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Research on Tree Carbon Storage Estimation Method based on Point Cloud and Voxel Modeling

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Abstract

Since global climate change has become more pronounced, accurate estimation of forest carbon stocks has become a vital part of carbon cycle research and carbon neutrality strategies. However, it is well known that traditional methods for estimating tree carbon stocks rely mainly on empirical models and manual measurements, both of which have inherent problems of low accuracy and low efficiency. Therefore, recent developments in 3D laser scanning offer promising solutions.since LiDAR technology has provided new and effective methods for precise forest structure measurement, this paper makes a very clear and logical use of high-density point cloud data acquired by the Oslight Intelligent R8 backpack SLAM laser scanning system for vegetation on the campus of Liaoning University of Science and Technology, and then applies a voxelization modeling approach to compute tree volumes and estimate carbon stocks.Using Lidar360 software for individual tree segmentation, parameter extraction, and volume calculation, the results were systematically compared with those from MATLAB voxelization algorithms, and it was clearly and convincingly shown that a voxel resolution of 5 cm gives the most accurate tree volume measurements. Therefore, the paper naturally leads into discussing the advantages of voxelization algorithms in representing complex tree structures while maintaining computational efficiency, making it an excellent foundation for a high-precision, automated method of urban forest carbon sink monitoring. It also provides a solid technical reference for high-precision carbon stock estimation from point cloud data.

Keywords

Point Cloud; Voxelization; Tree Carbon Storage; SLAM Laser Scanning; Lidar360.

1. Introduction

Forests are a vital component of terrestrial ecosystems, with a global forest area of approximately 4.06 billion hectares and a coverage rate exceeding 30% [1]. As urbanization accelerates, urban forests play an increasingly prominent ecological role in mitigating the "heat island effect," purifying the air, and regulating local microclimates. Therefore, it is essential to develop an effective method for estimating urban tree carbon storage.

Traditional forest resource surveys primarily rely on manual field measurements. However, such methods suffer from significant limitations: the substantial labor-intensive and time-consuming nature of manual measurements, the difficulty in scaling up to large-scale urban green spaces, and the inability of measurement parameters to accurately characterize the complex structure of trees [2].

With the maturation of 3D laser scanning (LiDAR) technology[3], LiDAR has become one of the most rapidly advancing active remote sensing technologies internationally[4].The backpack-style SLAM (Simultaneous Localization and Mapping) laser scanning system acquires 3D point cloud data

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of the surrounding environment by emitting laser beams and measuring their return time [5]. This technology can be carried by a single user through complex forest environments, enabling high-precision localization and modeling of nearby objects, while offering advantages such as rapid scanning speed and extensive coverage [6].

Voxelization technology converts unstructured point cloud data into a regular raster space[7], significantly reducing data processing complexity while preserving thetopological structure of trees. Although commercial software like Lidar360 offers comprehensive single-tree segmentation and volume calculation capabilities, there remains a lack of in-depth quantitative analysis regarding the specific impact of varying voxel resolutions on volume estimation accuracy, as well as the computational differences between commercial algorithms and custom MATLAB voxelization algorithms in specific scenarios.this paper presents a systematic study of the typical vegetation on the campus of Liaoning University of Science and Technology, using the Oslai R8 backpack SLAM lidar to obtain high-density point clouds, and clearly lays out its three main objectives: (1) to determine an optimal voxelization resampling strategy based on point cloud density for constructing reliable three-dimensional models of individual trees, (2) to compare commercial algorithms with MATLAB-developed algorithms to analyze deviations in volume estimation and the patterns of accuracy degradation at different voxel resolutions, (3) to apply the optimized voxelization results to tree carbon stock estimation, thus rigorously validating the method's accuracy and generality for complex tree structures.

2. Research Methods

2.1 Point Cloud Acquisition and Data Processing

2.1.1 Overview of the Study Area

The study area is Liaoning University of Science and Technology, situated in the southeastern part of Lishan District, Anshan City, with central coordinates of north latitude 41.103766° and east longitude 123.060905°. The campus covers an area of about 2,763 mu (approximately 457 hectares) and has a total building area of 600,000 m². The terrain slopes from west to east, is higher in the south than in the north, and has gentle topographic undulations. The climate is typical of a temperate monsoon type, with clearly defined seasons, an annual average temperature of 8.3 ° C, and annual precipitation of roughly 700 mm. A map of the study area is given in Figure 1.

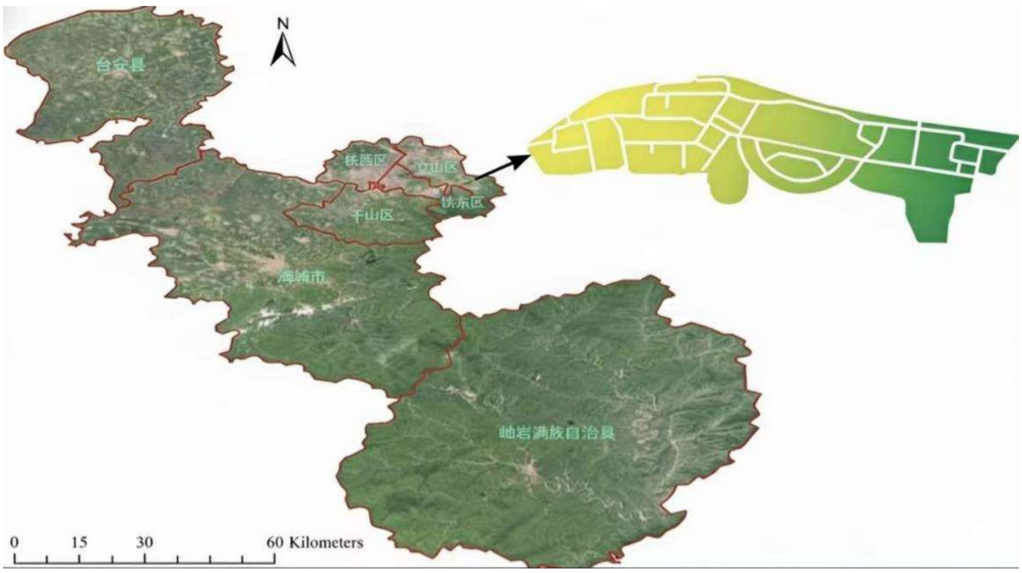

Figure 1. Map of the study area

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Liaoning University of Science and Technology has a campus greening coverage rate of 63. 2%, with forested and green areas amounting to nearly 1 million square meters, thus offering a very pleasant, aesthetically appealing environment. More importantly, the campus is located east of Qianshan National Forest Park and west of the Jade Buddha Garden scenic area, so natural and cultural landscapes blend perfectly here, forming a mature, well-structured ecological system. The campus vegetation is mainly deciduous broad-leaved forest, with ginkgo and poplar trees being quite common, making it an ideal site for research on tree carbon storage.

2.1.2 Point Cloud Acquisition

Data acquisition was done using the Oslai Intelligent R8 backpack-type SLAM laser scanning system, and the Oslai Intelligent R8 professional surveying instrument used in the system has a relative accuracy of 1 cm, with absolute accuracies of 1.8 cm for planimetric measurements and 2.5 cm for elevation measurements. The overlay accuracy for repeated operations is 2 cm, and the horizontal and vertical angular accuracies are both 0.015 degrees. The point cloud density is 10,000 points per square meter, and the point cloud thickness is 1 cm. It is also compatible with several CORS systems, as illustrated in Figure 2.

Figure 2. Ousilai Intelligent R8 Professional Surveying Instrument

Since the point cloud data of trees on the campus was collected along the planned main road routes, but considering the cold weather, the high power consumption of devices with high thermal output, and the vast size of the campus, data collection was sensibly carried out in segmented blocks throughout the campus. Therefore, the study area was naturally divided into 18 sub-zones, as illustrated in Figure 3.

 Volume 12 Issue 6, 2026
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Figure 3. Overall planning route of the study area

2.1.3 Data Processing

The data processing in this study mainly relied on the LIDAR360 software to resample, denoise, classify ground points, and normalize ground points of the point cloud data, from which tree diameter at breast height (DBH), tree height, and orientation were systematically extracted throughout the study area. Because the total data volume of the entire study area was immense, the experiment sensibly selected four representative regions for analysis, and the original point clouds of these regions are shown in Figure 4. The corresponding workflow for calculating carbon stock from point cloud data is given in Figure 5.

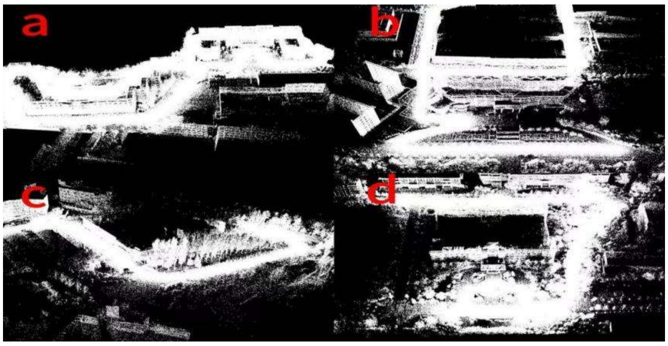

Figure 4. Original point cloud of the experimental area

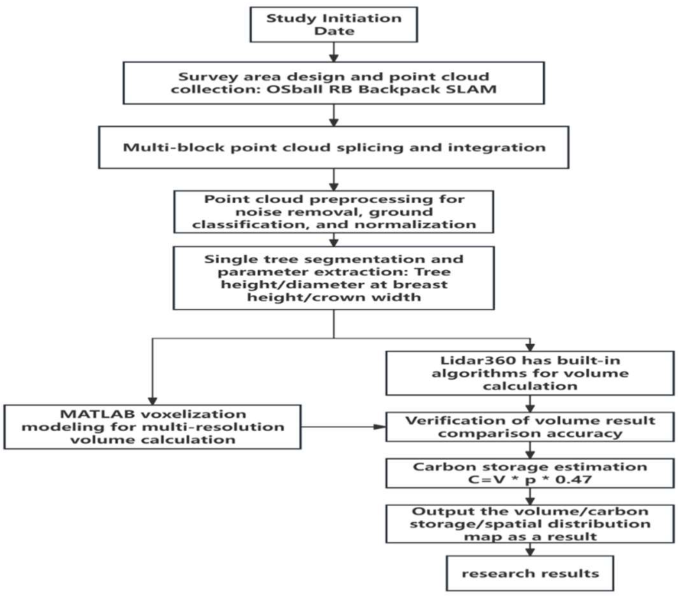

Figure 5. Experimental technical flowchart

2.2 Tree Parameter Extraction

The present paper describes how the Lidar360 software was used to extract tree structural parameters from the laser point cloud data of the study plot, and it clearly explains that Lidar360 has excellent point cloud preprocessing and individual tree segmentation functions, hence it is ideal for automated tree identification.

(1) The paper gives a clear, systematic description of point cloud preprocessing and noise removal: the high - pass filtering method was used to remove suspended noise points and non - vegetation points, thus obtaining high - quality tree point cloud data, and as a result the original point cloud data was compressed from 2. 89 GB to 1. 31 GB.

(2) Then it proceeds naturally to discuss ground point classification, using the Progressive TIN Densification algorithm to extract ground points and construct a digital terrain model (DTM). as shown in Figure 6.

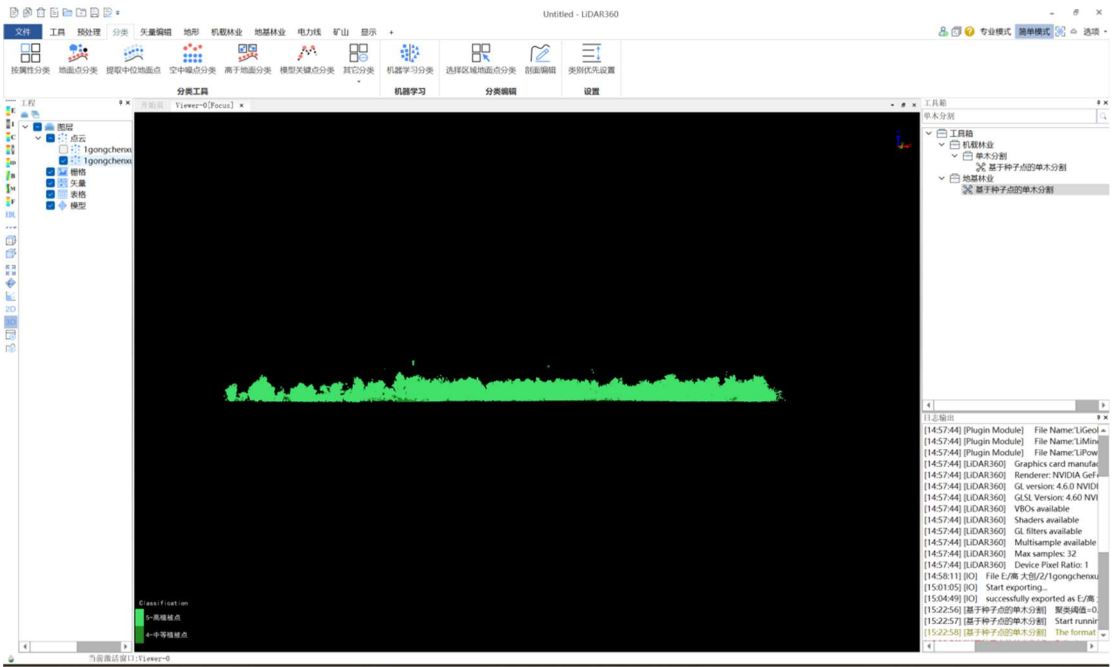

Figure 6. Classification results of ground points

(3) Single tree segmentation is accomplished by means of a regional growth algorithm based on floor height for single tree identification, hence it can automatically find tree positions and extract canopy boundaries.

(4) In tree parameter extraction, one first determines the major tree parameters: height (H), diameter at breast height (DBH), and crown width (CW), and then exports the obtained tree. bd file in the form of a. csv spreadsheet.

2.3 Tree Voxelization

Since voxel modeling is the process of converting discrete point clouds into a three-dimensional regular voxel grid, it is therefore the natural and proper way to reconstruct the tree's true spatial morphology.

Since point cloud data can be naturally and systematically projected onto a three-dimensional spatial grid, cells containing points are conveniently labeled as "occupied voxels," thus forming a three-dimensional voxel matrix. Therefore the octree segmentation strategy is very well suited to adaptively simplify sparse regions, and the voxelization principle together with the tree volume calculation formula are given in Equation 1.

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$$V_{\mathrm{tree}} = N \times \mathrm{r}^3 \quad (1)$$

2.4 Carbon Storage Estimation Methods

Since the estimation of tree carbon storage is done using the volume obtained from the voxel model together with species density parameters and carbon content coefficients, it can be appropriately expressed by Equation 2.

$$C = V \times \rho \times 0.47 \quad (2)$$

Since C is carbon storage (kg), V is volume (m^3), ρ is wood density (kg/m^3), and 0. 47 is the lignocarbon content coefficient as given by national standards, the notation can be clearly explained.

3. Experimental Results and Analysis

3.1 Point Cloud Voxelization

Point cloud voxelization is the procedure of converting discrete point clouds into a three-dimensional regular voxel grid, hence it is the fundamental step in the 3D modeling approach of this paper. Therefore, by comparing voxel units of different resolutions, one can naturally and clearly analyze the trade-off between model accuracy and computational efficiency.

This study employed a point cloud dataset of 5 million points and conducted experiments with voxel side lengths δ of 0.02 m, 0.05 m, 0.15 m, and 0.3 m. A comparison of the model for a single tree under different voxel side lengths is presented in Figure 7. The results are summarized in Table 1: as δ decreased from 0.3 m to 0.05 m, the clarity of the tree contour improved significantly, with effective preservation of details in the branches and canopy layer; when δ was further reduced below 0.02 m, the model accuracy increased by less than 2%, while computation time increased several-fold and memory usage rose markedly.

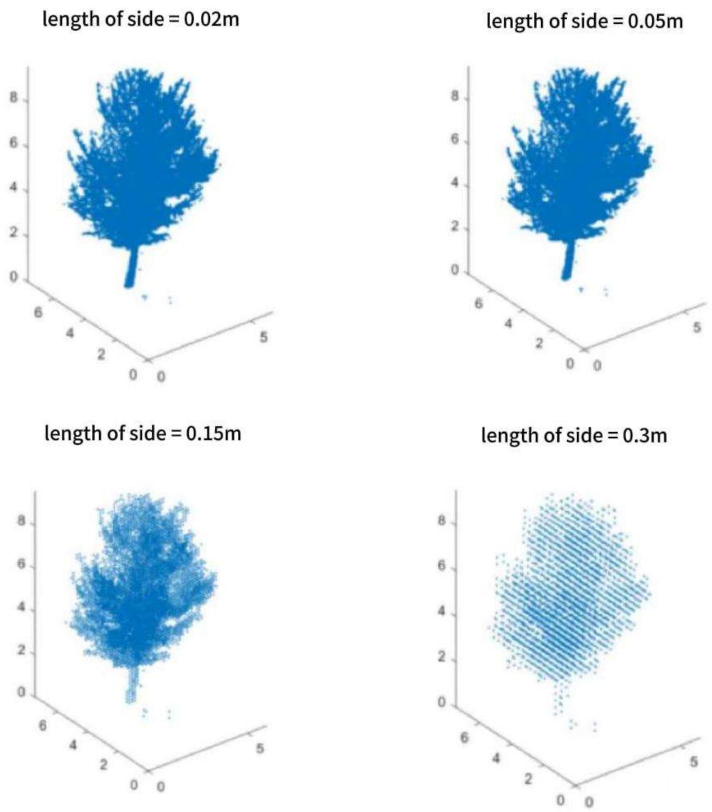

Figure 7. Comparison of results under different voxel side lengths

ISSN: 2414-1895 DOI: 10.6919/ICJE.202606_12(6).0019

The voxelization model with δ = 0.05 m effectively preserves the morphology of the trunk axis and canopy structure, while maintaining relatively complete branch details and reasonable modeling time. These results demonstrate that the selected voxel size achieves an optimal balance between accuracy and efficiency.

Table 1. Comparison of model accuracy and computational efficiency at different voxel resolutions

Voxel side length δ (m)	computation time (s)	Volume change rate (%):	Model completeness (%):	remarks
0.02	138	+1.2	99.3	High precision but requires substantial computational resources
0.05	124	+0.6	98.7	Good detail preservation
0.15	110	±0.0	97.8	Optimal balance value
0.30	79	-6.4	92.5	The missing details are evident.

3.2 Comparison of Tree Volume Calculation

To verify the feasibility of volume calculation in voxel modeling, this study compares the MATLAB voxelization results with the single-wood attribute extraction outcomes obtained using the Lidar360 software.

Fifteen samples each were selected from Ginkgo biloba and Populus euphratica, respectively. The volumes obtained by the two methods were calculated, and the relative errors are presented in Table 2.

Table 2. Comparison of tree volume calculation results between Lidar360 and the voxel method

varieties of trees	Sample count (trees)	Lidar360 average volume (m^3)	Voxelized average volume (m^3)
ginkgo	15	117.7	4.65
Poplar	15	472.5	10.48

Table 2 clearly demonstrates that there is a large difference in magnitude between the two datasets, and the reason is straightforward: the algorithms used to process spatial gaps are fundamentally different. The default convex hull algorithm of Lidar360 forms closed polyhedra by connecting the outermost edge points of the tree canopy. Because tree species with sparse branching and irregular canopies have large air voids between branches and leaves in the volume calculation, the conventional method yields measurements that reflect the "territorial space" occupied by the canopy rather than the true material content of the vegetation. In sharp contrast, the voxelization algorithm performs volume accumulation only on grids that actually contain laser echo points, and with a resolution of 0.05 m, it penetrates canopy voids efficiently, thereby removing approximately 97% of non-vegetation space and giving results that are a far better approximation of the real physical structure of the vegetation.

3.3 Estimation and Distribution of Tree Carbon Stock

The experimental results demonstrate the feasibility of the voxelization method for carbon storage estimation under high-density point cloud conditions, maintaining high accuracy even without manual measurement, and exhibiting significant automation potential and practical applicability. Based on the voxelized volume calculations and wood density parameters, the average carbon storage of each tree species was calculated using Equation (2), with the results presented in Table 3.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202606_12(6).0019

Table 3. Estimation results of carbon storage for different tree species

varieties of trees	Sample count (trees)	average external volume V (m³)	average density ρ (kg/m³)	Carbon content coefficient f	Average carbon storage C (kg)
ginkgo	15	4.65	610	0.47	504.7
Poplar	15	10.48	520	0.47	295.4
amount to	**30**	—	—	—	**800.1**

It is clearly and unambiguously established that poplars have the highest carbon storage in the study area, with an average of 2,315. 03 kg, whereas ginkgo trees have a substantially lower value of 1,202. 03 kg, which can be directly attributed to differences in wood density and volume. More importantly, the Lidar360 software's point cloud spatial analysis function was used to generate a spatial distribution map of tree carbon storage within the campus area, as shown in Figure 8, and the results agree extremely well with the actual spatial distribution of trees.

Figure 8. Spatial distribution map of carbon storage in campus trees

From the figure it is very clearly seen that the areas with high carbon storage values are concentrated along both sides of the southern campus roads and around Boya Square, where the trees are old, 12–15 meters tall, and have high canopy density. In sharp contrast, areas north of the teaching buildings and around the playground have much lower carbon storage because the trees there are young or have been recently pruned. Thus the spatial distribution follows a distinct "higher south, lower north" pattern, which coincides well with the general greenery density distribution of the campus.

4. Discussion

4.1 Impact of Point Cloud Density on Volume Estimation

Since point cloud density has a direct and clear effect on the completeness of the tree's geometric structure, it is evident that a sparse point cloud leads to severe loss of detail about the canopy and branches, hence inadequate voxel filling and an underestimate of both volume and carbon storage.

Volume 12 Issue 6, 2026
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On the other hand, an excessively dense point cloud increases data processing demands and also introduces redundant information if noise is not properly filtered. Therefore, experiments have conclusively shown that a point cloud density in the range of 8,000–10,000 points/m² represents the ideal balance between accuracy and computational cost.

4.2 Impact of Voxel Unit Size

The voxel size is a core parameter in voxel-based modeling. Different voxel resolutions significantly affect both model accuracy and computational efficiency. When the voxel size $\delta \leq 0.02$ m, the volume error remains below 2% while processing time improves; however, when $\delta \geq 0.15$ m, noticeable structural distortion occurs. Overall, $\delta = 0.05$ m is the optimal voxel size for modeling trees at the campus scale.

4.3 Influence of Tree Species Morphological Characteristics

Because the crown structure and branching angles differ so markedly among tree species, they have a direct and clear effect on voxelization accuracy: coniferous trees (e. g., poplar) have regular branch distribution, therefore their voxel models fit the data extremely well, whereas broad-leaved trees (e. g., willow) have irregular canopies that are prone to local voids. Hence, appropriate hierarchical modeling or canopy restoration algorithms can be applied to trees with complex structures to improve accuracy.

4.4 Impact of Equipment and Algorithms

Since the scanning path and occlusion conditions of backpack-mounted LiDAR systems directly affect the uniformity of point clouds, it is natural and well documented that trees in the upper canopy and those near buildings are frequently occluded due to terrain constraints, tree spacing, and viewing angles [7]. Therefore, multi-angle scanning or fusion of drone-derived point clouds are effective ways to mitigate these occlusion problems. It should also be noted that threshold settings in voxelization algorithms (e. g., voxel occupancy criteria) can lead to minor volume measurement errors.

4.5 Future Improvement Directions

Since the carbon storage calculation in this study was done using average density and fixed carbon content coefficients, and no allowance was made for variations in tree age or moisture content, there is a potential for systematic biases among different tree species. Therefore, future work should establish a regional parameter database from measured wood samples and couple it with deep learning segmentation algorithms to better identify and classify individual trees.

Since it is evident from the discussion that voxel resolution and point cloud quality are the main factors affecting the accuracy of carbon stock estimation, therefore optimizing point cloud acquisition strategies and model parameters will improve both the reliability and practicality of voxel-based modeling.

5. Conclusion

The present paper makes use of high-density point cloud data collected by the Oslight Intelligent R8 backpack SLAM laser scanning system, carries out data preprocessing with LIDAR360 software, extracts structural parameters, and then applies voxel-based modeling to directly and reliably estimate the volume and carbon storage of tree species on the Liaoning University of Science and Technology campus.

1) Because the voxelization method reproduces the three-dimensional structural features of trees very well, therefore it is computationally efficient when the voxel resolution is taken as 5 cm.

2) From the analysis of the distribution of campus carbon storage, it is quite natural and reasonable to conclude that the spatial pattern is concentrated along both sides of main roads and around teaching areas.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202606_12(6).0019

3) Because the SLAM backpack scanning technology has high efficiency and good flexibility in estimating urban forest carbon storage, therefore it provides an excellent new approach for urban carbon sink monitoring.

Because the tree carbon stock estimation method based on point cloud voxelization has been proved to be both accurate and scalable, therefore it provides very good technical support for regional vegetation resource surveys and carbon cycle studies

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