Advancing forest biodiversity conservation with the EL-BIOS digital twin: an integration of LiDAR and multispectral earth observation data

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ABSTRACT

The growing threat to biodiversity and ecosystem degradation necessitates innovative methods for monitoring and managing forested areas. This paper introduces the LIFE EL-BIOS project, a pioneering initiative to develop a Digital Twin for forest biodiversity analysis using terrestrial and airborne Light Detection and Ranging (LiDAR) technologies. The project utilizes advanced equipment, including the DJI Matrice 300 UAV with airborne LiDAR, DJI Mavic 3E, Quantum Systems Trinity F90+ with RGB and multispectral sensors, a GeoSLAM ZEB REVO terrestrial SLAM device, and a Leica BLK360 terrestrial laser scanner. Research spans over 40 forest plots, each 2000 square meters, in Greece's Kotychi-Strofilia Wetlands and Northern Pindos National Parks. The methodology integrates and georeferences point clouds from aerial and terrestrial sources to create unified point clouds for each area. Advanced software tools, such as 3DFIN and 3DFOREST, are then used to extract precise biodiversity-relevant parameters. This innovative data extraction method is compared with traditional in-situ measurements to evaluate the potential and limitations of the Digital Twin approach. A preliminary assessment focused on the time- and cost-effectiveness, accuracy, and robustness of this multiscale Earth Observation (EO) based mapping framework. Initial results suggest that the combined use of terrestrial and airborne LiDAR, multispectral data, and advanced analysis pipelines enhances the accuracy and speed of biodiversity measurements. Moreover, it allows for the extraction of additional information critical for developing biodiversity indicators. This study highlights the potential of multiscale and multisource EO data in creating digital twins of ecologically sensitive areas, offering a revolutionary approach to environmental conservation.

Keywords: Biodiversity, Digital Twin, LiDAR, SLAM, UAV, TLS, Remote Sensing, Environmental Observation, Forest Management.

1. INTRODUCTION

Biodiversity, the variety of life on Earth, encompasses the diversity of genes, species, and ecosystems, all of which contribute to the stability and health of our planet's ecological systems. It provides critical ecosystem services such as pollination, which is essential for the reproduction of many plants, including crops, nutrient cycling, which involves the decomposition of organic matter and the recycling of nutrients necessary for plant growth, and climate regulation, where diverse ecosystems like forests and wetlands play significant roles in sequestering carbon dioxide and moderating global temperatures [1]. These services are indispensable for human survival and well-being, supporting food security, clean water, and a stable climate. Today, biodiversity is under unprecedented threat from various anthropogenic factors. Habitat destruction, driven by urbanization, agriculture, and deforestation, leads to the fragmentation and loss of ecosystems [2]. Climate change, caused by increased greenhouse gas emissions, alters habitats and the distribution of species, threatening their survival. Pollution from industrial, agricultural, and domestic sources contaminates air, water, and soil, impacting the health of wildlife and ecosystems. Overexploitation of resources, such as overfishing, hunting, and logging, depletes populations of species and disrupts ecological balance [3].

Understanding and conserving biodiversity has thus become a global priority. In the area of forest biodiversity monitoring, traditional in-situ measurements, while accurate, are often costly and time-consuming. These methods require significant

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manpower and time to measure parameters such as Diameter at Breast Height (DBH), Crown Width (CW), and Tree Height (TH). The need for more efficient and scalable methods to monitor forest ecosystems has led to the exploration of advanced technologies. Recent advancements surveying technologies, such as Simultaneous Localization and Mapping (SLAM), Photogrammetry and Laser Scanning, offer promising alternatives. These technologies can rapidly acquire high-resolution spatial data over large areas, reducing the time and labor required for traditional field measurements. For instance, Unmanned Aerial Vehicles (UAVs) equipped with airborne Light Detection and Ranging (LiDAR) devices and multispectral sensors provide precise measurements of forest structure, including canopy height and ground topography. On the other hand, SLAM devices and stationary Terrestrial Laser Scanners (TLS) systems capture detailed point clouds of the forest floor and under canopy areas, complementing the aerial data [4].

In this context, the LIFE EL-BIOS project, titled "Hellenic Biodiversity Information System: An innovative tool for biodiversity conservation", has undertaken significant research efforts to monitor and analyze biodiversity using the aforementioned advanced surveying technologies. This project aims to create a comprehensive biodiversity information system to aid in conservation efforts across Greece. This study focuses on the application of these advanced scanning and surveying technologies at two key sites: the Kotychi-Strofilia Wetlands and the Northern Pindos National Parks. By creating Digital Twins of multiple forest plot areas in both regions, this research provides valuable insights into the methodology of the measurement process, data collection, and analysis using these modern technologies. The study discusses approaches to the challenges encountered, identifies potential weaknesses, and ultimately compares the results with traditional in-situ measurements to derive useful conclusions. Through this comparative analysis, the research aims to demonstrate the effectiveness of integrating traditional and modern methods for forest biodiversity monitoring, thereby supporting more efficient and accurate conservation strategies.

2. METHODOLOGY

Study Areas

This study focuses on National Parks of Kotychi-Strofilia Wetlands, and Nothern Pindos. Both areas are protected and recognized for their significant natural beauty and rich biodiversity. The selection of these sites was purposeful: Kotychi-Strofilia represents a coastal wetland ecosystem, while Pindos National Park is part of a mountainous range:

The National Park of Kotychi-Strofilia Wetlands, located in the coastal zone of northwestern Peloponnese, stretches from the Gulf of Patras and Cape Araxos in the north to Lechaina and just before Kyllini in the south. It is the largest wetland ecosystem in the Peloponnese and has been designated a National Park since 2009. It features wetlands of international importance and an extensive coastal zone with dunes and sandy beaches. Representative plant species among others in the Strofilia forest include the stone pine (Pinus pinea), Aleppo pine (Pinus halepensis) and Valonia oak (Quercus ithaburensis) [5].

The Northern Pindos National Park, the largest national park in Greece, spans nearly two million hectares. The park located to Greece's second-highest mountain, Smolikas. It hosts many rare, endemic, and threatened species, contributing to its exceptional biodiversity. In this study, the data acquisition process focuses on the Valia Kalda area, which includes dense beech forests (Fagus sylvatica), black pine forests (Pinus nigra), Bosnian pine (Pinus heldreichii) above 1,500 meters, numerous springs, and mountain lakes [6].

Plot Areas Selection

The field campaigns were conducted in two different periods. Specifically, data collection in the Strofilia forest took place in November 2022, while the corresponding collection in the Northern Pindos National Park occurred in July 2023. In both cases, the survey areas were carefully selected to encompass as many distinct species and varying vegetation conditions as possible. This included reforested areas, regions with denser or sparser vegetation, areas adjacent to streams and wetlands, zones with different plant species, and regions with varied terrain, especially in the case of Pindos. The accessibility of the sites was a crucial factor in their selection. The coverage area for these sites ranged from one to two hectares. The centers of these areas were preliminarily identified using satellite images and were then fixed on the study field based on multiple parameters such as accessibility on foot and the diverse conditions mentioned above.

Ultimately, 13 plots were selected in the Strofilia forest, and 21 plots were chosen in Northern Pindos National Park. This strategic selection ensured a comprehensive representation of the biodiversity, and ecological conditions present in each national park, facilitating a more thorough and effective data collection process (see Figure 1).

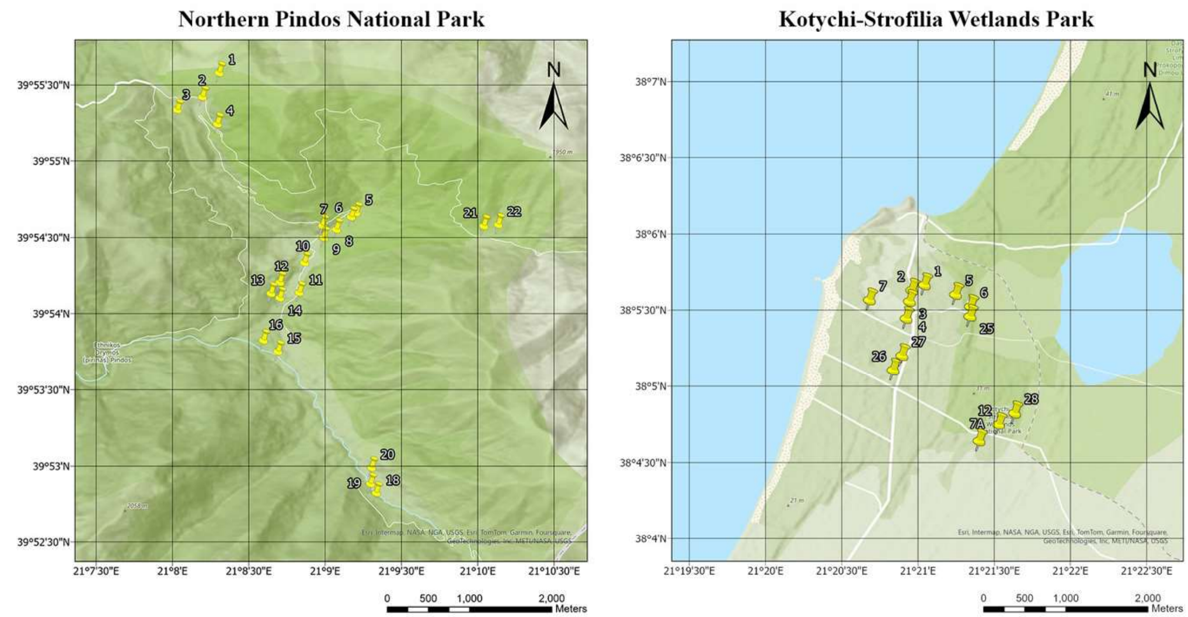


Figure 1. The locations of the plot areas centers in the Kotychi-Strofilia and Northern Pindos National Parks were determined with careful consideration. The identification of these points does not follow sequential numbering.

Data Acquisition

The measurement phase of the selected plot areas involved aerial data capture using UAVs and ground measurements within the surfaces using SLAM device and, selectively, TLS equipment. For georeferencing the resulting point clouds, GNSS receivers implementing the Network Real-Time Kinematic (NRTK) technique were used in areas where GNSS signals and mobile network coverage were available.

For the photogrammetric survey of the Strofilia forest, the fixed-wing UAV, Quantum-Systems Trinity F90+, was employed. The primary sensor payload for this UAV was the RGB Sony UMC R10C 20.1 MP camera. The F90+ provides Post Process Kinematic (PPK) capabilities, ensuring quick georeferencing of the captured photos and the extracted point clouds. It also supports Vertical Take-off and Landing (VTOL), meaning it can take off vertically, perform the pre-programmed flight path, and land vertically. However, it requires a large open area for takeoff and landing because it ascends and descends in wide circles around the launch or landing site. This requirement led to the decision to select a specific obstacle-free area for takeoff and landing and to survey a larger region than the selected plot areas. During post-processing, the areas of interest were identified and isolated for use in the data fusion phase [7].

The Quantum-Systems Trinity F90+ played a crucial role in the rapid and efficient surveying of the study areas in the Strofilia forest, where the terrain does not exhibit significant variation. This UAV is characterized by its lightweight and speed, allowing it to scan large areas in a short amount of time. Additionally, its battery life can last up to 90 minutes, enabling the coverage of all study areas in the Strofilia forest with just three separate flights. The collection of photographs in the Strofilia forest was conducted from a flight altitude of 70 meters Above Ground Level (AGL) with a Ground Sampling Distance (GSD) of 1.86 cm/px.

While these features provide significant advantages, the operational characteristics of this drone make it more vulnerable in areas with steep terrain changes. In case of Northern Pindos National Park, where there are substantial elevation gradients, the Trinity F90+ is less suitable for flight activities compared to a quadcopter. This is because it lacks the immediate obstacle avoidance capability provided by rapid altitude changes. Furthermore, in steep terrains, the drone struggles to maintain a consistent Ground Sampling Distance (GSD) during photogrammetric surveys, leading to lower quality data. The design of the Trinity F90+ also makes it quite sensitive to wind variations, which can disrupt its ability to follow a steady flight path and ensure the planned overlap between successive photos. This sensitivity can compromise the data quality, making it challenging to achieve the required accuracy for detailed mapping in complex terrains. Despite these limitations, the Trinity F90+ remains highly effective in flat and open areas, making it an excellent choice for surveys in regions like the Strofilia Forest (see Figure 2).

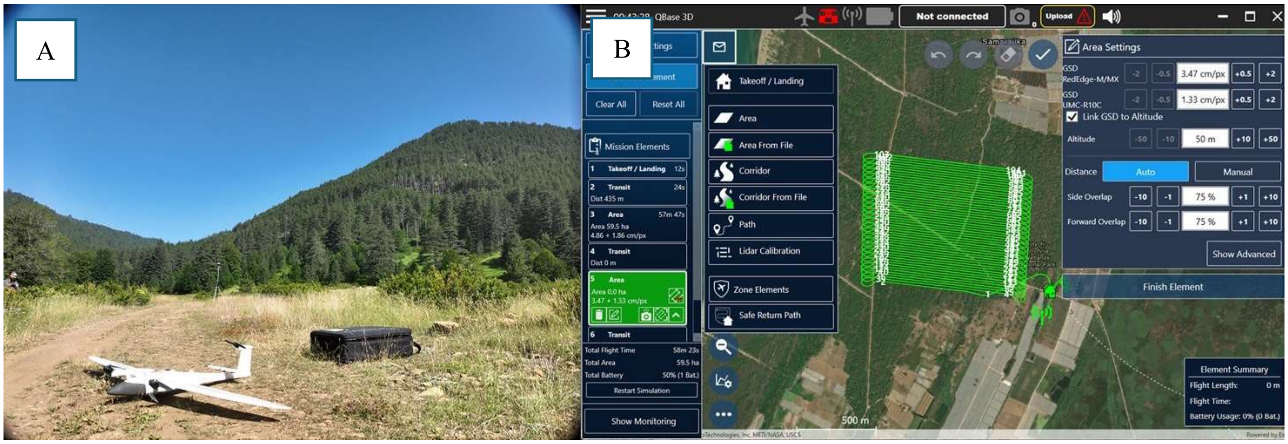


Figure 2. The Quantum Systems Trinity F90+ Fixed Wing VTOL UAV with the RGB Sony UMC R10C 20.1 MP camera payload (Left). Flight planning with QBBase 3D software in Strofilia forest (Right).

For these reasons, the Mavic 3E quadcopter was employed for the photogrammetric survey of the plot areas of interest in Northern Pindos. The Mavic 3E is equipped with a 4/3 CMOS 20 MP lens and a mechanical shutter, weighing approximately 900 grams. Its compact size and nature as a quadcopter with obstacle avoidance sensors provided significant flexibility in Northern Pindos. The drone's capability to take off and land within areas of dense vegetation allowed it to survey selected regions effectively. The Mavic 3E's battery life of approximately 30 minutes was instrumental in covering larger areas without the need for frequent battery changes and recharges. This feature was particularly advantageous given the challenging accessibility of Valia Kalda area, which is at least an hour away from the nearest Village. The real-time monitoring capability provided by the Mavic 3E's controller was crucial in ensuring the quality of the data collected during the survey. This feature allowed for immediate adjustments to flight plans, enhancing the adaptability of the system to the dynamic conditions of the mountainous terrain [8]. Additionally, the drone's ability to collect RTK data through its integrated GNSS antenna significantly aided the data processing phase. The data were already georeferenced to the Hellenic Geodetic Reference System (GGRS 87), and the projection TM87, streamlining the post-processing workflow. The flights conducted in Valia Kalda area to cover all plot areas were 10 in total. They were conducted from a flight altitude of 50 meters AGL with a GSD of 1.37 cm/px (see Figure 3).

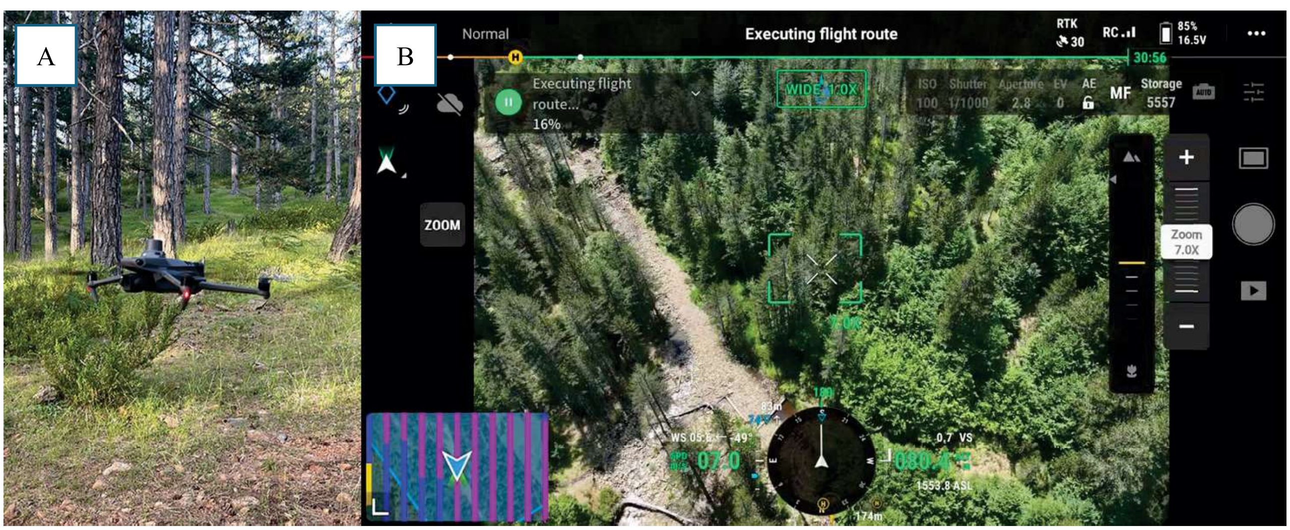


Figure 3. The DJI Mavic 3E UAV (A). Screenshot from the Mavic 3E remote controller executing a flight route in Northern Pindos National Park (B).

Photogrammetry, while highly effective and commonly used in aerial surveys, is not the optimal choice for forest environments when used alone. Although accurate results can be achieved, these results are insufficient for the complex structure of forests like those in Strofilia and Valia Kalda, which consist of very tall trees situated close together. This dense canopy prevents aircraft from capturing images of the ground or lower parts of the trees, resulting in a 3D model that predominantly represents the upper canopy. Therefore, integrating LiDAR technology has become essential in modern forest studies. LiDAR operates by emitting laser pulses and measuring the time it takes for these pulses to return after striking an object, enabling the creation of detailed three-dimensional models of both the forest canopy and the ground. A key advantage of LiDAR in UAV-based forest mapping is its ability to penetrate the canopy, capturing data from the upper vegetation layer, the understory, and the ground level. This capability is crucial for assessing the vertical structure of the forest, including vegetation distribution at different heights. Traditional photogrammetry alone struggles to provide such detailed vertical information due to canopy penetration limitations. LiDAR excels in capturing intricate forest morphology details, including ground elevation variations and topographic changes such as slopes and valleys. It also facilitates the creation of Digital Terrain Models (DTMs) and Digital Surface Models (DSMs), which are critical in forest applications. DTMs represent the bare earth surface, offering insights into the physical topography, while DSMs include the forest canopy, providing a comprehensive view of the landscape. This distinction is vital for tasks such as canopy height calculation and biomass volume estimation [9].

For the airborne LiDAR data acquisition in selected plot areas, the DJI Matrice 300 RTK UAV was used, equipped with the CHCNAV AlphaAir 450 LiDAR system. This setup combines various sensors, including GNSS for satellite data acquisition, an Inertial Measurement Unit (IMU) for rapid recording of rotational and acceleration data, and an RGB camera for capturing images to colorize the point cloud collected by the LiDAR sensor. The AlphaAir 450 relies on the Livox Avia sensor, which supports three return pulses, making it suitable for fast and efficient scanning of the study areas. The integrated 26 MP high-resolution camera has the same Field of View (FOV) as the Livox Avia, ensuring complete point cloud coverage with RGB coloration. Georeferencing was performed using the PPK method with a built-in GNSS receiver, separate from the primary GNSS receiver on the DJI Matrice 300. For flight planning in the field, the UGCS software was utilized (see Figure 4). This software is specifically designed to assist operators in automatically generating waypoints for the UAV, ensuring thorough scanning of the required area and calibrating the IMU of the sensor. Flights were conducted from an altitude of 70 meters. A total of nine flights were conducted to cover the plots in Valia Kalda, and six flights were carried out in the Strofilia forest, over a period of three and two days, respectively. The DJI Matrice 300, with the specified payload, has a maximum flight time of 20 minutes. Therefore, transporting multiple batteries and power stations to the field was crucial to avoid time loss due to relocations and recharging, ensuring continuous and efficient data collection [10].

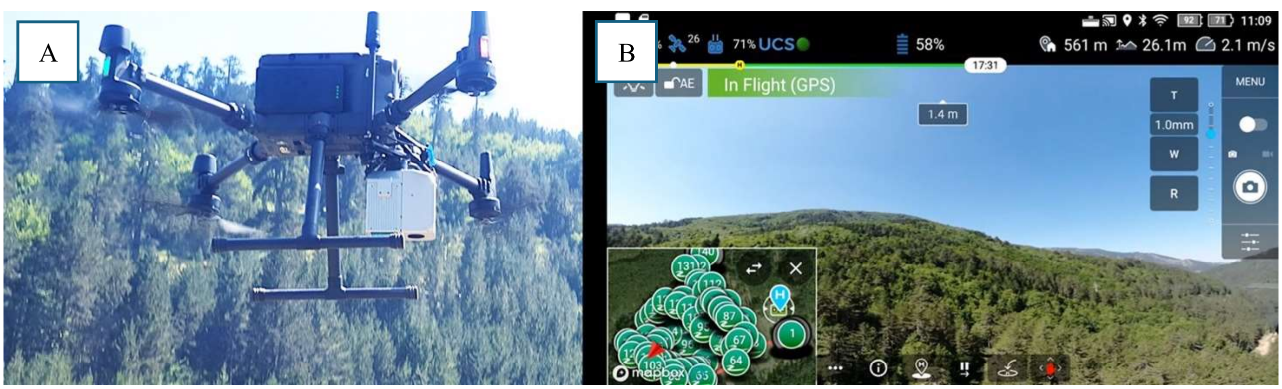


Figure 4. The DJI Matrice 300 UAV with CHCNAV AlphaAir 450 LiDAR (A). Screenshot from Matrice 300 remote controller executing a flight route using UGCS software, in Northern Pindos National Park (B).

In addition to airborne LiDAR, a SLAM device was employed in our study. SLAM technology combines data from the system's LiDAR sensor with data from its IMU. Using complex algorithms and mathematical tools, such as Kalman filtering, SLAM allows the user to move through space while simultaneously recording tens of thousands of points per second. In this study we used the ZEB REVO SLAM system by GeoSLAM. While the GeoSLAM ZEB REVO has the disadvantage of not producing colorized point clouds due to the absence of an RGB sensor, this did not impact our case. The geometric information extracted from the point cloud, which is critical for using segmentation software and 3D tree modeling, relies purely on geometric data rather than RGB information. The decision to use this technology was driven by its exceptional speed in the field, enabling the operator to cover extensive areas in a short period. This efficiency stands in contrast to traditional surveying techniques, which utilize theodolites and laser distance devices. Even TLS instruments require significantly more time to capture the geometry. The internal accuracy of the SLAM technology, yielding results within a few centimeters, combined with the high density of recorded point clouds, was deemed highly satisfactory for the project's requirements. The combined use of airborne measurements with data derived from the SLAM system leads to the creation of a digital twin for the area of interest. This digital twin provides valuable geometric information, facilitating further analysis and data processing to obtain essential tree metrics. These metrics, which can only be accurately measured beneath the canopy, include Canopy Cover (CC), Canopy Height (CH), and DBH, among others. The GeoSLAM ZEB REVO SLAM device was used to measure all the selected plot areas in this study [11].

The measurement approach for each selected plot area relied on fixed Ground Control Points (GCPs) for the GeoSLAM ZEB REVO system. For each plot area, approximately five GCPs were chosen. According to the manufacturer's guidelines, georeferencing the extracted point cloud from the ZEB REVO system requires the device to remain stationary for more than 20 seconds over fixed points with precisely known coordinates. This operational method relies on detecting this 20-second pause through the zeroing of acceleration in the device's IMU. Consequently, for each area, the system had to remain over each such point. These points were marked on the ground with various indicators, usually pre-printed targets. The GCPs were strategically placed around the perimeter of each study area, ensuring optimal geometry. Due to the dense forest canopy and mobile data connectivity loss, it was often not possible to accurately determine these points using NRTK methods with standalone GNSS Rover receiver. Therefore, the placement of the GCPs was based on locating clearings in the canopy to ensure visibility from aerial platforms, specifically UAVs used for photogrammetry with RGB sensors (Trinity F90+ and Mavic 3E). Both UAVs employed, contained GNSS receivers capable of PPK and RTK, enabling the precise determination of the coordinates for these GCPs during photogrammetric processing and point cloud generation in the Data Processing stage. These coordinates were then referenced to the local GGRS87 coordinate system. The SLAM process began at the center of each plot area and extended outward to the perimeter, covering the entire volume. The measurement process typically took about 2-4 minutes, depending on each plot area size (see Figure 5).

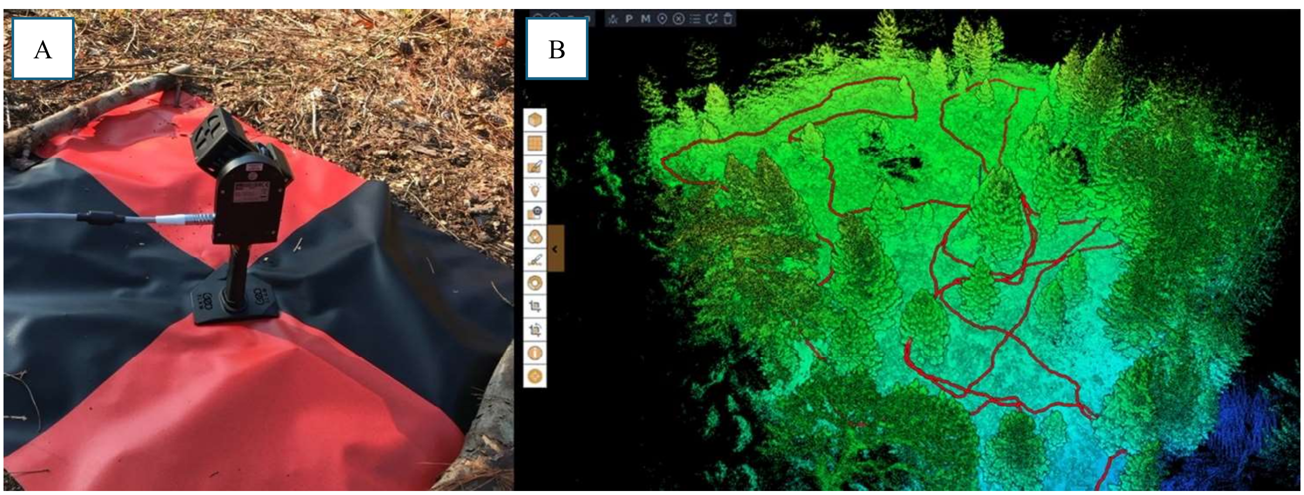


Figure 5. The GeoSLAM ZEB REVO on a GCP as a printed marker (A). The resulting point cloud and the trajectory followed by the operator within the plot area (B).

For the optimal measurement of biodiversity and to address the limitations of the RGB colorized point cloud under the canopy, the Leica Geosystems BLK360 TLS was employed in three selected plot areas (two in Strofilia forest and one in Valia Kalda). This was done to capture more detailed textures in the digital twin being created, specifically parameters such as microhabitats [12]. Although TLS systems are generally considered superior in terms of accuracy compared to SLAM systems, their use can present certain challenges in specific conditions. The surveying of forested areas with TLS proved to be more time-consuming. This technology operates by placing the measurement instrument at strategically selected points in the space, where it remains stationary for approximately five to seven minutes. In a dense forest environment like Strofilia forest and Valia Kalda with considerable undergrowth, numerous such stops are required, significantly slowing down the measurement process. Specifically, the number of scans conducted in the plot areas of Strofilia forest was 39 and 43, and 29 for the Valia Kalda plot. However, it should be noted that the resulting data was superior in terms of surveying accuracy (by few centimeters) compared to SLAM, which is crucial for many surveying tasks but not necessarily for biomass extraction cases. In the context of forest surface surveying, external factors such as wind, which causes movement at the higher points of trees, introduce a measurement uncertainty of about ten to twenty centimeters, equivalent to the sway of the trees. Thus, achieving centimeter-level accuracy is practically unattainable. The georeferencing of the point cloud was performed using common GCPs in this case as well (see Figure 6).

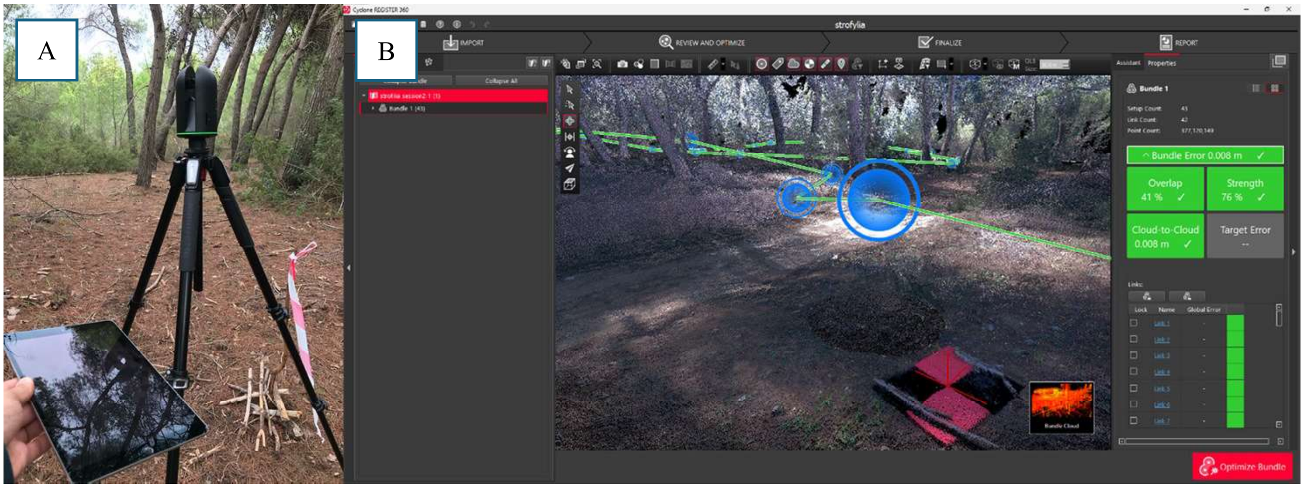


Figure 6. Leica Geosystems BLK360 (A). The resulting point cloud and the scan stations in the plot area. The point cloud georeferencing process is done using GCPs (B).

Two GNSS Rover receivers, specifically the Emlid Reach RS2 units, were used to aid in data collection. These receivers are capable of implementing the NRTK technique as well as recording static raw data. The receivers were utilized individually at various GCPs where sufficient mobile data coverage was available. Additionally, they were used together as a Base-Rover pair in areas lacking mobile data coverage, thanks to their integrated LoRa modems. The GNSS receivers were also employed during the UAV flights to collect synchronized reference epochs, facilitating the application of the PPK method [13]. This parallel usage ensured accurate georeferencing of the UAV data, enhancing the overall spatial accuracy of the captured point clouds (see Figure 7).

Figure 7. Emlid Reach RS2 GNSS Receiver. The receiver is positioned on a GCP, recording RAW data.

Measurements were conducted using traditional methods and equipment, including calipers, laser rangefinders, compasses, and measuring tapes. Each study plot was divided into quadrants. Starting from the center of each plot, the position of each tree (azimuth and distance) within each quadrant was determined, along with its key characteristics such as average DBH, crown height, and crown width. Upon completion of the measurements for each quadrant, the data was meticulously digitized into Excel spreadsheets. Subsequently, the data was imported into a Geographic Information System (GIS), where it was converted into shape files format for further analysis and integration with other datasets. This systematic approach ensured detailed and accurate mapping of the forest structure, providing a valuable baseline for comparison with the modern surveying techniques [14].

The collection of all measurements was conducted by the authors of this paper. The authors are certified UAV operators according to European Union Aviation Safety Agency (EASA) standards, holding A1/A3 and A2 licenses. The flight activities were carried out with the necessary permissions from the relevant authorities. Specifically, for the area of Northern Pindos National Park, permission was obtained from the management authority of the national park in conjunction with the Hellenic Civil Aviation Authority. For Strofilia National Park, the permit was granted by the Hellenic Air Force, with the Hellenic Civil Aviation Authority being informed, as the flight activity took place near the military airport of Araxos.

Data Processing

After collecting all the data, it was extracted and organized into folders based on the measurement source. The data from the selected areas in the Strofilia forest and Valia Kalda exceeded 2 TB in total. Initially, the photogrammetric data was processed. For the Trinity F90+, the accompanying software QBase 3D was used to georeference the images using PPK method. This process involved using Receiver Independent Exchange Format (RINEX) static measurements from the Emlid Reach RS2 station. From this procedure, final CSV files were generated for each flight, containing the ID of each photo, the geographic coordinates of the camera capture center, positional accuracy, and rotation parameters (pitch, yaw, roll). The geographic coordinates from the files were transformed into the GGRS87 reference system and projected into TM87, with orthometric heights adjusted using specific geoid model. In case of UAV Mavic 3E, the CSV georeferencing files were mostly ready from the drone due to its RTK enabled GNSS receiver. The primary processing needed in this case was transforming the geographic coordinates into the TM87 projection. In a few instances where the UAV controller lacked mobile data in the field, the PPK technique was used. In these cases, georeferencing was performed using Emlid Studio software, based on RINEX files from a stationary Emlid Reach RS2 receiver in the field. Agisoft Metashape software was utilized for photogrammetric processing and extraction of point clouds, DSM, DTM, and orthophotos for the plot areas covered by the flight missions [15]. This process also involved identifying GCPs in the captured photos and extracting their coordinates (see Figure 8).

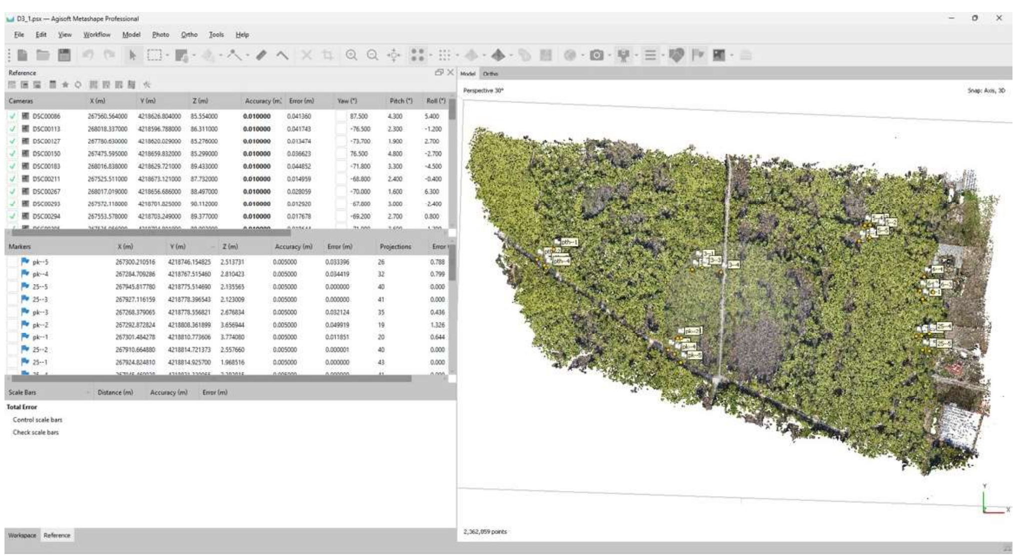


Figure 8. Processing a flight mission of Trinity F90+ in Kotychi-Strofilia Wetlands using Agisoft Metashape. The camera referenced parameters, was extracted using QBase 3D software. The geographic coordinates of georeferenced images were transformed into the GGRS87 reference system and projected into TM87. Accurate coordinates for the GCPs in the plot areas were provided from the photogrammetric resolution.

Next, the Airborne LiDAR data from the AlphaAir 450 sensor was processed. This data processing was performed using the accompanying CHCNAV CoPre software. Raw data in RINEX format from the Emlid Reach RS receiver was used in this case as well. CoPre handles the georeferencing and solves the trajectory followed by the UAV during its flight, as well as extracting the final colorized point cloud into LAS files (see Figure 9).

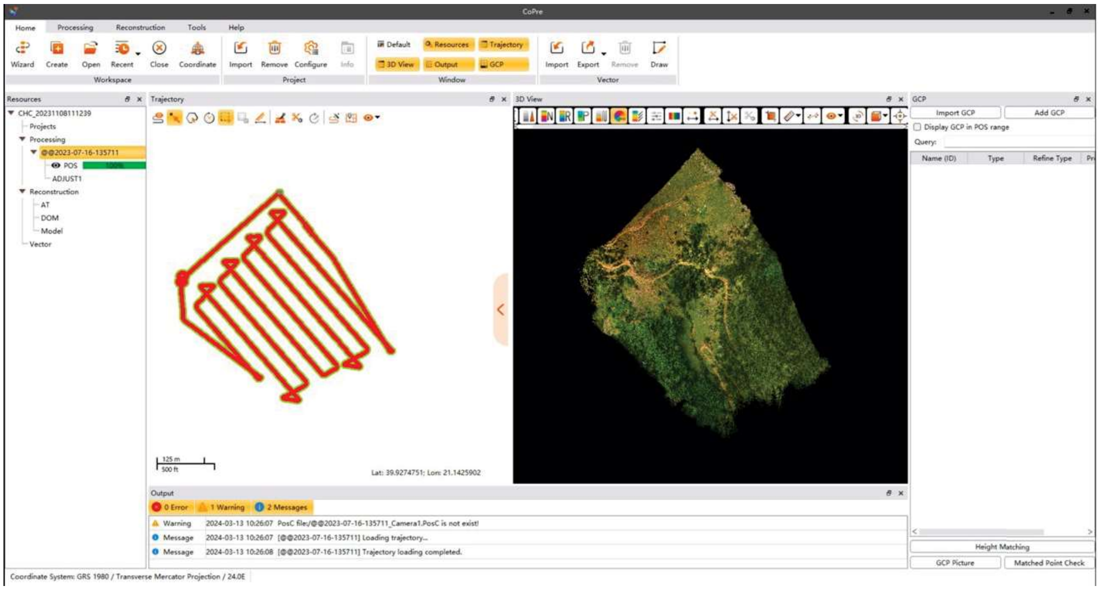
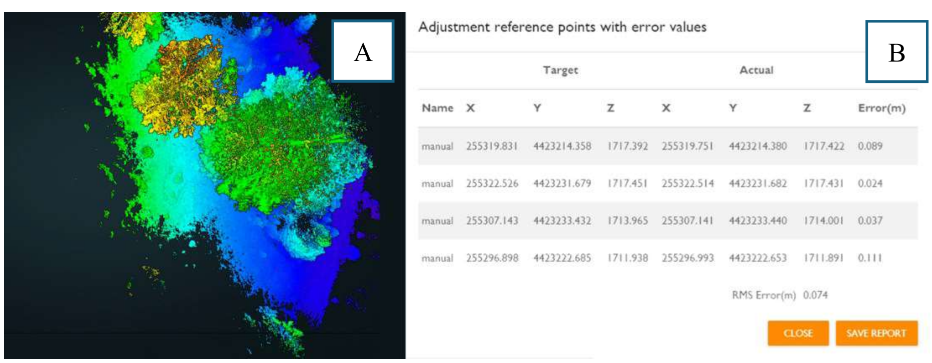


Figure 9. Trajectory processing and colorized point cloud extraction from a flight route in Northern Pindos National Park, using DJI Matrice 300 and AlphaAir 450 LiDAR sensor, with CHCNAV CoPre software

The extraction of the point cloud from the GeoSLAM ZEB REVO system was carried out using the GeoSLAM Connect software. In many cases, the point clouds generated by the SLAM sensor contained errors such as internal trajectory errors and noise. This necessitated the reprocessing of the data obtained from the SLAM sensor using different processing settings. During SLAM reprocessing, the primary goal is to optimize the algorithmic parameters. This involves fine-tuning the algorithms used for mapping and localization by changing the default settings in GeoSLAM Connect. The initial errors were due to the sloped terrain especially in Northern Pindos National Park, which created issues for the system's IMU. For instance, if the user made a sudden movement to maintain balance in the field, this could introduce a systematic error in the computed trajectory. Another factor was the field of view within the plot areas. At times, the SLAM user had to pass through narrow areas within the plots, introducing processing errors as the number of feature points captured at that moment might not have been sufficient to combine the individual data frames. After successfully resolving and extracting the point clouds, georeferencing was performed using the same software. The coordinates of the GCPs for each area were entered, and a non-rigid transformation was conducted by the software [16]. In most cases, the RMS error of this transformation was within a few centimeters (see Figure 10).



Adjustment reference points with error values

	Target			Actual			
Name	X	Y	Z	X	Y	Z	Error(m)
manual	255319.831	4423214.358	1717.392	255319.751	4423214.380	1717.422	0.089
manual	255322.526	4423231.679	1717.451	255322.514	4423231.682	1717.431	0.024
manual	255307.143	4423233.432	1713.965	255307.141	4423233.440	1714.001	0.037
manual	255296.898	4423222.685	1711.938	255296.993	4423222.653	1711.891	0.111

RMS Error(m) 0.074

CLOSE SAVE REPORT

Figure 10. The point cloud extraction of a plot area from GeoSLAM ZEB REVO, using GeoSLAM Connect software (A). The RMS error of non-rigid transformation adjustment of referenced points in the plot areas was within few cm, in most cases (B).

Registration and processing of point cloud data from the BLK360 was done using Leica Cyclone Register 360 software. During the registration and optimization of the bundle cloud, the coordinates of the GCPs visible in the generated RGB point cloud were also added to obtain the cloud georeferencing process. For the reference plot areas measured with the BLK360 scanner, the resulting bundle error was approximately one centimeter (see Figure 11).

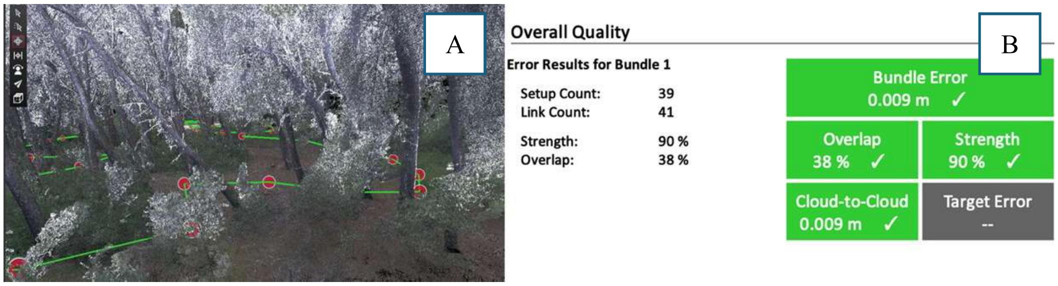


Figure 11. The point cloud generated in a selected plot area in the Strofilia forest (A). The bundle error of the selected areas, after processing, was approximately 1 cm (B).

In each case, the large volume of information complicated the processing and visualization of the data in the various software used. The computer used for data processing had high-performance hardware. Specifically, its key technical specifications included an Intel Core i9 12900k processor, an Nvidia GeForce RTX 4090 graphics card with 24GB VRAM, 128 GB of DDR5 RAM, and a 2 TB NVME PCIe 4.0 SSD.

Data Fusion

In both locations, the Pindos National Park and the Kotychi-Strofilia Wetlands National Park, aerial and terrestrial point clouds were collected with the goal of merging these datasets to create three-dimensional models (digital twins) of the plot areas. Following the individual processing of each data source, which resulted in point clouds from the separate solutions, the next step was to fuse these datasets. At this stage, it was necessary to select software capable of importing the data in appropriate formats (typically E57 and LAS) to facilitate proper integration. CloudCompare software was chosen for data fusion due to its flexibility and powerful capabilities for processing and analyzing data from various sources, including Phtogrammetry, TLS and LiDAR. CloudCompare offers several key features ideal for this task. It supports surface reconstruction, statistical extraction, point cloud merging and alignment, and object detection, enabling precise and efficient data processing. Its advanced visualization capabilities help users to better understand the data by exploring and analyzing it through graphical representations and visualization tools. The data fusion was achieved through georeferencing. Positional information for all datasets was provided in a common reference system (GGRS 87). Due to the initial georeferencing provided by the GNSS systems used by the UAVs, further cloud-to-cloud registration or manual alignment of the point clouds was not necessary in most cases. Using CloudCompare software, the areas were segmented to match the plot boundaries as defined spatially during the in-situ field measurements. During this process, any excess areas covered by the UAV data were removed [17]. This ensured better management of the large volume of unified data, facilitating its subsequent processing in the 3D Forest software (see Figure 12).

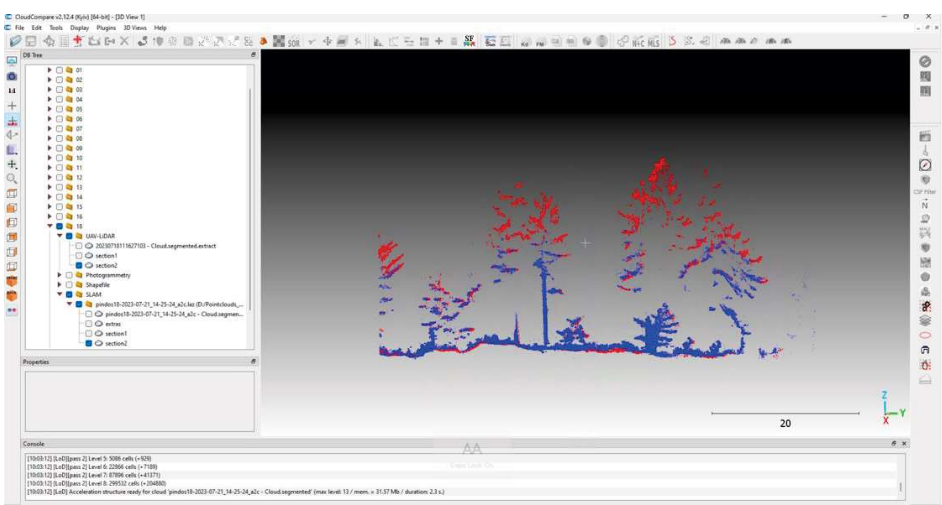


Figure 12. Point cloud fusion from aerial and terrestrial scanning using open-source CloudComapre software. With red color, the point cloud from Matrice 300 and AlphaAir 450, and with blue, the point cloud extracted from terrestrial SLAM system, the GeoSLAM ZEB REVO.

Tree Segmentation and Dedrometrics Extraction

After successfully merging the aerial and terrestrial data, a reliable digital twin of all the plot areas was created. The final stage involved importing this data into software packages capable of providing useful forestry information. The open source software 3D Forest is a tool used for analyzing and visualizing data from TLS and Airborne LiDAR in the context of forest assessment and study. 3D Forest allows for processing these data to extract information about forest structure, timber exploitation, biomass estimation and more. The primary workflow begins with data import, where LiDAR data is introduced into the software. Next, the data undergoes processing to remove any noise or unwanted elements and prepare it for analysis. Following this, the software provides tools for analyzing the data, such as estimating tree heights, tree density, height distribution, and change detection. The results of the analysis are then exported in the form of reports or graphs, which can be used for decision-making regarding forest management. Based on the analysis results, strategies can be developed for sustainable forest management, such as identifying areas with high biodiversity or recognizing regions with specific management needs. The practical implementation of this workflow may vary depending on the exact needs and characteristics of the project [18]. The process involved importing the data into the software, defining the ground level, and then having the software identify each tree individually to calculate its parameters (average DBH, CH, etc.). Initially, the classification results were not encouraging, as there were many instances where the geometric features were not recognized correctly, leading to the merging of trees with other vegetation geometries that should not have been combined (see Figure 13).

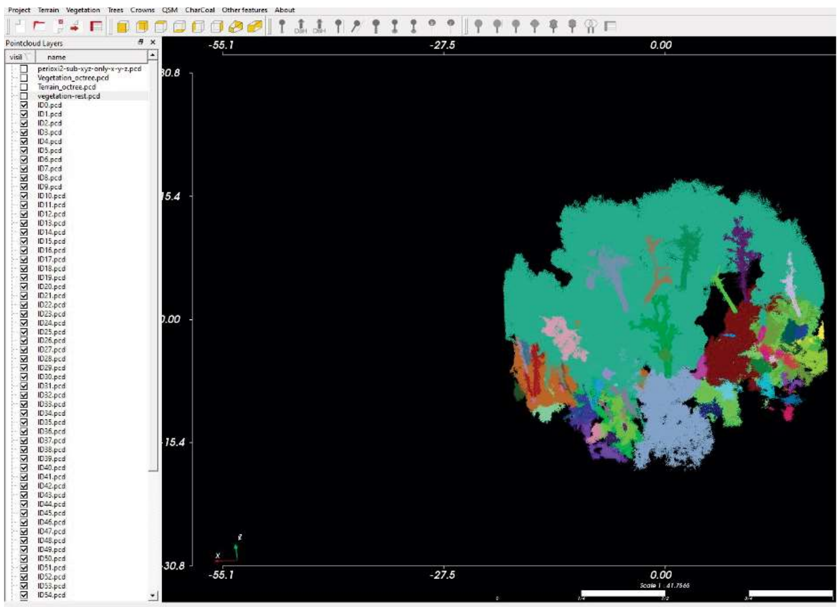


Figure 13. Initial classification results in the 3D Forest software showing instances where geometric features were not correctly recognized, leading to the merging of trees with other vegetation geometries (green color).

The parameters required by the software depend heavily on the type of data being input. The density of the data was a critical factor; very dense point clouds from multiple measurement sources sometimes negatively affected the processing, as the program consumed more RAM, causing operational crashes. This required generalizing the data and re-importing it into the software. After numerous attempts, the parameters were optimized, resulting in a well-classified datasets for selected plot areas. These datasest now provides accurate geometry characteristics for each tree, enabling informed strategic decisions for the management of these forest areas (see Figure 14). To ensure precise tree measurements, the lowest point of each tree relative to its z-coordinate was determined. This step was crucial for accurate tree base positioning and was performed on an individual tree level to prevent the software from crashing, which often occurred when multiple trees were processed simultaneously. Misclassified objects were removed from the tree list beforehand to streamline the process and ensure that the input tree cloud list contained only valid tree objects. Once the lowest tree positions were determined, other parameters, such as DBH (Diameter at Breast Height) and tree height, were calculated for all tree objects using the relevant multiple selection option from menu. These calculations were then exported in tabular form as a CSV file for further processing.

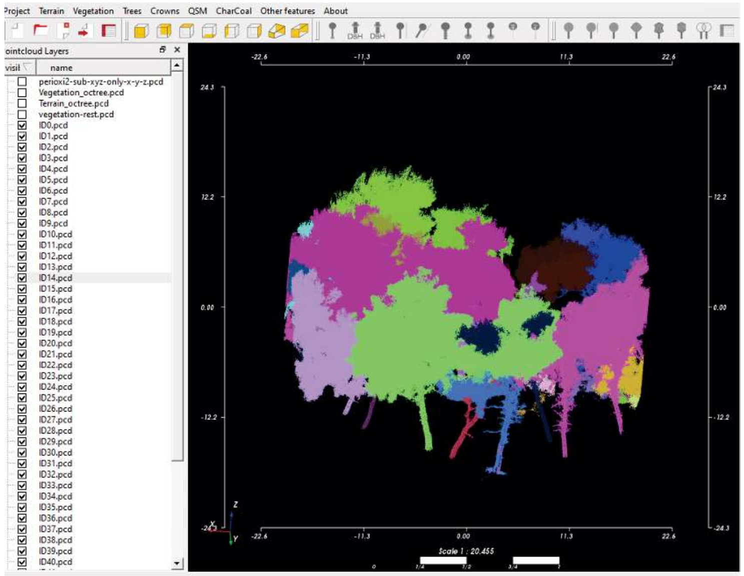


Figure 14. The optimization of 3D Forest parameters after numerous attempts resulted in well-classified datasets for selected plot areas.

3. RESULTS

Plot Areas Synthetic Point Clouds

The distribution and storage of all synthetic data for all plot areas were consolidated into two unified .bin files in CloudCompare, one for each National Park (Kotychi-Strofilia Wetlands and Northern Pindos National Park). Within these .bin files, all the point clouds derived from aerial and terrestrial surveys are categorized into folders and segmented according to the plot boundaries. This archiving method greatly facilitated the efficient distribution and sectional extraction of the desired geometric information for each plot in LAS format, enabling their import into the 3D Forest software. Each of these files exceeds 100 GB in size (see Figure 15).

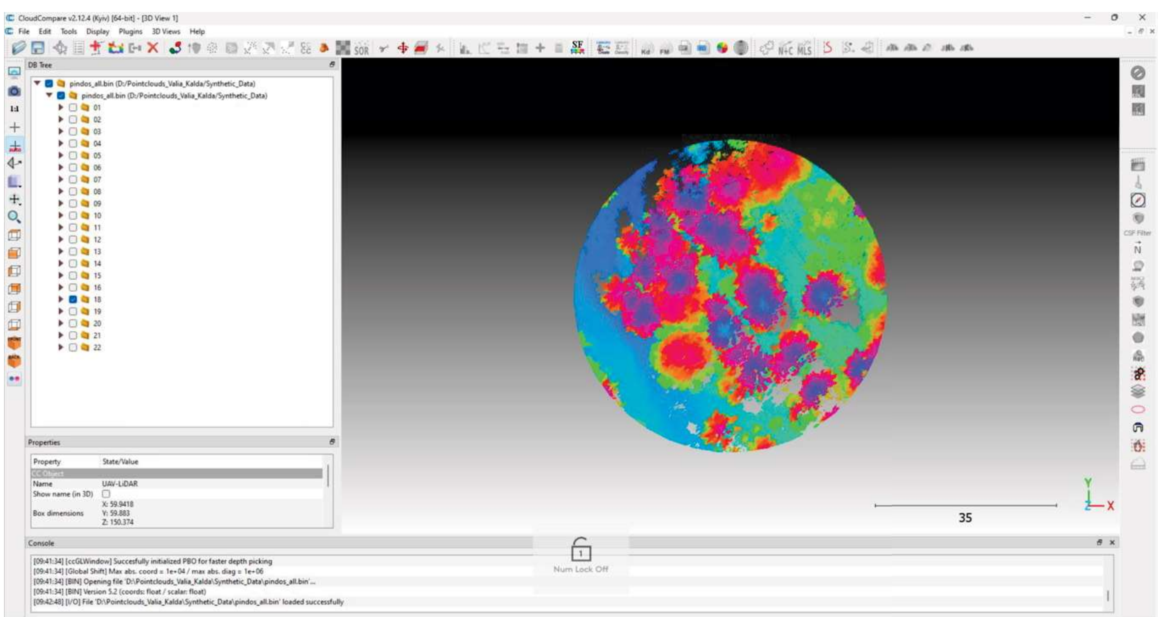


Figure 15. The synthetic data for all plot areas were consolidated into two .bin files in CloudCompare, one for each National Park (Kotychi-Strofilia Wetlands and Northern Pindos).

Tree Segmentations and Dedrometrics

For selected plot areas, the synthetic cloud data was imported and processed in the 3D Forest software to automate the recognition and segmentation of the trees within these areas and to extract their dendrometric characteristics into CSV files. Based on this process, the coordinates of the tree position lowest points were extracted in the GRRS87 geodetic reference system. These positions were then imported into the open-source software QGIS and matched with the in-situ measurements taken at the specific plots. A database was created for the selected plots, containing the dendrometric characteristics derived from the automated processing in 3D Forest using the synthetic point clouds, as well as data from the in-situ measurements with classic instruments (see Figure 16).

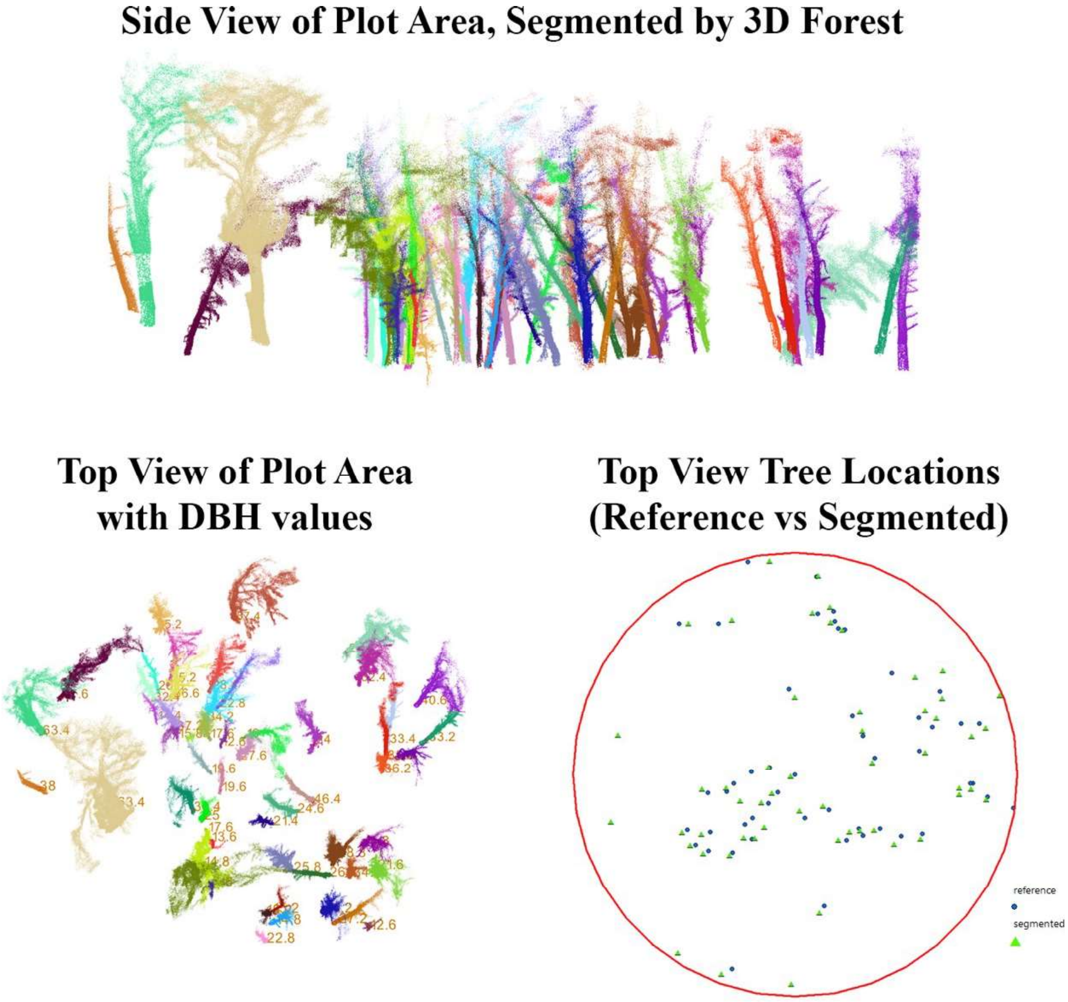


Figure 16. Synthetic cloud data for selected plot areas imported and processed in 3D Forest software. The images show tree segmentation, DBH values, and a comparison of tree locations between in-situ classic measurements and segmented data.

Preliminary Comparison of Extracted Dedrometrics

In the current phase of the LIFE EL-BIOS project, efforts are being made to automate the extraction of dendrometric data from the 3D Forest software for all study areas where synthetic scanning measurements were conducted. Figure 17 presents a comparison of the DBH index for area plot 3 in the Strofilia forest, identified as ID3 (see Figure 1). The chart illustrates the relationship between the diameter at breast height measurements taken in situ with traditional instruments and those automatically extracted through the 3D Forest application. The points on the chart represent the pairing of these two measurements. The R^2 (coefficient of determination) value is approximately 0.957. This indicates that about 95.7% of the variability in the 3D Forest extracted DBH measurements can be explained by the in-situ measurements of DBH on the selected plot area trees. Such a high R^2 value signifies a very strong correlation between the two data sets, demonstrating that the extracted measurements are highly accurate compared to the in-situ measurements. This is further confirmed by the slope of the trendline. The trendline has a slope of approximately 1.011 and a y-intercept of around 0.041, indicating an almost linear relationship between the two datasets. The 3D Forest extracted measurements are very close to the in-situ measurements. These results suggest that laser scanning technology can provide reliable estimates for forest management, enabling accurate and efficient measurements. However, it should be noted that the data can be influenced by various factors such as foliage density, terrain morphology, and equipment quality. The study is ongoing and is expected to provide comparisons for the dendrometric characteristics of all plots measured under the LIFE EL-BIOS project in the future.

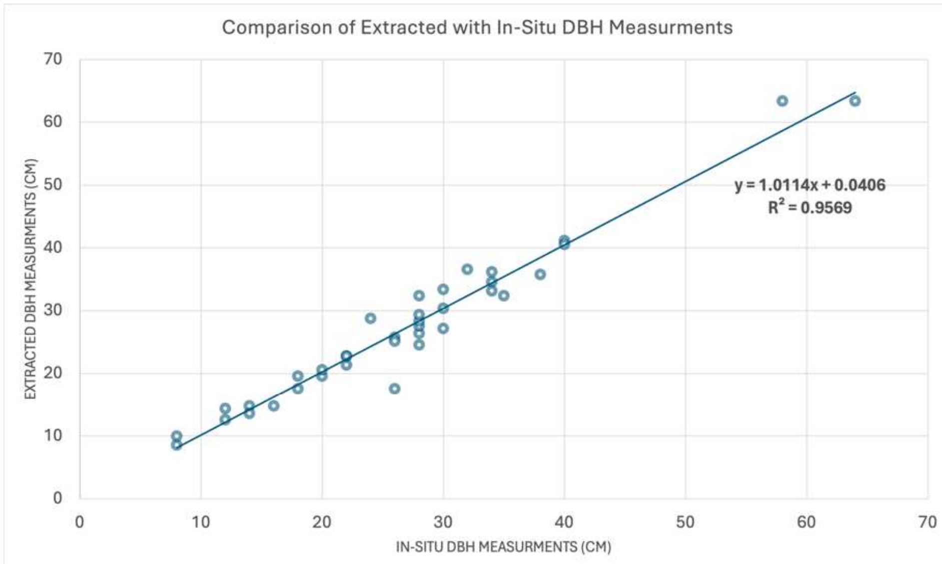


Figure 17. Comparison of the DBH index for plot 3 in the Strofilia forest (ID3). The chart shows a strong correlation ($R^2 \approx 0.957$) between in situ DBH measurements and those extracted automatically by the 3D Forest application, indicating high accuracy of the automated method.

4. CONCLUSIONS

The LIFE EL-BIOS project demonstrates a significant advancement in forest biodiversity monitoring through the integration of terrestrial and airborne LiDAR technologies along with multispectral earth observation data. The primary goal was to create Digital Twins of forested areas in the Kotychi-Strofilia Wetlands and Northern Pindos National Parks, utilizing a variety of advanced equipment and methodologies to achieve high-precision biodiversity measurements. The combined use of UAV-based airborne LiDAR and terrestrial SLAM devices significantly improved the accuracy and comprehensiveness of forest structure data. The integration of these technologies allowed for detailed vertical and horizontal measurements, which are critical for assessing forest biodiversity and structure. The methodologies employed, including the use of advanced UAVs and LiDAR systems, proved to be time-efficient and cost-effective compared to traditional in-situ measurements. This efficiency is particularly evident in the large areas covered in relatively short periods, reducing the manpower and time required for comprehensive biodiversity assessments. Open-source software tools like 3D Forest, and CloudCompare were utilized for data fusion, georeferencing, and processing, enabling the creation of unified point clouds and detailed 3D models of the study areas. These models provide essential insights into forest structure and health, facilitating the extraction of biodiversity-relevant parameters. The study included a comparative analysis between the new Digital Twin approach and traditional in-situ measurements. The project highlighted the potential of multiscale and multisource Earth Observation (EO) data in creating detailed digital representations of ecologically sensitive areas. These digital twins can significantly enhance environmental conservation efforts by providing accurate and actionable data on forest biodiversity and health.

The project is ongoing, with future efforts aimed at automating dendrometric data extraction across all study areas and further refining the methodologies to enhance accuracy and robustness in various environmental conditions. In conclusion, the LIFE EL-BIOS project represents a significant step forward in forest biodiversity conservation, leveraging advanced technologies to provide accurate, efficient, and comprehensive data for monitoring and managing forest ecosystems

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