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LiDAR-Based 3D Mapping Approach for Estimating Tree Carbon Stock: A University Campus Case Study †

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Abstract

This study aims to develop and demonstrate a low-cost LiDAR-based 3D mapping approach for estimating tree carbon stock in university campuses. Unlike conventional field-based measurements, which are labor-intensive and error-prone, the proposed system integrates a 2D LiDAR sensor with a servo motor and odometry data to generate three-dimensional point clouds of trees. From these data, key biometric parameters such as diameter at breast height (DBH) and total height are automatically extracted and incorporated into species-specific and generalized allometric equations, in line with IPCC 2006/2019 guidelines, to estimate above-ground biomass, below-ground biomass, and total carbon storage. The experimental study is conducted over approximately 70,000 m^2 of green space at Gazi University, Ankara, where six dominant species have been identified, including Cedrus libani, Pinus nigra, Platanus orientalis, and Ailanthus altissima. Results revealed a total carbon stock of 16.82 t C, corresponding to 61.66 t CO_2eq. Among species, Cedrus libani (29,468.86 kg C) and Ailanthus altissima (13,544.83 kg C) showed the highest contributions, while Picea orientalis accounted for the lowest. The findings confirm that the proposed system offers a reliable, portable, cost-effective alternative to professional LiDAR scanners. This approach supports sustainable campus management and highlights the broader applicability of low-cost LiDAR technologies for urban carbon accounting and climate change mitigation strategies.

Keywords: LiDAR-based 3D mapping; carbon stock; biomass estimation; urban green areas; sustainable campus management

1. Introduction

Global climate change has become one of the most critical challenges of the 21st century, primarily driven by increasing atmospheric carbon dioxide (CO_2) concentrations. Urban green spaces, especially trees, are vital in mitigating these impacts by storing atmospheric carbon and acting as natural carbon sinks [1]. University campuses, often characterized by dense vegetation, provide a unique opportunity to quantify and monitor carbon stock potential locally, supporting sustainability initiatives and climate change mitigation strategies [1].

Traditional methods for estimating tree biomass and carbon stock rely on manual field measurements, such as diameter at breast height (DBH) and tree height (H), which are time-consuming and prone to human error [2]. Light Detection and Ranging (LiDAR)

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technology has emerged as a powerful alternative, offering non-destructive, accurate, and efficient measurement of tree parameters. LiDAR-based systems have been successfully applied to assess tree volume, biomass, and carbon storage in diverse environments, including university campuses [1–3]. However, high costs associated with commercial LiDAR scanners often limit their accessibility for small-scale research and educational institutions [3].

Several campus-based studies have demonstrated the effectiveness of combining allometric models with LiDAR data for assessing carbon stock. For instance, Sharma et al. [1] quantified the carbon sequestration of 1997 trees at Amity University, India, estimating a sequestration potential of approximately 139.9 tons of CO_2. Similarly, Canadian and European campus studies have highlighted the potential of LiDAR to provide reliable estimations of tree metrics at reduced costs [3]. In Turkey, research on forest ecosystems has also highlighted the importance of temporal carbon and oxygen dynamics for sustainable land-use planning [4].

In addition to these efforts, recent advances in low-cost LiDAR and sensor fusion techniques have enabled the development of portable mobile mapping systems. Tantrairatn et al. [2] confirm that LiDAR-based DBH and H measurements can achieve high accuracy, with error margins as low as 1.734% for DBH and 1.572% for H, supporting their application in carbon assessment workflows.

Durkaya et al. [5] conducted a study on pure cedar stands in Antalya, using 36 sample trees to estimate biomass and carbon content for all tree components. They reported that approximately 51% of fresh biomass corresponds to dry Biomass, with carbon content ranging from 49.5% to 52.8%. The results showed that 100 m^3 of stem volume corresponds to 70.27 tons of biomass and 35.56 tons of stored carbon, underlining the high storage capacity of Cedrus libani [5]. Similarly, Durkaya et al. [6] developed equations for aboveground biomass in pure Pinus nigra stands in Zonguldak, demonstrating that models incorporating both DBH and H achieve strong correlations ($R^2 > 0.95$) and provide reliable estimates for carbon sequestration and biomass energy potential [6]. In the context of urban ecosystems, Shadman et al. [7] investigated a park in Dhaka, Bangladesh, finding a total lifetime storage of 660.8 t CO_2eq with an annual sequestration of 33.24 t CO_2eq. They also emphasized the role of species selection in maximizing urban carbon sinks [7].

Building upon these developments, this study proposes a low-cost LiDAR-based 3D mapping system designed to estimate the carbon stock potential of trees within the Gazi University campus. By integrating a 2D LiDAR sensor with a servo motor and odometry data, the system generates 3D point clouds of individual trees. DBH and H values are extracted from these point clouds, and biomass equations are applied to compute the stored carbon and CO_2 equivalents. This work aims to demonstrate that affordable LiDAR-based systems can provide reliable estimations of campus-level carbon stock, supporting sustainable urban planning and climate-focused decision-making.

2. Methods and Materials

2.1. System Design

Today, 3D LiDAR systems are widely preferred for high-precision environmental scanning; however, they remain expensive hardware solutions. This high cost poses a significant barrier to their widespread use, particularly in research, education, and prototyping applications. In this context, the present system combines low-cost components to provide an accessible and flexible solution that addresses the need for 3D mapping.

This system architecture represents a modular 3D mapping solution mounted on a mobile robotic platform as shown in Figure 1. A YDLidar G2 sensor, installed on a platform rotated by a Tower Pro MG996R servo motor, enables 3D environmental scanning

by generating slices of 2D scans [8]. Each scan is captured at 0.5-degree intervals and sequentially added to the previous one, constructing a 3D scan from 2D data. Additionally, odometry data is generated through DC motors driven by an L298N module, controlled by an Arduino Mega 2560, based on motion commands received via an HC-06 Bluetooth module from a mobile application [9,10]. These odometry-based movements allow the system to perform scans over larger areas.

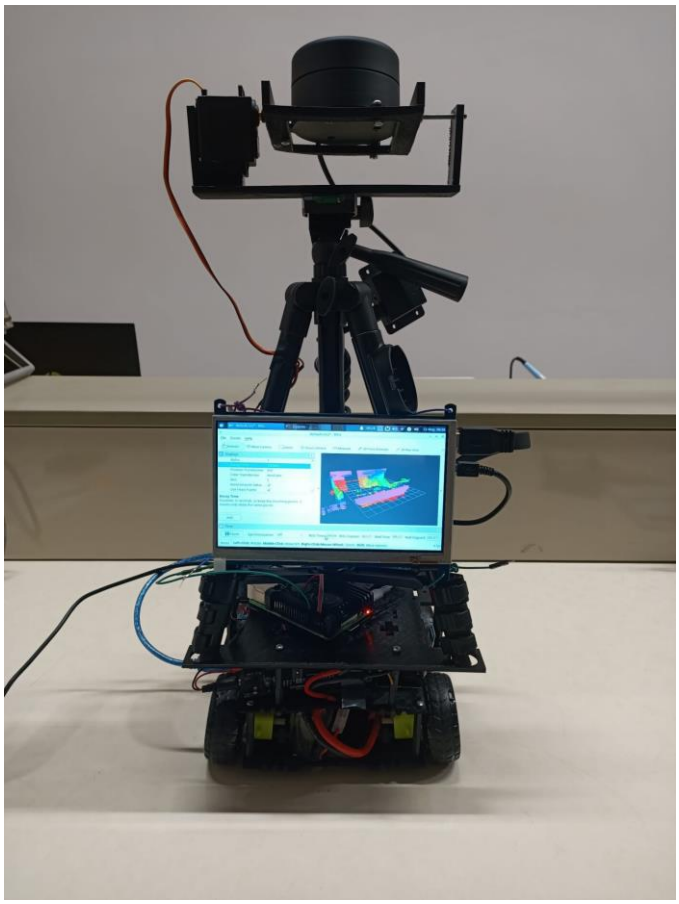


Figure 1. LiDAR-based outdoor 3D mapping system.

The control of the LiDAR and servo motor and the processing of acquired data is handled by a Raspberry Pi 4 (8 GB), which also communicates with the Arduino Mega 2560 to receive odometry data. The system incorporates a 7-inch WaveShare HDMI capacitive touchscreen display for real-time outdoor mapping and visualization. Processed maps and records are stored on a 128 GB SD card, ensuring long-term data storage. The entire software stack is built on the Robot Operating System (ROS) [11], which provides a flexible framework for sensor integration, data handling, and visualization. This integrated architecture supports real-time mapping, data visualization, and system control in outdoor environments.

The scans are saved as bag files for further analysis. These bag files can be replayed in the RViz application, allowing users to generate a 3D map that can be observed from different perspectives. On this map, essential measurements can be performed, such as determining tree heights and diameters. Additionally, the tf transformation library is utilized to perform sensor fusion, ensuring accurate alignment between LiDAR scans, servo rotation angles, and odometry data, which yields consistent and reliable 3D maps [12].

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2.2. Tree Inventory and Carbon Estimation

The study is conducted in the green areas of Gazi University campus. To assess the carbon stock capacity of the study area, the campus map is divided into three zones based on the spatial distribution of vegetation density and land use characteristics. A map view of the campus and its zones is shown in Figure 2. Tree inventories are prepared within each zone by identifying the dominant species present. The principal species included Cedrus libani (Lebanon cedar), Pinus nigra (Black pine), Platanus orientalis (Oriental. plane), Picea orientalis (Oriental spruce), Ailanthus altissima (Tree-of-heaven), and Cupressus arizonica (Arizona cypress).



Figure 2. Zones of the campus.

From the LiDAR-derived point cloud, diameter at breast height (DBH) and tree height (H) are extracted as the fundamental biometric parameters. These measurements served as inputs to species-specific or allometric equations widely used for estimating biomass and carbon.

The calculation steps are summarized as follows:

Individual trees' above-ground biomass (AGB) is estimated using species-specific or generalized allometric equations. A widely used pantropical model developed by Chave et al. [13] is expressed as:

$$AGB = 0.0673 \times (\rho D^2 H)^{0.976} \quad (1)$$

where D is the DBH (cm), H is the total tree height (m), and ρ is the wood density (g/cm^3), obtained from published wood density values [14,15].

Root biomass (Below-Ground Biomass (BGB)) is estimated as a fraction of AGB, following the IPCC 2006/2019 Guidelines [16,17]. The relationship is:

$$BGB = R \times AGB \quad (2)$$

where R is the root-to-shoot ratio, for planted coniferous stands with low-to-medium biomass ($\leq$125 t ha^{-1}), a value of R = 0.34 is recommended (IPCC, 2019 [17]).

Total Biomass (TB) equation is:

$$TB = AGB + BGB \quad (3)$$

Biomass is converted to carbon stock using dry biomass's carbon fraction (CF). According to IPCC 2006/2019 Guidelines [16,17], the default value is CF = 0.47–0.50. Carbon Stock equation is (C):

$$C = CF \times TB \quad (4)$$

Finally, the amount of sequestered CO_2 is obtained by converting carbon mass into CO_2 equivalent using the molecular weight ratio:

$$CO_{2eq} = C_{total} \times 44/12 \quad (5)$$

For Cedrus libani (Lebanon cedar), biomass estimation is carried out using a species-specific equation developed by Durkaya et al. [5], which employs Diameter at Breast Height (DBH, $d_{1.30}$) and tree height (H) as independent variables in the Above-Ground Biomass (AGB) equation. Here, D is expressed in centimeters, H in meters, and AGB in kilograms (oven-dry AGB).

$$AGB = 51.38543 - 12.2998 \times d_{1.30} - 2.75361 \times H + 0.543984 \times {d_{1.30}}^2 + 0.896138 \times H^2 \quad (6)$$

This equation, with a high coefficient of determination ($R^2 = 0.97$), provides reliable results, and the estimated biomass values are subsequently converted into carbon and CO_2 equivalents using carbon conversion factors. The remainder of the Cedrus libani calculations is carried out the same way as for allometric equations.

Biomass estimation for Pinus Nigra (Black Pine) is performed using the Above Ground Biomass (AGB) equation developed by Durkaya et al. [6], which incorporates DBH ($d_{1.30}$) and tree height (H) as independent variables. Here, D is expressed in cm, H m, and AGB is expressed in kg (oven-dry AGB).

$$AGB = 106.6611 - 11.5098 \times d_{1.30} - 11.481 \times H + 0.5972 \times {d_{1.30}}^2 + 0.7758 \times H^2 \quad (7)$$

This equation, with a high coefficient of determination ($R^2 = 0.86$), provides reliable results, and the estimated biomass values are subsequently converted into carbon and CO_2 equivalents using carbon conversion factors. The remainder of the calculations for Pinus Nigra are carried out in the same way as for allometric equations.

3. Results and Discussion

This study analyzed the green areas of Gazi University campus using a LiDAR-based scanning system. The study area covered approximately 70,000 m^2 [18] within the Faculty of Engineering region of Gazi University, located at coordinates 39°55′54.4″ N and 32°50′47.6″ E. Trees within the campus are scanned using the developed system, as illustrated in Figure 1, and the acquired data are subsequently processed to generate three-dimensional point clouds, as shown in Figure 3. The coloring applied to the point clouds enabled a more distinct distinction of tree stems and crowns from surrounding objects, thereby facilitating more precise measurements of diameter at breast height (DBH) and total tree height (H). Example visualizations representing three different study zones (Zone I, Zone II, and Zone III) provide evidence of the methodology's effectiveness in characterizing campus vegetation.

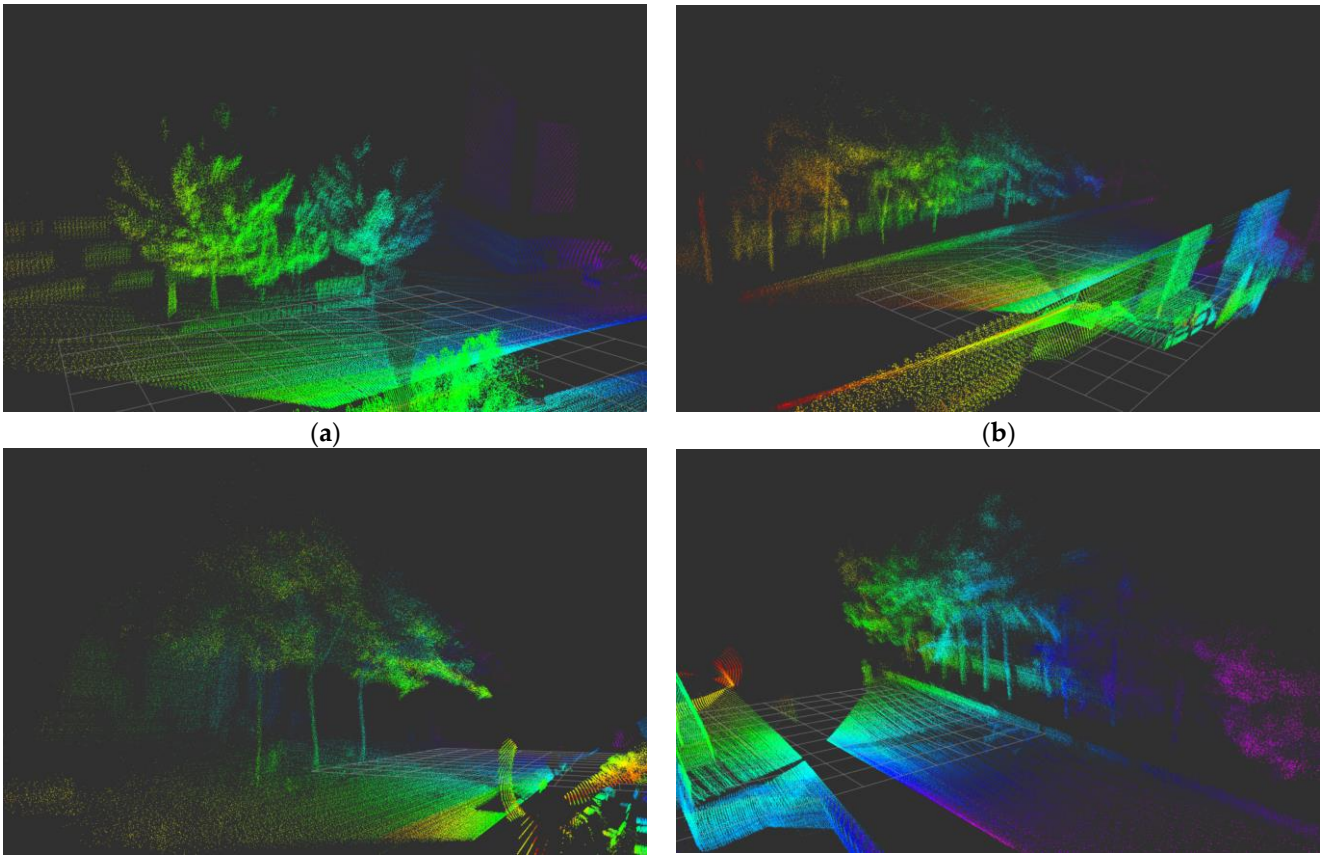


Figure 3. Three-dimensional visualization of trees in the campus samples. (**a**) Zone III scan example 1; (**b**) Zone I scan example 1; (**c**) Zone III scan example 2; (**d**) Zone I scan example 2.

The extracted DBH and H values are classified by species using RViz, and the results are summarized in Table 1. The table reports average DBH and height, the number of individuals per species across the zones, carbon stock per tree, and total carbon stock.

Table 1. Carbon stock and CO_2 equivalent results by tree species in the campus.

Tree Spices	Average DBH (cm)	Average Height (m)	N Zone Number			Carbon Stock per Tree (kg)	Total Carbon Stock (kg)	CO_2 Equivalent per Tree (kg)	Total CO_2 Equivalent (kg)
			I	II	III				
Cedrus Libani	23.61	14.81	35	22	1	138.57	8036.96	508.08	29,468.86
Pinus Nigra	26.73	12.15	6	0	3	126.42	1137.78	463.54	4171.87
Platanus Orientalis	26.04	21.31	0	0	13	237.79	3091.30	871.90	11,334.76
Picea Orientalis	14.61	5.04	0	0	8	14.61	116.91	53.58	428.66
Ailanthus Altissima	52.52	19.42	2	0	2	923.51	3694.04	3386.21	13,544.83
Cupressus Arizonica	17.19	9.75	0	12	4	46.28	740.53	169.71	2715.29

The results demonstrate distinct variations in carbon storage capacity among species. Cedrus libani emerged as the most significant contributor, storing 29,468.86 kg C across 58 individuals, primarily due to its abundance and robust size. Despite consisting of only 13 individuals, Platanus orientalis achieved a total of 11,334.76 kg C, owing to its high per-tree carbon stock (871.90 kg). Similarly, Ailanthus altissima, represented by only four individuals, contributed 13,544.83 kg C due to its large DBH and height values. In contrast,

Pinus nigra (9 individuals) accounted for 4171.87 kg C, Cupressus arizonica (16 individuals) for 2715.29 kg C, and Picea orientalis (8 individuals) stored only 428.66 kg C, marking the lowest contribution.

Overall, the cumulative carbon stock of campus trees is approximately 16.82 t C, equivalent to 61.66 t CO_2eq when applying the conversion factor (44/12). These findings highlight that species-specific traits and their distribution within the campus directly affect total carbon stock. Dominant and fast-growing broadleaf species (e.g., Platanus orientalis, Ailanthus altissima) exhibited disproportionately higher storage capacity. In contrast, coniferous species (Picea orientalis, Cupressus arizonica) contributed less due to smaller sizes and lower abundance.

In comparison with previous studies, the results are consistent with the literature reporting the role of urban green spaces as local carbon sinks. For instance, Nowak and Crane [19] emphasized that urban trees significantly mitigate CO_2 emissions, while Durkaya et al. [5,6] demonstrated that Cedrus libani and Pinus nigra are effective carbon-sequestering species in Turkish forests. Chave et al. [13] also confirmed the importance of integrating wood density and tree height in allometric models to minimize uncertainties, a practice adopted in this study. Finally, applying IPCC guidelines [16,17] ensured methodological consistency in biomass-to-carbon conversion and the estimation of below-ground biomass.

These results underscore the dual contribution of both species richness and measurement technology: while the species composition of the campus ecosystem determines the magnitude of stored carbon, the LiDAR-based, low-cost scanning system has proven to be an efficient, scalable, and non-destructive method for monitoring urban vegetation and assessing carbon sequestration potential at a local scale.

4. Conclusions

This study demonstrated the potential of a low-cost LiDAR-based 3D mapping system to estimate carbon stock in university campuses. By integrating a 2D LiDAR sensor with a servo motor and odometry data, three-dimensional point clouds of trees are generated and used to extract fundamental biometric parameters such as DBH and total height. Combined with species-specific and generalized allometric equations, these parameters enabled reliable estimation of above-ground biomass, below-ground biomass, and total carbon stock.

The experimental results from the Gazi University campus revealed a total carbon stock of approximately 16.82 t C, equivalent to 61.66 t CO_2eq, highlighting the role of campus vegetation as a significant local carbon sink. Species such as Cedrus libani, Platanus orientalis, and Ailanthus altissima exhibited disproportionately high contributions due to their size and growth characteristics. In contrast, species like Picea orientalis and Cupressus arizonica contributed less. These findings underline that species composition and distribution strongly influence urban green areas' overall carbon sequestration capacity.

Compared with previous literature, the results are consistent with international studies emphasizing the importance of urban trees in mitigating carbon emissions. Moreover, the application of IPCC guidelines ensured methodological robustness in biomass-to-carbon conversion. The proposed system thus provides a scalable, affordable, and non-destructive alternative to high-cost professional LiDAR systems, making it especially suitable for educational institutions and local-scale sustainability projects.

Future work can focus on expanding the system with sensor fusion techniques and integration with Geographic Information Systems (GIS) to enhance urban carbon management strategies. Overall, the developed approach contributes to advancing sustainable campus

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management and demonstrates the broader applicability of low-cost LiDAR technologies in climate change mitigation efforts.

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