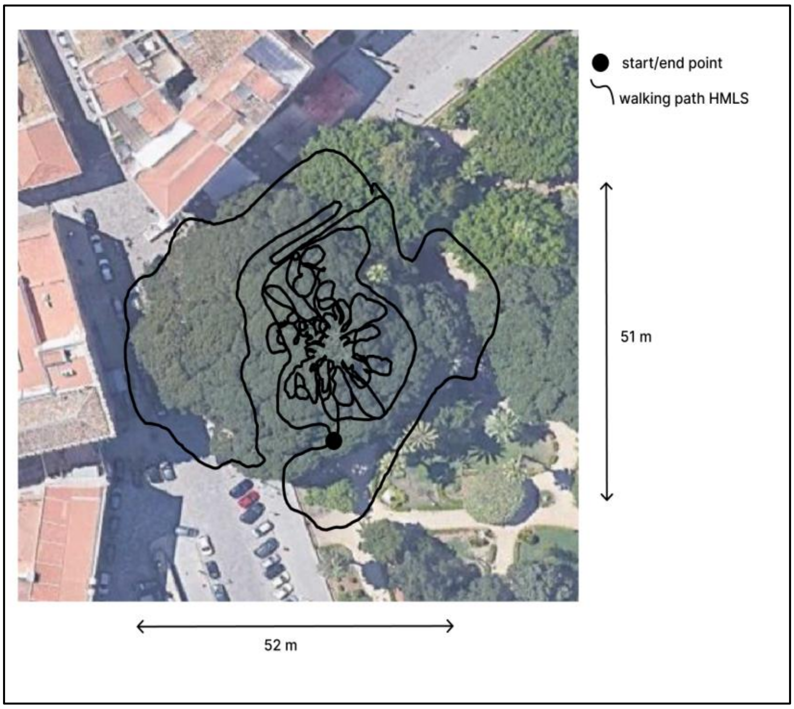


Figure n. 22 - Scheme of walking path during HLS applied into the sixth case study around the Garibaldi Garden’s *Ficus macrophylla* subsp. *Columnaris* tree.

2.2. LIDAR Point Cloud Processing and Extraction of single-tree attributes

The method of processing LIDAR data is modified from "Sofia *et al.*, 2022" and applied in all cases studies.

Processing of "Point Cloud" output LIDAR data as follows six main steps:

(1) Registration and conversion of collected 3D data into LAS format;

(2) Statistical removal of high and low-level outliers and Filtering of ground points;

(3) Removing the impact of terrain on the elevation values of individual laser points;

(4) Identification of cylindrical elements in point cloud through Batch Extraction of DBH;

(5) Point Cloud Segmentation from cylindrical elements identified;

(6) Extraction of Individual other dendrometric values (tree positions and height) (Sofia *et al.*, 2021).

The main working steps can be seen in Figure n. 23.

In the first step, the 3D data acquired from the laser scanning are processed with several automatic processing steps to be converted into LAS format using the GeoSLAM Hub 6.1 desktop software (GeoSLAM Hub 6.1 Development Team, 2021).

Parameter settings used in the software for export of LAS format are "100% of points", "point color: time", "timestamp: None" and "Smooth accepted".

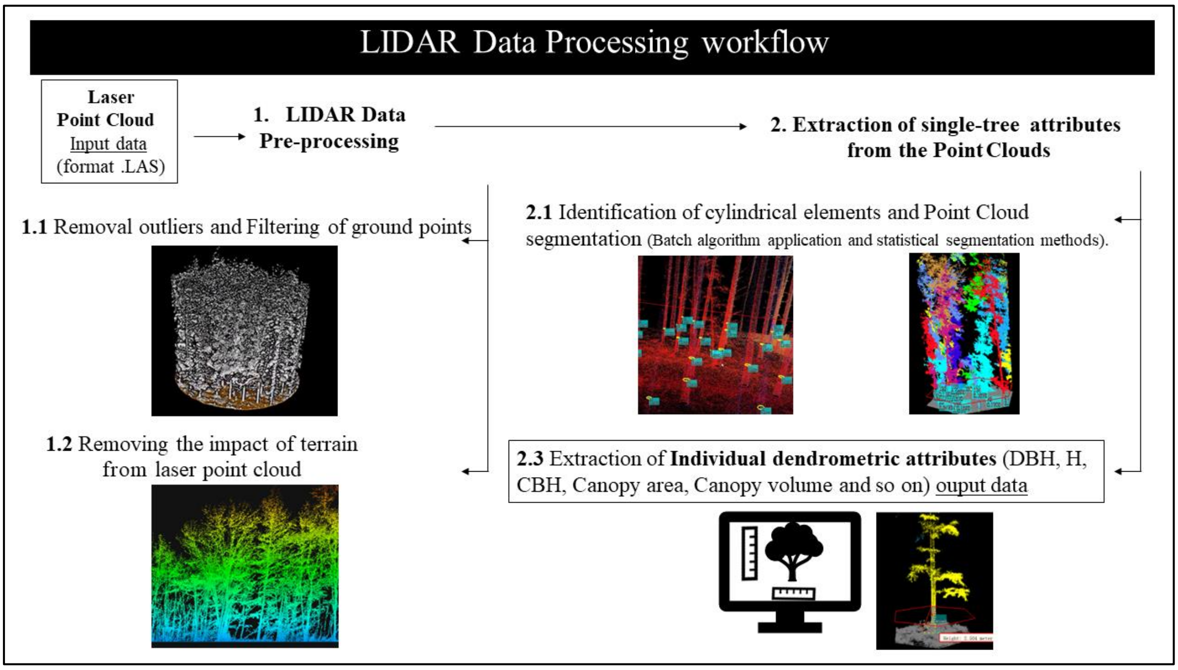


Figure n. 23 – the procedure used to automatically extract the single tree attribute from HLS point clouds.

LIDAR360 software was used for other phases of processing. Before the application of plugins for subsequent processing steps, it is necessary to crop the Point Cloud into a square section according to the demarcated boundary of the survey area. Thanks to the software's specific "remove outliers" tool (2° step), the statistical noise (low and high-level outliers) was removed. This algorithm searches for each point's neighbors and calculates the average distance between the point and its neighboring points and the standard deviation of these distances. If the average distance of a point from its neighbors is larger than the maximum distance (maximum distance = mean + n * standard deviation, where n is user defined multiple numbers), it is considered an outlier and removed from the original point cloud. High-level error is usually caused by the returns of high-flying objects (such as birds) during the process of data collection; low-level gross errors are returns with extremely low attitudes caused by the multipath effect of a laser pulse. Other software tools for the 3° step of LIDAR data processing such as "Filter Ground Points" (extraction ground points from TLS point cloud data) and "Normalize by Ground Points" (removing the effects of the topographic survey on the elevation value of the point cloud data) allow having a point cloud without noise in order to extrapolate dendrometric datas with other automatic informatic algoritms (Chen *et al.*, 2019; LIDAR360 Development Team, 2020). For the transition to 4°, the applied algorithm combines different statistics such as the fit confidence of the tree trunk and the DBH circle to classify it into three levels: Low, Medium, and High. It is important to give attention to the results of the identification of cylindrical elements from the LIDAR360 software. The min-max height range greater than 0.4 m - when fitting DBH in batch extraction mode singular cylindrical elements with a low confidence level – can be detected and removed. The point cloud segmentation method developed by Tao *et al.*, 2015, for TLS data using a bottom-up approach to identify individual trees was applied in the last steps. This type of method is worth the HLS data because the TLS data, such as the HLS data, are often acquired below the canopy where tree stems can be readily observed. The final result is a spreadsheet-based CSV format with the complete information of every stem present in sample plots (Tao *et al.*, 2015; LIDAR360 Development Team, 2020). An example of final point cloud data from the graphical user interface of LIDAR360 is presented in Figure n. 24.

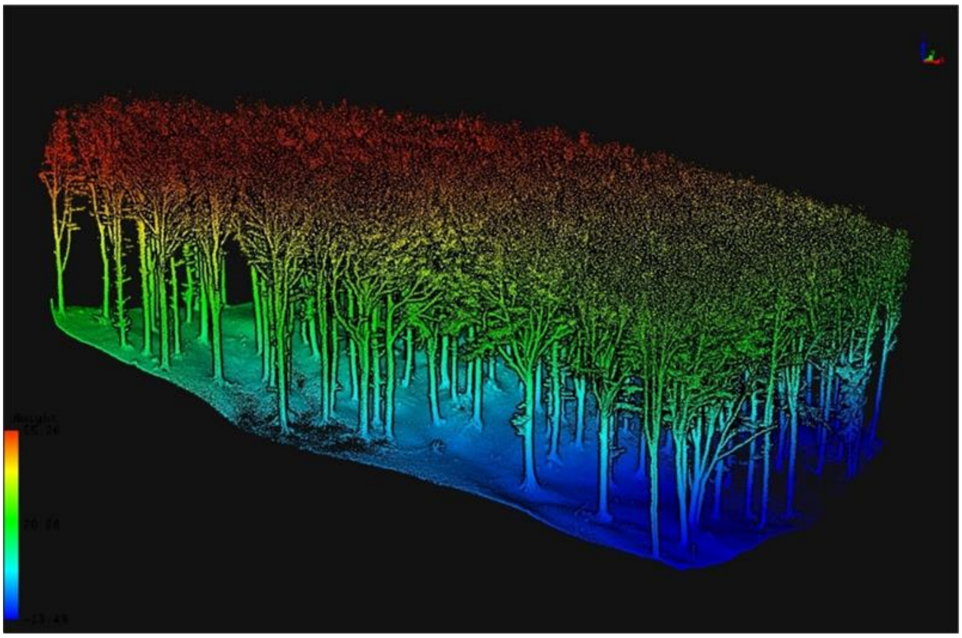


Figure n. 24 - Camaldoli survey area Point Cloud from the graphical user interface of LIDAR360

2.3. Voxelization and Classification of LIDAR data according to the Prometheus system

In the case study III, LIDAR HLS data from the Bosco Niscemi reliefs have been prepared according to the following steps:

1- realization vertical layer of dimension 10m*60m for each square area (4000 m 2),

2- the voxelization of LIDAR data layers,

3- the classification of LIDAR data according to the Prometheus system.

In the first step, starting from the LIDAR data in .las format, one of the editing and pre-processing tools for point clouds in the LIDAR360 Software was used. After the LIDAR data was processed and normalized by Ground Points (processing steps described in chapter 2.5), a vertical cutout was made along the length of the entire survey area (about 60 m) resulting in a portion of the point cloud measuring 10m*60m.

In the second phase of work, it was performed "the voxelization" was performed through the use of one of the packages present in R (version 4.1.2) called "LidR" (version 3.2.3). The voxelization condenses point cloud data into volumetric units called "voxels" (R Core Team, 2022). This process is commonly used in bibliography for studying forest structure and fuel inventories (Ryding *et al.*, 2015; Hawley *et al.*, 2018; Calders *et al.*, 2020; Rowell *et al.* 2020; Donager *et al.*, 2021). From the validation of the voxelization for the classification of fuels at a fine scale of the recently published thesis it was considered a small reference voxel size 1 cm (Post *et al.*, 2022). Inside the LidR package in R there are functions that allow the automatic counting of filled voxels and graphical representations of spatial distribution of voxels in vertical profile, specialized for airborne LIDAR data and terrestrial and LIDAR data (Roussel *et al.*, 2020) (Table 13).

Table n. 13 - R "LidR" code commands applied for LIDAR HLS Point Clouds for the case study III (Rousell *et al.*, 2020).

Mean commands applied in R "LidR" code procedure
lasReader ()
Description: Read a LAS file.
voxelize_points ()
Description: Is a 3D version of pixel_metrics. Reduce the number of points by voxelizing the point cloud. If the Intensity is part of the attributes, it is preserved and aggregated as mean (Intensity). Other attributes cannot be aggregated and are lost. The resolution of the voxels. res = 1 for 1x1x1 cubic voxels. Optionally res = c (1,2) for non-cubic voxels (1x1x2 cuboid voxel).
voxel_metrics ()
Description: Is a 3D version of pixel_metrics. It creates a 3D matrix of voxels with a given resolution. It creates a voxel from the cloud of points if there is at least one point. The output is a data. frame.

Because of the risk of underestimation of the results considering only the density of the points. It can be influenced by several external and internal technical factors such as distance from target, walking speed or scanner height (Ryding *et al.*, 2015; Del Perugia *et al.*, 2019). In the last work step, the classification of the LIDAR HLS voxelized data and the mapping of fuels following the European Prometheus system were performed.

The European Prometheus System (Arroyo *et al.*, 2008) identifies 7 types of fuel based on the spatial distribution of the green vegetation present in the survey area according to the percentage of ground cover of the foliage and the vertical stratification of the plant component. The type of fuel is distinguished considering the height of the fuel (obtained from the Point Cloud Segmentation from cylindrical elements identified, described in sub-chapter 2.5) and its density (obtained from the density of the voxels along the vertical profile). The characteristics of the 7 fuel types described by the Prometheus system are summarized in Figure n.25.

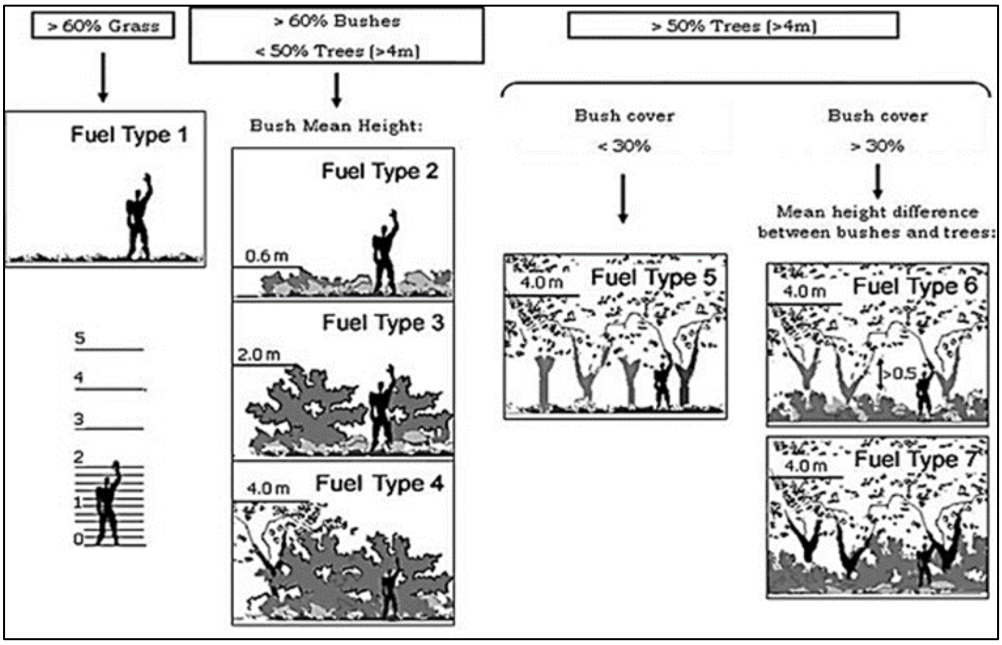


Figure n. 25 - Prometheus fuel type classification system (Chuvieco *et al.*, 2003).

The voxelized LIDAR data were divided into layers with a height of 0.5m from 0 to 7 m above the ground. All points above this threshold have been grouped into a single layer. Using Equation (Forbes *et al.*, 2022) the ladder fuel density was calculated using voxel points above 0 m in the denominator, according to the following formula:

$$\text{Ladder Fuel Density } \frac{\text{voxel points in strata}}{\text{voxel points in and below strata}} \qquad (1)$$

(Equation of Forbes *et al.*, 2022, modified)

From the stratification and the quantification in percentage of voxel densities between 0 to 4 m and possible vertical continuity we performed the classification of forest fuel types. The Prometheus classification is suitable for Mediterranean environmental characteristics describing quantitatively the fuel load present within the investigation area (Riaño *et al.*, 2002).

2.4. Validation of a stem straightness scoring system from LIDAR data

In the case study IV, a deeper analysis was performed on stem straightness in tree standing by LIDAR HLS surveys, the most important single factor for trunk quality.

The methodology applied in this case study was performed through the use of a specific tool within the LIDAR 360 software, created specifically for this type of study, called "the straightness of a tree", present in the module "Forestry"- section "Measure Individual Tree Attributes".

The scoring process was carried out automatically through the utilization of the LIDAR360 tool, in accordance with the protocol established by Macdonald *et al.* (2001). The software platform facilitated the selection of each segment of the LIDAR point cloud that pertained to a specific plant, which was subsequently used as a reference for executing the tools. The final output file comprised assigned straightness score values for each individual plant, with reference to the LIDAR data that was analyzed. In the protocol defined by Methley in 1998 and updated by Macdonald in 2001, the benchmark for scoring from 1 (less straight) to 7 (straighter) is the length of the straight logs identified in the first 5 m of the stem (Methley *et al.*, 1998). Macdonald *et al.* (2001) inside the categorization of "strighteness" in his experimental design introduced this following statement "*The arc shall not exceed 1 cm for every 1 m in length and this in one plane and in one direction. Arching is measured as the maximum deviation at any point of a straight line joining the centers of each end of the trunk from the actual centerline of the trunk*" (Macdonald *et al.*, 2001).

Table n. 14 and figure n. 26 report the Straightness scoring system (Macdonald *et al.* 2001. Macdonald *et al.*, 2009).

Table n. 14 - the Straightness scoring system (taken from Macdonald *et al.* 2009).

Score	Number and length of straight log lengths counted in butt 6 m
1	No straight lengths ≥2 m
2	One straight length ≥2 m but <3 m
3	Two straight lengths ≥2 m but <3 m
4	One straight length ≥3 m but <4 m
5	One straight length ≥2 m but <3 m and 1 straight length ≥3 m but <4 m
6	One straight length ≥4 m but <5 m
7	One straight length ≥5 m

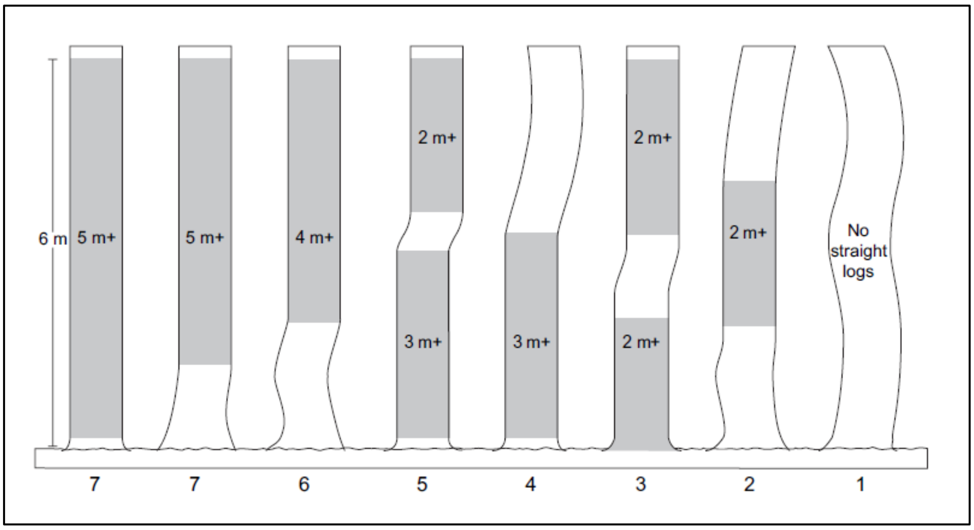


Figure n. 26 - Visual representation of the Straightness scoring system (taken from Macdonald *et al.* 2009).

The overall average straightness score of the stand is the average of all individual tree scores in the ten plots of 0.01 ha randomly distributed for each analysed forest stand. It has been possible to differentiate the qualities of the populations examined using the following quality classes (A-E) in Figure n. 27 (taken from Macdonald *et al.*, 2001) based on the proportion of trees evaluated in each of the seven classes of straightness scores.

Grade A – ≥ 40% of trees scored 6 or 7

Grade B – > 50% of trees scored 4, 5, 6 or 7 but < 40% score 6 or 7

Grade C – ≥ 35% of trees scored 3, 4, 5, 6 or 7 but ≤ 50% score 4, 5, 6 and 7

Grade D – < 35% of trees scored 3, 4, 5, 6 and 7 but ≤ 50% score 1

Grade E – as for Grade D but > 50% of trees scored 1

Figure n. 27 - the five stand quality classes defined by Macdonald *et al.* 2001 according the Protocol for Stem Straightness Assessment.

The scoring system described in the MacDonald *et al.* 2001 article is recommended as a standard scoring system to be applied to stands and was validated by Stirling *et al.*, 2000 at 270 Conifer Forest sites in Scotland (Stirling *et al.*, 2000).

The classification score allowed for a distribution of straightness scores within the stand. This could provide forest owners and managers with valuable information on the quality of logs. This information can be integrated into geographic information systems or used as supporting data in decision-making related to forest management, such as thinning requirements or production forecasts (Macdonald *et al.*, 2001; Macdonald *et al.*, 2009).

2.5. Traditional survey

In all cases studies applied studies in the forest environment have been performed using traditional dendrometric surveys to obtain comparative data in order to assess the accuracy of the data obtained from the HLS survey.

For traditional surveys, the main phases are as follows:

(1) Preliminary analysis of the site (identification of the forest area to be surveyed, choice of the size of the survey area, organization of means, instruments, and personnel for the field survey);

(2) Collection of qualitative data on the forest area under examination;

(3) Carrying out the dendrometric survey (collection of the diametres and altimetric heights of all the trees and the heights of some plants present in the survey area);

(4) Estimation of stand volume according to the mathematical models developed by Tabacchi *et al.* (2011).

In each sample plot, the trees were marked and numbered in the field and the DBH was measured with steel callipers from two directions perpendicular to each other at approximately 1.3 m. All trees taller than 1.5 m (H>1.5m) within the plot area were stem-mapped using azimuth and distance from plot center and the height (H) of all trunks larger than 9.5 cm (DBH ≥9.5) was measured with a Haglöf Vertex laser hypsometer (Vertex IV Hypsometer/Transponder 360 Package; Haglöf Sweden AB, Långsele, Sweden). The Vertex Laser Geo 360 has a precision of 0.01 m, with a nominal accuracy of 0.04 m over a range of 700 m.

The individual tree attributes obtained through the traditional survey were assumed to be error-free and used as reference data for evaluating the results of the HLS scans.

The relief of the forest investigated area's tree heights allowed for the creation of ipsometric curves for the most represented tree species, and based on this data, tables were prepared for the trees volume canopy estimation. Table 15 provides the equations for the hypometric curves of the most-represented species for each individual forest case study.

Table n. 15 - Hypsometric curves formulas applied for all forest study cases studies.

Species	**R^2**	**Formula**	**Study area**	**Case study**
Abies alba	0.82	5.0766* ln (DBH) + 6.5967	Alpe di Catenaia (Tuscany, Italy)	I
Pseudotsuga menziesii	0.71	12.156* ln (DBH) - 11.198	Alpe di Catenaia (Tuscany, Italy)	I
Pinus nigra	0.61	10.982* ln (DBH) - 10.478	Alpe di Catenaia (Tuscany, Italy)	I
Fagus sylvatica	0.83	6.6115* ln (DBH) - 0.8051	Alpe di Catenaia (Tuscany, Italy)	I
Quercus cerris	0.87	9.0048* ln (DBH) - 6.8863	Alpe di Catenaia (Tuscany, Italy)	I
Castanea sativa	0.88	0.5301*(DBH) + 5.2571	Alpe di Catenaia (Tuscany, Italy)	I
Fagus sylvatica	0.75	5.5163*ln (DBH) + 3.028	Camaldoli (Tuscany, Italy)	II
Quercus ilex	0.85	6.0043*ln (DBH) - 6.4715	Bosco della Ramusa - Ficuzza (Sicily, Italy)	II
Quercus pubescens	0.24	10.69*ln (DBH) - 23.564	Bosco del Fanuso- Ficuzza (Sicily, Italy)	V
Quercus pubescens	0.13	6.8413*ln (DBH) - 7.8142	Bosco di Gurgo - Santa Maria del Bosco (Sicily, Italy)	V

In these cases, the volume of the stems was calculated with the double entry tables prepared with the National Inventory of Forests and Carbon INFC of 2011 (Tabacchi *et al.*, 2011). The prediction equation is as follows: V=b1+b2*D2 *H+b3*D (where D is the diameter in cm and H the height in m).

The coefficients b1, b2, b3 are reported in the following table n. 16.

Table n. 16 - INFC Volume formula coefficients applied all study cases (Tabacchi *et al.*, 2011)

Species	b1	b2	b3
Abies alba	-1.84	0.04	0.4
Pseudotsuga menziesii	-7.9946	0.03334	1.2186
Pinus nigra	-21.48	0.03345	2.9088
Fagus sylvatica	0.81151	0.03897	0
Quercus cerris	0.81151	0.03897	0
Castanea sativa	-2.001	0.03652	0.74466
Quercus ilex	-2.2219	0.03969	0.62762
Quercus pubescens	0.51025	0.04518	-0.3603

In the case study I, the diameter increase was also measured on the same trees where the height was measured, while in coppice forest areas the age was determined. This will allow, in coppices, to determine the age of culmination of the average increase in maturity and interpolate a stretch of allometric curve that allows for the estimation of the volume of stands at the time of cutting by the formula: Icm x age (wood per year of felling) x density (estimated from traditional measurements and expressed in decimal places).

In the case study II, it was possible to quantify the time spent in the forest for the traditional measurement of all the trees present in the study areas. The mean time necessary to measure all trees in one test square plot (area of 2500 square metres) was five hours.

In the case study VI, it was possible to perform a distribution of structural elements typical of Ficus tree (principal stem, prop roots, secondary stem, aerial roots) differentiating them by diameter class in order to obtain a better representation of the diameter variability presented in a single individual.

2.6. Statistical analysis

The accuracy of results (tree DBH and H) taken from HLS LIDAR scan results and traditional surveys were evaluated with the coefficient of determination (R^2), the root-mean-square error (RMSE), the percentage RMSE (RMSE%) and the bias, according to the following formula:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{TS}-X_{HLS})^2}{n}} \qquad (2)$$

$$RMSE(\%) = \frac{RMSE}{\bar{X}} * 100 \qquad (3)$$

$$bias = \frac{\sum_{i=1}^{n}(X_{TS}-X_{HLS})}{n} \qquad (4)$$

Where n = number of trees resulting from the traditional survey (TS),
XTS = value of the tree attribute measured in TS,
XHLS = estimated value of the attribute for each i-th tree via HLS scan,
$\bar{X}$= the mean of the reference data (values fr theom traditional survey).

Moreover, in several cases study R^2 has been applied in the phase of determination of the ipsometric curves in dendrometric surveys in order to evaluate the variability of the data valuing the structural development of the plants under consideration. The determination of this statistical index allows the ipsometric curve to choose the volume of the topsoil estimated that corresponds to the right combination diameter-height (Hellrigl, 1986).

2.7. 3D model restitution of sampled tree

In the case study VI, three volumetric estimation methodologies were applied with the aim to obtain a better structural and architectural analysis of the canopy of the sampled trees. Different digital 3D modeling platforms and softwares used are:

- TREESQM (MatLab package),
- Vox R (R package),
- Screened Poisson Surface Reconstruction - SPSR (Meshlab).

The first methodology mentioned concerns the TREESQM modeling methodology widely used in many LIDAR TLS data modeling cases studies, MatLab package (Raumonen *et al.* 2013, Calders *et al.* 2015, Raumonen *et al.* 2015, De Tanago *et al.* 2018, Ducup *et al.* 2021). It is a modeling method that reconstructs quantitative structure models (QSMs) for trees from point clouds. A QSM consists of a hierarchical collection of cylinders that estimate the topological, geometrical, and volumetric details of the tree's woody structure. It is a model of the tree's woody structure that quantitatively describes its basic (branching structure), geometrical and volumetric values. These include properties such as the number of branches in total and in any branching order, the parent-child relationships of branches and lengths, volumes and angles of individual branches, and branch size distributions. A QSM consists of building blocks, which are usually geometric primitives such as cylinders and cones. In this case, the circular cylinder is used, which is the most robust and (in most cases) very accurate choice for estimating the diameters, volumes, and angles of individual branches and branch size distributions.

The software works at least with MATLAB version R2022a 64-bit (Mac OS X). TreeQSM is free software (GNU General public license version 3), for other information about the softwares see table n1. Tables n. 17 and 18 illustrate the input parameters and MATLAB code commands applied for a single *Ficus macrophylla* subsp. *columnaris*.

Table n. 17 - MatLab Inputs structure parameters for Matlab TREESQM code applied for tree sampled LIDAR HLS Point Cloud for the case study VI.

Inputs structure parameters	
Tree	1
Model	1
PatchDiam1	0.08
BallRad1	0.095
PatchDiam1	0.08
PatchDiam2Min	0.02
PatchDiam2Max	0.07
BallRad2	0.08
Tria	0
OnlyTree	1
Tria	0
Dist	1
MinCylRad	0.0025
ParentCor	1
TaperCor	1
GrowthVolCor	0
GrowthVolFac	1.5
filter.k	10
filter.radius	0
filter.nsigma	1.5
filter.PatchDiam1	0.05
filter.BallRad1	0.075
filter.ncomp	2
filter.EdgeLength	0.004
filter.plot	1

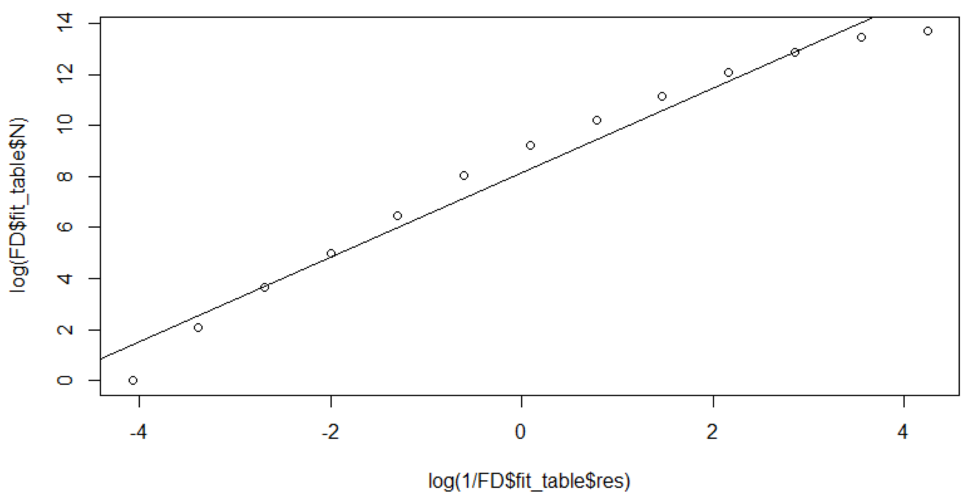
Table n. 18 - Matlab TREESQM code commands applied for tree sampled LIDAR HLS Point Cloud for the case study VI.

Mean commands applied in MatLab TREESQM code procedure
lasReader ()
ptCloud.Location ()
P-mean ()
define_input ()
define_cover set ()
treeqsm ()

The R called "VoxR" package assumes that a voxel can be understood as a portion of space explored by the tree (i.e., containing at least an arbitrary number of TLS LIDAR points). The size of the voxel should not be defined as a function of physical or computational considerations and is therefore guided only by the quality of the data. This allows the volumetric nature of voxels to be exploited to compensate for the discontinuity of the point cloud caused by occlusion (Béland *et al.* 2014, R Core Team, 2020).

Multiple metrics derived from TLS data describe how a tree occupies three-dimensional space, both quantitatively by estimating the volume of space explored by the tree and qualitatively, for example by locating biomass within a canopy (Lecigne *et al.*, 2018).

Inside of this package R the volume is computed as the volume of a 3D convex hull that wraps the point cloud. The software needs R software version 2022 64-bit. It is a free package R for LIDAR TLS data analysis. Other information about the R package "VoxR" are summarized in table n1. Is it possible to observe formulas and coefficient values used for the estimation of Volume from "VoxR" in Figure n. 28.




```
> FD$fractal_dim
[1] 1.653775
> FD$fit_summary

Call:
lm(formula = log(temp$N) ~ log(1/temp$res))

Residuals:
    Min      1Q  Median      3Q     Max 
-1.4940 -0.4870  0.1108  0.5715  0.9082 

Coefficients:
                Estimate Std. Error t value Pr(>|t|)    
(Intercept)      8.16195    0.23186   35.20 1.17e-12 ***
log(1/temp$res)  1.65377    0.08936   18.51 1.23e-09 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.8356 on 11 degrees of freedom
Multiple R-squared:  0.9689,	Adjusted R-squared:  0.9661 
F-statistic: 342.5 on 1 and 11 DF,  p-value: 1.226e-09
```

Figure n.28 - formulas and coefficient values, with "box counting" plot, used for the estimation of Volume from "VoxR" code for the case study VI.

Poisson’s surface reconstruction on MeshLab is one of the algorithms used to generate 3D surfaces from dense point clouds obtained using digital images of the elements. Poisson Screened Poisson’s surface reconstruction algorithm is currently the best method for reconstructing triangulated geometries starting from point clouds (+ normal) or 3D models. The Poisson surface reconstruction method (Kazhdan *et al.*, 2006) formulates a Poisson equation to find the best surface fit for a dense point cloud.

SPSR assumes that both the position of the points and the normal vectors of the surface of the reconstructed object are known. In Poisson’s original reconstruction approach (Kazhdan *et al.,* 2006), all points of a point cloud were used to extract the reconstructed surface. Kazhdan and Hoppe (2013) extended the Poisson surface reconstruction technique, incorporating sample weight values assigned for interpolation of missing points (Kazhdan and Hoppe, 2013). Li *et al.* (2010) proposed an improvement of Poisson’s reconstruction algorithm. "Octree depth", a useful parameter during the reconstruction of the surface of Poisson, plays a fundamental role in the generation of surfaces from clouds of dense points. Increasing the value of the parameter results in a high-resolution 3D mesh, thereby improving the overall surface quality (Li *et al.,* 2010).

The "Samples per node" parameter is another important parameter that affects the quality of the 3D surface generated with the Poisson reconstruction algorithm. Increasing the value of this parameter adds more 3D points. Thanks to these parameters the clouds of noisy and low density points can be accurately reconstructed using higher values of samples per node (Kazhdan and Hoppe, 2013; Maiti and Chakravarty, 2016). The software works at least with MeshLab open source software version 2022 to 64-bit. An image of point Cloud LIDAR data representation from the graphical user interface of MeshLab is presented in Figure n. 29.

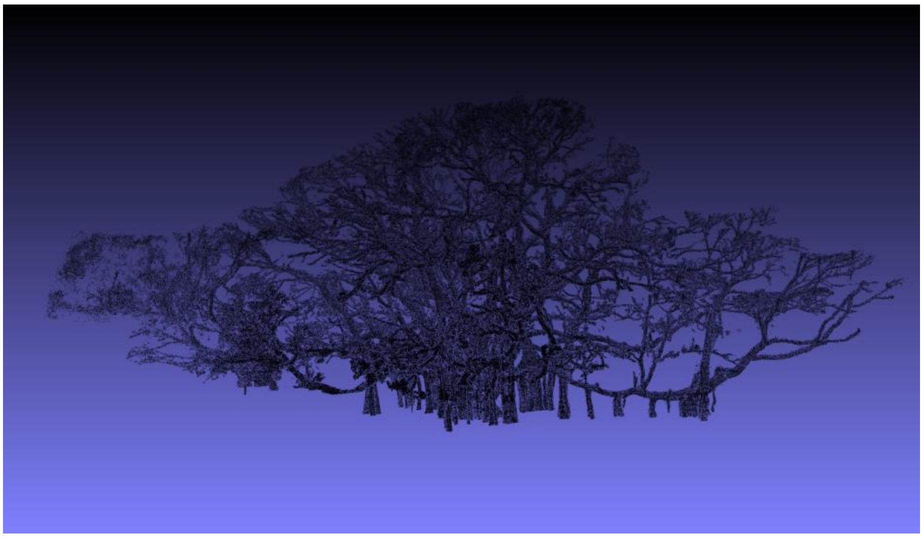


Figure n.29 - a Point Cloud representation from the graphical user interface of MeshLab.

3. RESULTS AND DISCUSSIONS

3.1. Strengths and Weaknesses of the mobile LIDAR system in the forest company

3.1.1. The case study I: Investigation of HLS LIDAR scanning efficiency in several plots of high forest (Alpe di Catenaia, Tuscany, Italy)

Within the study area of Alpe di Catenaia with its 15 forest test plots it was possible to analyze the efficiency of the LIDAR HLS technology comparing with the survey method with traditional tools. The dominant species of test plots were silver fir (*Abies alba*), Douglas fir (*Pseudotsuga menziesii*), black pine (*Pinus nigra*), Turkey oak (*Quercus cerris*) and Beech (*Fagus sylvatica*). It is possible to see the 3D representations of the HLS relief in Figure n. 30 (a), 30(b), 30 (c), 30(d) and 30(e).

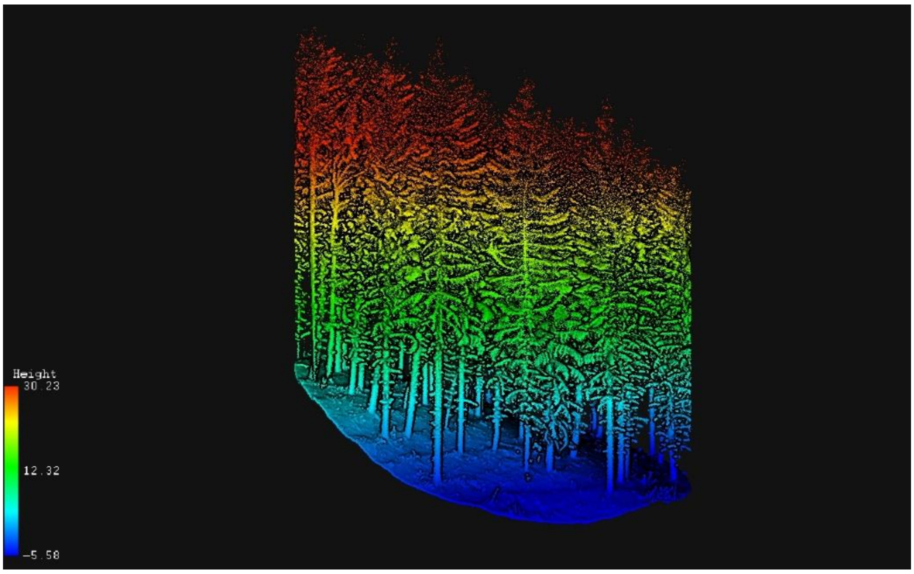


Figure n. 30 (a) - a Point Cloud representation of sampled Forest stands from the graphical user interface of LIDAR360 for the case study I in the *Abies alba* Plot.

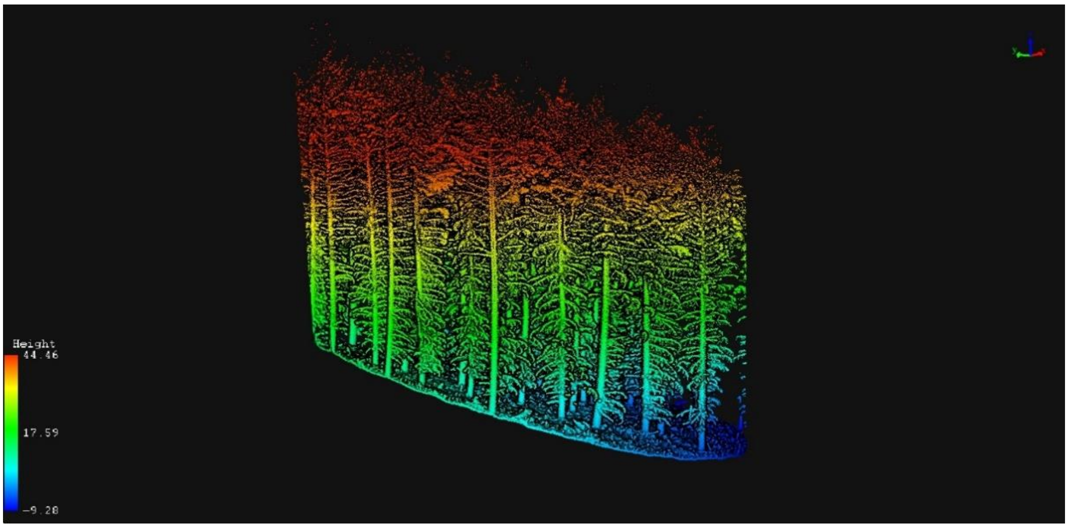


Figure n. 30 (b) - a Point Cloud representation of sampled Forest stands from the graphical user interface of LIDAR360 for the case study I in the *Pseudotsuga menziesii* plot.

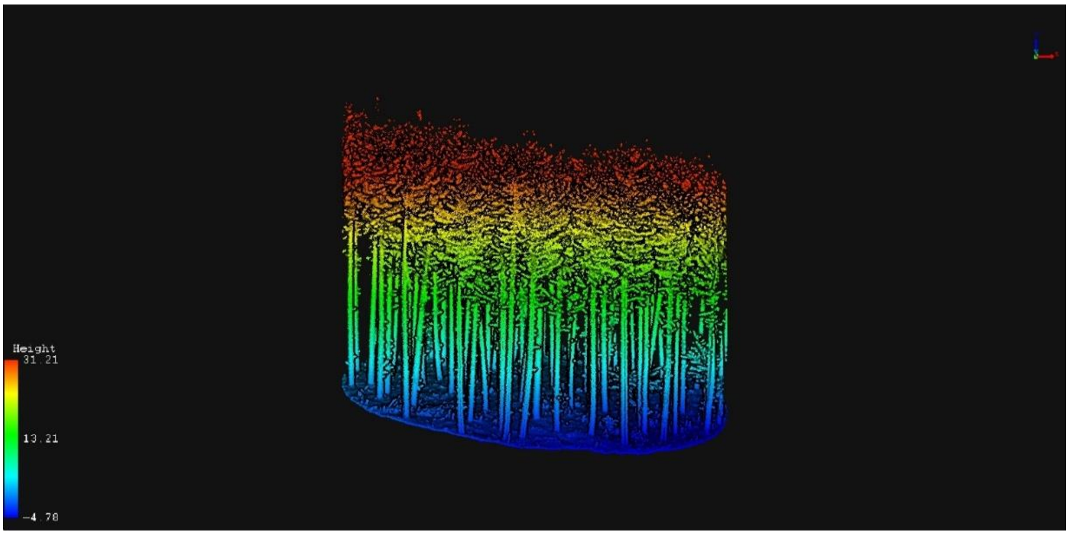


Figure n. 30 (c) - a Point Cloud representation of sampled Forest stands from the graphical user interface of LIDAR360 for the case study I in the *Pinus nigra* plot.

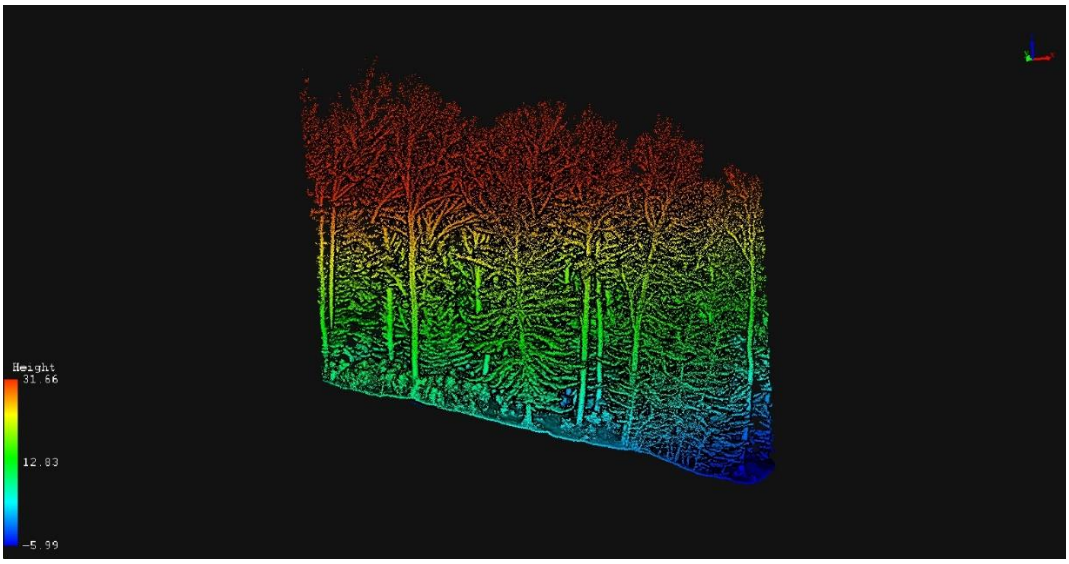
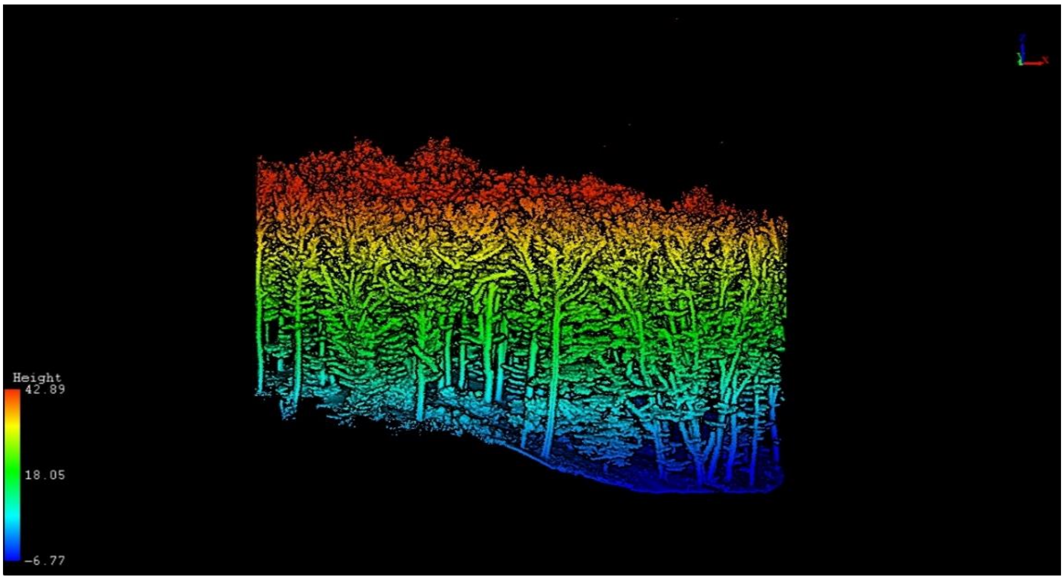


Figure n. 30 (d) - a Point Cloud representation of sampled Forest stands from the graphical user interface of LIDAR360 for the case study I in the *Quercus cerris* plot.



(e)

Figure n. 30 (e) - a Point Cloud representation of sampled Forest stands from the graphical user interface of LIDAR360 for the case study I in the *Fagus sylvatica* plot.

The table n. 19 presents a summary of data from all individual circular test plots (PLOT ID) for hectare. For each test plot, dendrometric informations were taken through two types of survey: Traditional Survey (conducted using traditional instruments such as tree gauge and hypsometer) and Hand-Held Laser Scanner Survey. Data obtained from the comparison is essential to understand the real state of the forest and they are necessary to draw up a forest management plan. From the reported results there is no significant difference between the two survey methodologies (traditional and HLS LIDAR scanning).

The table n. 20 shows the accuracy of the individual attributes calculated from the Traditional Survey (TS) and the innovative Hand-held Laser Scanner survey (HLSS) in every test plot. Accuracies of individual attribute estimations were gauged using R-squared (R^2), root-mean-square error (RMSE) and relative bias. With regards to DBH, the coefficient of determination across all plots was higher than 0.96 revealing a robust correlation between the HLS LIDAR scans and the reference data from the traditional surveys. The RMSE was 3.52 and the bias was 2.40. For H, the coefficient of determination across all broadleaf plots with an additional 0.20 with the RMSE e bias values of 4.52 and 1.09. While in the case of conifer plots was other 0.58 with the RMSE and bias values of 3.45 and -0.83.

Table n. 19 - Number of trees -N (n. tree/ha), Total volume - Vtot (m^3/ha), Basal Area - G (m^2 /ha) estimated by traditional surveys and HLS scans of all plots for the case study I.

		Plot ID														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
N (n. tree/ha)	**TS**	772	669	517	1004	270	955	517	509	493	366	509	533	366	629	613
	HLSS	1146	708	716	1089	311	836	541	462	852	557	637	653	414	661	629
Vtot (m^3/ha)	**TS**	775	501	911	742	781	343	464	340	380	306	393	467	454	393	834
	HLSS	508	397	729	606	661	274	375	356	433	222	332	385	426	345	596
G (m^2 /ha)	**TS**	61	43	63	61	52	29	35	26	37	26	35	40	38	37	68
	HLSS	46	37	54	51	42	26	29	29	40	21	31	31	34	30	53

HLSS: Handheld Laser Scanner Survey, TS: Traditional Survey.

Table n. 20 - Summary statistics of single-tree attributes (DBH and H) computed by traditional survey and HLS scans for the case study I.

		Plot ID														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
DBH	**R^2**	0.98	0.95	0.95	1.00	0.98	0.99	0.95	0.98	0.95	0.98	0.90	0.97	0.97	0.90	0.98
(cm)	**RMSE**	4.62	3.99	4.02	2.91	4.79	2.49	4.19	1.97	2.86	3.96	3.52	4.62	3.39	3.31	2.15
	RMSE%	15.05	15.45	10.55	10.83	10.10	15.07	15.17	7.69	10.52	14.02	12.61	15.55	9.58	12.44	5.58
	bias	4.36	2.94	3.31	2.41	4.26	-0.29	2.85	0.09	-1.17	3.59	2.47	3.83	3.16	2.30	1.90
H	**R^2**	0.31	0.80	0.50	0.99	0.56	0.61	0.47	0.51	0.28	0.51	0.00	0.02	0.01	0.16	0.06
(m)	**RMSE**	5.24	4.13	5.85	2.18	2.49	6.28	4.38	5.65	2.11	3.31	4.30	4.04	4.43	3.27	2.74
	RMSE%	18.53	18.99	20.38	8.95	7.21	37.79	18.40	26.80	9.59	14.62	20.77	17.85	19.09	15.85	10.91
	bias	3.58	1.93	2.52	0.39	-1.65	2.97	-0.36	-0.62	-0.29	1.66	-1.01	-3.29	-2.88	-2.23	2.18

It is possible to observe the evolution of the relationship between diameter and height for each forest species examined through the ipsometric curves in Figures n.31(a), 31(b), 31 (c), 31(d), 31(e) and the frequency distributions in diameter classes of 5 cm in Figures n. 32(a), 32(b), 32(c), 32(d), 32(e).

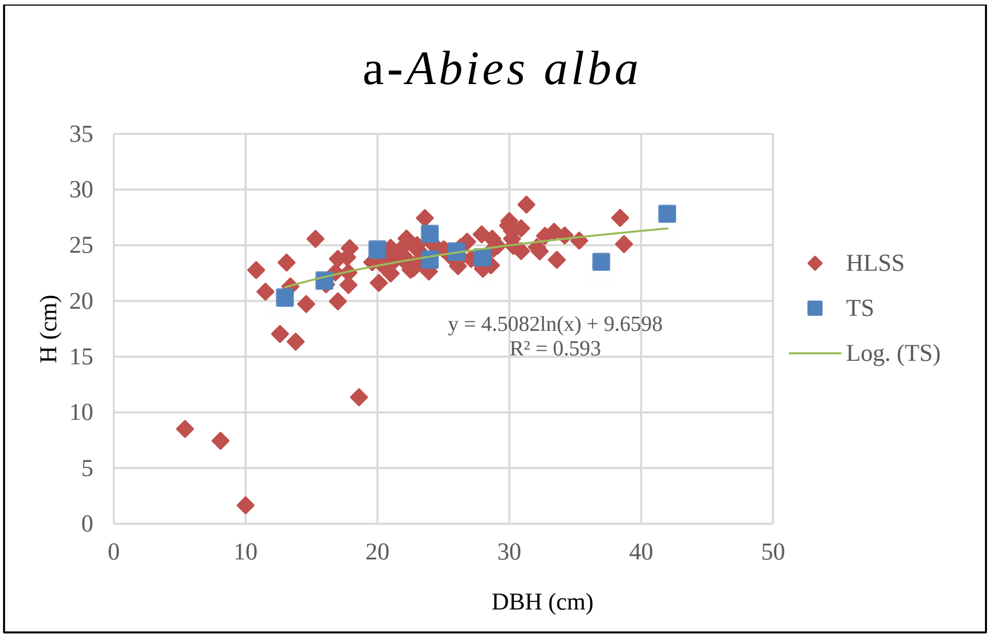


Figure n. 31 (a) - The hypsometric curve of *Abies alba* for the case study I, HLSS: Handheld Laser Scanner Survey, TS: Traditional Survey.

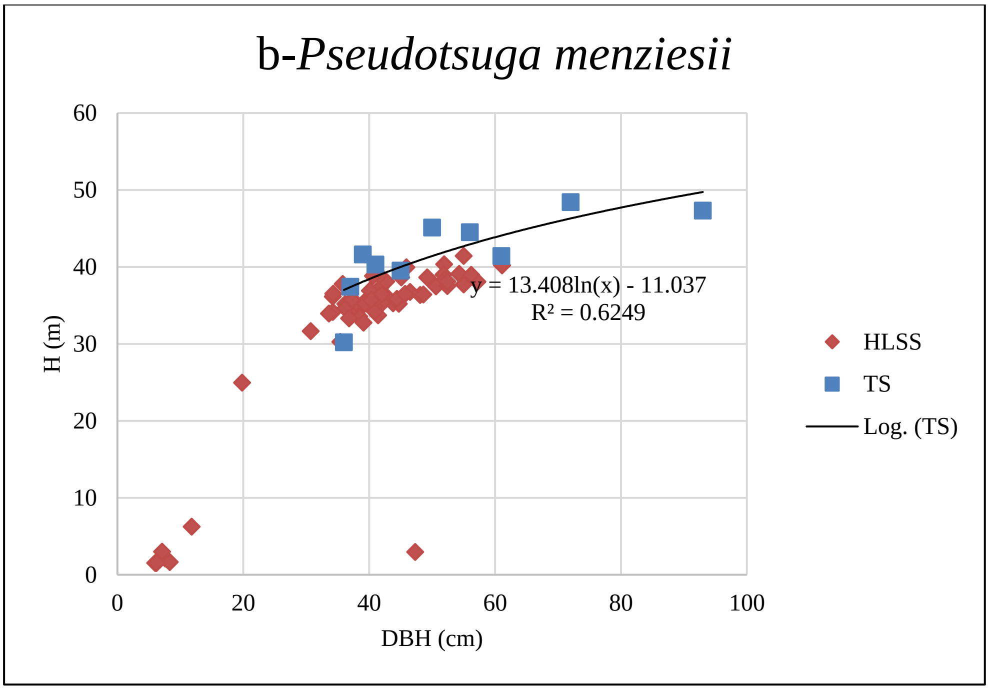


Figure n. 31 (b) - The hypsometric curve of *Pseudotsuga menziesii* for the case study I, HLSS: Handheld Laser Scanner Survey, TS: Traditional Survey.

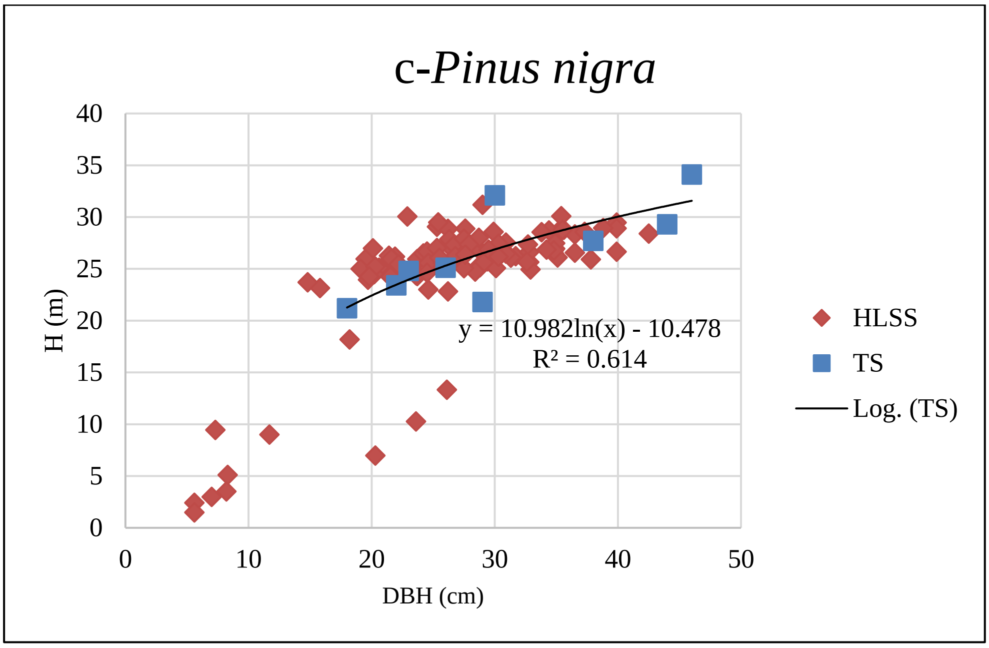


Figure n. 31(c) - The hypsometric curve of *Pinus nigra* for the case study I, HLSS: Handheld Laser Scanner Survey, TS: Traditional Survey.

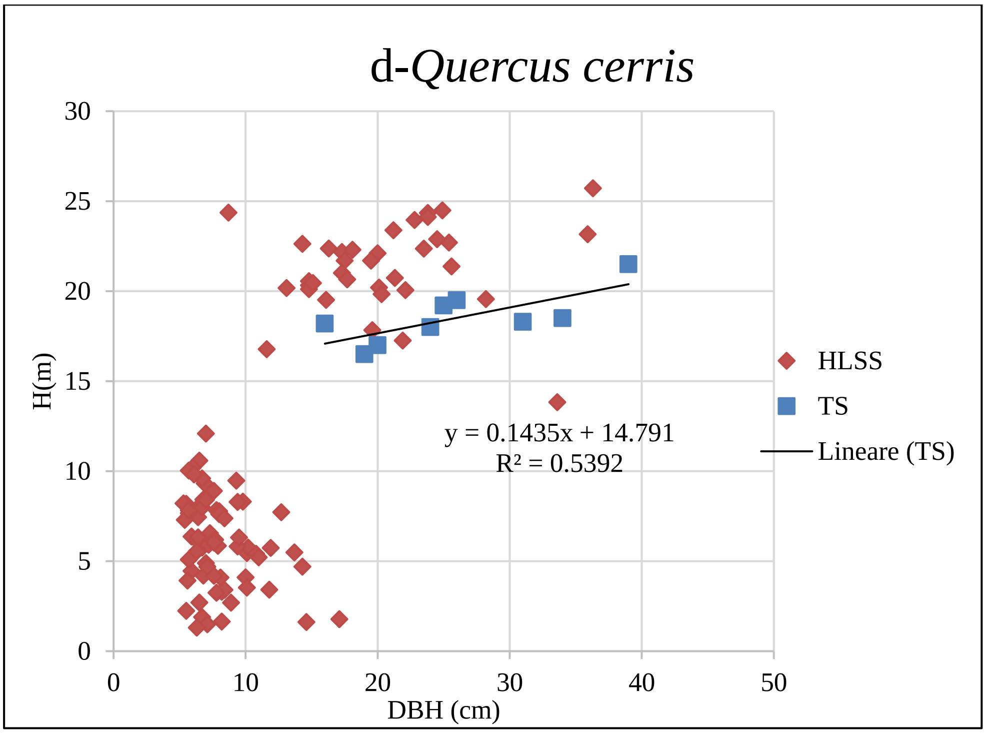


Figure n. 31(d) - The hypsometric curve of *Quercus cerris*, for the case study I, HLSS: Handheld Laser Scanner Survey, TS: Traditional Survey.

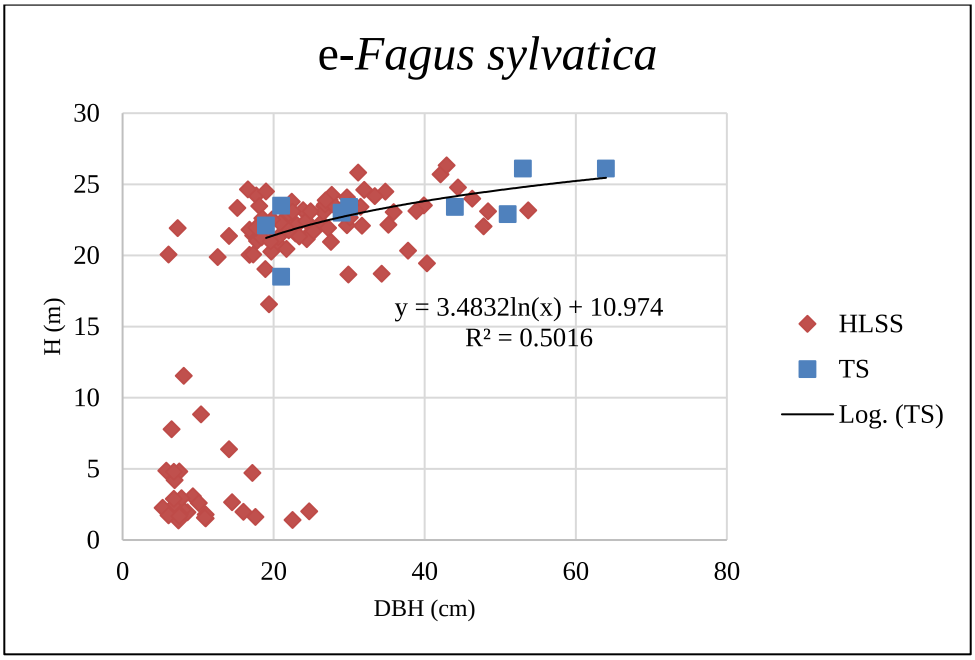


Figure n. 31(e) - The hypsometric curve of *Fagus sylvatica* for the case study I, HLSS: Handheld Laser Scanner Survey, TS: Traditional Survey.

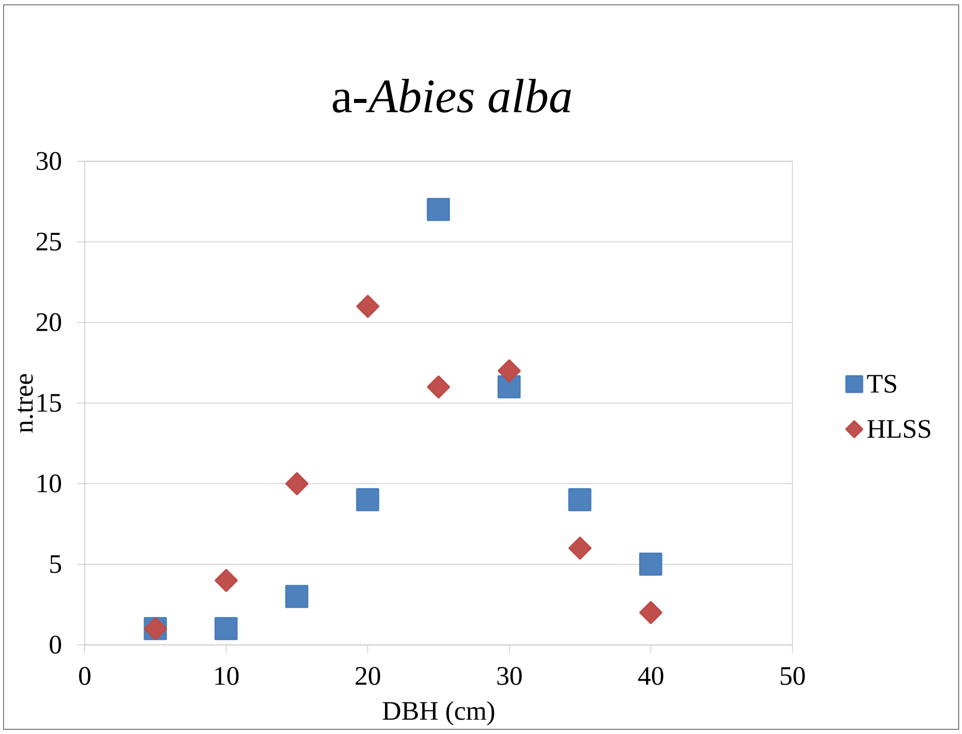


Figure n. 32 (a) - The frequency distributions in diameter classes of *Abies alba* plot for the case study I, HLSS: Handheld Laser Scanner Survey, TS: Traditional Survey.

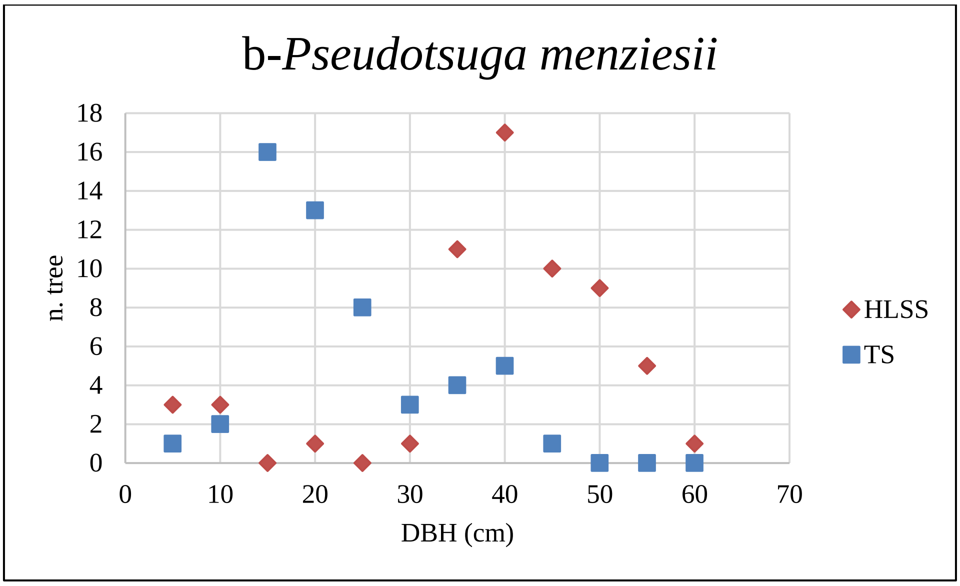


Figure n. 32 (b) - The frequency distributions in diameter classes of *Pseudotsuga menziesii* plots for the case study I, HLSS: Handheld Laser Scanner Survey, TS: Traditional Survey.

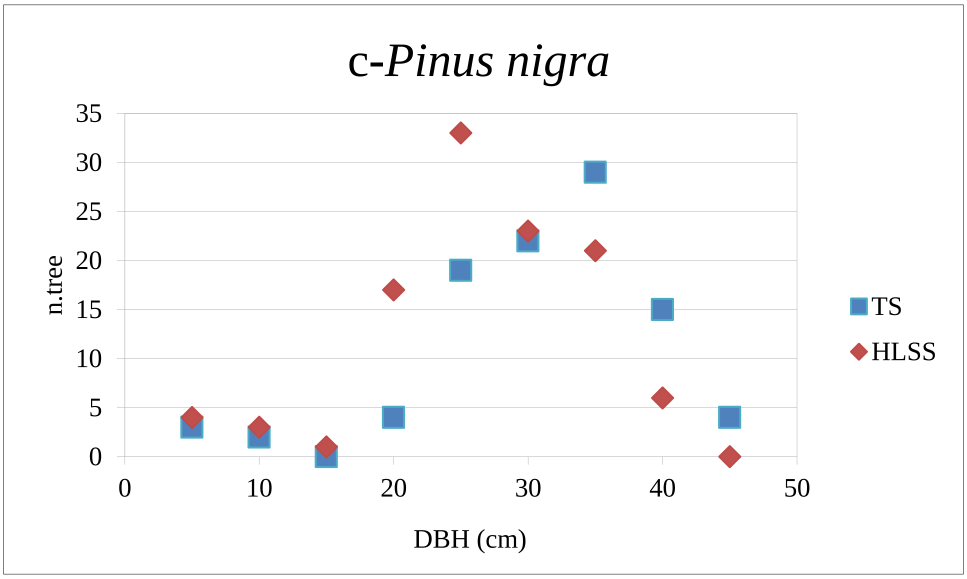


Figure n. 32 (c) - The frequency distributions in diameter classes of *Pinus nigra* plots for the case study I, HLSS: Handheld Laser Scanner Survey, TS: Traditional Survey.

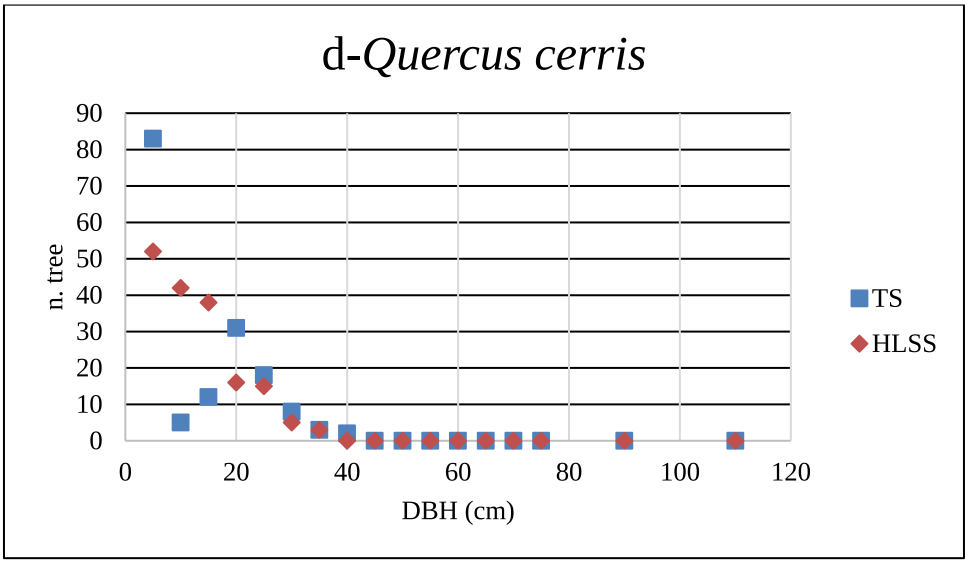


Figure n. 32 (d) - The frequency distributions in diameter classes of *Quercus cerris* plots for the case study I, HLSS: Handheld Laser Scanner Survey, TS: Traditional Survey.

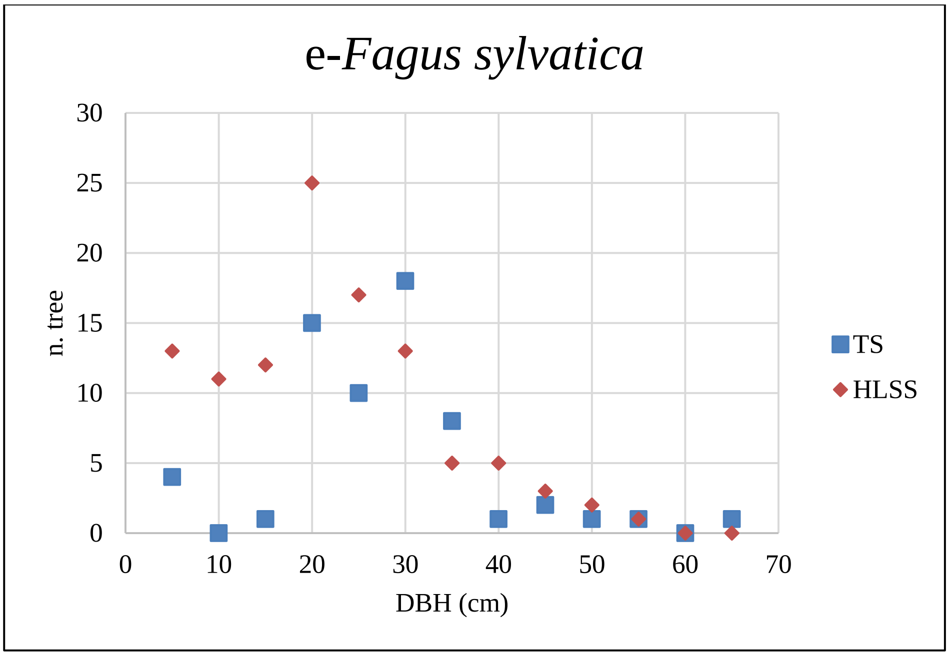


Figure n. 32 (e) - The frequency distributions in diameter classes of *Fagus sylvatica* plots for the case study I, HLSS: Handheld Laser Scanner Survey, TS: Traditional Survey.

In our results it was possible to witness the variability of the results showing the differences only with two different forest plots, belonging to the categories Broadleaf and conifer as plot n. 6-Silver Fir and plot n. 13-Beech. In case of *Abies alba*, there is a value of RMSE di 2.91 cm (DBH) and 2.17 m (H) and a value of the bias of 2.41 cm (DBH) and 0.38 m (T) for scans data and field data, see the Figures n. 33(a) and 33(b). The DBH assessment provided good results compared to field data.

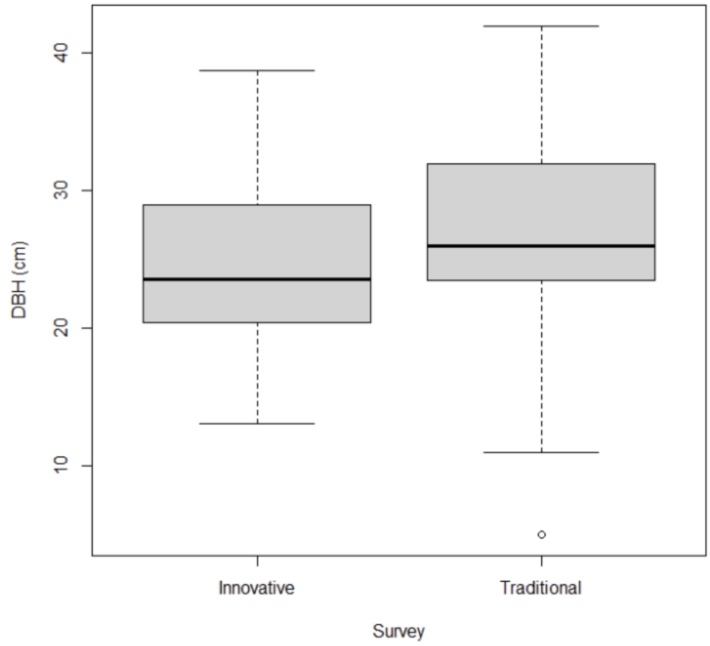
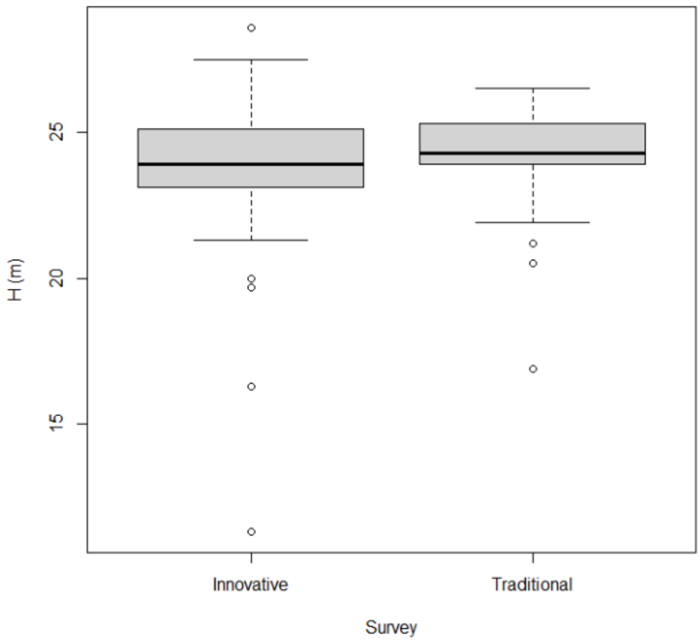


Figure n. 33 (a) - The Boxplots of values of DBH (a) of plot 6-*Abies alba* Forest on the case study I (taken by Sofia *et al.*, 2021).



(b)

Figure n. 33 (b) -The Boxplots of values of H of plot 6-*Abies alba* Forest on the case study I (taken by Sofia *et al.*, 2021).

Regarding the results of beech forest plot, the RMSE of all plots of beech was 3.284 cm (DBH) and 4.071 m (H) and the bias was 1.8404 cm (DBH) and 0.4727 m (H) for scans data and field data, respectively, see Figures n. 34 (a) and 34(b).

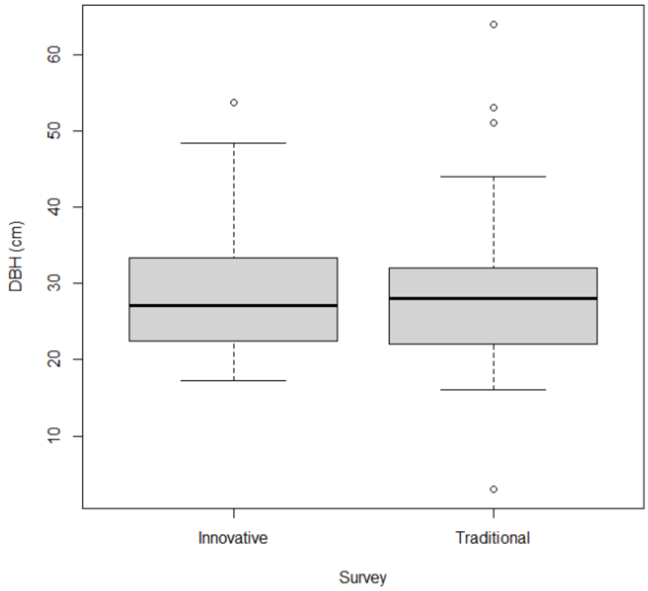
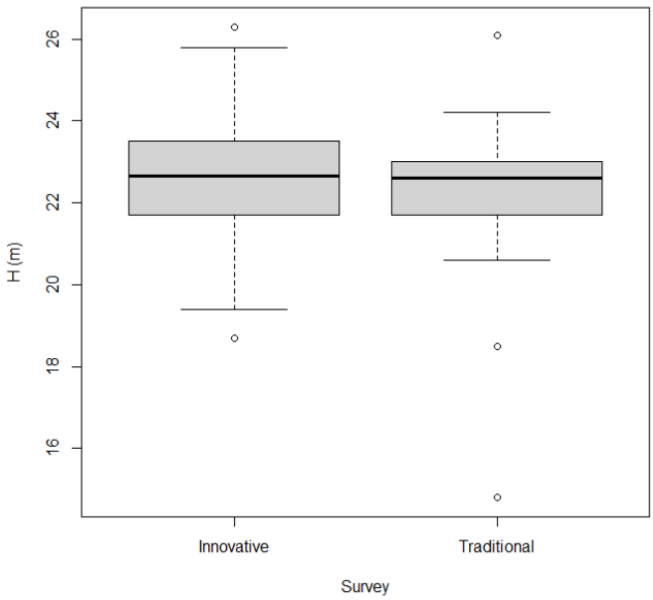


Figure n. 34(a) - The Boxplots of values of DBH (a) of plot 13-*Fagus sylvatica* forest on the case study I (taken by Sofia *et al.*, 2021).



(b)

Figure n. 34(b) - The Boxplots of values of H (b) of plot 13-*Fagus sylvatica* forest on the case study I (taken by Sofia *et al.*, 2021).

Our results are slightly higher to those reported by Giannetti *et al.* 2018 and Oveland *et al.* 2018 (Giannetti *et al.*, 2018; Oveland *et al.* 2018). These results show that an irregular structure of stem and more side branches of different trees can compromise the extraction of dendrometric values through the automatic algorithms. Another obstacle met during the extraction of DBH is related to the complexity of ecosystems featured by multiple layers in the forest structure and a significant presence of shrub vegetation under the canopy of dominant tree species or the presence of ivy (*Hedera sp.*) around the trunk obtnaning larger errors in the final DBH results.

These results show that HLS system can produce an accurate structural forest attributes estimation in the coniferous sampling plots due to the simple linear structure (i. e. straight form of timber, few branches, absence of understory, etc.) of this forest ecosystem. While in the case of broadleaf stands the presence of dense vegetation layers and multilayer structure hinder the achievement of low values of RMSE and bias.

The methodology applied in the Handheld laser scanner survey enabled the estimation of forest stand volumes with an acceptable error, rendering it suitable for planning purposes. It was possible to witness our results through the publication of two scientific articles in 2021 and 2022 (Sofia *et al.*, 2021; Sofia *et al.*, 2022).

In the article of Sofia *et al.*, 2022, it was possible to carry out an analysis SWOT, following key points of the potential of HLS tools compared to the traditional survey method in forest ecosystems. One of the objectives of this article is to emphasize the main differences from traditional tools and to create dialogues and future reflections for forest owners who wish to approach technological innovation in their professional careers. This SWOT analysis is presented in Table n. 21. The SWOT analysis confirms that the Handheld laser scanner survey method improves survey productivity by producing acceptable results in a short time and with high measurement accuracy. Additionally, obtaining enhanced tree information (position, diameter, height, canopy cover density, tree trunk profile, vegetation volume estimation, leaf area index, leaf area density) within 50–100 m of laser scanning is made possible. However, the primary limitation of the HLS method concerns the technical skills necessary to extrapolate dendrometric data from HLS survey output data using specific software. Another technical disadvantage is that the laser detects everything in the survey area without distinguishing objects other than plants and tree elements (Sofia *et al.*, 2022).

Table n. 21 - SWOT analysis between a Traditional and Handheld Laser Scanner Survey on the case study I (taken from Sofia *et al.*, 2022).

Strength	
Traditional Survey	**Handheld Laser Scanner Survey**
– Quality analysis of the forest by the operator in the field. – Visual investigation of the structural criticalities of the trees – Result obtained after carrying out the field survey.	– High amount of dendrometric and volumetric data within 50-100 metres of laser scanning. – Reduced cost of the survey compared to traditional surveys. – Reduced time required for laser scanning in the forestcompared to traditional surveys.
Weaknesses	
Traditional Survey	**Handheld Laser Scanner Survey**
– Longer surveying time. – Higher cost for the number of staff to be employed. – Higher number of staff employed for surveying.	– Difficulties in surveying stands with large, intersecting canopys during vegetation periods (broadleaf stands); – Technical complexity in extrapolating dendrometric data from the LIDAR survey output using specific software; – Non-recognition of forest specie.
Opportunities	
Traditional Survey	**Handheld Laser Scanner Survey**
– Performing dendrometric surveys in the field at any time of the year – Available data used immediately for decisions in management plans.	– Better information (position, diameter, height, canopy cover area , tree trunk profile) that can be used for decision making in management plans.
Threats	
Traditional Survey	**Handheld Laser Scanner Survey**
– Presence of fog and humidity at the survey site. – High presence of falling trees considered dangerous to the safety of foresters in survey area.	– Presence of fog or moisture at the site of the survey. – Forest areas with dense vegetation in the dominated layer.

3.1.2. **The applicability/versatility of the LIDAR HLS tool for sustainable forest management applications**

3.1.3. <u>The case study II: Benefit analysis of LIDAR HLS survey based on different types of walking paths (Camaldoli, Tuscany, Ficuzza, Sicily, Italy)</u>

This present study investigates the ideal walking path to follow during HLS scanning to survey trees and estimate the biometric parameters of forest stands by testing three distinct schemes in the literature performed in the same survey area differentiating the study areas by slope, no. of trees, and different tree dendrometric values. Specifically, two different forest ecosystems are considered in experimental HLS LIDAR surveys, a beech-dominated deciduous forest and an oak-dominated deciduous forest. One sampled plot for each forest ecosystem is divided in 4 squares of 2500 m^2. There are 3D representations of high-resolution HLS relief data for the two different forest ecosystems shown in Figure n. 35.

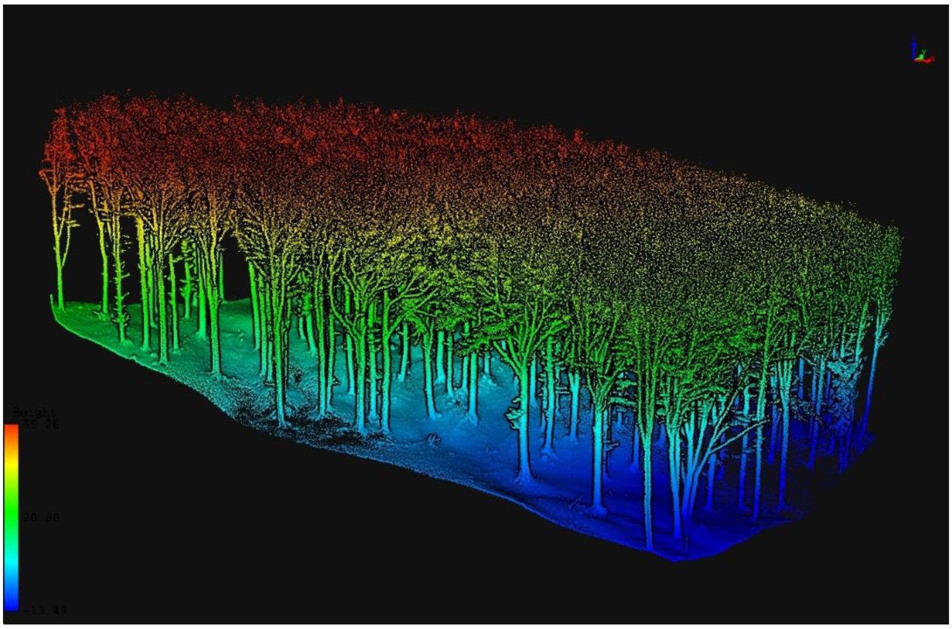


Figure n. 35 - a Point Cloud representation of each plot site on the graphical user interface of LIDAR360 for the case study II.

Table n. 22 shows the results of the accuracy of the individual attributes for the study areas of beech forests located in Camaldoli (Tuscany) and table n. 23 for the study areas of *holm oak* forests located in Ficuzza (Sicily). In particular, we compared the accuracy values of the individual attributes from the traditional survey and the LIDAR HLS scans by calculating the R-squared (R^2), root-mean-square error (RMSE), and relative bias. A control analysis is also performed of the traditional method without LIDAR.

Table n. 22 - Summary statistics of single-tree attributes (DBH and H) computed by traditional survey and HLS scans in every test sample plot of the Camaldoli site (PLOT ID) on the case study II.

ID Plot	Path type	DBH (cm)				H (m)			
		RMSE (cm)	Bias (cm)	RMSE (%)	R^2	RMSE (m)	Bias (m)	RMSE (%)	R^2
C tot	Star	2.99	1.71	10	0.88	2.07	-0.82	10	0.59
	Grid	2.58	0.89	9	0.94	2.08	-1.04	10	0.57
	Border	2.97	0.93	10	0.87	1.83	-0.62	9	0.62
C1	Star	3.87	2.32	13	0.80	2.22	-1.30	11	0.11
	Grid	3.35	1.81	12	0.72	1.90	-0.89	9	0.15
	Border	2.70	1.12	9	0.86	1.65	-0.60	8	0.21
C2	Star	2.48	1.69	8	0.91	1.84	-0.88	9	0.69
	Grid	1.77	0.71	6	0.93	1.91	-0.86	9	0.63
	Border	2.39	0.65	8	0.90	1.92	-0.39	9	0.57
C3	Star	1.97	1.02	6	0.93	2.14	-0.94	10	0.73
	Grid	2.28	1.13	7	0.92	2.27	-0.99	10	0.72
	Border	2.95	0.92	10	0.90	2.20	-1.00	10	0.73
C4	Star	2.96	1.69	10	0.88	1.69	-0.56	8	0.67
	Grid	2.75	-0.24	9	0.88	2.31	-1.56	10	0.57
	Border	4.10	0.82	14	0.75	1.75	-0.38	8	0.56

Table n. 23 - Summary statistics of single-tree attributes (DBH and H) computed by traditional survey and HLS scans in every test sample plot of the Ficuzza site (PLOT ID) on the case study II.

ID Plot	Path type	DBH (cm)				H (m)			
		RMSE (cm)	Bias (cm)	RMSE (%)	R^2	RMSE (m)	Bias (m)	RMSE (%)	R^2
F tot	Star	3.16	0.56	11	0.75	2.25	-0.06	16	0.26
	Grid	3.59	0.26	12	0.71	2.26	-0.07	16	0.34
	Border	3.63	0.01	13	0.68	2.10	-0.28	15	0.29
F1	Star	2.40	0.60	9	0.80	1.90	-0.60	14	0.34
	Grid	3.54	-0.10	12	0.64	1.89	-0.56	14	0.32
	Border	3.89	-0.21	14	0.66	1.84	-0.42	14	0.41
F2	Star	3.62	0.50	12	0.68	2.36	0.35	17	0.13
	Grid	3.95	0.18	13	0.60	2.21	-0.50	16	0.08
	Border	3.70	0.51	13	0.69	2.07	0.19	15	0.20
F3	Star	2.88	0.58	10	0.82	2.25	-0.06	15	0.45
	Grid	3.00	0.45	10	0.80	2.01	-0.16	14	0.58
	Border	4.02	-0.26	14	0.65	2.62	-0.53	18	0.11
F4	Star	3.61	0.53	13	0.61	2.49	0.17	19	0.02
	Grid	3.80	0.05	14	0.59	2.24	-0.15	17	0.02
	Border	3.11	0.11	11	0.73	1.89	-0.43	14	0.39

Our tests show high variability of results in the different sampling areas and a general tendency to obtain higher values of each variable with the HLS scan path schemes than with the values calculated with the traditional method.

In the case of the beech forests to Camaldoli, for the estimation of DBH values, considering the simplest walk path scheme (BORDER) and the plot site with a high slope (C4 plot site with 48% slope) the coefficient of determination was higher than 0.75, with the RMSE of 4.1 and the bias of 0.82. With the same walking path scheme, applied to the plot site with a high number of trees (C1 with 205 trees/ha) the coefficient of determination was higher than 0.86, with The RMSE of 2.70 and the bias of 1.12. For the most complex walking path scheme (GRID) in the plot site (C2) with the lowest n. trees (138 trees/ha) and slope (16%) the coefficient of determination was higher than 0.93, with The RMSE of 1.77 and bias of 0.71. However, a good level of fit between the HLS scan and the reference data is shown considering the STAR walking path scheme especially in the more complex plot site same C4 (high slope and no. trees/ha). His coefficient of determination was 0.88 with the RMSE of 2.96 and bias of 1.69. The walking path scheme STAR is a good LIDAR survey scheme in forest ecosystems because the amount of error in measurements (3 cm in RMSE of DBH, shown in Table n. 21) is an acceptable value in forest planning. Considering the results of H accuracy, the walking path STAR scheme is efficient in almost all plot sites in beech forests. For example, in the case of the most complex plot site (C4 with 48% slope), a determination coefficient value of 0.67 was obtained with an RMSE of 1.69 and a bias of -0.56, while in the simplest plot site for LIDAR scanning (C2), the determination coefficient was 0.69, with an RMSE of 1.84 and a bias of -0.88, proving to be suitable for height determination. As far as the survey areas in Ficuzza are concerned, characterized by holm oak forests with an abundance of shrubs, the results change. In the case of the determination of the DBH, the results of the accuracy of the survey with the BORDER walking path scheme in the plot site (F3), which is more complex due to the no. of trees/ha (135) and the slope (20%), the coefficient of determination values of 0.65, with RMSE of 4.02 and bias of -0.26 were obtained. In the opposite case, the results of the survey accuracy with the GRID walking path scheme in the optimal plot site for the LIDAR surveys (F4) with lower n. of trees/ha (115) and low slope (10%) resulted in a R^2 of 0.59, with a RMSE of 3.80 and bias of 0.05. However, it is possible to note in all the plots of the Ficuzza survey area, that the STAR walking path scheme is acceptable for measuring the diameters by presenting an average value of the coefficient of determination of 0.75 with an average RMSE of 3.16 and bias 0.56 and, even in this case, obtained in short times compared to the times performed in the case of the GRID walking path scheme, shown in Table n. 22.

For the determination of the heights, lower than expected R^2 values resulted in all plots, with RMSE values on the two m difference compared to the reference values obtained from the traditional surveys. In particular, it is possible to observe in plot site F3 (no. of trees/ha 135 and slope 20%) that the BORDER walking path scheme is not so reliable for heights, also because to have a more complete three-dimensional geometric representation of the tree, it would be advisable to carry out a survey that covers at least all the angles of the object under examination. A better value was obtained adopting the walking path GRID on the same plot site. The reference value for comparison could also be incorrect, as traditional measurements carry errors related to the field experience of the forester. This means the presence of an overall lower accuracy value. This could be one motivation. A second motivation is also the reliability of the segmentation algorithm within the identified software, which might not be suitable for the optimal extraction of these dendrometric parameters for determining heights. Algorithms are often constructed from databases of data derived from forest samples that are suitable for uniform forest environments and not inhomogeneous as in the case of Ficuzza, where the spatial distribution of several elements can affect the determination of the final data in LIDAR data processing. To testify to this data, it was possible to perform a bibliographic survey of LIDAR surveys in recent years carried out by the same type of LIDAR instrument. In the case of Gollob *et al.* (2020) in 20 circular plots of 20 m radius with a density of 126 n. trees/ha and a slope of 29% located within a broadleaved forest, an RMSE value of 2.32 is demonstrated with a random walking path scheme within the survey area. In the case of Tockner *et al.*, 2021, an RMSE value of 3.94 with a bias of -0.67 was found in mixed montane forest environments. Furthermore, for the investigation of the accuracy values for the determination of heights in this case study, the article was useful for obtaining a response from the bibliography as few were found, resulting in RMSE values for the determination of heights of 2.25 m with a bias of -0.92. More bibliographic comparison values can be found in Table n. 24.

Table n. 24 - The accuracy results of the ZEB-HORIZON HLS surveys for the survey of diameters and heights in recent years in the bibliography with some information on the forest study areas.

STUDY	**Species**	**Test plot**	**STEM Density**	**SLOPE**	**Number of reference tree**	**Reference (ground-truth) data**	**RMSE of DBH (cm)**	**Bias of DBH (cm)**	**DBH threshold (cm)**	**RMSE of H (m)**	**Bias of H(m)**	**H threshold (m)**
Hyyppä *et al*. (2020)	Pine, Spruce, Birch	2 plots (32×32 m)	410	0	42	TLS scanner database	1.3	–0.4	>5	1.4	–1.1	7–25
Gollob *et al*. (2020)	mixed forest	20 circular plots (r=20 m)	981	29%	126	Conventional field data	2.32	0.21	>5	-	-	-
Jurjević *et al*. (2021)	deciduous forest (*Quercus robur*)	6 plots (r=15 m)	305	2%	130	Conventional field data	-	-	-	1.11	0.45	9–33
Tockner *et al*. (2021)	Mixed forest	one plot area of 4.000 m²	870	-	235	Conventional field data	3.94	-0.67	-	2.25	-0.92	-
Gollob *et al*. (2021)	broadleaved, coniferous, mixed forest	21 plots (r=7m)	424	27.1%	20	Conventional field data	1.90	-0.04	>5	-	-	-
Ahola *et al*. (2021)	*Pinus sylvestris*	7 Scots pine trees	500	0%	7	Conventional field data	0.94 cm	− 0.47	>25	-	-	-

Regarding practical application, the resulting evaluation of field survey technology can help foresters integrate these techniques into their basic tool kit for forest planning and management processes. In the case of analysis of LIDAR walking path schemes from the production point of view it is possible to observe that in all the forest surveys in both forest environments (beech and holm oak forests) there is a 90% success rate of tree localization, in particular an average value of 93% success rate in the case of the STAR LIDAR walking path scheme, a higher value than the average values found in the other walking path schemes results. The individual comparison attributes of the LIDAR scanning results are present in Figure n. 36 in the case of beech forests (Camaldoli) and in Figure n. 37 in the case of oak forests (Ficuzza).

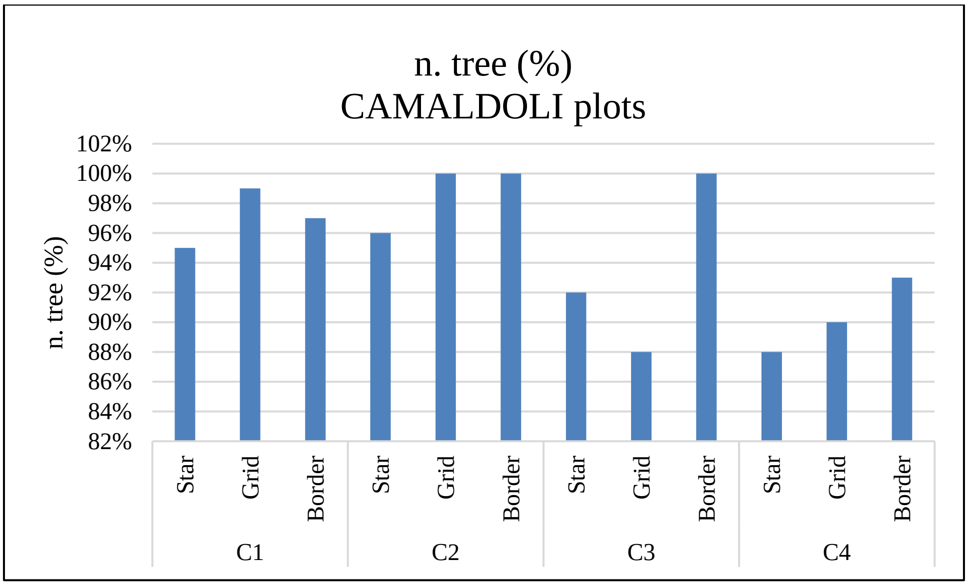


Figure n. 36 - the plot of rate n. tree localization (%) from all individual test plots of Camaldoli site, for the case study II.

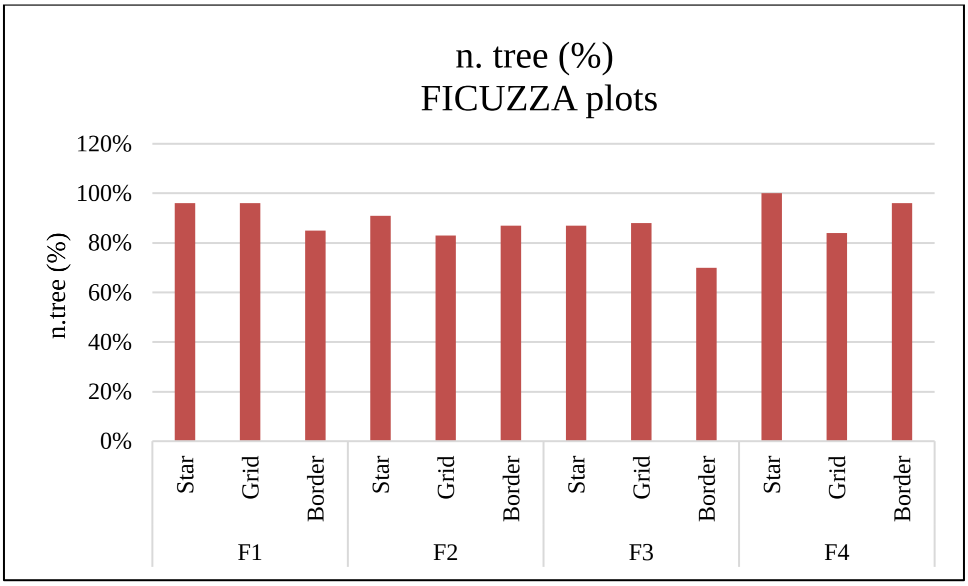


Figure n. 37 - the plot of rate n. tree localization (%) from all individual test plots of Ficuzza site, for the case study II.

If this data is accompanied by the accuracy data analyzed above, we can confirm that the data obtained from each individual LIDAR survey, regardless of the type of walking path schemes, can be reliable as supporting data for planning decisions. Considering the time taken to carry out the LIDAR survey in the field and to process the data in the laboratory, we find an average time value of 1 hour and 51 minutes, really a smaller time value compared to the classic traditional surveys (5 hours in the field for data collection and 20 minutes in the office for loading the data collected and estimating the dendrometric parameters). As seen in Table n. 25, we can state that the time spent and the staff employed for the first field survey (with LIDAR) are lower than for the second one, carried out with classical tools.

Table n. 25 - Scheme of working time and costs of innovative surveys with HLS surveys and traditional surveys in a Beech Forest (Camaldoli) and Oak Forest (Ficuzza) on the case study II.

PATH TYPE		CAMALDOLI Star	CAMALDOLI Grid	CAMALDOLI Border	FICUZZA Star	FICUZZA Grid	FICUZZA Border	TRADITIONAL SURVEY	
n. of personnel		1	1	1	1	1	1	2	
Working time (min)	Hand-held laser scanning time	12 min 18 sec	30 min 35 sec	7 min 8 sec	9 min 41 sec	18 min 20 sec	7 min 26 sec	Collection data time in field	5 h
	Data processing	1 h 42 min	2 h 25 min	1 h 13 min	1 h 38 min	1 h 58 min	1 h 3 min	Estimation of dendrometric values	20 min
	Total time (min)	1 h 54 min 18 sec	2 h 55 min 35 sec	1 h 20 min 8 sec	1 h 47 min 41 sec	2 h 16 min 20 sec	1 h 10 min 26 sec	5 h 20 min	
Job price (euro)	Hand-held laser scanning (1 person)	22,44 €	26,07 €	21,56 €	21,88 €	23,64 €	21,37 €	Hand-held laser scanning (2 people)	180 €
	Data processing (1 person)	28,33 €	45,00 €	22,67 €	27,67 €	31,67 €	20,67 €	Estimation of dendrometric values (1 person)	6.67 €
	Total Job Price (Euro)	50,77 €	71,07 €	44,23 €	49,55 €	55,31 €	42,04 €	186.67 €	

In order to explore the costs of classical and HLS surveys, we compared two surveying scenarios in the same areas, that differ in the available equipment, the first carried out with the HLS LIDAR instrumentation and the second carried out traditional surveys. In addition, we considered the national tariff schedule of forestry workers for cost estimation. The data collection time of the HLS survey included the time spent on automatic calibration at the beginning of data collection and automatic recording at the end. After the field data collection, a LIDAR data processing phase followed, in which the dendrometric parameters were extrapolated in the office. For the traditional method, this included determining the sample area and collecting the DBH and height of all trees within the sample area. Finally, the data were uploaded and processed in their final form, such as V/ha, G/ha, etc. In addition, we considered a staff of two people for the traditional survey and one for the innovative survey. Regarding the estimate of the cost of the surveys, it is specified that the amortization cost of the purchase of the equipment was not taken into account, but reference was made only to the net costs related to time of personnel employed. These two key factors drastically reduce the cost of carrying out forest surveys, resulting in an average difference in survey costs between the two scenarios of 72%. These data also result in time and cost differences, as witnessed in other articles such as Sofia *et al.* 2022. The main objective is to apply LIDAR technology in forest surveys in order to perform volumetric assays and follow the needs of the forester. Setting up a system of technologies in the field of forest surveys will help the forester to integrate these techniques among the basic instrumentation in the processes of forest planning and management.

3.1.4. The case study III: The fine-scale combustible matter classification in the context of the Mediterranean forest from HLS LIDAR data (Bosco Niscemi, Sicily, Italy)

This present study realized a specific quantitative classification of fuels and the preliminary description of the structural and spatial development of a local Mediterranean forest called "Bosco Niscemi" by LIDAR HLS surveys for the purposes of drafting fire prevention interventions. Specifically, the study area is considered in experimental HLS LIDAR surveys, an aged coppice forest with a predominance of holm oak characterized by an intensive presence of Shrub layer with local species of Mediterranean forest ecosystems into the city of Palermo. One sampled plot is divided into 16 squares of 4000 m^2. There are 3D representations of the HLS relief of the forest area investigated in Figure n. 38.

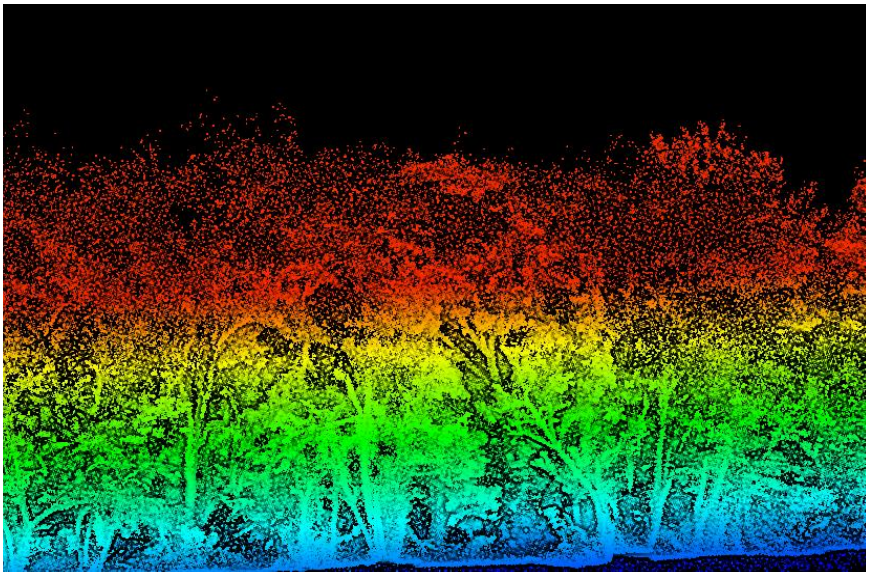


Figure n. 38 - a Point Cloud representation of plot site on the graphical user interface of LIDAR360 for the third case study.

The table n. 26 presents a summary of data from all individual squares test plots (PLOT ID) for hectare and the average values of DBH and H predominant in each plot. While, in figures n.39(a), 39(b), 39(c) and 39(d) presents the frequency distributions in diameter classes of 5 cm for each plot. Thanks to the results of LIDAR surveys in this particular Mediterranean contest It is possible to observe the evolution of multilayer forest structure characterized by a tangled relationship between different local Mediterranean shrub and tree species. In fact, is it possible to see an elevated value of n. tree/ha and an abundance presence of species with a range value of 10-15 cm of DBH in all plot sites. These pieces of information are essential to know the real state of the forest and necessary to draw up a forest management plan according to fire prevention interventions.

Table n. 26 - Number of trees -N (n. tree/ha), Basal Area - G (m^2 /ha), average DBH (DBHm), average H (Hm) estimated by HLS scans of all plots for the case study III.

Plot ID	N (n.tree/ha)	G (m^2/ha)	DBHm	Hm
Q1-1	6375	76.1	12.3	6.3
Q1-2	9158	55.1	8.8	5.3
Q1-3	2170	83.7	22.2	7.1
Q1-4	6653	65.7	11.2	6.1
Q2-1	8468	52.6	8.9	5.4
Q2-2	2400	100.6	23.1	6.3
Q2-3	5983	83.5	13.3	6.7
Q2-4	3690	100.96	18.66	5.87
Q3-1	4828	81.1	14.6	6.4
Q3-2	2550	147.4	27.1	6.3
Q3-3	4418	124.5	18.9	5.9
Q3-4	5578	79.7	13.5	6.2
Q4-1	3273	131.9	22.7	6.4
Q4-2	3098	113	22	6.7
Q4-3	2738	95.0	21.0	6.6
Q4-4	6713	74.7	11.9	6.3

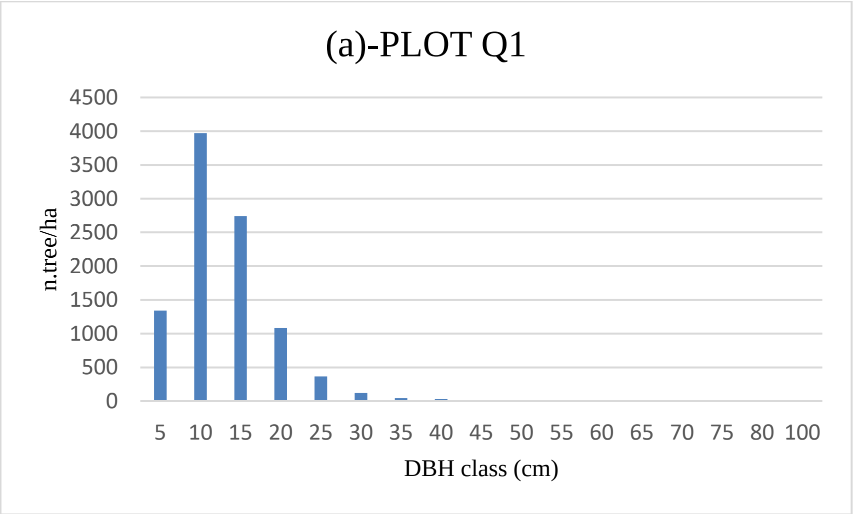


Figure n. 39 (a) - The frequency distributions in diameter classes for single square plot site Q1 for the case study III.

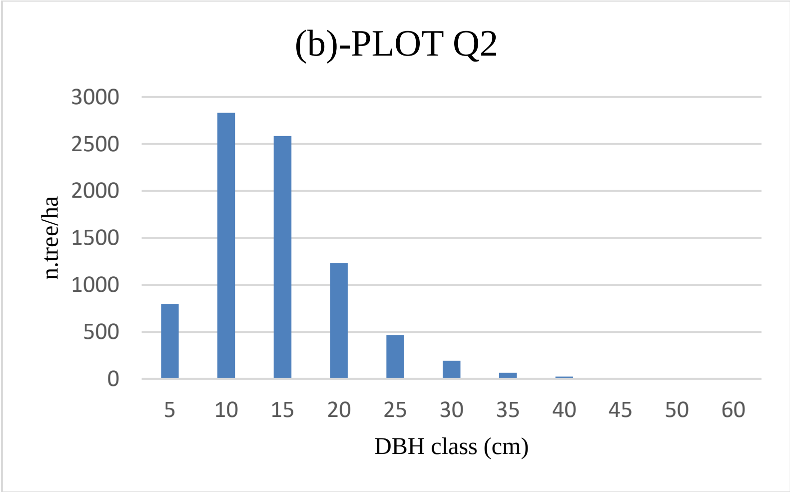


Figure n. 39 (b) - The frequency distributions in diameter classes for single square plot site Q2 for the case study III.

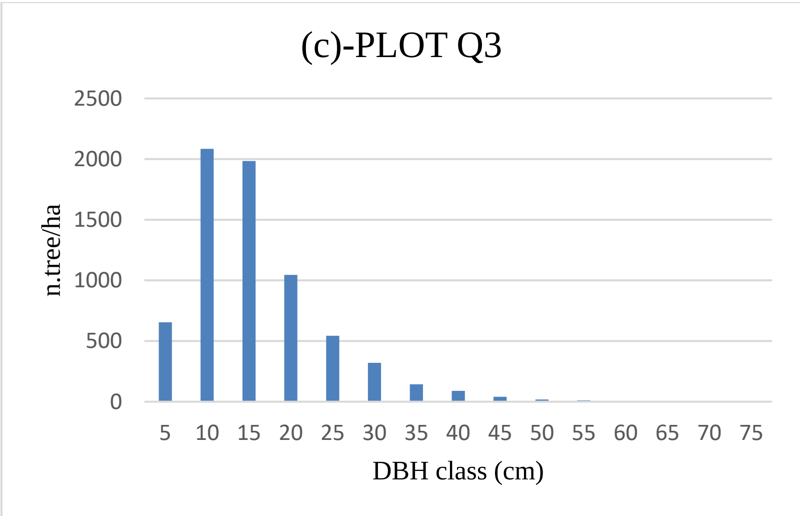


Figure n. 39 (c) - The frequency distributions in diameter classes for single square plot site Q3 for the case study III.

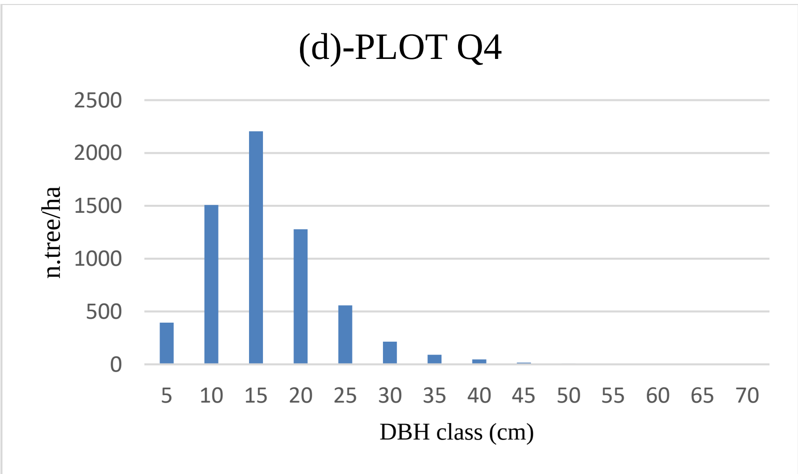


Figure n. 39 (d) - The frequency distributions in diameter classes for single square plot site Q4 for the the case study III.

The table n. 27 shows the accuracy of the individual attributes calculated from the LIDAR survey applied into two circular test plots. Accuracies of individual attribute estimations were gauged using R-squared (R^2), root-mean-square error (RMSE) and relative bias.

Table n. 27 - Summary statistics of single-tree attributes (DBH) computed by HLS scans in each circular test plot of the Bosco Niscemi site (ADS-ID) on the case study III.

ADS-ID	R^2 (DBH)	RMSE_DBH	bias_DBH
ADS1	0.95	3.4	1.1
ADS2	0.7	2.8	0.7

With regards to DBH, the coefficient of determination across all circular plots was higher than 0.80 revealing a robust correlation between the HLS LIDAR scans and the reference data from the traditional surveys applied in the same test plots. The average values of RMSE were 3.1 and the bias was 0.90. For H, the coefficient of determination across all plots was around 0.64 with the RMSE and bias values of around 0.70 and 1.24 (Table n. 28). These data reveal a robust correlation between LIDAR HLS scans and traditional survey reference data. Good reliability of LIDAR survey in Mediterranean forest environment is represented.

Table n. 28 - Summary statistics of single-tree attributes (H) of two circular plot site computed by traditional survey and HLS scans for the case study III.

ADS-ID	R^2 (H)	R^2 (H)	bias_H
ADS1	0.7	1.15	0.85
ADS2	0.58	0.31	1.63

In this case study the priority objective was to obtain key information in order to allow us to carry out a quantification of the fuels present within the study area using the results of the LIDAR surveys following the indications described in previous chapter (chapter 2.6- "Voxelization and Classification of LIDAR data according to the Prometheus system"). Following this objective, it was possible to realize as the first phase of preliminary data collection a spatial distribution of plants presents within the study area differentiating for different levels of height. This spatial distribution is shown in Figure n. 40.

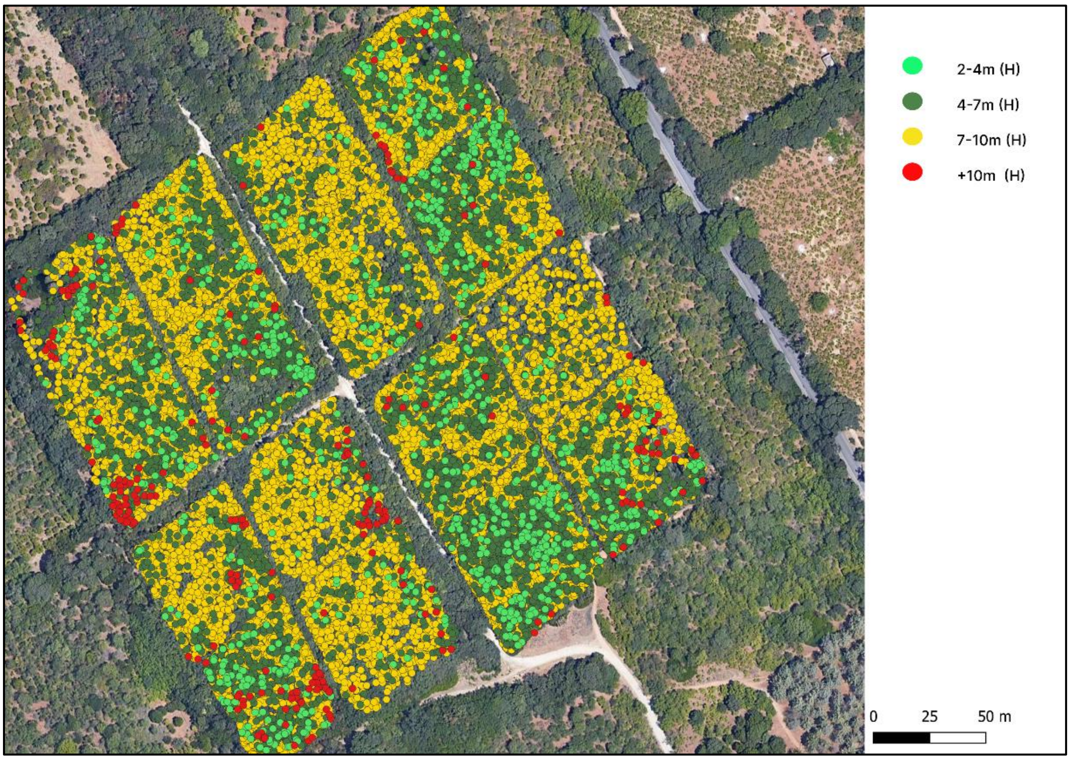


Figure n. 40 - Map of spatial distribution of Tree present in the study area according different level of height computed by traditional survey and HLS scans for the case study III.

From the maps we can observe a high spatial variability along the vertical profile of the forest passing from quadrant to quadrant (PLOT ID). In particular, it is observed that for each group of main sites of the squares, called Q1-Q2-Q3-Q4, there is an internal differentiation between the single 4 component squares close to each other. Considering only the threshold of the 4 m of height, inside the study area composed of the 16 squares of 4000 m^2, 4 plot sites have characters of high numerical abundance of vegetative elements, above the average (PLOT ID: Q1-2, Q2-1, Q3-4, Q4-2). While other 4 different squares (PLOT ID: Q1-3, Q2-4, Q3-2, Q3-3), present instead a reduced presence, below the average, of vegetal elements. Regarding the threshold from 4 m to 7 m, it is possible to observe an above-mean numerical abundance in Q1-4, Q3-3 and Q4-2 and a below-mean numerical reduction in the squares Q1 -3, Q2- 2, Q3-2, Q4-4. From the notes submitted it was possible to observe that the quadrant Q3-2 presents a reduced presence of elements in the spatial distribution within which the individual elements are very distant from each other, thus allowing a probable regrowth of the scrub vegetation in those areas. In addition, in the quadrant Q4-2 instead presents a spatial distribution within which there is a greater accumulation of shrub and tree vegetation, an area not to be underestimated for a future predisposition of firefighting. In a different quadrant such as Q2-4 it has an abundance of trees with openings in the shrub vegetation. This could have allowed it to have a better ground cover from the sun and therefore would represent a better predisposition to host some elements of high local faunal and floral biodiversity. All this allows us to understand not only the altitude variability of the forest but to know the development trend in height of the local Mediterranean scrub in the site. Thanks to these data, the existence of a continuity in height of the vegetation, a communicating bridge for the propagation of the fire, is increasingly known, an essential indication for the preparation of fire protection for probable cases of development of flame fronts. From the scans of the LIDAR surveys performed within the Mediterranean forest Ecosystems it was also possible to characterize Ladder Fuel Density present in the study area taking into account the abundance of LIDAR points in the form of voxels (as described in chapter 2.6) per square metre, expressed as a percentage, differentiating by layer of 0.5m starting from 0 up to 7 m of height development. You can see the results of Average plot-level percentage of voxel points by stratum in the table n. 29-30.

Table n. 29 - Table of density (n. point/m^2) for the description of Ladder Fuel Density estimation in the case study III.

Layer H	Plot ID															
	Q1-1	**Q1-2**	**Q1-3**	**Q1-4**	**Q2-1**	**Q2-2**	**Q2-3**	**Q2-4**	**Q3-1**	**Q3-2**	**Q3-3**	**Q3-4**	**Q4-1**	**Q4-2**	**Q4-3**	**Q4-4**
0-0.5 m	17137	18655	15822	20085	17397	16838	18896	18653	16590	12882	25928	12187	12498	19105	16515	17598
0.5-1 m	17049	24095	18177	17186	19952	17689	18274	19312	18762	15244	35016	17709	13371	22052	19610	18947
1-1.5 m	19111	24679	19763	21620	20900	17976	20474	19568	20132	15612	31257	24463	14198	24107	20723	19575
1.5-2 m	20255	24910	21259	23717	20481	18864	19249	19387	20642	14977	25728	27226	15536	23786	20851	19286
2-2.5 m	20799	24170	20823	23772	20886	18319	20853	16727	21609	14458	25122	28522	17244	22198	20900	18291
2.5-3 m	18196	20941	18053	22385	18816	17868	18700	18506	19046	13510	27092	27423	17509	20174	18191	16190
3-3.5 m	15454	18154	15120	18782	15607	16019	16693	15021	15510	12509	23285	25536	16975	16596	15367	14661
3.5-4 m	14865	16646	13285	16298	13690	14149	15730	13296	13905	11768	18315	21701	15908	14024	13565	13210
4-4.5 m	13392	14503	12385	14007	12401	12767	15059	11998	12609	11351	16408	16820	14022	12933	12607	12388
4.5-5 m	12311	13514	11776	12606	11694	12055	13781	11375	11896	10989	15578	14551	12676	11714	11693	11806
5-5.5 m	12150	12707	11129	11892	11325	11437	13136	10873	11451	10788	16590	13265	12150	11354	11207	11169
5.5-6 m	11505	12136	10801	11365	10937	11173	13200	10751	11077	10643	16863	12272	11628	11064	10875	10759
6-6.5 m	11407	11584	10561	11067	10663	10868	12205	10632	10812	10601	15591	12047	11232	10804	10687	10598
6.5-7 m	12023	11319	10304	10756	10390	10767	12410	10445	10753	10565	16031	11582	10957	10558	10564	10465
0-7 m	215655	248012	209258	235537	215137	206789	228661	206544	214795	175897	308805	265305	195904	230469	213355	204943

Table n. 30 - Table of Ladder Fuel Density estimation's average values (%) for the case study III.

Layer H	Plot ID															
	Q1-1	**Q1-2**	**Q1-3**	**Q1-4**	**Q2-1**	**Q2-2**	**Q2-3**	**Q2-4**	**Q3-1**	**Q3-2**	**Q3-3**	**Q3-4**	**Q4-1**	**Q4-2**	**Q4-3**	**Q4-4**
0-0.5 m	2.90	2.45	1.93	2.45	1.83	1.96	2.20	2.17	1.82	1.42	2.85	1.65	1.69	2.10	2.23	2.38
0.5-1 m	2.89	3.17	2.22	2.10	2.10	2.06	2.12	2.25	2.06	1.68	3.85	2.39	1.81	2.42	2.65	2.56
1-1.5 m	3.24	3.25	2.41	2.64	2.20	2.09	2.38	2.28	2.21	1.72	3.43	3.31	1.92	2.65	2.80	2.65
1.5-2 m	2.67	3.28	2.59	2.89	2.16	2.19	2.24	2.25	2.27	1.65	2.83	3.68	2.10	2.61	2.82	2.61
2-2.5 m	2.74	3.18	2.54	2.90	2.20	2.13	2.42	1.94	2.37	1.59	2.76	3.85	2.33	2.44	2.82	2.47
2.5-3 m	2.39	2.76	2.20	2.73	1.98	2.08	2.17	2.15	2.09	1.48	2.98	3.71	2.37	2.22	2.46	2.19
3-3.5 m	2.03	2.39	1.84	2.29	1.64	1.86	1.94	1.75	1.70	1.37	2.56	3.45	2.29	1.82	2.08	1.98
3.5-4 m	1.96	2.19	1.62	1.99	1.44	1.65	1.83	1.55	1.53	1.29	2.01	2.93	2.15	1.54	1.83	1.79
4-4.5 m	1.76	1.91	1.51	1.71	1.31	1.48	1.75	1.40	1.39	1.25	1.80	2.27	1.89	1.42	1.70	1.67
4.5-5 m	1.62	1.78	1.44	1.54	1.23	1.40	1.60	1.32	1.31	1.21	1.71	1.97	1.71	1.29	1.58	1.60
5-5.5 m	1.60	1.67	1.36	1.45	1.19	1.33	1.53	1.26	1.26	1.19	1.82	1.79	1.64	1.25	1.51	1.51
5.5-6 m	1.51	1.60	1.32	1.39	1.15	1.30	1.53	1.25	1.22	1.17	1.85	1.66	1.57	1.22	1.47	1.45
6-6.5 m	1.50	1.52	1.29	1.35	1.12	1.26	1.42	1.24	1.19	1.16	1.71	1.63	1.52	1.19	1.44	1.43
6.5-7 m	1.58	1.49	1.26	1.31	1.09	1.25	1.44	1.21	1.18	1.16	1.76	1.57	1.48	1.16	1.43	1.41
0-7m	30.40	32.63	25.52	28.72	22.65	24.05	26.59	24.02	23.60	19.33	33.93	35.85	26.47	25.33	28.83	27.69

Through the average percentage of Ladder Fuel Density, the vertical stratification and the spatial distribution of the forest structure, the description of the portion of territory under study with the 7 Types (fuel models) is obtained by the Prometheus European System (Arroyo *et al.*, 2008). of Fuel. It is possible to observe the results of this typical scheme in Figure n. 41.

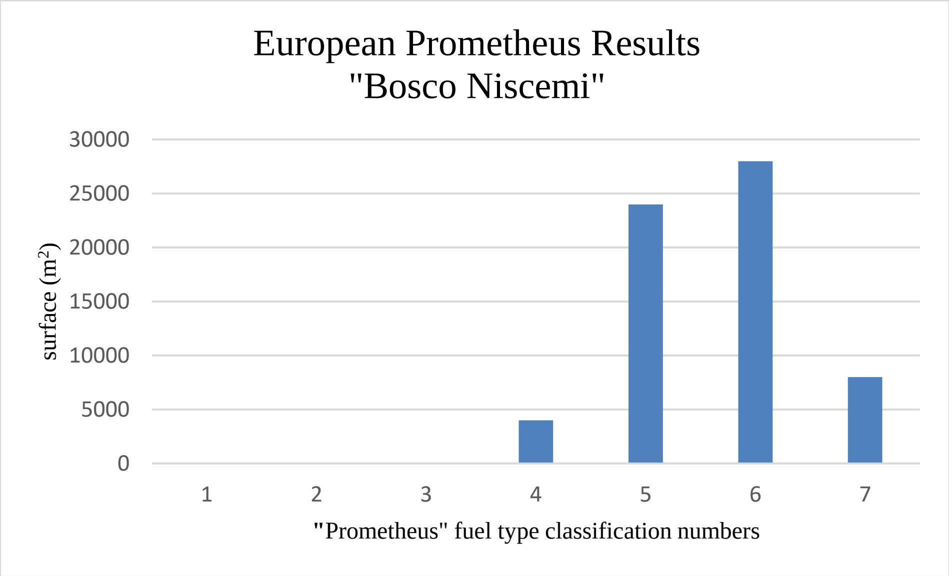


Figure n. 41 - The Result of European Prometheus Scheme obtained in 4 quadrant plot sites for the the case study III.

From the table obtained from the Prometheus classification it is possible to observe that in the 16 squares plot sites there are at least 7 squares belonging to the FUEL TYPE-6 category, while there are 6 squares belonging to the FUEL TYPE-5 category. No other squares belong to the categories FUEL TYPE-1, FUEL TYPE-2, FUEL TYPE-3. In the most extreme situations of this case study, in the FUEL TYPE-7 category there are two squares such as Q1-4 and Q3-1. While the only dial belonging to the FUEL TYPE-4 category is the Q2-2 dial.

The results of the case study just illustrated demonstrate the possibilities of applying and processing terrestrial LIDAR data in order to obtain in-depth knowledge on the quantification and categorization of fuels in a Mediterranean forest context. This would represent an opportunity to have a mass of robust data for a future predisposition and organization of forest fire protection interventions, especially in these urban forest contexts with a close constant contact between man and nature.

3.1.5. The case study IV: application of a method for assessing and scoring stem straightness in tree standing by LIDAR HLS surveys to quantify differences between stands of different log quality. (Mt. Chortiatis on Macedonia, Greece, Camaldoli on Tuscany, Ficuzza on Sicily, Italy).

In this case study, four different forest square areas (each square area: 2500 m^2) are analyzed in order to apply a particular stand quality classification based on the stem straightness score in each tree using the HLS LIDAR survey data. The area of different forest environments selected in two European countries (Italy, Greece) are as follows:

- Single-layer beech forest (Fagus sylvatica),
- transitional stand of deciduous trees (Quercus ilex),
- Ancient high forest monoplane (Castanea sativa),
- Adult monoplane high forest (Pinus nigra plantation). The 3D representations of the HLS relief is shown in figure n. 42(a), 42(b), 42(c) and 42(d).

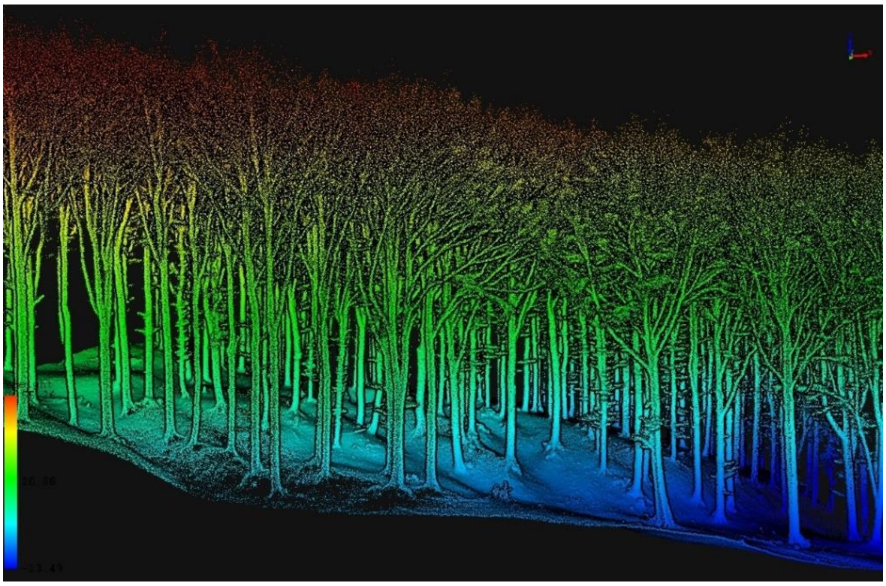


Figure n.42 (a) - a Point Cloud representation of sampled *Fagus sylvatica* stands in the plot from the graphical user interface of LIDAR360 for the case study IV.

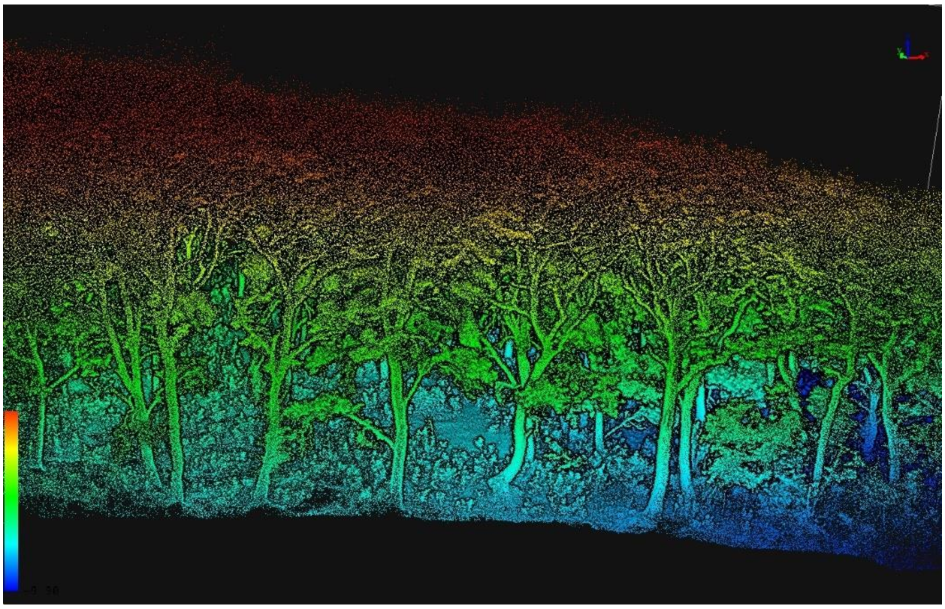


Figure n.42 (b) - a Point Cloud representation of sampled *Quercus ilex*’s Forest stands from the graphical user interface of LIDAR360 for the the case study IV.

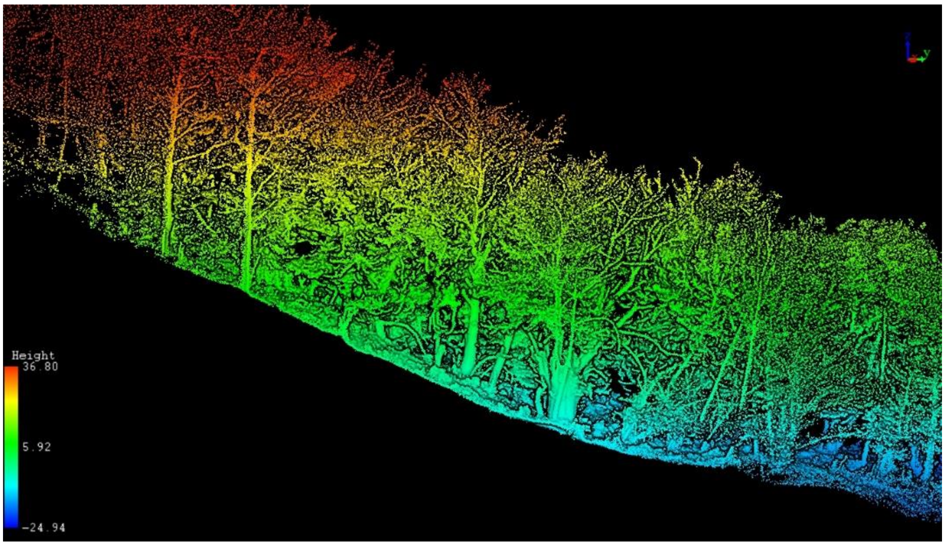


Figure n.42 (c) - a Point Cloud representation of sampled *Castanea sativa* ‘s Forest stands from the graphical user interface of LIDAR360 for the case study IV.

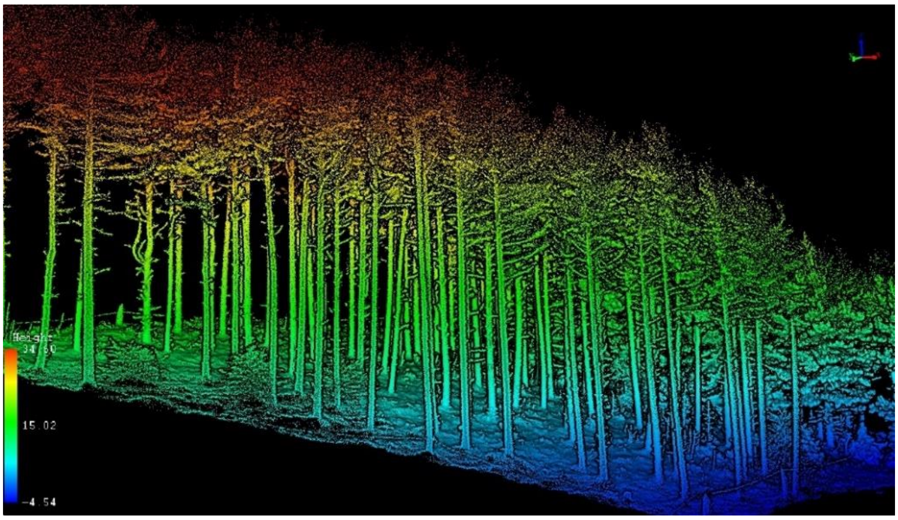


Figure n.42 (d) - a Point Cloud representation of sampled *Pinus nigra* ‘s Forest stands from the graphical user interface of LIDAR360 for the case study IV.

The table n. 31 presents a summary of data from all individual square test plots (PLOT ID) for hectare. For each test plot, dendrometric information of hectares was used to better understand the structure of all stands and to investigate the external factors that contributed to having the final values of scoring stem straightness. For example, the presence of more plants per hectare represents an opportunity to have long straight stems in nex time because of a minor horizontal space and elevate competitions of resource and light between all plants.

Table n. 31 - Number of trees -N (n. tree/ha), Total Volume- Vtot (m^3/ha), Basal Area - G (m^2 /ha), estimated by HLS scans of all plots for the case study IV.

Species	G (m^2/ha)	V (m^3/ha)	N (n.tree/ha)
Fagus sylvatica	34.80	383.00	548
Quercus ilex	58.60	426.80	1072
Castanea sativa	39.40	244.50	936
Pinus nigra	34.40	294.70	528

Another essential information to take for each square plot before the scoring stem straightness application are the average values of H and DBH (Table n. 32), the average tapering index for diameter classes in sampled forest type stands (Table n. 33) and the frequency distributions in diametric classes for each sampled forest species, see Figures n. 43(a), 43(b), 43(c) and 43(d). These pieces of information are essential to understand the evolution of forest structure during the growth phases, especially in the final stage of a tree's life, and to anticipate future negative phenomena such as stem quality issues like crashed trees or debarking, which were observed in many of our sampled plots.

Table n. 32 - Average values of single-tree attributes (DBHm and Hm) for sampled plot computed by traditional survey and HLS scans in the case study IV.

Species	DBHm	Hm
Fagus sylvatica	27.70	22.10
Quercus ilex	25.50	13.90
Castanea sativa	20.30	13.40
Pinus nigra	28.20	18.20

Table n.33 - The average tapering index for diameter classes for sampled plot computed by traditional survey and HLS scans in the case study IV.

Diameter classes	*Fagus sylvatica*	*Quercus ilex*	*Castanea sativa*	*Pinus nigra*
20	104	62	55	79
25	87	53	47	71
30	75	47	46	61
35	65	42	40	54
40	59	38	35	46
45	53	34	34	39
50	46	0	0	0
55	0	0	29	0
60	0	0	0	0
65	0	0	23	0

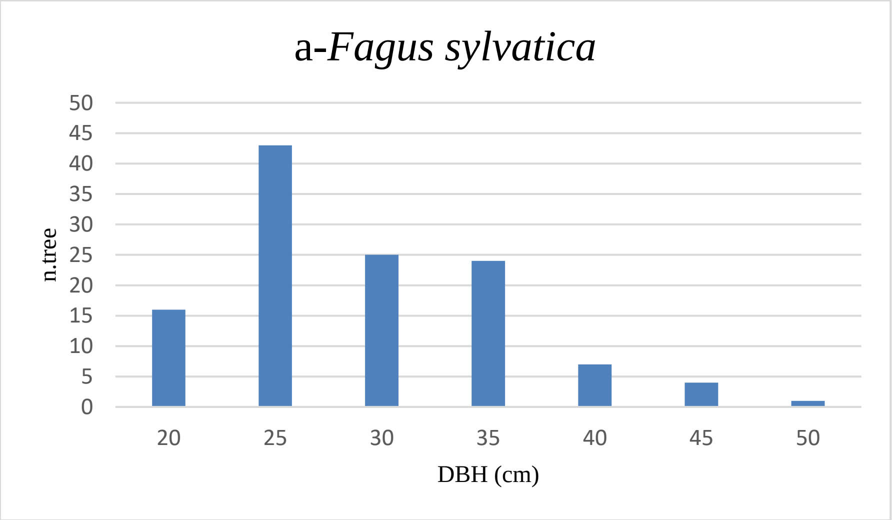


Figure n. 43(a) - The frequency distributions in diameter classes of *Fagus sylvatica* plot for the case study IV.

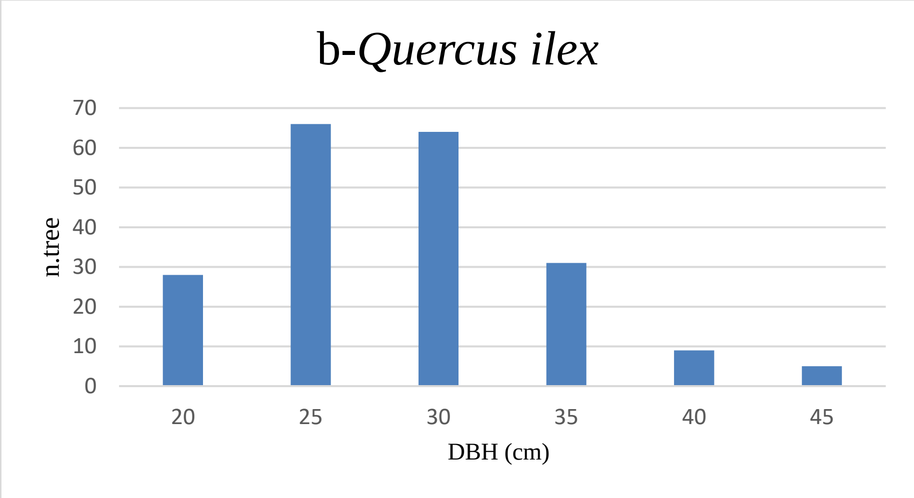


Figure n. 43 (b) - The frequency distributions in diameter classes of *Quercus ilex* plot for the case study IV.

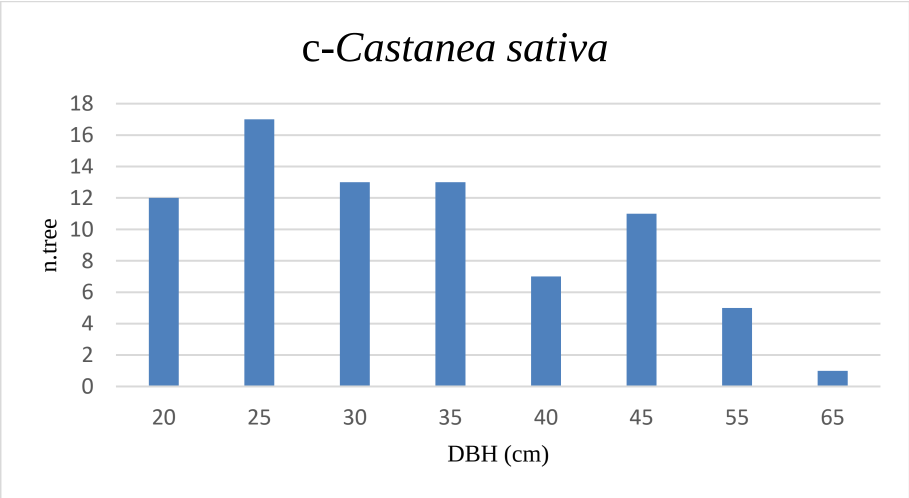
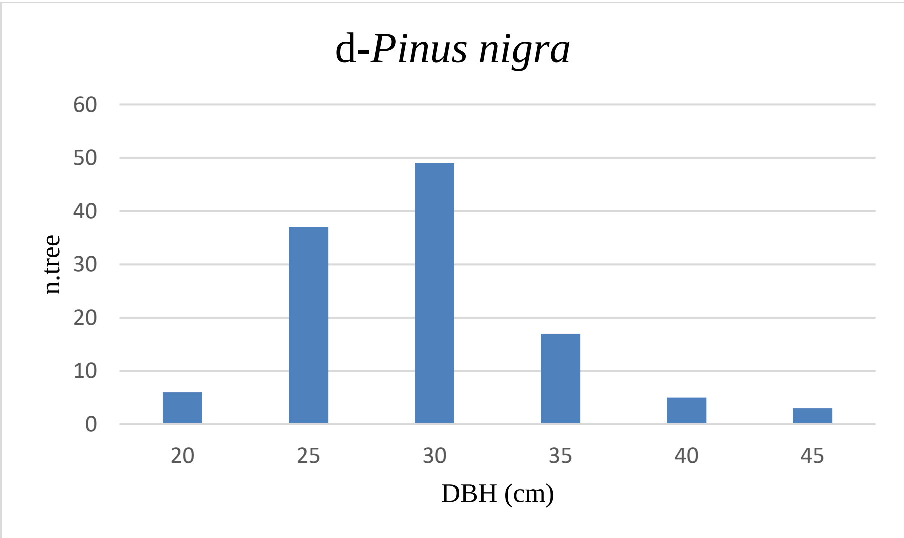


Figure n. 43 (c) - The frequency distributions in diameter classes of *Castanea sativa* plot the case study IV.



(d)

Figure n. 43 (d) - The frequency distributions in diameter classes of *Pinus nigra* plot for the the case study IV.

According to the stem straightness scoring system established from Macdonald *et al.* 2009 (more details of methodology on cap. 2.7) it is possible to realize a distribution on percentage of values of stem straightness scoring for each sampled forest stand. You can see the results at table n.34.

Table n. 34 - the Result of stem straightness scoring system (on percent for each scoring type values) in 4 square plot sites for the case study IV.

Straightness TYPE CODE	***Fagus sylvatica* (%)**	***Quercus ilex* (%)**	***Castanea sativa* (%)**	***Pinus nigra* (%)**
1	72	19	4	0
2	0	24	6	0
3	22	14	7	1
4	6	23	25	5
5	0	12	20	30
6	0	8	27	36
7	0	0	11	28

The result shows that in the case of the *Fagus sylvatica* square plot there is an elevate number of stems with many sweeps in 1 hectare (72% of stems scored 1, as reported in table 33). Generally, beech is a species with a columnar habit and it tends to have straight stems under optimal conditions. In the forest context that was examined, there is a low value of stem straightness, probably due to external environmental factors that influence this result. Regarding the Quercus ilex square plot many trees show an elevate presence of linear stem between 2-3 m (24% scored 2, 23% scored 4, as reported in table 33), while Castanea sativa plot results emphasize an elevate presence of stem in 1 hectare with a lineal length of 3-4 m (20% with a score 5,27% with an score 6 on the table n.33). This information served to estimate the percent of wood material to take from these areas to obtain wood materials for firewood or pole elements. Finally, in the case of *Pinus nigra* square plot there is an elevated number of trees with a very straight stem with a length of 3-5 m onwards (30% with a score 5, 36% with a score 6, 28% with a score 7 on the table n.33). In this particular case these results show that the Pinus Nigra area has the good potential to have wood material for carpentry. The final results taken in this case study is the classification of quality stands taken from our stem straightness scoring system application, present in the table n. 35.

Table n. 35 - The result the stand quality classes, from the Protocol for Stem Straightness Assessment (Macdonald *et al.*, 2001), for the case study IV.

	***Fagus sylvatica* (%)**	***Quercus ilex* (%)**	***Castanea sativa* (%)**	***Pinus nigra* (%)**
GRADE of stand quality classe	E	D	D	C

From the latest results we can observe that it is possible to use HLS LIDAR data to obtain good information to guide the analysis of the quality of living tree stands. In fact, the straightness values belong to a different reference parameter for forest sites in the case of tree felling procedures, with the results of investigations on sound nodes coinciding with the presence of green or already dry but not rotten branches, and the analysis of straightness deviation in each shaft. Information from the HLS LIDAR data survey is used to identify an assortment of commercial interest through the length of upright stem present in an individual tree, which must be at least 2 m long. It is clear that the purpose of this case study is to investigate the potential of the HLS LIDAR to identify the portion of the stem from which an assortment of commercial interest can be represented and to evaluate the productive capacity of a tree plantation, the first step for the procedure for better planning of the operational phases in a forest site.

3.2. Single tree analysis from HLS LIDAR data

3.2.1. The case study V: Characterization of Old-Growth Forest with a HLS LIDAR tool (Santa Maria del Bosco and Ficuzza, Sicily, Italy).

This study has examined the main characteristics of old-growth trees in a Mediterranean forest in Sicily according to the criteria established by the bibliography and in-depth structural studies for large trees.

The total plots taken in this case study are ten and its are characterized by an adult Mediterranean high forest with a predominance of white oak, five plot located in “Bosco del Fanuso” within the Ficuzza Reserve and five plots in “Il Bosco di Gurgo” in Santa Maria del Bosco in Sicily, Italy. There are 3D representations of high-resolution HLS relief data for the two locations shown in Figures n. 44 (a) and 44(b).

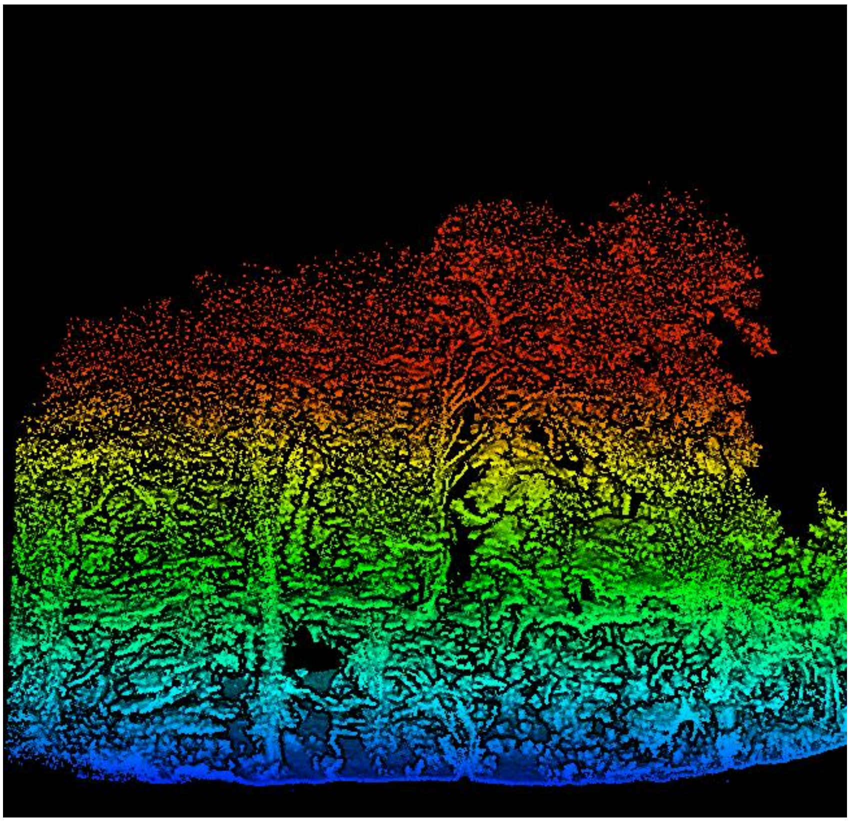


Figure n. 44(a) - a 3D representation of Fanuso Wood plot site on the graphical user interface of LIDAR360 for the case study V.

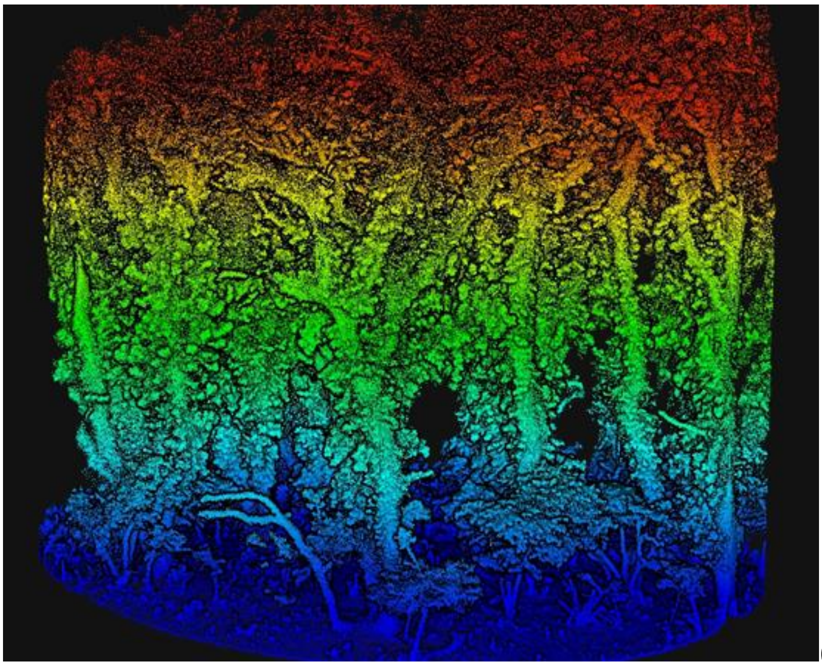

(b)

Figure n. 44(b) - a 3D representation of Gurgo Wood plot site on the graphical user interface of LIDAR360 for the case study V.

The table n. 36 presents a summary of dendrometric parameters taken from the LIDAR relief from all circular sampled plots (PLOT ID) for each hectare and the average values of DBH and H predominant in each plot for two area study.

Table n. 36 - Number of trees -N (n. tree/ha), Basal Area - G (m^2/ha), average values of DBH (DBHm) and average values of H (Hm), estimated by HLS scans of the Fanuso wood and the Gurgo wood sites (PLOT ID) with trees (DBH>40cm) for the case study V.

PLOT ID	**N (n.tree/ha)**	**G (m^3/ha)**	**DBHm**	**Hm**
F-1	175	21.58	39.62	15.91
F-2	111	26.43	54.96	19.84
F-3	80	14.92	48.87	14.64
F-4	72	16.73	54.53	17.73
F-5	111	21.99	50.13	19.09
all	110	20.33	49.62	17.44
G-1	143	21.80	44.10	14.40
G-2	127	21.01	42.40	14.70
G-3	167	29.63	44.60	13.60
G-4	223	42.33	44.30	13.60
G-5	104	18.43	46.50	14.60
all	153	26.64	44.38	14.18

The results of LIDAR surveys show that this technology not only manages to obtain a good 3D visual rendering of the forest environment but also to identify some peculiarities of old growth forest related to dimensionality through the application of automatic algorithm of segmentations according to the methodology described in chapter 2.5.

In particular, it was possible to identify the spatial positions of plants with a diameter greater than 40 cm (reference DBH parameters of the old growth forest criteria established by the bibliography) with the remaining trees within the plot. You can see the spatial distribution of the individual study areas as a data supplement at chapter 6.1.

In this case study to test the reliability of the LIDAR survey in the Mediterranean forest environment was possible thanks to the comparison between the values of DBH and H of sampled plots obtained from LIDAR surveys and the reliefs obtained from traditional instrumentation. Accuracies of individual attribute estimations were gauged using root-mean-square error (RMSE) and relative bias present for two study areas in table n. 37.

Table n. 37 - Summary statistics of single-tree attributes (DBH and H) computed by HLS scans in each circular test plot of the Fanuso wood and the Gurgo wood sites (PLOT ID) on the case study V.

PLOT ID	RMSE_DBH	RMSE_DBH (%)	bias_DBH	RMSE_H	RMSE_H (%)	bias_H
F-1	9.49	25.81	8.39	6.45	40.53	4.40
F-2	9.46	26.48	-8.17	5.97	45.99	-2.44
F-3	6.38	29.79	-4.18	3.53	40.34	-1.25
F-4	5.22	21.12	-2.75	4.87	46.19	-3.14
F-5	5.73	20.89	-0.35	5.00	38.82	0.37
all	7.25	24.82	-1.41	5.17	42.37	-0.41
G-1	13.10	36.10	-5.40	5.40	33.30	1.90
G-2	7.70	17.00	2.10	5.00	28.40	2.80
G-3	14.30	30.40	5.00	7.20	40.90	4.10
G-4	17.00	34.70	6.80	8.70	45.00	5.60
G-5	11.90	25.60	-0.60	6.00	31.60	4.30
all	13.00	28.70	2.60	6.60	36.10	3.70

In the study area of “Bosco del Fanuso - Ficuzza” the average RMSE of DBH across all plots was around 24% (7cm with a bias value of -1.41). The average RMSE of H of all plots is 42% (5 m with a bias value of -0.41).

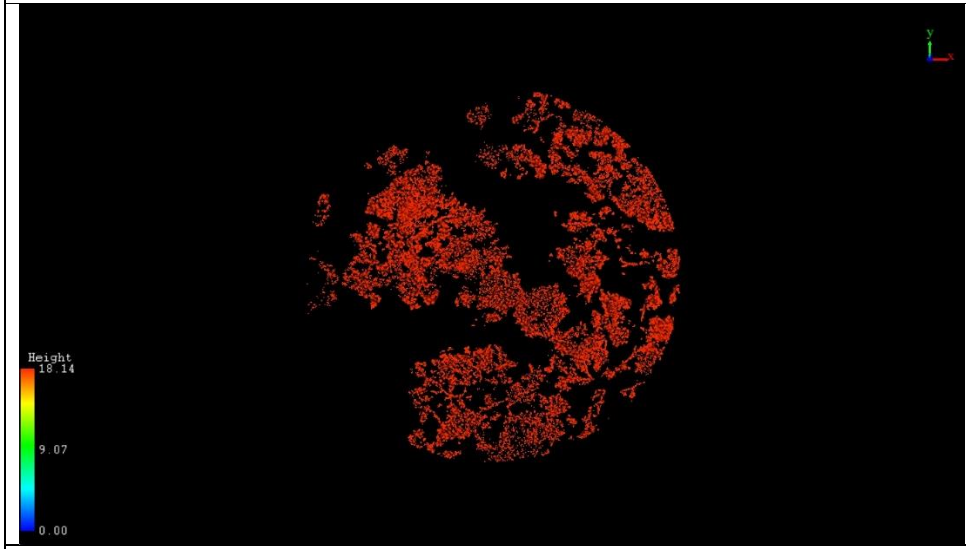
In the study area of “Il Bosco di Gurgo-Santa Maria del Bosco”, however, the average RMSE of DBH across all plots was around 28% (13 cm with a bias value of 2.60). The average RMSE of H of all plots is 36% (6.60 m with a bias value of 3.30). In this case study the overall accuracy values show a lower value than the mean of the accuracy values obtained in the previous case studies. One of the reasons might be that the benchmark for comparison could also be wrong, as traditional measurements involve errors related to the field experience of forestry.

Finally, an aspect to be highlighted in this case study concerns the determination of the horizontal projections of the canopy of the large trees present in the study areas according to the height value that corresponds to the maximum expansion of the canopy of the trees present. You can observe the 2D representations of canopy gaps for each individual PLOT ID in Figure n. 45.

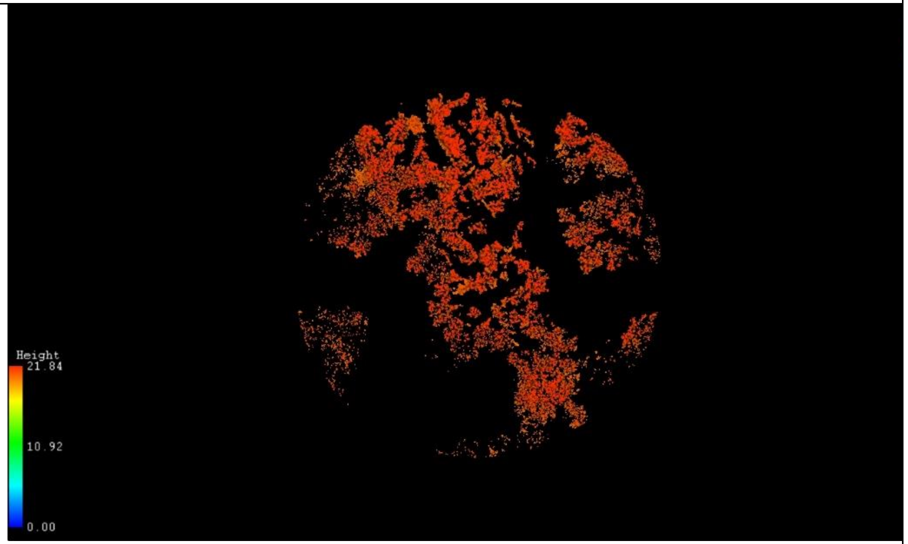
This would allow a better understanding of the structural development of the Mediterranean forest environment and an overall estimate of possible forest cover gaps in the study areas. The presence of these gaps would contribute to the growth of the undergrowth and the development of forest ecological succession. From the data obtained as a whole, the potential of the LIDAR tool to extrapolate new dimensional information to the forest environment of different composition was confirmed. These tools have made it possible to know the state of these old growth forest environments and to plan the best future sustainable forest interventions in these delicate contexts.

PLOT ID F-1

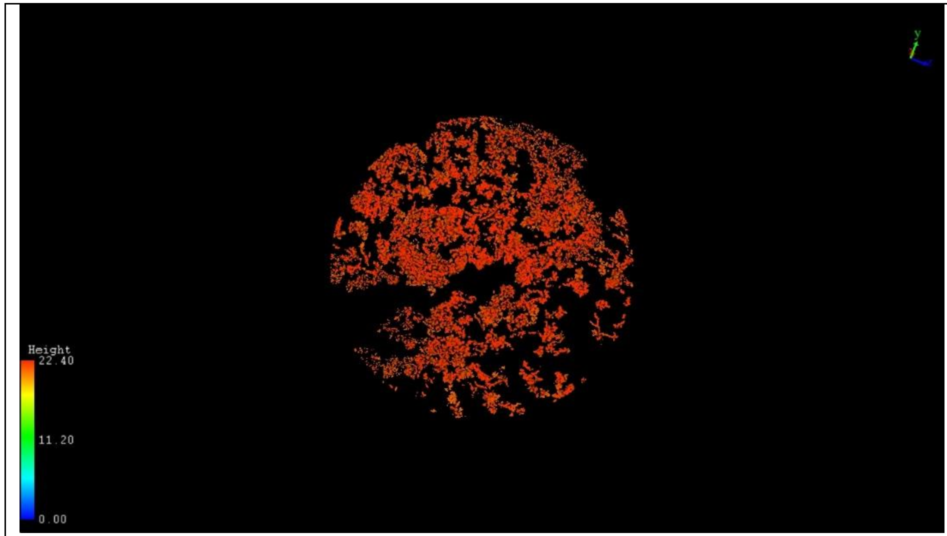
PLOT ID F-2



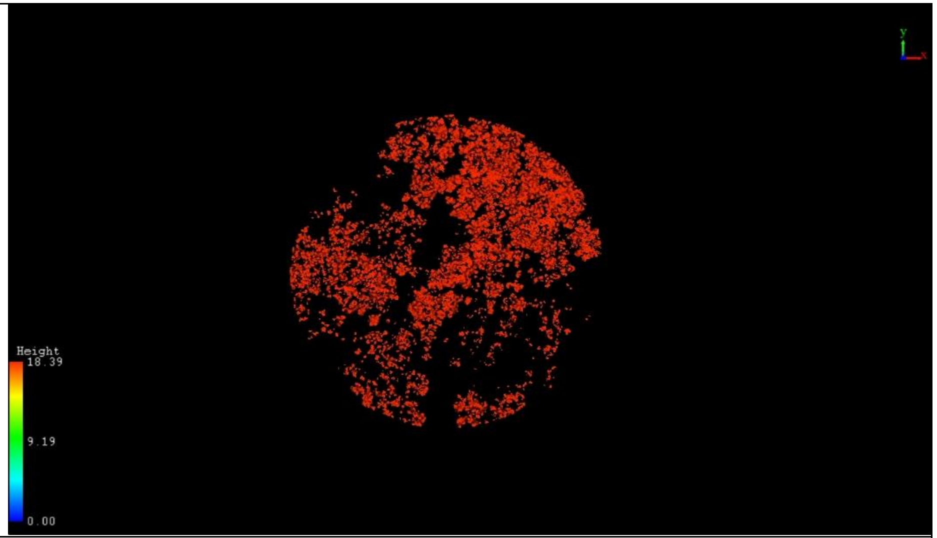
PLOT ID F-3



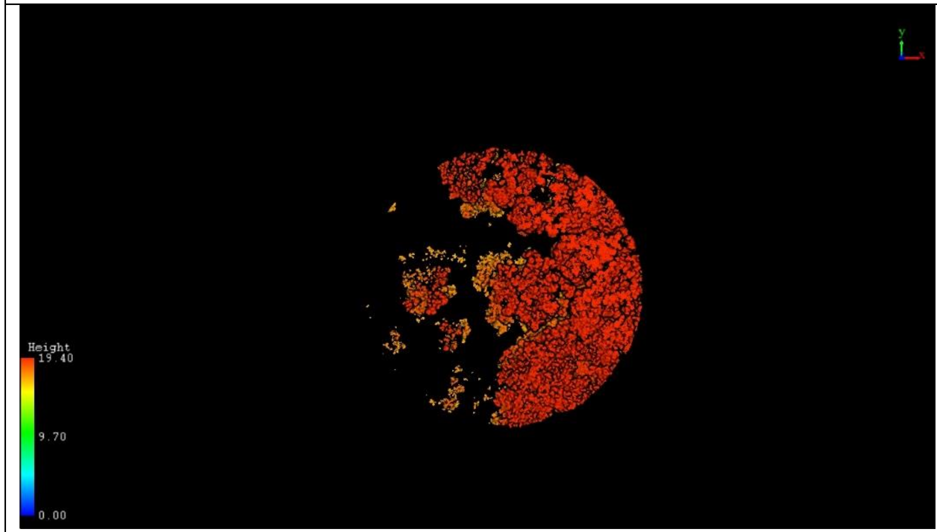
PLOT ID F-4



PLOT ID F-5



PLOT ID G-1



PLOT ID G-2

PLOT ID G-3

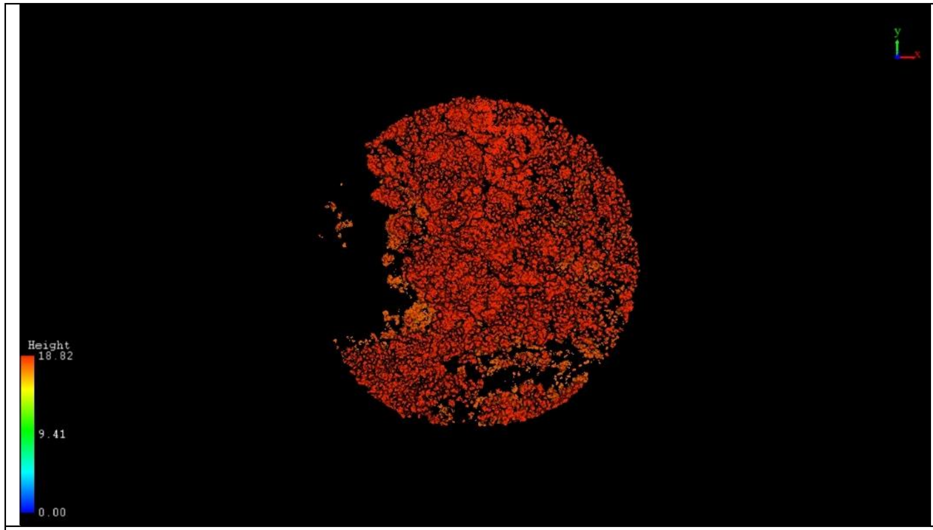
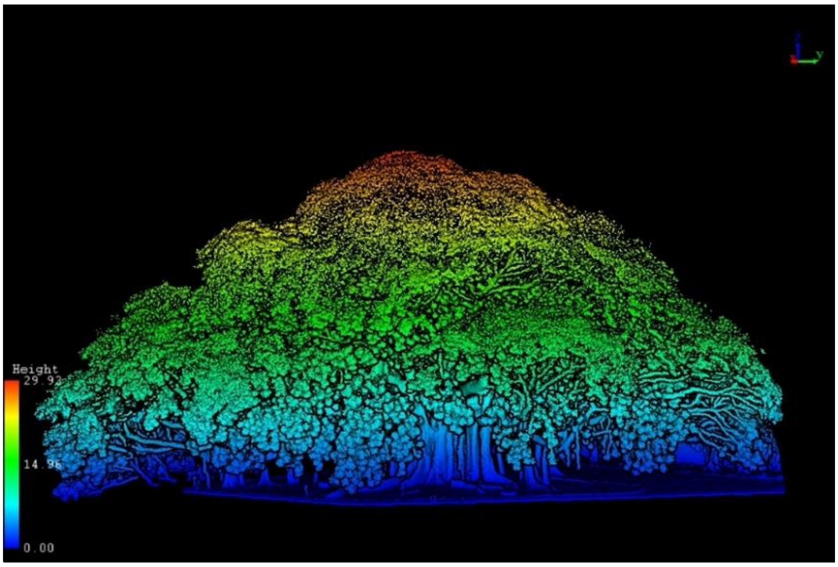
	
PLOT ID G-4	PLOT ID G-5

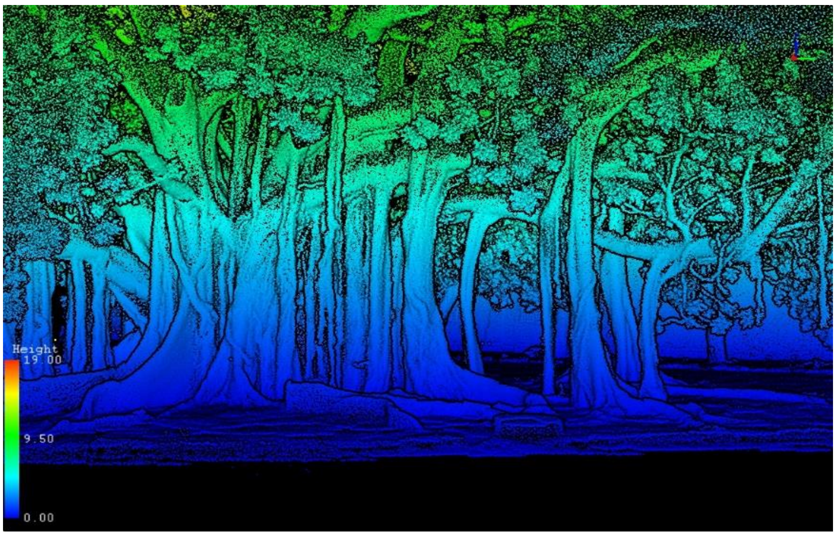
Figure n. 45 - Representations 2D of old growth forest canopy gaps sampled plot site (PLOT ID) localizated by HLS scans for the case study V.

3.2.2 The case study VI: Characterization of monumental single trees with a HLS LIDAR tool (*Ficus macrophylla* subsp. *columnaris*, Palermo Botanical Garden, Sicily, Italy).

Within the two sample trees "*Ficus macrophylla* subsp. *columnaris* localizated on historical garden city of Palermo (Sicily, Italy) it was possible to extrapolate dimensional and structural information of the two trees of high value of the size of the canopy. This species has the tendency of dropping aerial roots from its branches, which thicken into supplementary trunks upon reaching the ground, which help support the weight of its canopy. Because of these characteristics, it was necessary to have a full knowledge of canopy and stem dimension. You can see the 3D creation of the HLS relief in Figures n. 46 (a), 46(b), 46(c) and 46(d).

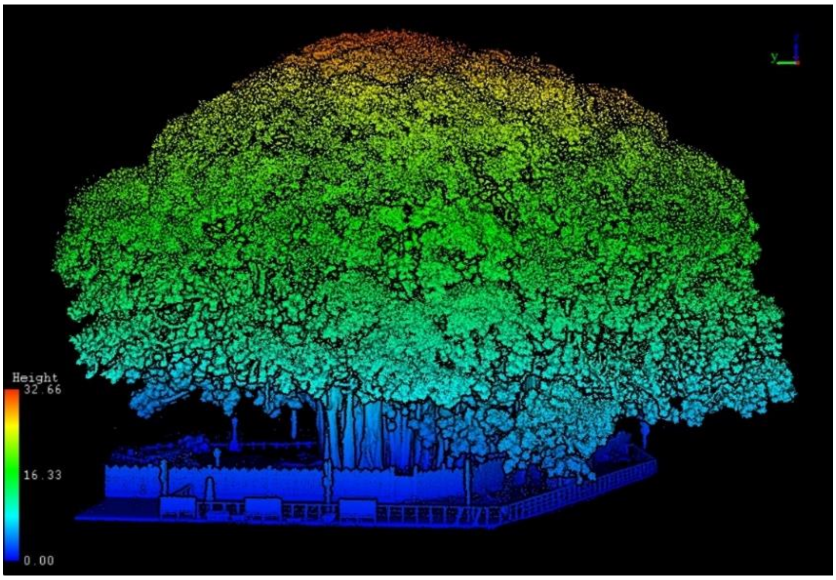


46(a)



46 (b)

Figure n. 46 (a), 46(b) - a Point Cloud representation of Palermo Botanical Garden's Ficus tree on the graphical user interface of LIDAR360 for the case study VI.



46(c)

46(d)

Figure n. 46 (c), 46(d) - a Point Cloud representation of Garibaldi Garden's Ficus tree on the graphical user interface of LIDAR360 for the case study VI.

The table n. 38 presents a summary of essential data from all individual trees considering the values of H, values of CBH and Canopy surface (m^2). This information has been confirmed by the direct comparison of the dendrometric values present in the FICUS identification form within the national census of monumental trees of Italy, protected by Italian law n. 10/2013 and Decree 23 October 2014.

Table n. 38 - Values of H, values of CBH, Canopy surface (m^2) estimated by HLS scans of all trees for the case study VI.

TREE ID	H (m)	CBH (m)	Canopy surface (m^2)
FICUS (Palermo Botanical Garden)	29	10.67	2390
FICUS (Garibaldi Garden)	32	12.09	1980

Regarding the values of DBH, in this case study it is possible to have a good study of the main classification of type of stem with a total counting of elements (table n. 39).

Table n. 39 - Classification of type of stem and number counting for each tree for the case study VI.

TREE ID	total elements	main stem & prop roots	secondary stem	aerial roots	Density
FICUS (Palermo Botanical Garden)	144	40	97	7	0.06
FICUS (Garibaldi Garden)	234	173	46	15	0.118

*Density= n. total elements/ Canopy surface

Regarding the tree present in the Botanical Garden, we have to remark that there is a high number of secondary stems compared to the second tree, present at Villa Garibaldi, which has a high number of main stems & prop roots. Thanks to the 3D Figure of the tree obtained from the Point Cloud processing the spatial distribution of the stem according to the level of height of 0.5 m-1.30 m and 4 m is created, see Figures n. 47(a) and 47(b).

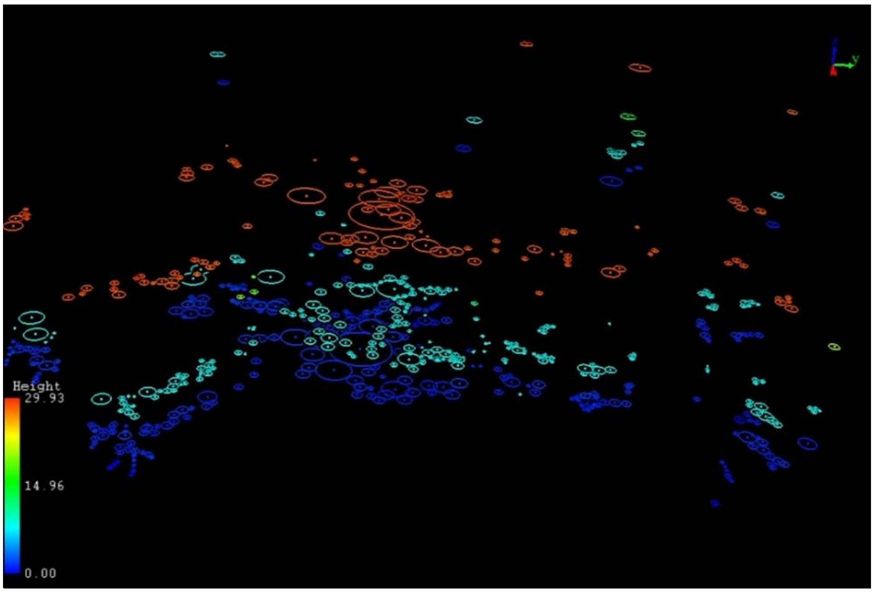
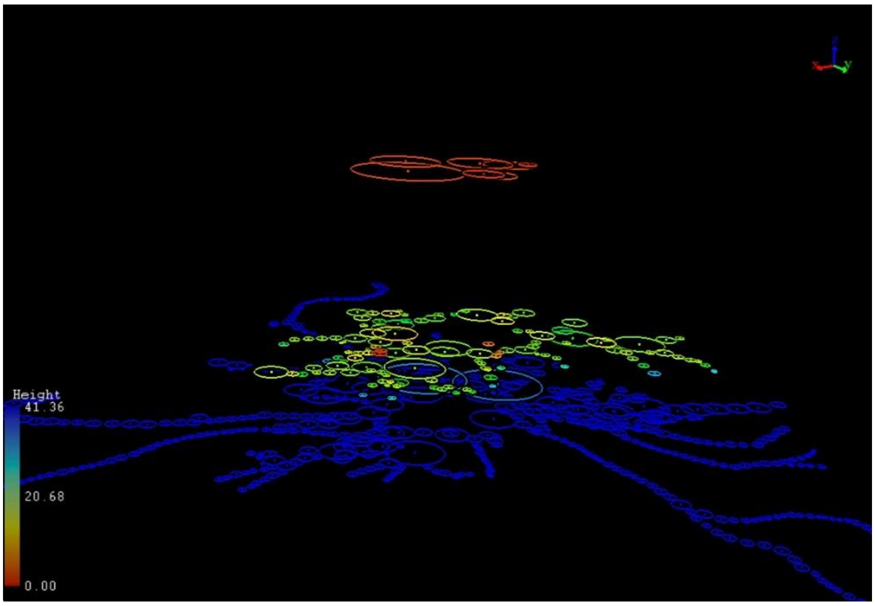


Figure n. 47 (a) - Spatial distribution of Palermo Botanical Garden's Ficus tree stem according the level of height of 0.5 m-1.30 m and 4 m for the case study VI, the height layers coloures of 0.5 m (blue), 1.30 m (light-blue) and 4 m (red).



(b)

Figure n. 47 (b) - Spatial distribution of Garibaldi Garden's Ficus tree stem according the level of height of 0.5 m-1.30 m and 4 m for the case study VI) the Ficus tree with the height layers coloures of 0.5 m (blue) -1.30 m (green) and 4 m (red).

The variability of our results shows how each individual plant, having the need to develop towards a specific direction for its mechanical stability, needs to be supported in different points of the canopy through the regeneration of new secondary stems (the peculiarity is typical of species Ficus).Within the same case study, it was performed a direct comparison of tree newly published code and point cloud processing tool to obtain a better architectural analysis and the total volume of the sampled tree. From the comparison it was possible to estimate the level of accuracy considering the result obtained from the processing performed by the LIDAR360 software as reference data. Table n. 40 shows the values of total volume (m 3) and height (m) obtained from the elaborations performed by the LIDAR360 software using some direct measurement tools.

Table n. 40 - Total volume of one Ficus tree (m^3) and Height (m) of two trees obtained from LIDAR360 software processing for the case study VI.

TREE ID	**Vol. total (m^3)**	**H (m)**
FICUS (Palermo Botanical Garden)	18866,26	29,20
FICUS (Garibaldi Garden)	26388,31	32,00

It is important to consider that the cloud of points of the sampled plant, before being elaborated by the tools or queues of comparison, was first passed under a phase of classification of the portions of the LIDAR point cloud according to the intensity level of the portions of the point cloud. Within the point cloud it is possible to distinguish different portions of points with sparse (linear) geometric characteristics to other portions of points with scattered geometric characteristics. The non-scattered portion category represents the main woody volume, while the scattered point portion category represents the leaf biomass and twigs (Ma *et al.*, 2016; Zhu *et al.*, 2018). From this distinction we were able to identify that portion of the cloud of the LIDAR points suitable for estimating the total woody volume of the sampled plant.

The tools or packages executed in different digital 3D modelling platforms/softwares, mentioned in some recently published articles, used for this case study are as follows:

- TREESQM (MatLab package),
- Vox R (R package),
- Screened Poisson Surface Reconstruction - SPSR (Meshlab).

It is possible to observe some images of digital models of the sampled trees according to different applications of 3D modelling tools or packages in Figures n. 48(a), 48(b) and 48(c).

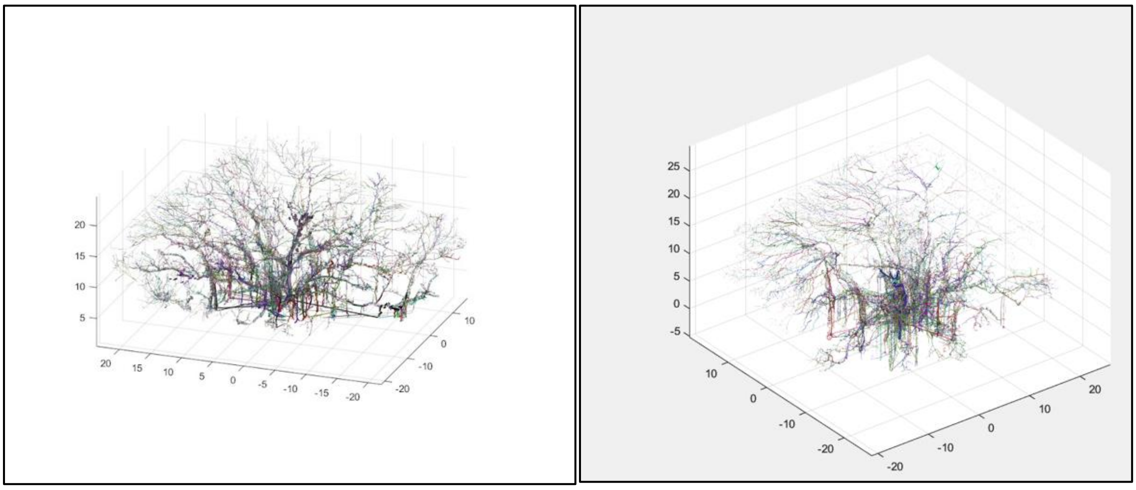


Figure n. 48 (a) - Images of 3D creations in detail from TREESQM code to estimate the total volume of the ficus trees (Palermo Botanical Garden and Garibaldi Garden).

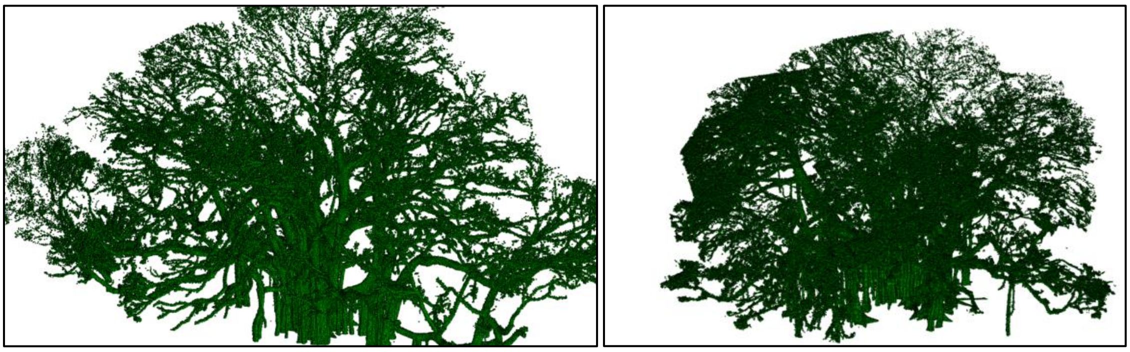


Figure n. 48 (b) - Images of 3D creations in detail from Vox R tool to estimate the total volume of the ficus trees (Palermo Botanical Garden and Garibaldi Garden).

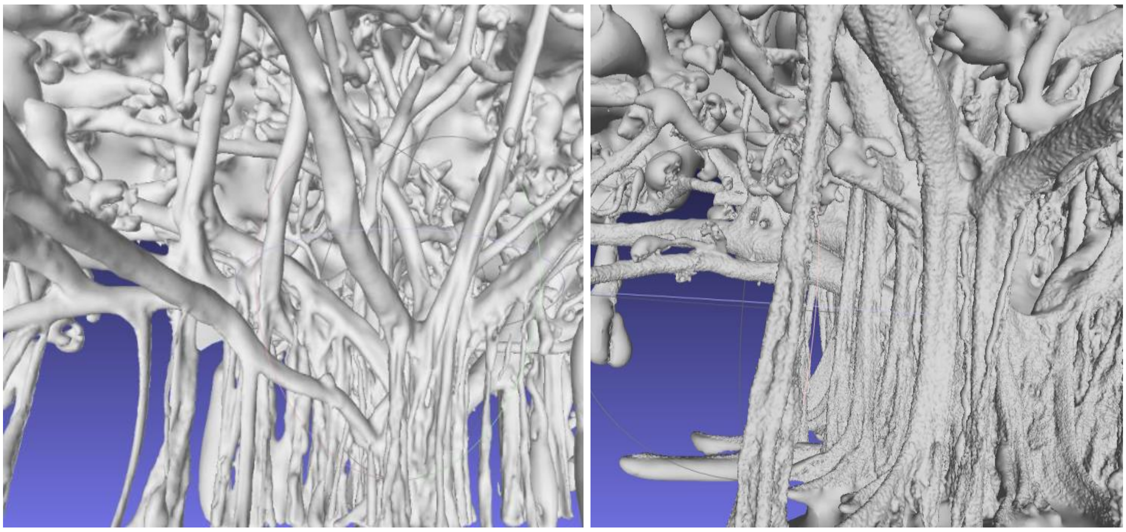


Figure n. 48 (c) - Images of 3D creations in detail from Screened Poisson Surface Reconstruction - SPSR (Meshlab) tool to estimate the total volume of the ficus trees (Palermo Botanical Garden and Garibaldi Garden).

In table n. 41 the values of total volumes estimated from the three informatic tools/tails of this case study are present and the level of accuracy data from the comparison of the same results. Accuracy of individual attribute estimations was gauged using root-mean-square error (RMSE).

Table n. 41 - Total volume (m^3) and height (m) of two trees obtained from three informatic point cloud processing tools/codes and values of accuracy (RMSE) for the case study VI.

	FICUS (Palermo Botanical Garden)						FICUS (Garibaldi Garden)					
Type of the tool/code	**Vol. total (m^3)**	**RMSE**	**RMSE (%)**	**h (m)**	**RMSE**	**RMSE (%)**	**Vol. total (m^3)**	**RMSE**	**RMSE (%)**	**h (m)**	**RMSE**	**RMSE (%)**
Matlab	27462	8595	31	27.2	2	7	32577	6188	19	32.2	0.65	0
VoxR	32850	13983	43	25.7	3.46	13	36540	26388	31	30.5	1.45	5
Meshlab	18913	47	0	26.1	3.09	12	33645	7257.	22	28.8	3.20	11

The analysis and application of the tools/codes compared for this case study confirms a difference in the values of woody volumes and heights less than 50%. This would represent a step forward in the reliability of these tools/codes.

Considering the Ficus of the botanical garden of Palermo, it is shown that the tool/code with a lower value of RMSE (%) for the determination of the woody volume is "Meshlab" with its plugin entitled "Screened Poisson Surface Reconstruction" (RMSE: 0.25%). For height determination, the tool/code with a lower RMSE value (%) is the TREESQM (matlab package) code (RMSE: 7%). As for the Ficus of the Garibaldi Garden of Palermo, the tool/code with a lower value of RMSE (%) for the determination of the woody volume and height is the TREESQM (matlab package) code with a value of 19%.

There is not much evidence in the literature highlighting the effectiveness of these tools/codes in cases of extrapolating dimensional information on the species *Ficus macrophylla* subsp. *columnaris* with its particular dimensional aspect characterized by a high number of main stems & prop roots in an urban context through the use of HLS systems.

However, it was possible to witness the effectiveness of the latest tool/code applied in this case study (MATLAB TREESQM code) through the publication of the results of the article Wang *et al.*, 2022 (Wang *et al.*, 2022). In this work, the researchers examined the structural characteristics of various tropical species, such as *Ficus altissima*, using the same handheld laser scanner model applied to case study VI in order to collect basic information for use as a training dataset for an automatic species classification algorithm resulting in an average classification accuracy of 78%. In this paper, it was possible to demonstrate how LIDAR HLS data with the appropriate tool such as TREESQM tool demonstrate a high level of accuracy by determining an RMSE of DBH of 4cm and an RMSE of height of 0.52 m.

The results presented in this case study (VI) cannot be compared with the data from this last work of Wang et al., 2022 because the Ficus (*Ficus altissima*) trees examined are characterized by a single longilinear stem and a different morphology than the Ficus in case study VI. The Wang et al. 2022 article, like our cases demonstrates that handheld laser scanning data can provide detailed information on the structural characteristics of plants, useful for forest management and biodiversity assessment. From the results obtained of this case study we can reiterate that these processing methodologies and volume extrapolations through mobile LIDAR input data are effective in their 3D modeling role. In this case it was possible to discover the potential of these tools/ codes in the preliminary stages of urban green planning. Specifically, in the case of the TREESQM code (matlab package) in the phase of extrapolation of the volumes it was possible to have further dendrometric data through the automatic creation of graphs related to the architectural aspect of the investigated tree. These plots are present as a data supplement at chapter 6.2. While, about the tool "Meshlab" it has been noticed that the ease of execution of the steps for the application of the tool inside the software is an advantage for those who want to approach 3D modeling. However, the dimensional aspect of *Ficus macrophylla* subsp. *columnaris*, characterized by a high number of stem and props, might influence the complexity of extrapolating the final data both in terms of time and complexity of examination procedures. It is important to investigate the complexity of extrapolation from well complex plants such as the case of *Ficus macrophylla* subsp. *columnaris*, with the aim of identifying the limitations and potential of these tools/codes in the field of precision urban silviculture.

In the field of precision urban forestry, the researchers and professionals studying natural monumental heritage, have benefited greatly from recent advancements in proximal sensing technology. By utilizing LIDAR datas, various processing techniques were employed through specialized computer algorithms, leading to the extraction of biometric measurements related to the above-ground parts of trees, essentials for developing management tools for monumental greenery. In particular, research advancements for analyzing tree canopies have yielded useful information beyond the basic knowledge of tree parameters, such as the spatial distribution of tree stems under the canopy, estimated total canopy volume, and dimensional information of first-order branches (Herrero-Huerta et al., 2018, Pérez-Martín et al., 2021). Furthermore, many researchs has shown that the additional structural information obtained from the HLS survey can help identify possible anomalies or defects in trees, which is essential for categorizing greenery into failure propensity classes (CPC) according to the SIA (Italian Society of Arboriculture) protocol (Herrero-Huerta et al., 2018; Ghanbari Parmehr et al., 2021, Wang et al., 2022).

In this case study on the characterization of a monumental single trees with a HLS LIDAR tool, these proven tools/codes have proved to be a valuable resource for obtaining future insights and analyzing the multifaceted role that monumental trees play in their surrounding urban environment.

4. CONCLUSIONS

It is clear that Precision Forestry, with its focus on the integration of innovative technologies in spatial planning and management processes, has a significant potential to benefit the forestry sector. In this thesis address the vulnerable points of knowledge related to terrestrial LIDAR technologies supported by mobile platforms on the forest management answering the following hypotheses posed about the HLS system's potential benefits for forestry companies as the following:

H.1) HLS can improve the quality and efficiency of obtaining precise data in forestry by increasing the productivity of a forest company;

H.2) HLS can be influenced by some forest characters such as the structural complexity and species composition of a forest environment;

H.3) HLS can extract new information about a single tree and/or high quality forest environment.

Regarding the hypothesis H.1, this thesis focuses on the strengths and weaknesses of the mobile LIDAR system in the forest company through the results obtained from the case study I ("Investigation of HLS LIDAR scanning efficiency in several plots of high forest"). This study evaluates the efficiency of LIDAR HLS technology in comparison to traditional survey methods in the "Alpe di Catenaia" forest test plots. The study shows that the HLS system can produce accurate forest structural attributes estimation in coniferous sampling plots due to their simple linear structure, while broadleaf stands' complex structure hinders achieving high values of RMSE and bias. The study also carries out an analysis SWOT, following key points of the potential of HLS LIDAR tools compared to traditional survey methods in forest ecosystems. The study shows that a forestry company can obtain advantages in terms of productivity and efficiency by using the HLS LIDAR system in its business activity. For example, the innovative method using HLS scans reduced cost and time of the survey compared to traditional surveys. It is also supported by other articles as Bettella *et al.*, 2018; Beland *et al.*, 2019; Chen *et al.*, 2019; Del Perugia *et al.*, 2019. Furthermore, we can extrapolate a high amount of data about the structure aspect of the forest stand (as position, diameter, height, density of canopy cover, tree trunk profile, estimation of vegetation volume, leaf area index, leaf area density) that can be used for decision-making in management plans. In addition, you can create cartographic materials (The Canopy Height Model (CHM), Digital Terrain Models (DTMs), Digital Surface Model (DSM)) to support decision-making in operational activities. However, if a forest company wants to approach the use of the latest LIDAR technologies, they must also have a good technical support of advanced training on 3D modeling and LIDAR data processing. More details are given in an article Sofia *et al.*, 2022. With recent advances in LIDAR technology, especially the emergence of Hand-held Laser Scanner (HLS) systems that can provide accurate and efficient forest data, it has become increasingly possible to draw up effective forest management plans. If a forestry company partners with a university and combines their multidisciplinary expertise and research hypotheses with the needs of the company, this can lead to significant advances in the field of precision forestry.

Concerning the hypothesis H.2, the thesis directs attention to the variability of forest influenced by the dendrometric results taken from the LIDAR HLS scans and the versatility of LIDAH HLS tool to support the forest management planning. The case study II ("Benefit analysis of LIDAR HLS survey based on different types of walking paths") investigates the best walking path for HLS scanning to survey trees and estimate the biometric parameters of two forest stands (a beech-dominated deciduous forest and an oak-dominated deciduous forest). The study tests three different schemes in the literature performed in the same survey area, differentiating the study areas by slope, number of trees, and different tree dendrometric values. The study showed that the walking path scheme STAR demonstrated to be efficient in almost all plot sites in beech forests and suitable for height determination. In the case of oak forest, the same walking path scheme is acceptable for measuring the diameters but it is no more efficient than the others for the determination of heights. This case study confirms that each characteristic of forest structure influences the phases of extrapolation of dendrometric data from LIDAR HLS scans, increasing the time and complexity of Point Cloud processing and segmentation processes. For example, an increase in slope of the terrain and the numerical density within a hectare not only increase the time required for point cloud processing and segmentation working phases, but it also reduces the reliability of the results, especially regarding heights. However, this study analyzes some of the external variables of the forest and follows specific LIDAR data analysis methodologies. It is possible that in the future, more efficient algorithms and specific LIDAR processing or more functional HLS LIDAR instruments will be developed and made available for more complex forest contexts. Considering the flexibility of HLS systems in forest environments, this thesis has demonstrated the potential of the technology even in more complex situations, such as in the case study conducted in the Mediterranean forest characterized by an abundance of shrubland macchia ("The fine-scale combustible matter classification in the context of the Mediterranean forest from HLS LIDAR data"). The study classifies the fuels material and understands the forest structure for drafting fire prevention interventions in a case of aged coppice forest dominated by holm oak. It reveals the existence of continuity in vegetation height and provides the opportunity to estimate the volume of vegetation present in the forest, which is essential information for preparing protection intervetions against possible fire hazards. Another case study that exponed the potential to applicate the LIDAR HLS technology for forest fields is the case study IV titled "Application of a method for assessing and scoring stem straightness in tree standing by LIDAR HLS surveys to quantify differences between stands of different log quality". This case study focuses on analyzing four different forest areas using LIDAR HLS survey data to classify the quality of the stand based on stem straightness, considering single layered stand of beech (Fagus sylvatica), transitional stand of broad-leaved trees (Quercus ilex), ancient high forest monoplane stand (Castanea sativa) and adult monoplane stand (Pinus nigra plantation). The results showed that each forest area had different percentages of stem straightness scores, indicating their potential for woody material for different purposes such as firewood or carpentry. Overall, the deliverables included a stand quality classification based on the stem straightness scoring system with the aim of providing the best support for live tree quality analysis for future logging operations.

In relation to the hypothesis H.3, the thesis emphasizes the application of LIDAR HLS data. In terms of single tree analysis, the potential of LIDAR HLS technology for determining dimensional parameters is enhanced in cases that require particular attention. For instance, in the case study V titled "Characterization of Old-Growth Forest with a HLS LIDAR tool" the dimensional features of Mediterranean forest areas (high forests with a predominance of white oak) were examined, and parameters suitable for the classification of old-growth forest according to established criteria were identified. In this particular study the better 3D restitution of the old-growth forest environment contributed to exploring the major details of dimensional canopy of these trees and to better organizing future sustainable forestry interventions. Furthermore, it was possible to estimate the presence of canopy gaps that may occur in the future through the horizontal projections of the canopy of large trees obtained from HLS LIDAR data, with the aim of investigating the development of ecological forest succession for these old-growth forest ecosystems. Another case study demonstrated the opportunity to carry out a dimensional and structural description of individual plants using the LIDAR survey. This case study examined Mediterranean Ficus trees to identify the distinctive information of the monumental species. In detail, height, canopy diameter, canopy surface, stem size and woody volume were analyzed using different digital 3D modeling softwares. Additionally, this case study discusses the use of 3D modeling tools and mobile LIDAR input data to obtain dimensional and structural information about trees. This case study shows that the processing methodologies and volume extrapolations through mobile LIDAR input data are effective in their 3D modelling role and this LIDAR technology provides suggestions for future studies in urban green planning. In the light of the results of the last two cases, we can say for the hypothesis H.3 by stating that HLS instrumentations can be a turning point for determining new information that will support the planning of future single-tree care and treatment interventions.

This thesis contributes to the news knowledge on precision forestry by offering valuable information on the feasibility and productivity of implementing innovative technologies to observe and understand forest ecosystems. This research focuses on addressing gaps in the use of advanced HLS technologies in forestry, as well as exploring additional research opportunities that have not yet been fully explored in the literature.

Future research should address opportunities for applying this type HLS system in forestry in order:

- to obtain better data quality of complex forest vegetation conditions combining with other active or passive optical tools;
- to also identify the better procedures of point cloud segmentation for every forest type, by testing other algorithms as in the bibliography;
- to learn a lot about the imperfections and peculiarities of tree stems and be used to improve biodiversity evaluations and ensure good management.

Nowadays, these technologies and knowledge would make it possible to establish new reference parameters for sustainable forest planning, making surveys ever more important with innovative measuring instruments and following the ecological needs of the forest ecosystem, also with reference to the single individual tree.

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Acronyms:

HLS: Handheld Laser Scanning

LIDAR: Light Detection And Ranging

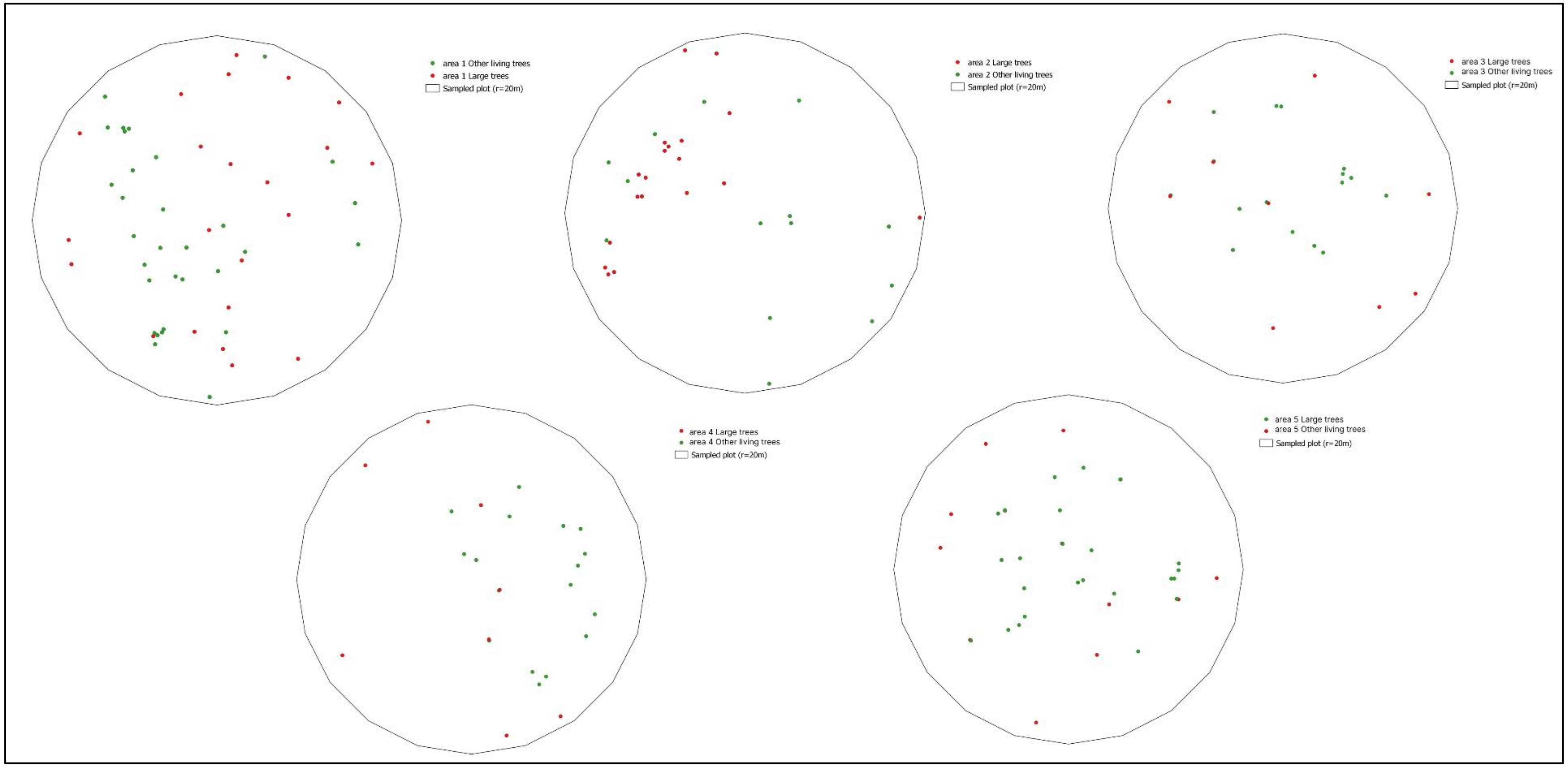
SLAM: Simultaneous Localization and Mapping

VLP =Velodyne's Puck LIDAR sensor

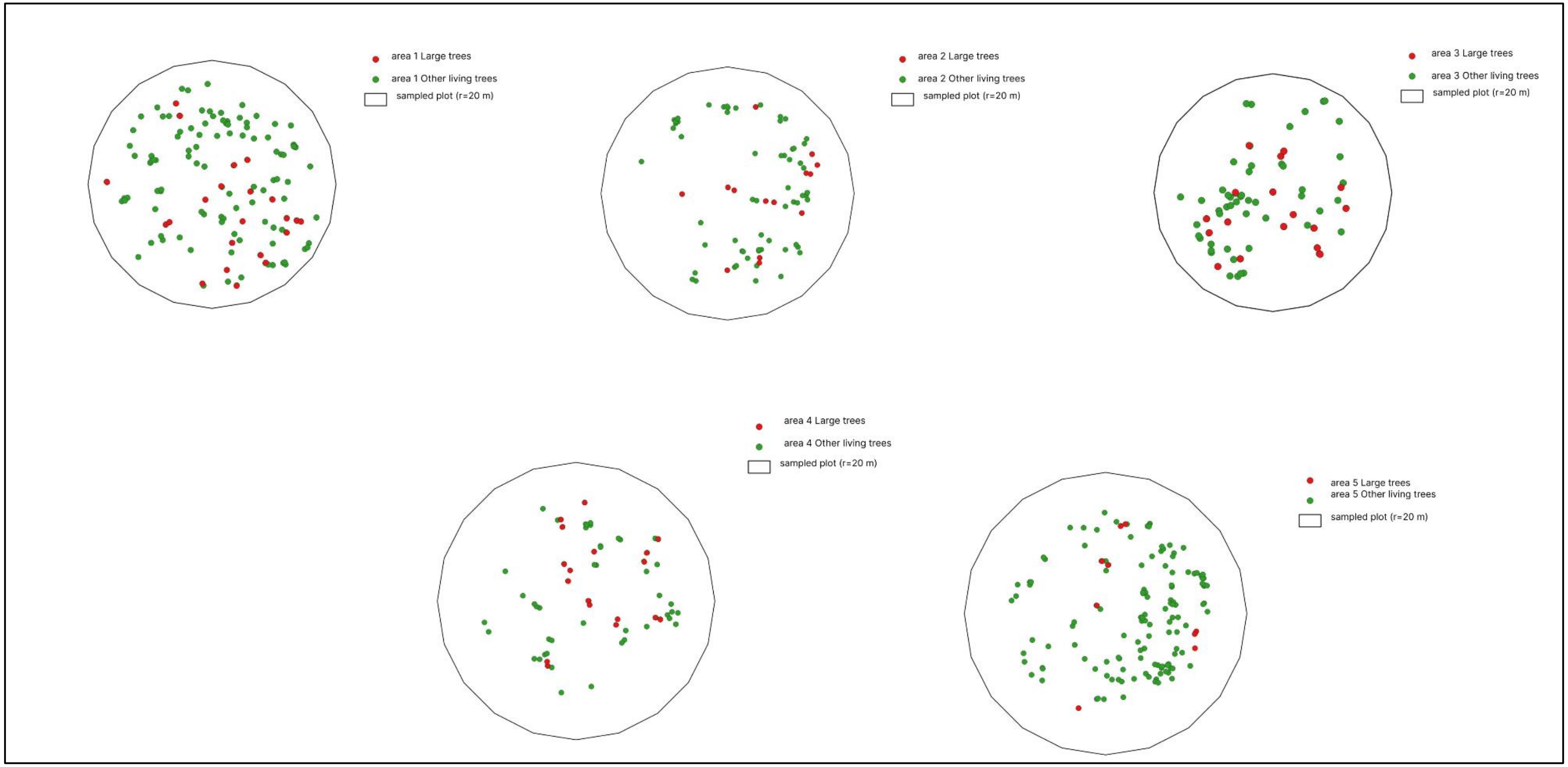
6. APPENDIX

6.1 Maps of 5th case study: Spatial distribution of individual Old Growth trees in each survey plot.

6.1.1 “Bosco del Fanuso” (Ficuzza) spatial distribution map.

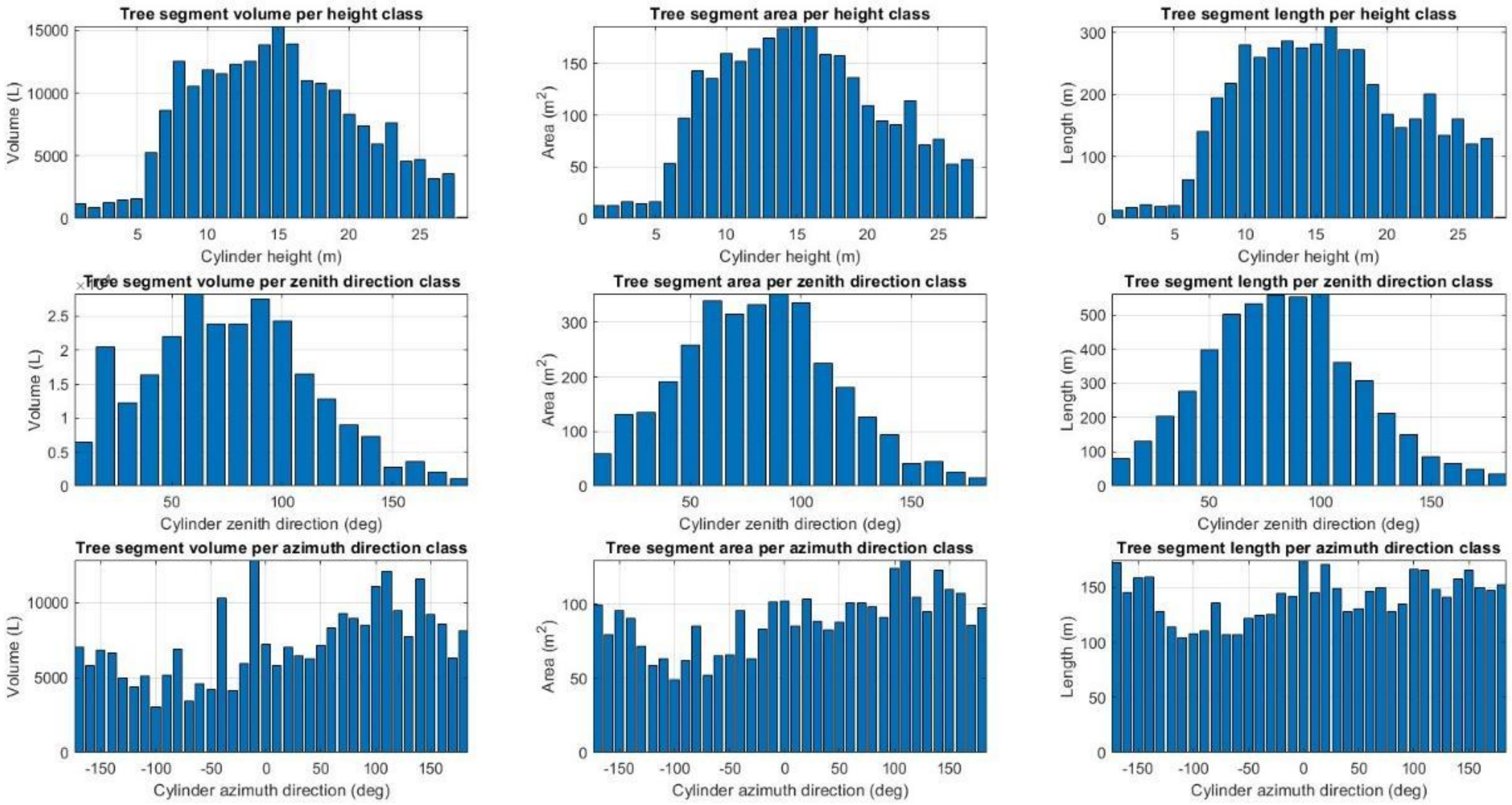


6.1.2 “Bosco del Gurgo” (Santa Maria del Bosco) spatial distribution map.

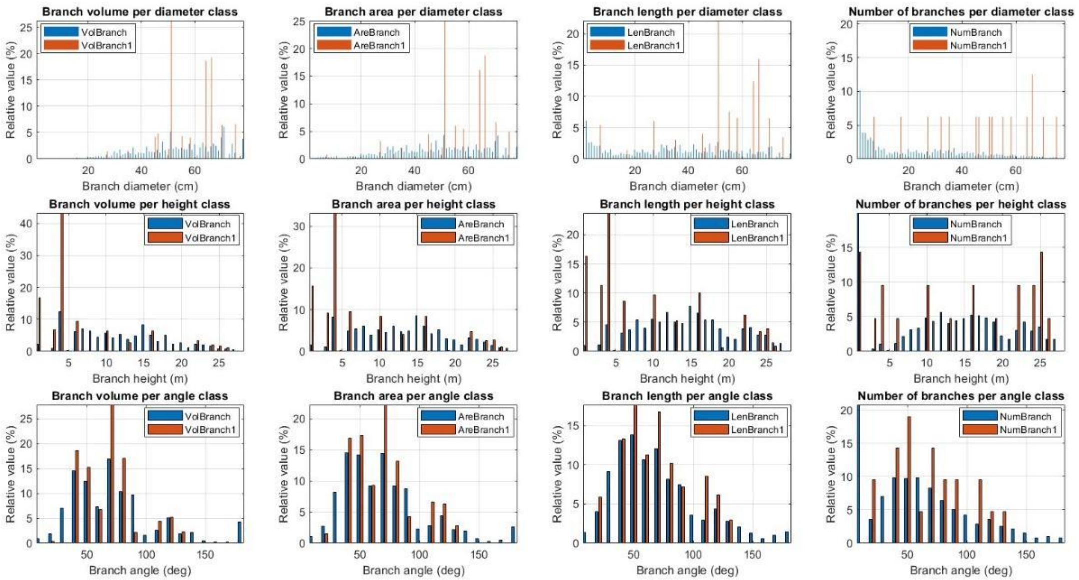


6.2 Addit supplement material of 6th case study: Boxplots and Grafical restitutions of code TREESQM (MatLab package).

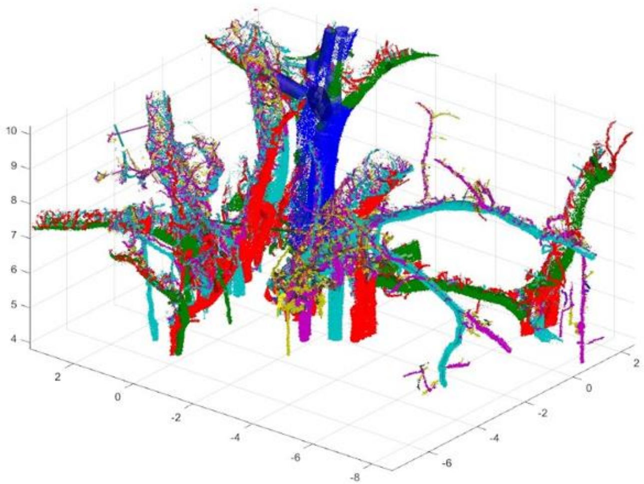
6.2.1 Ficus tree of Palermo Botanical Garden results, (a) “Tree segment" volume box-plots, (b) Distribution of All branch in diameter, heigh and branching angle classes, (c) TreeSQM Grafical restitutions.



(a)

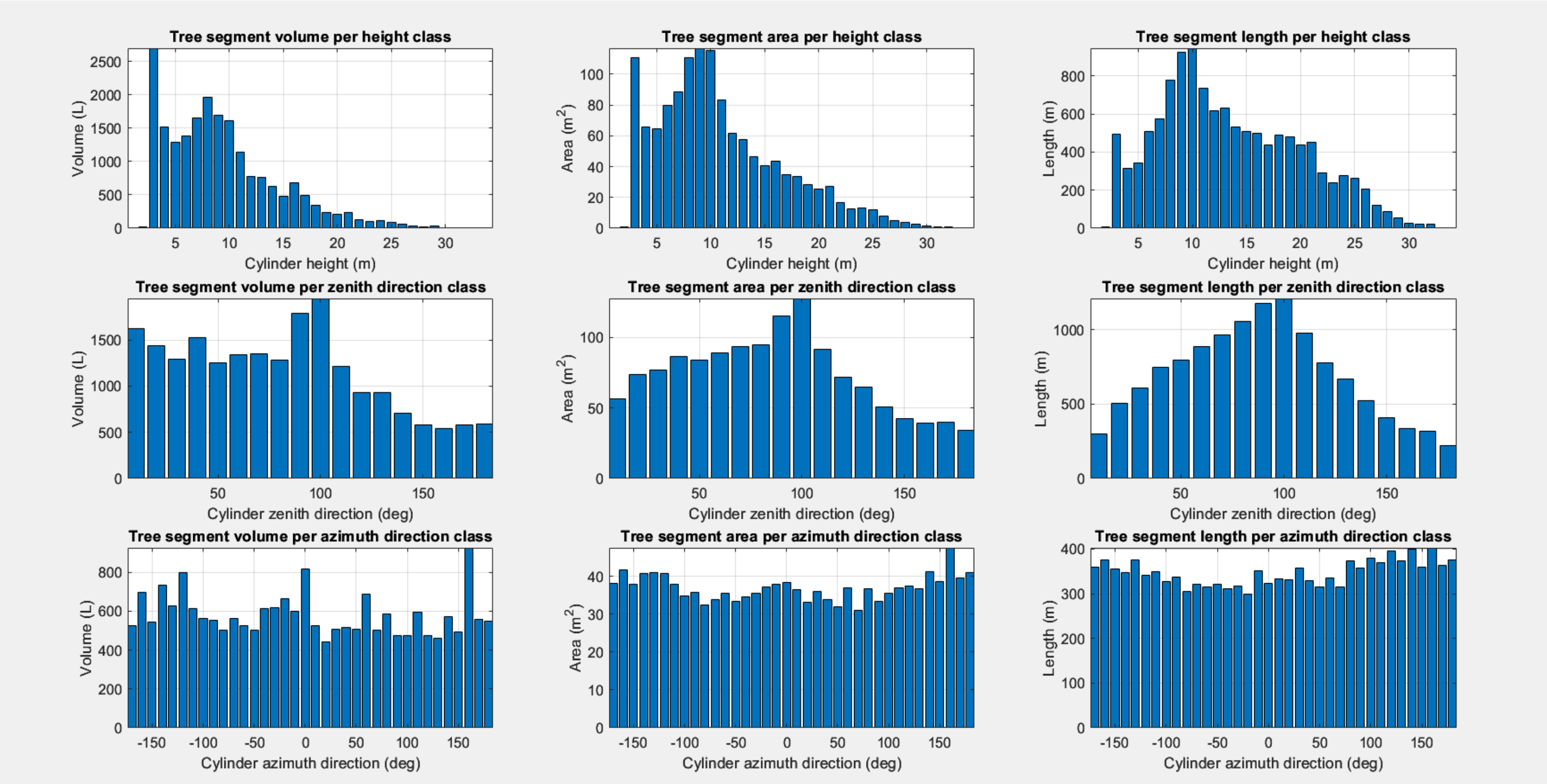

Branch volume per diameter class
Branch area per diameter class
Branch length per diameter class
Number of branches per diameter class
Branch volume per height class
Branch area per height class
Branch length per height class
Number of branches per height class
Branch volume per angle class
Branch area per angle class
Branch length per angle class
Number of branches per angle class
VolBranch
VolBranch1
AreBranch
AreBranch1
LenBranch
LenBranch1
NumBranch
NumBranch1
Relative value (%)
Branch diameter (cm)
Branch height (m)
Branch angle (deg)

(b)

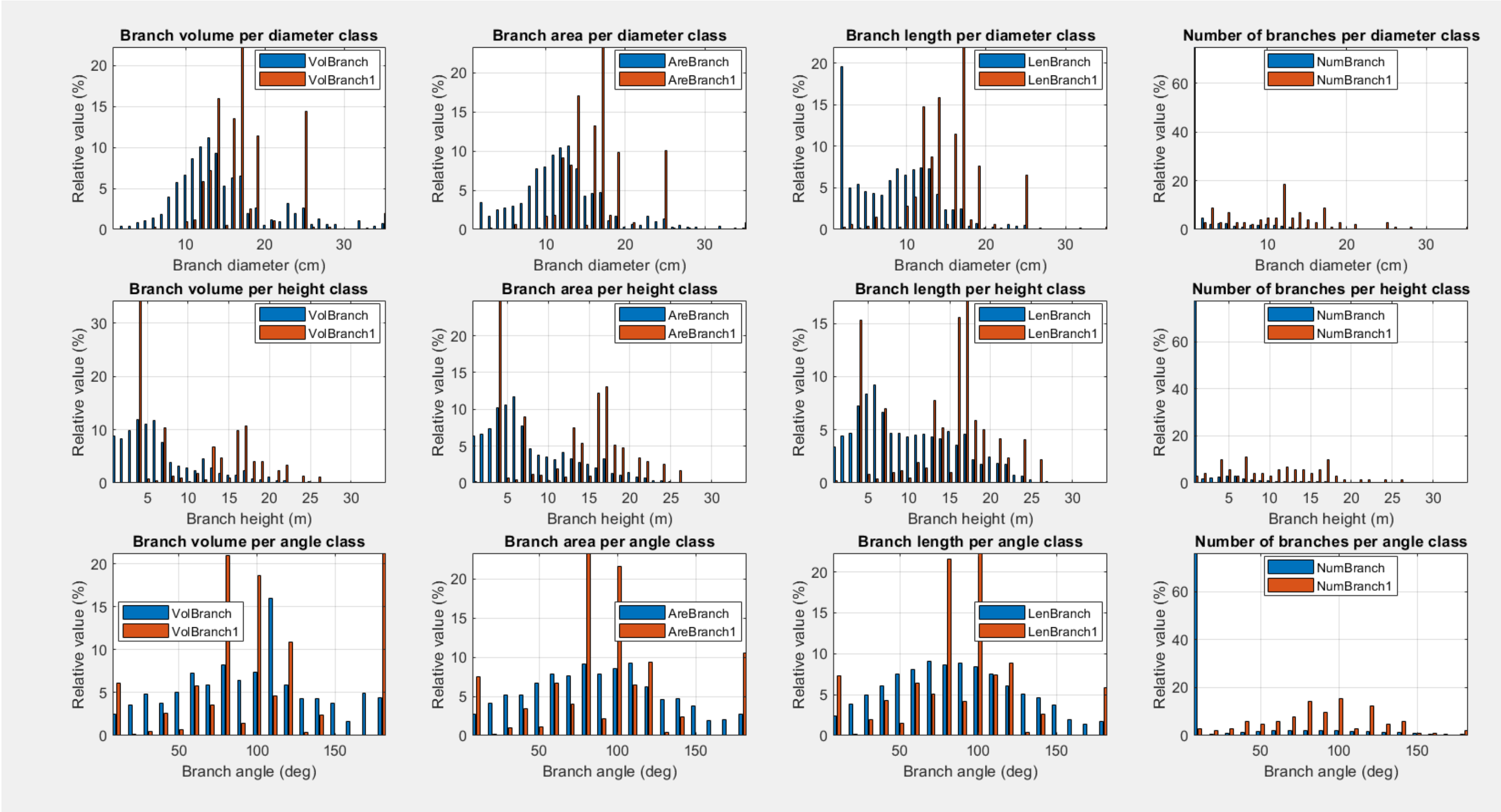


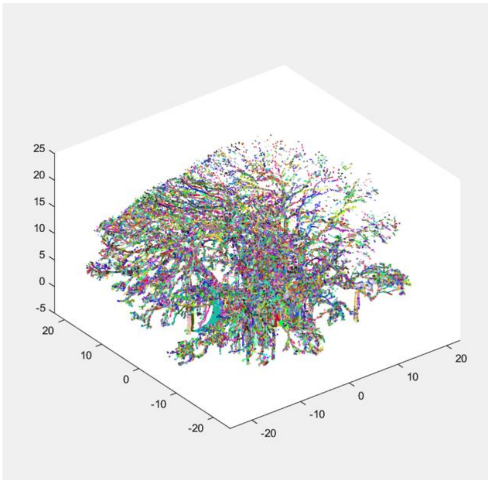
(c)

6.2.2 Ficus tree of Garibaldi Garden results, (a) “Tree segment" volume box-plots, (b) Distribution of All branch in diameter, heigh and branching angle classes, (c) TreeSQM Grafical restitutions.



(a)


Branch volume per diameter class
Branch area per diameter class
Branch length per diameter class
Number of branches per diameter class
Branch volume per height class
Branch area per height class
Branch length per height class
Number of branches per height class
Branch volume per angle class
Branch area per angle class
Branch length per angle class
Number of branches per angle class
VolBranch
VolBranch1
AreBranch
AreBranch1
LenBranch
LenBranch1
NumBranch
NumBranch1
Relative value (%)
Branch diameter (cm)
Branch height (m)
Branch angle (deg)
(b)


(c)