A Digital Twin Framework for Carbon Sequestration Estimation of Urban Green Spaces

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Abstract: Quantifying and mapping the carbon sequestration of urban green spaces (UGSs) play a critical role in the scientific management of these areas and in enhancing their capacity to mitigate the impacts of climate change. However, the process of quantifying carbon sequestration in UGSs is complex, requiring the collection, analysis, and visualization of multi-source heterogeneous data. Therefore, it is essential to develop a digital twin (DT) platform tailored for carbon sequestration estimation, enabling automatic data integration, measurement, updating, and visualization. This study compares the advantages and disadvantages of WebGIS and ArcGIS secondary development frameworks, ultimately selecting WebGIS for constructing the DT foundation of UGSs. The research establishes the overall framework of the DT platform, the data flow framework, and the carbon sequestration estimation framework based on DT technology. These outcomes clarify the logic behind the intelligent estimation and visualization of carbon sequestration and carbon density across multiple scales of UGSs. By adopting an open-source development strategy, the proposed solution reduces software costs while providing users with capabilities for intelligent estimation and in-depth analysis of carbon sequestration. This approach enhances the level of intelligence in the research and management of carbon sequestration in UGSs.

Keywords: Urban green space (UGS), carbon sequestration estimation, digital twin (DT), WebGIS, framework

1 Introduction

Urban green spaces, as a critical component of urban ecosystems, form the foundation for sustainable urban landscapes (SANTAGATA et al. 2020). Being the only element within urban areas that directly enhances carbon sequestration and indirectly reduces emissions (WANG et al. 2021), quantifying carbon sequestration in UGSs is essential for their scientific management and for strengthening their capacity to address climate change (JIN et al. 2023).

However, the urban environment is characterized by high heterogeneity, rich species diversity, complex community structures, and fragmented spatial distribution, making UGSs more intricate than typical forest ecosystems (WU et al. 2022). Compared to forests, accurately quantifying the spatial and temporal distribution of carbon sequestration in UGSs presents significant challenges. Currently, methods for estimation can be broadly classified into plot-based inventory method (including the average biomass method, biomass conversion factor method, and model estimation method) and remote sensing inversion method (DONG et al. 2024). Plot-based inventory methods focus on small-scale carbon stock estimation, while remote sensing inversion methods are better suited for large-scale applications. The estimation involves complex data and intricate procedures, often posing difficulties for non-experts to implement (POORAZIMY et al. 2020). However, carbon sequestration in UGSs is not only of interest to researchers but also to urban managers and the public (LIU & RUSSO 2021). Therefore, it is imperative to enhance the intelligence of carbon sequestration estimation methods and the visualization of their results, enabling intuitive access to and display of data.

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Considering the unique requirements of carbon sequestration research and management, developing intelligent methods is essential.

The Digital Twin (DT) utilizes digital technologies to map physical objects or systems within a virtual environment (WANG & VU 2023, WEIL et al. 2023). As an integrated approach, DT plays a significant role in data-driven management and environmental sustainability efforts (PARK et al. 2019). Multi-source heterogeneous data can be effectively integrated within a DT environment, enabling visualization, real-time retrieval, and access (IVANOV et al. 2020). Leveraging DT holds promise for precise measurement, dynamic monitoring, and simulation of carbon sequestration in UGSs. However, the consensus has yet to be reached on the specific technological pathways to implement DT solutions in this context (BUJARI et al. 2021).

This study aims to achieve intelligent estimation and access of carbon sequestration in UGSs within a DT. The concept of "intelligence" in this context primarily encompasses three aspects:

(1) Automated Measurement: The platform can automatically match parameters and measure the carbon stock of trees based on input tree specification data. Users do not need to understand the measurement principles; they only need to input the required values following the program's instructions. (2) Dynamic Data Updates: Leveraging the "twinning" feature, the foundational data used for measurements can be automatically downloaded and updated according to preset time intervals. (3) Geospatial Visualization: The platform can automatically visualize and map the measurement results within the geographic space.

Based on these objectives, this study focuses on addressing two key questions:

(1) What framework should be used to develop the DT platform for carbon sequestration estimation? This framework must meet core requirements, including integration of multi-scale and multi-resolution datasets, data visualization, automated measurements, and multi-user interaction. (2) How can intelligent estimation of carbon sequestration of vegetation community in UGSs be achieved within the DT environment?

2 Data and Methods

2.1 Data

This study employs multiple data acquisition methods, including online map servers (Tianditu WMTS), remote sensing image databases, oblique photography cameras, LiDAR, manual modeling, planning/surveying files, and field surveys. The detailed data types and acquisition methods used in this study are as follows: (1) Online Map Data: Tian map's WMTS is used for online real-time transmission of map data. (2) Remote Sensing Data: Sentinel-2 data is downloaded from the Copernicus Data Space. (3) Oblique Photography and LiDAR: The "DJI Zenmuse L2" oblique photography camera, mounted on the DJI M350RTK, is used for airborne data collection. Simultaneously, the LiDAR system, using the OmniSLAM RTK-SLAM R6, collects three-dimensional point cloud data of the ground. (4) Manual Modeling: Dynamic 3D plant models are constructed using SpeedTree, incorporating plant information at different time points. (5) Planning/Surveying Files: CAD files provided by surveying departments. (6) Field Survey Data: Includes plant types, community types, community structure, geographic coordinates, and photographs. After integration, the data is organized into a CSV file.

2.2 Comparison of Development Frameworks

Due to the spatial heterogeneity of vegetation in UGSs, carbon sequestration in these areas exhibits spatial variability. Understanding the spatial distribution of carbon sequestration is crucial for effective management. Since our goal is to estimate carbon sequestration within a DT environment, the primary task is to regularly measure and spatially represent the data.

We selected GIS as the foundational platform for three reasons: (1) GIS excels in data spatialization and analysis, with automated tools widely used in earth science processes (PRADHAN & LEE 2010, YUE et al. 2015). (2) GIS offers mature pathways for web and secondary development, facilitating feature customization (PUARUNGROJ et al. 2021). (3) GIS supports Internet access for regular data updates, essential for twinning (XIA et al., 2022). Given these advantages, we compare two GIS development approaches: WebGIS and ArcGIS secondary development.

2.3 Methodology for Estimating Carbon Sequestration in UGSs

This study used the biomass conversion method to estimate carbon sequestration. On a small scale, tree specifications are obtained from LiDAR point cloud data, biomass is measured using the biomass equation or biomass expansion factor, and carbon stock is calculated based on tree carbon content (BÉLAND et al. 2011). Carbon sequestration is determined by subtracting carbon stock values from two years. On a larger scale, remote sensing data are used to derive the normalized vegetation index (NDVI), which is modeled with the carbon stock of sample sites to estimate carbon stock in the intact space (CHEN et al., 2024).

3 Results

3.1 Comparison of GIS-based Development Frameworks

3.1.1 WebGIS

WebGIS (Web-based Geographic Information System) is a geographic system built on Web technology, providing map display, spatial query, and data processing through a browser (RANDAZZO et al. 2021). It is typically developed using open-source frameworks, enabling flexible integration of geographic data and cross-platform access. WebGIS emphasizes lightweight design, user interaction, and customizability, making it ideal for visualization, data sharing, and basic analysis. It facilitates real-time data sharing among users and stakeholders, enhancing accessibility (PHODOR & ZENTAI 2017, SCHUTZE & VATTERROTT 2007). However, WebGIS has drawbacks, including large development workload, limited GIS functions, high maintenance costs, and data security challenges (ROWLAND et al. 2020).

3.1.2 ArcGIS Secondary Development

ArcGIS secondary development refers to the customization or extension of ArcGIS software provided by Esri. Using tools like the ArcGIS API, SDK, or Python scripts, developers can enhance ArcGIS products to meet specific needs in spatial analysis, data management, and visualization (PRICE 2023). As desktop software, ArcGIS offers high data handling performance, enabling direct data read/write from local disks and supporting multi-threaded environments for large data volumes – capabilities not achievable on the Web (FAST & HOSSAIN 2020). Table 1 shows the advantages and disadvantages of both.

Table 1: Comparison of advantages and disadvantages of WebGIS and ArcGIS secondary development

Development frameworks	**WebGIS**	**ArcGIS secondary development**
Definition	Web technology-based GIS using an open-source framework for map display and data processing.	Personalized development based on the ArcGIS platform, using APIs and SDKs to extend functionality.
Costs	Moderate, based on open source technology stack, free or low cost.	High licensing fees, suitable for corporate or government programs with large budgets.
Customization	High, customizable development on demand.	Low, limited customization capabilities, some features may be limited by the ArcGIS platform.
Functionality	Moderate, suitable for basic map display and lightweight spatial analysis.	High, support for complex spatial analysis, geoprocessing and multidimensional modeling.
Development difficulty	High, need to be turned into a development to realize some of the complex functions, such as spatial analysis.	Moderate, the platform offers a wealth of built-in functionality. Suitable for scenarios requiring specialized GIS support.
Data compatibility	Moderate, support a variety of data formats, such as GeoJSON, KML, 3D Tiles, etc.	High, supports a variety of spatial data formats, especially suitable for BIM and remote sensing data.
Platform support	High, cross-platform support, suitable for Web, PC, cell phones and tablets and other multi-terminal.	Low, multi-device support, but mostly dependent on the Esri ecosystem.
Applicable scene	Lightweight visualization, real-time data presentation, web-side interaction.	Complex analysis, geoprocessing, urban modeling, enterprise or government level projects.
Maintenance & support	Maintaining and updating the code on your own, with much of the technical support coming from the open-source community.	Esri provides professional technical support and rich documentation resources, reducing the difficulty of maintenance.
Development technology stack	Based on JavaScript, HTML, CSS, commonly used frameworks such as Leaflet, OpenLayers, Cesium, etc.	Dependency on ArcGIS APIs and SDKs, such as ArcGIS API for JavaScript, ArcPy, etc.

3.2 General Framework of the DT Platform

As shown in Figure 1, the geospatial service base of the DT platform is derived from the WMTS of Tian Map, which transmits base map data over the Internet. The platform consists of a system of interconnected HTML pages, enabling users to switch between different scales and modes. Multiple data, formulas, and models are integrated through HTML structure. Each page contains JavaScript code that calls WebGL open-source libraries (e. g., Cesium.js and Three.js) hosted on the web server.

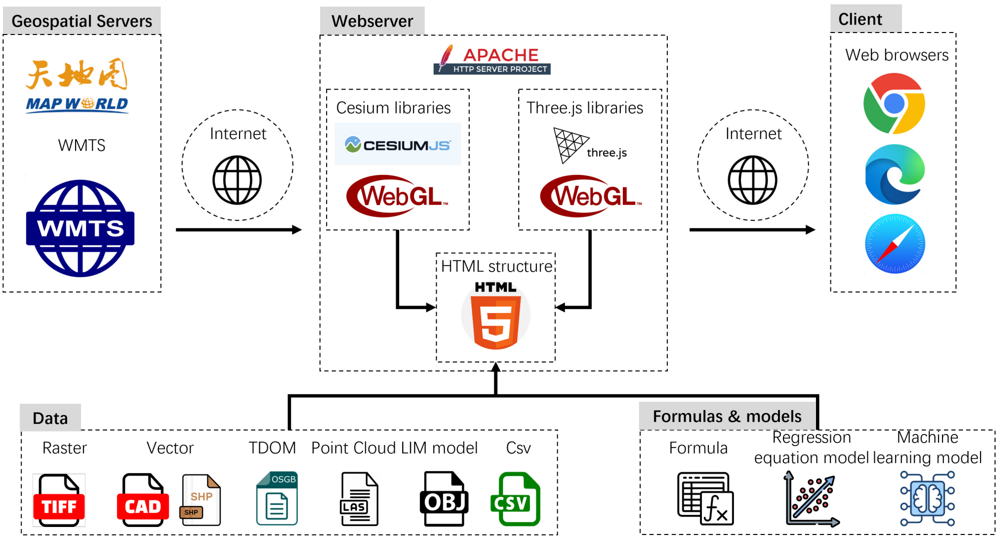

Fig. 1: A DT framework for estimating carbon sequestration in UGSs

3.3 Data Flow Framework

To implement the DT platform, a structured data flow is required. We developed a data flow system that includes data updating, storage, fusion, and visualization.

3.3.1 Data Update

Data is updated in three modes: monthly, annually, or based on specific requirements. Tian Map base map data is updated monthly. Remote sensing imagery, inclined photography models, and point cloud data for carbon sequestration are updated annually. CAD planning/mapping data, LIM model data, and field survey data are updated as needed.

3.3.2 Data Storage

Data storage includes undirected storage and database storage. Non-directly stored data is retrieved from the online server via WMTS. The database, located on NAS, is organized into spatial and relational databases, managed with PostGIS and PostgreSQL, respectively.

3.3.3 Data Fusion

All data coordinate systems are standardized to CGCS2000 and converted into lightweight formats such as GeoJSON and 3DTiles using the GDAL and PDAL toolsets. Spatial indexes are created to speed up the search for specific records in the spatial database (Figure 2).

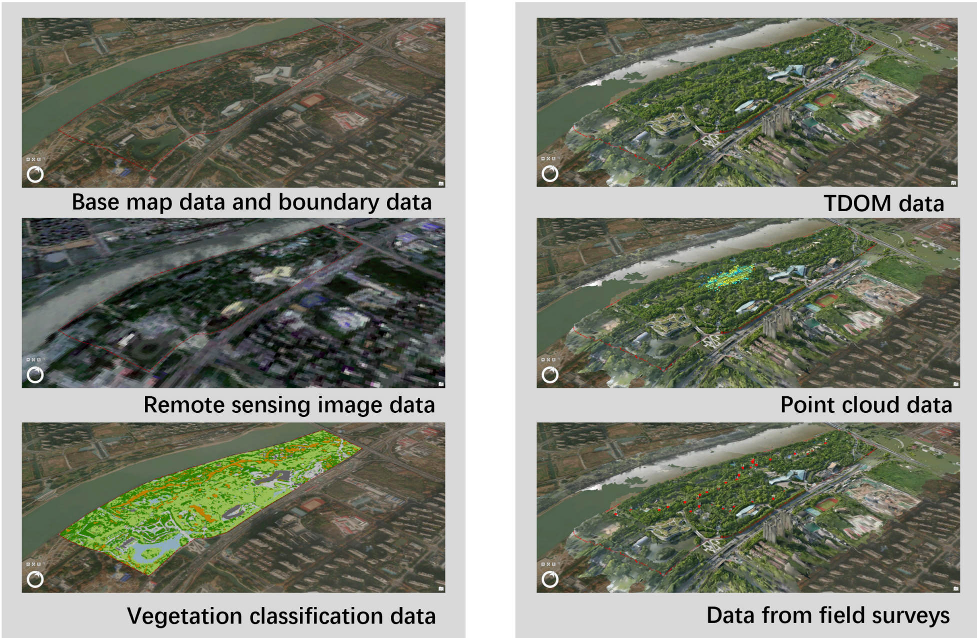

Fig. 2: Data fusion in the DT

3.3.4 Data Visualization

As shown in Figure 3, the platform's data visualization is divided into four layers, using two geographic data visualization libraries. At the city scale, it visualizes the distribution, boundaries, types of green space, vegetation, and carbon stocks in a coarser 3D form. At the plot scale, point cloud models and photographs display the finer 3D morphology of green spaces. At the vegetation community scale, data such as species and specifications are visualized to show finer vegetation 3D morphology. At the single tree scale, dynamic 3D plant morphology is visualized using plant LIM model data at different time points. Cesium.js is used for 3D visualization at the city scale, while Three.js is used for the plot, community, and single tree scales. The corresponding data is shown in Figure 4.

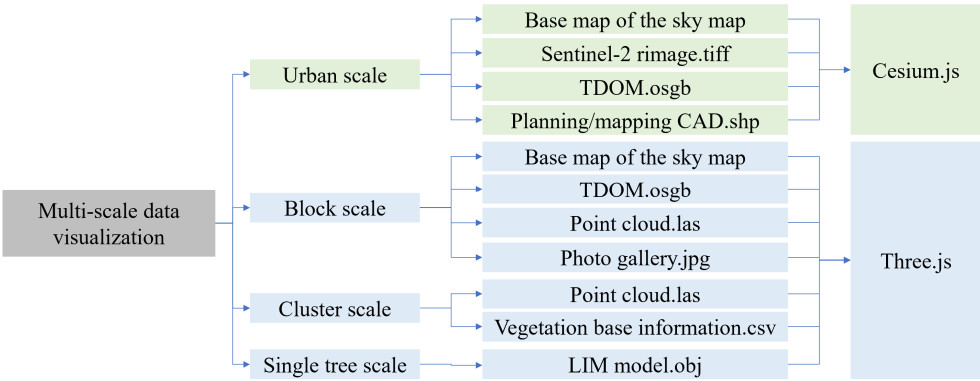

Fig. 3: Data Visualization Framework of the DT

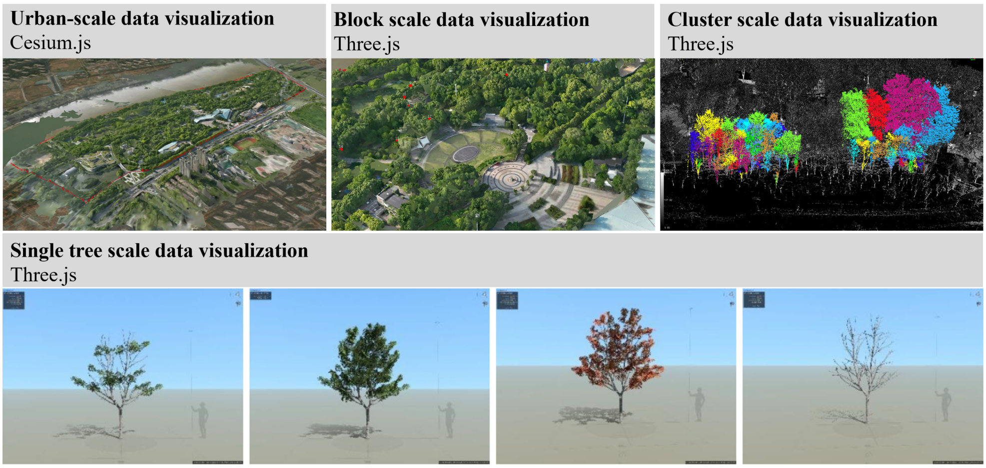

Fig. 4: Visualizing data at different scales

3.4 Framework for Measuring Carbon Sequestration in UGSs in the Platform

3.4.1 Carbon Stock Measurement in Sample Plots based on Point cloud

Based on LiDAR-derived point cloud data and supported by biomass-carbon stock conversion technology, an intelligent framework for carbon stock measurement in urban green spaces is developed (Figure 5). First, the point cloud data from LiDAR is used to quickly and accurately extract vegetation specifications (e. g., diameter at breast height (DBH), tree height, crown width, and three-dimensional green volume) and tree species data from field research. Next, the algorithm matches biomass equations (or biomass expansion factors) to estimate stand biomass. Finally, tree carbon stock is calculated using the carbon content rate and specific forest tree carbon stock formula. In the platform, users can select plant communities to query and measure information (Figure 6). The measurement process is as follows:

(1) P Prepare a CSV table with tree information: tree number (No.), longitude (Long.), latitude (Lat.), species (S), DBH, height (H), crown dimension (CD), crown area (CA), and three-dimensional green volume (GV).

(2) Preparation of biomass conversion formula: (i) Biomass equation method: biomass equation, root-stalk ratio (RSR). (ii) Biomass conversion factor method: volume conversion factor (g), wood volume (V), wood density (WD), biomass expansion factor (BEF), and RSR.

(3) Calculate the biomass of a tree: (i) If the biomass equation of the stand can be obtained, calculate the biomass (B) according to the biomass equation; (ii) If not, calculate biomass (B) according to the biomass conversion factor method, which has the following procedure:

First, calculate the wood volume (V) conversion factor g, the formula is:

$$g = \left(\frac{DBH}{2.2}\right)^{\pi}$$

where, g is the wood volume conversion factor; DBH is the diameter at breast height (DBH) of the tree, cm.

Second, tree volume of wood (V) was calculated with the formula:

$$V = H \times g \times 0.4$$

where V is tree volume, m^3; H is tree height, m; g is volume conversion factor.

Third, tree biomass (B) was calculated with the formula:

$$B = V \times WD \times BEF \times (1 + \mathrm{RSR})$$

where B is tree biomass, t; V is tree volume, m^3; WD is wood density, t/m^3; and RSR is rootstock ratio.

(4) Preparation of data on the carbon content (CF) of various types of trees

(5) Calculate the tree carbon stock (C) based on biomass (B), carbon content (CF), and the formula:

$$C = B \times CF$$

where C is tree carbon stock, t; B is biomass, t/m^3; and CF is carbon content.

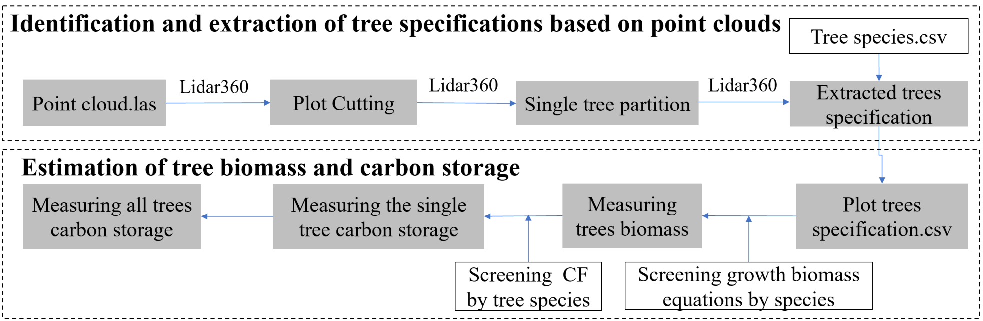

Fig. 5: A framework for intelligent measurement of carbon stocks in sample plots based on point clouds

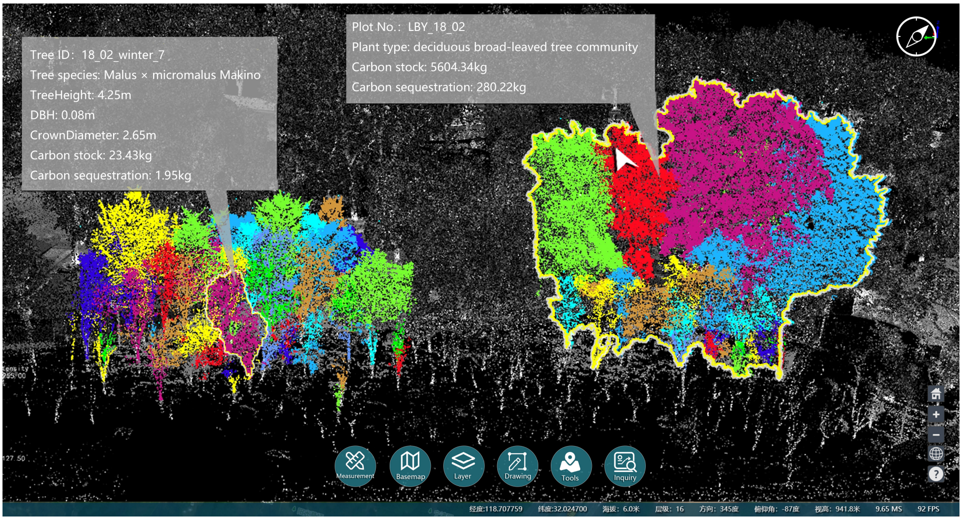

Fig. 6: Displaying and querying plant community-scale carbon sequestration information on the DT platform

3.4.2 Carbon Stock and Carbon Density Measurement of Urban Green Space Based on Remote Sensing Inversion

The process of measuring carbon stock and carbon density in UGSs using remote sensing inversion involves three main steps: (1) automatic downloading and updating of remote sensing images, (2) image interpretation and indicator measurement, and (3) carbon stock and density calculation for various UGS types (Figure 7). Users can display and query block-scale carbon sequestration data on the platform (Figure 8). The measurement process follows these steps:

(1) Automatic downloading and updating of remote sensing images: Annual updates of remote sensing data are crucial for carbon stock monitoring. The algorithm selects suitable data based on location and parameters (e. g., cloud cover, weather) and automatically downloads and stitches the images. The download range is defined on the map interface, and Sentinel-2 images are retrieved from the Copernicus Data Open Center using the Sentinelsat algorithm and stored in the database.

(2) Remote sensing image interpretation and indicator measurement: Remote sensing images are processed in ENVI using IDL scripts, and the vegetation index (NDVI) is calculated.

(3) Carbon stock and density measurement for various UGS types: Carbon stock is estimated from NDVI using a regression model (“vegetation index – carbon stock”). The carbon stock within each UGS boundary is measured in WebGIS. Carbon density for each grid is calculated by dividing the carbon stock by the grid area. Carbon sequestration is determined by subtracting the previous year's carbon stock from the current year’s within the same range.

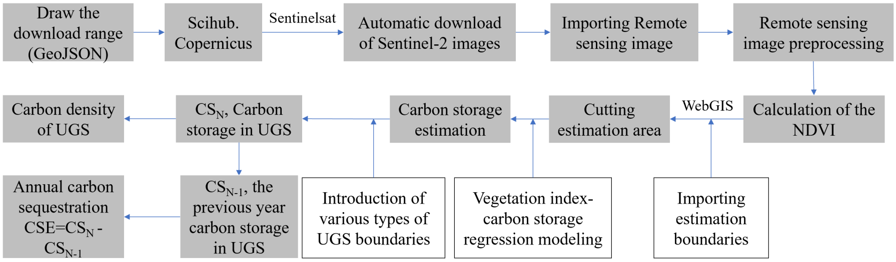

Fig. 7: A framework for intelligent estimation of carbon stocks and carbon density in UGSs based on remote sensing inversion

Fig. 8: Displaying and querying block-scale carbon sequestration information on the DT platform

4 Discussion

(1) Advantages and Disadvantages of WebGIS Platform to Support DT of Carbon Stock in UGSs

This study presents a pathway to integrate heterogeneous data from multiple urban green space sources on the Web and build a digital twin base for measuring carbon sequestration in UGSs. This platform can be further expanded to include modules for real-time data visualization and intelligent carbon sequestration measurement.

WebGIS development leverages an extensive open-source technology stack, such as Cesium.js and Three.js, allowing for flexible, in-depth customization based on project needs. Open-source technologies eliminate licensing fees, making WebGIS a cost-effective option for projects with limited budgets or long-term development goals. WebGIS easily integrates data in multiple formats (e. g., GeoJSON, KML, 3D Tiles) and is ideal for real-time data and large-scale 3D data. Simple HTML structures facilitate integration of encoded strings that activate real-time data acquisition and database connections for 3D visualization. This approach is useful for online visualization of heterogeneous 3D model datasets without specialized software. However, there is room for optimization, especially in supporting high-precision data such as point clouds (LA GUARDIA & KOEVA 2023).

Despite its advantages, WebGIS has drawbacks. First, limitations in dataset dimensionality on Web navigation can be challenging. Second, WebGIS requires programming knowledge to add background data, which may complicate data loading for non-experts. Third, all data must be uploaded to the network for management, leading to high operational costs and security risks. In contrast, ArcGIS secondary development allows for local software configuration (e. g., Access), without reliance on third-party cloud services for operation and maintenance. Finally, compared to ArcGIS, a specialized GIS system, the open-source WebGIS platform may be less efficient for handling large-scale, complex spatial data, particularly large-scale 3D geographic models.

(2) Innovations in Intelligent Measurement Methods

Integrating carbon sequestration measurement in UGSs into the WebGIS-based DT environment is a novel approach to achieve intelligent carbon sequestration measurement across multiple scales. This "intelligence" manifests in several ways: First, through the automatic transformation of "general data" into "value data." Information from various 2D and 3D data sources, such as remote sensing and point cloud data, is converted into meaningful numbers, substituted into specific formulas, and outputted. This allows users to easily obtain the desired measurements without needing to understand the underlying principles. Second, by visually integrating spatial and attribute data. WebGIS overcomes existing GIS limitations by integrating geographic data with detailed 3D model information in Cesium, enabling users to view and select models while accessing structural information. Vegetation morphology and carbon stock data can be analyzed and compared in UGS environments without site visits, addressing the limitations of text-based records. Third, regression and machine learning models embedded within the DT environment enable accurate scaling of data from small to larger scales.

(3) Limitations and Perspectives

This study only proposes a logical framework for estimating carbon sequestration in UGSs based on DTs, but further technical aspects need to be solved. Therefore, the next step is to develop a WebGIS-based data processing process toolset based on the logic constructed in this study to form an automated calculation and analysis workflow, and to publish the results to the platform maps on the Web side.

5 Conclusion

This study relies on WebGIS technology to construct a DT platform, compares the advantages and disadvantages of different development framework, and chooses WEBGIS to construct the platform framework, data flow framework and estimation framework. Then, through a specific workflow, the intelligent measurement and visualization of multi-scale carbon sequestration, carbon density and other indicators in UGSs are realized. Multi-scenario uses by researchers, government, public and students is provided on the WEB side. It adopts open-source strategy to develop the solution and reduce the investment of software cost. It also provides users with seamless data interaction and in-depth visualization capability to easily access the information of the data. This research can be expected to enhance the intelligence of research and control of carbon sequestration in UGSs.

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