Exploring Carbon Sequestration at the National Museum of Natural Science: Sustainability in Nature-Based Educational Landscapes

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***Abstract*—The role of museum green spaces in urban carbon sequestration and sustainable development has long been overlooked. This study investigates the potential ecological contribution of the National Museum of Natural Science of Taiwan by employing the i-Tree Canopy tool to estimate carbon storage and its associated economic value. Through randomized aerial image sampling and land cover classification, the results reveal that, by 2025, the museum's landscape contains approximately 17.84 metric tons of carbon. This corresponds to an estimated market value of USD 21,360 under Taiwan's current carbon pricing framework. The findings underscore that museums, in addition to serving cultural and educational purposes, can also provide concrete ecological services. In the context of accelerating carbon pricing policies, such spaces exhibit significant potential for integration into climate and sustainability strategies. This study advocates for greater recognition of the multifunctional role of cultural institutions and recommends their inclusion in urban carbon management and climate adaptation planning.**

***Keywords*—green infrastructure, urban forests, urban carbon sequestration, i-Tree canopy, carbon pricing**

I. Introduction

In the context of growing global concern about sustainable development and climate change, urban environments and educational institutions have been increasingly recognized as potential carbon sinks. However, within the interdisciplinary realm of environmental science and cultural studies, the carbon sequestration potential of outdoor museum spaces has received limited attention. Traditionally, museums have been assigned to preserve cultural heritage and the cultivation of collective memory [1], while also acting as educational platforms through exhibitions and participatory programs [2]. Since the International Council of Museums (ICOM) formally incorporated environmental responsibility into its professional standards in 2016, museum landscapes have become viewed as extensions of the 'expanded museum' [3]. Modern museum architecture has increasingly evolved into integrated ecological systems that combine design, sustainability, and spatial comfort [4]. Although the significance of museum landscapes has begun to gain recognition in cultural and architectural discourse, empirical studies on their carbon sequestration functions remain scarce. Existing research tends to focus on the conservation of biodiversity within museum interiors [5, 6] or the promotion of environmental education and sustainability awareness [7], while empirical investigations of the ecological services of outdoor museum green spaces remain limited.

In light of increasing policy emphasis on carbon pricing and carbon offsets, museum campuses should be reconsidered as integral components of climate action strategies. Soil organic carbon sequestration, by transferring atmospheric carbon dioxide into the soil, plays a crucial role in mitigating climate change [8]. Long-term maintenance of lawns provides an effective strategy for carbon management, capable of compensating for the impacts of climate change and supporting ecosystem restoration [9]. In this context, museum green spaces can be regarded as unique carriers of soil organic carbon sequestration within urban environments. As semi-enclosed and well-maintained landscapes, they typically contain diverse vegetation structures, stable soil conditions, and limited anthropogenic disturbance—factors that collectively enhance long-term carbon accumulation in the soil. Moreover, museum campuses are often managed under consistent maintenance regimes, providing a relatively controlled setting for examining soil–vegetation interactions and carbon dynamics. Their dual role as educational and ecological spaces further allows them to serve as living laboratories for demonstrating the environmental value of cultural institutions in achieving carbon neutrality goals. Urban green spaces are essential for carbon regulation; however, research on their carbon sequestration efficiency has received limited attention [10]. This study aims to fill this research gap by employing high resolution remote sensing techniques and standardized carbon estimation tools to assess the carbon sequestration functions and potential of educational landscapes from an ecological and spatially integrated perspective.

This study applied the i-Tree Canopy system to conduct a systematic quantification of carbon storage in the urban forest of the National Museum of Natural Science for the first time. By integrating high-resolution remote sensing imagery with a random sampling approach, it not only provides accurate estimates of tree canopy cover, but also allows for a detailed assessment of carbon storage potential across different tree species, age classes, and landscape units. Furthermore, by linking urban forest carbon storage with the design of the surrounding landscape, educational functions, and public participation, the study offers a multidimensional analysis of ecological and social values. Quantified carbon sequestration data provide actionable scientific evidence for urban green space planning, climate policy, and carbon management. This approach goes beyond mere ecological indicator estimation, connecting ecological benefits with urban management decisions and demonstrating cross-disciplinary innovation.

Rather than conventional research approaches that focus primarily on indoor exhibitions or educational programming, this study concentrates on external green spaces of museums. Using tools such as the i-Tree canopy carbon model, we propose a replicable framework for assessing carbon sequestration in green spaces associated with educational institutions. This innovative approach not only contributes to theoretical discourse but also responds to the global shift toward expanding the environmental responsibilities of museums.

Taking the National Museum of Natural Science (NMNS) in Taiwan as a case study, this research examines the function of carbon sequestration and potential policy contributions of educational landscapes within urban environments. Specifically, the study uses the i-Tree Canopy model to assess green cover and carbon sink capacity. The objectives are threefold: to analyze how educational landscapes contribute to carbon sequestration; to evaluate the carbon storage potential of the NMNS campus; and to explore how such efforts align with broader global climate action initiatives. Furthermore, the study seeks to compare the carbon management efficiency of institutional green spaces with that of conservation-driven natural landscapes.

II. Methods

A. Study Area

The NMNS, located in the north district of Taichung City, Taiwan, is an urban multifunctional complex that integrates education, cultural dissemination, and ecological exhibition, as illustrated in Fig. 1. As the first science museum completed under Taiwan's Twelve Major Construction Projects, its development has proceeded in four phases since its public opening in 1986, with continuous expansion of facilities and exhibition areas. The completion of the Botanical Garden in 1999 further enhanced the ecological scope and spatial scale of the museum campus.

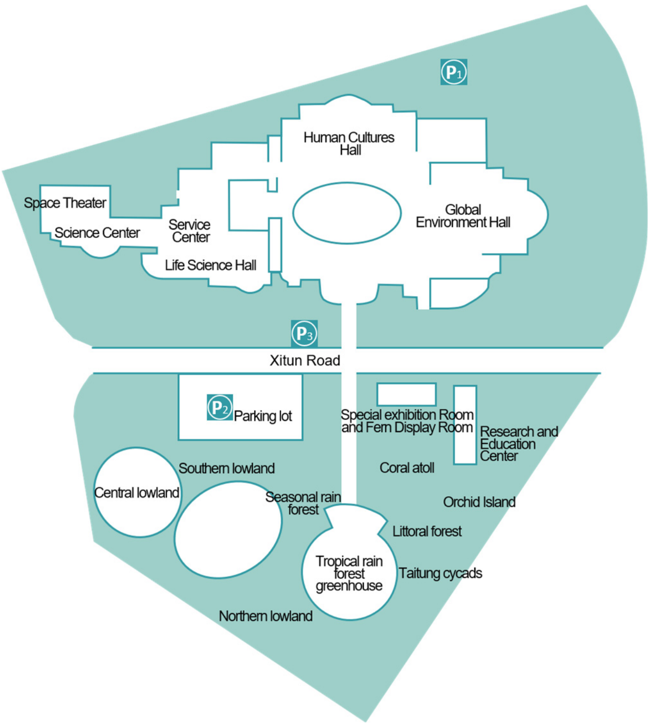
Note: The information presented in this study was obtained from the official website of the National Museum of Natural Science of Taiwan.
Fig. 1. Exterior landscape of the National Museum of Natural Science, Taichung, Taiwan.

Geographically, the museum is located at 24.1579°N latitude and 120.6653°E longitude. It lies within a subtropical monsoon climate zone, bordering the tropical monsoon climate classification. The region experiences an average annual temperature of approximately 23.3 °C, with warm to hot daytime conditions, and receives over 1,700 mm of annual precipitation, with summer being the main rainy season. These climatic conditions support dense vegetation and rich biodiversity, contributing to a diversified green landscape. Such ecological characteristics not only enhance the natural atmosphere but also provide a strong potential for carbon sequestration and biodiversity conservation. Consequently, the NMNS campus serves as a critical site for the investigation of this study into the carbon storage capacity of educational landscapes in urban environments.

B. Land Use and Architectural Features

The NMNS functions as a multifunctional integrated complex, with land use that encompasses various aspects such as scientific exhibitions, plant conservation, academic research, and public recreation. The core area includes major exhibition halls such as the Science Centre, Life Sciences

Hall, Human Cultures Hall, and Earth Environment Hall, each dedicated to distinct scientific domains and presented through specialized thematic displays. The independently established botanical garden on campus houses a rich variety of plant species and natural ecological environments, offering outdoor learning and recreational spaces for the public. Additionally, immersive facilities such as the Space Theatre and 3D Theater employ multimedia and interactive technologies to enhance the effectiveness of science communication. The entire architectural complex adopts a modernist design style, emphasizing geometric forms and axial spatial organization, thereby integrating functional requirements with educational significance. Although constructed in multiple phases, the buildings maintain stylistic consistency and harmonize with the surrounding green landscape, collectively shaping an educational museum campus that combines knowledge dissemination with urban recreational functions, as illustrated in Fig. 2.



Note: The information presented in this study was obtained from the official website of the National Museum of Natural Science of Taiwan.
Fig. 2. Site layout of the National Museum of Natural Science.

C. Ecological Significance and Distribution of Green Spaces

The NMNS campus covers a total area of approximately 13.38 hectares, comprising an 8.9-hectare main museum area and a 4.48-hectare botanical garden. The total footprint of the building is approximately 101,554.01 square meters, which includes key facilities such as the Science Centre, Life Sciences Hall, Human Cultures Hall, Earth Environment Hall, Space Theatre, and 3D Theater. Beyond the built environment, the campus includes plazas, outdoor gardens, evolutionary history trails, and landscaped water features, creating a multilayered outdoor environment with educational functions. The botanical garden spans approximately 4.48 hectares, characterized by high green coverage and plant diversity, and contains greenhouses and various themed exhibition zones that provide the public with spaces for ecological observation and environmental learning. Overall, the campus integrates urban ecological services with cultural and educational values, contributing not only to enhancing urban green coverage and microclimate regulation, but also as a representative empirical site to investigate the carbon sequestration potential in educational landscapes in this study.

D. i-Tree canopy model for Vegetation and Carbon Sequestration Assessment

To systematically evaluate the vegetation structure and carbon sequestration potential of the study area, this research employed the i-Tree Canopy model as a primary analytical tool. The following subsections outline the procedures involved in data acquisition, image classification, and estimation of carbon storage.

1) Data collection and processing

The i-Tree Canopy model, developed by the Forest Service of the United States Department of Agriculture, is widely used to estimate tree canopy, the impervious surface ratios, and the composition of the vegetation within specified areas. This model integrates high resolution aerial imagery with random point sampling, employing manual interpretation for land cover classification, which enhances the accuracy and consistency of land cover estimations [11].

The calculation of i-Tree Canopy data primarily relies on user-based sampling of remote sensing imagery within a designated study area. The workflow typically begins with the user defining the research boundary, after which the system randomly generates a set of sampling points. At each point, the type of user classifies the land cover (for example, trees, grass, buildings, or water). These annotations are then aggregated and statistically analyzed to estimate the proportion of vegetation cover and the distribution of other types of land cover across the entire area. Rather than relying on field measurements, i-Tree Canopy combines remote sensing imagery with user-sampled interpretation to infer tree canopy coverage and related ecological indicators. The workflow of the i-Tree Canopy data source is illustrated in Fig. 3.

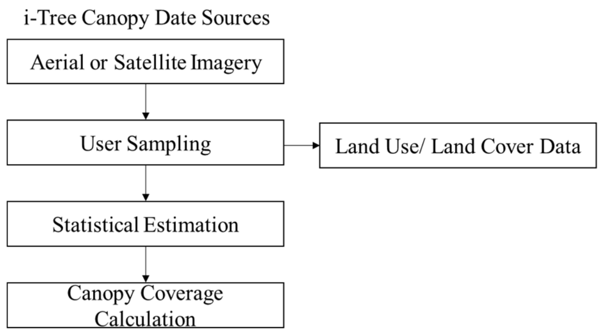


Fig. 3. Workflow of i-Tree Canopy data sources.

In this study, the campus of the geographic boundary of the National Museum of Natural Science, which is approximately 13.38 hectares, was delineated using GIS software and imported into the i-Tree Canopy system. Within this limit, 200 random sampling points were generated and each point was manually interpreted and classified using high-resolution imagery from Google Earth. This methodology effectively estimates the spatial distribution of various types of land cover within the study area and serves as fundamental data for subsequent assessments of the carbon sequestration potential. The point-by-point interpretation and classification of carbon storage at the National Museum of Natural Science are illustrated in Fig. 4.

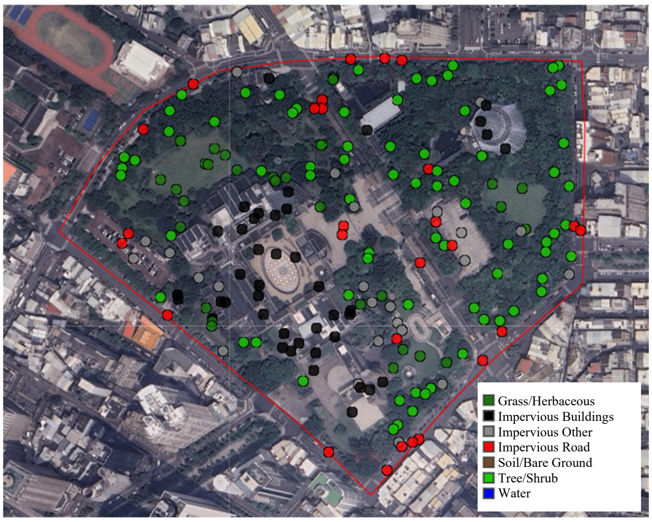


Fig. 4. Point-by-point interpretation and classification using high-resolution Google Earth images results.

III. Results

A. *Carbon Storage of the Urban Forest in the Museum (Based on i-Tree Canopy Assessment)*

Since Taiwan currently lacks a database to assign appropriate tree benefit values to land cover types in i-Tree's canopy cover analysis, this study used the US urban database as the calculation basis. The i-Tree Canopy analysis evaluates tree canopy contributions and carbon sequestration efficiency within urbanized landscapes. The results (see Table 1) quantitatively estimate the annual carbon storage and sequestration rates, effectively supplementing the assessment of ecological benefits provided by urban green spaces. The study indicates that within the 13.38-hectare study area, the total carbon storage is approximately 17.84 ± 1.63 metric tons of carbon, equivalent to 65.41 ± 5.97 metric tons of equivalent carbon dioxide (CO_2). Furthermore, the estimated annual carbon sequestration is 447.98 ± 40.90 kilograms of carbon per year, corresponding to 1,642.61 ± 149.95 kilograms of CO_2 annually. These findings demonstrate that the urban forest green spaces of the National Museum of Natural Science serve as a stable and continuous carbon sink in the urban environment, contributing positively to environmental sustainability.

Table 1. Carbon storage in trees, carbon sequestration benefits and market valuation

Description	Area (ha)	Carbon (t)	CO_2 Equiv. (t)	Value (USD)
Sequestered annually in trees	8.24	17.84±1.63	65.41±5.97	$8,509±777
Stored in trees (Note: this benefit is not an annual rate)	8.24	447.98±40.90	1,642.61±149.95	$213,688±19,507

Table 2. Land cover classification and area estimates based on i-Tree canopy analysis

Abbr.	Cover Class	Description	Area (ha) ± SE
T	Tree/Shrub	Canopy-forming woody vegetation	5.83 ± 0.53
H	Grass/Herbaceous	Vegetation cover in low-lying areas	2.41 ± 0.40
IO	Impervious Other	Paved and non-vegetated surfaces	1.87 ± 0.36
IR	Impervious Road	Road and Transportation Sector	2.18 ± 0.38
S	Soil/Bare Ground	Bare soil or barren land	0.00 ± 0.00
IB	Impervious Buildings	**Structures and Built Environment**	3.26 ± 0.45
W	Water	Water bodies and aquatic features	0.00 ± 0.00
Total			15.55

B. *Contribution of Canopy Cover and Land Cover Types to Carbon Storage*

The land cover classification system employed by i-Tree Canopy facilitates an in-depth analysis of vegetation distribution and its varying roles in carbon sequestration. The results indicate that within the total study area of 13.38 hectares, the cover of trees and shrubs represents 5.83 hectares, representing the primary carbon sink within the region (see Table 2). In addition, the grasslands cover approximately 2.41 hectares. Although grasslands have lower carbon storage capacity compared to arboreal vegetation, they still demonstrate moderate carbon sequestration potential and provide ecological benefits, particularly in maintaining soil health and mitigating urban heat island effects.

In contrast, impervious surfaces account for only 1.87 hectares and bare soil covers 0.00 hectares, contributing minimally to carbon storage due to the absence of plant biomass capable of long-term carbon fixation. Roads (2.18 hectares) and building areas (3.26 hectares), without vegetation cover, possess virtually no sequestration potential. The presence of these types of abiotic land cover further underscores the critical role of green spaces in improving the capacity of urban carbon sinks. In general, the classification and analysis conducted through i-Tree Canopy clearly delineate the functional differences of various types of cover types within the carbon storage system, providing a scientific basis for future urban green space planning and carbon sink management strategies.

These findings indicate that expanding the coverage of tree-dominated green spaces within the museum landscape would enhance the overall carbon sequestration efficiency. Efforts must be made to minimize the proportion of impervious surfaces to reduce carbon loss and degradation of ecological service functions. Through optimizing vegetation arrangements and green space design, carbon sink capabilities can be strengthened while also promoting climate adaptation and environmental sustainability. This further highlights the proactive role of the National Museum of Natural Science within the urban ecosystem.

C. *Economic Valuation of Urban Forest Carbon Storage*

We evaluated the economic value of carbon sequestration provided by the urban forest using three major global carbon credit trading mechanisms: 1) the European Energy Exchange; 2) the California Cap-and-Trade Program; and 3) the Australian Carbon Credit Units. This study applied different economic models to estimate the carbon sequestration value of the urban forest of the National Museum of Natural Science. Carbon prices used were the most recent market rates published in July 2025: €75 per ton CO_2 for the European Union Emission Allowances, $35 per ton CO_2 for the California Cap-and-Trade System, and $20 per ton CO_2 for the Australian Carbon Credit Units. Exchange rates were based on the announcement of the Bank of Taiwan on July 21, 2025, at NT$34.77 per euro and NT 29.68 per US dollar (Bank of Taiwan, 2025). The results of the economic evaluation, based on the i-Tree Canopy carbon sequestration estimates of i-Tree Canopy, are presented in Table 3. These data underscore the economic importance of the museum's urban forest and highlight its substantial potential for application within carbon offset markets.

To ensure comparability across different carbon credit trading markets, this study adopted the 2025 currency exchange rates for financial data standardization. The conversion rates applied were: 1 EUR = 1.168 USD and 1 AUD = 0.654 USD. This standardization approach facilitates a consistent and equitable economic valuation of the carbon sequestration potential of the urban forest of the National Museum of Natural Science, within the framework of international carbon pricing systems.

Table 3. Carbon storage and market valuation of trees and grasslands

Area (ha)	Total CO Storage (t)	EEX(USD)	CARB(USD)	ACCU(USD)
8.24	65.41±5.97	4,905.75 ± $447.75	2,289.35 ± $208.95	1,308.20 ± $119.40

Table 4. Air purification benefits of trees: Pollutant removal and economic valuation

Abbr.	Description	Annual Removal (kg/year)	Amount (kg)	Value (USD)
CO	Carbon Monoxide removed annually	6.23±0.57	1.069	10±1
NO_2	Nitrogen Dioxide removed annually	24.64±2.25	4.227	4±0
O_3	Ozone removed annually	296.98±27.11	50.944	191±17
SO_2	Sulphur Dioxide removed annually	53.16±4.85	9.119	1±0
$PM_{2.5}$	Particulate matter less than 2.5 microns removed annually	15.51±1.42	2.660	402±37
PM_{10}	Particulate matter greater than 2.5 microns and less than 10 microns removed annually	119.08±10.87	20.428	887±81
Total		515.60±47.07	86.49	1,495±136

D. Quantification of Air Pollutant Removal by Urban Forest

The urban forest area (8.24 hectares) within the study site effectively eliminated multiple major atmospheric pollutants during the study period, including carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), Sulphur dioxide (SO_2), fine particulate matter ($PM_{2.5}$) and coarse particulate matter (PM_{10}). The total annual amount of pollutants removed exceeded 515.60 kilograms, corresponding to an estimated economic value of US $ 1,495 ± 136 (see Table 4). These findings highlight the significant role of the urban forest in improving air quality and providing essential ecosystem services.

Among the various air pollutants removed, fine particulate matter ($PM_{2.5}$) and coarse particulate matter (PM_{10}) contributed the greatest economic benefits, highlighting the critical role of the urban forest in mitigating air pollution and reducing health risks associated with respiratory diseases. In particular, the annual removal of ozone (O_3) exceeded 1,468 ± 72 kg, highlighting its significant contribution to suppressing ground-level ozone formation, alleviating photochemical smog, and mitigating related environmental impacts. Furthermore, gaseous pollutants such as carbon monoxide (CO), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) were also effectively removed, indicating the capacity of the urban forest to reduce harmful emissions from vehicular and industrial sources.

In terms of total removal volume and efficiency, ozone (O_3) ranked highest, followed by coarse particulate matter (PM_{10}) and Sulphur dioxide (SO_2). On the contrary, the removal efficiencies of nitrogen dioxide (NO_2), fine particulate matter ($PM_{2.5}$), and carbon monoxide (CO) were comparatively lower. In general, these findings demonstrate the essential ecological service function of urban trees in air purification and urban environmental health enhancement, supporting the strategic integration of green infrastructure to improve environmental quality and public well-being.

IV. Discussion

This study used the i-Tree Canopy model to perform a detailed evaluation of the carbon sequestration potential of the urban forest surrounding the National Museum of Natural Science. The findings reveal that the 13.38-hectare study area stores approximately 17.84 ± 1.63 metric tons of carbon, equivalent to 65.41 ± 5.97 metric tons of carbon dioxide (CO_2) equivalent, with an annual carbon sequestration rate of 447.98 ± 40.90 kilograms of carbon. These results underscore the critical role of tree-dominated urban landscapes in the ongoing uptake of carbon, aligning with previous research and supporting its inclusion as an essential component of nature-based climate mitigation strategies [12, 13]. However, the efficiency of carbon sequestration is significantly influenced by canopy density, and increasing climate variability, such as monsoon irregularities and the increase in the frequency of drought—may limit tree growth rates, thereby constraining the sustained expansion of carbon sinks [14]. Consequently, future urban forest management must prioritize adaptive biomass protection and soil carbon stability to ensure long-term effectiveness of carbon sequestration [15].

Urban forests also play an important role in air quality management. Within the 8.24-hectare urban forest area of the study site, approximately 515.60 kilograms of atmospheric pollutants are removed annually, producing an estimated economic benefit of USD 1,495 ± 136. In particular, removal of ozone (O_3) accounts for 296.98 ± 27.11 kilograms, highlighting its importance in reducing ground-level ozone concentrations and mitigate the associated respiratory health risks [16]. Additionally, the removal of particulate matter, 119.08 kilograms of PM_{10} and 15.15 kilograms of $PM_{2.5}$, is critical to improving air quality and lowering the incidence of cardiopulmonary diseases [17, 18]. The reductions in nitrogen dioxide (NO_2) and Sulphur dioxide (SO_2) further demonstrate the ecological value of the urban forest in alleviating emissions from traffic and industry emissions, as well as in reducing acid rain formation [19].

However, the contributions of urban forests to air quality are often underestimated in policy making processes [20]. This study reinforces that well-managed and protected urban forests tend to offer superior air purification benefits compared to conventional urban parks, primarily due to their higher canopy density and biomass [21]. For example, while the average carbon storage of typical urban parks is approximately 15.3 metric tons per hectare, the urban forest surrounding the museum exceeds 17.84 metric tons per hectare, demonstrating its substantial potential as a high-density carbon sink [22].

Beyond air purification, the urban forest also plays a crucial role in urban thermal regulation. The removal of $PM_{2.5}$ and PM_{10} not only improves air quality but also reduces atmospheric heat absorption, lowers radiative forcing, and mitigates the urban heat island effect [23]. At the same time, the uptake of ozone and nitrogen dioxide helps suppress smog formation and dampens temperature fluctuations caused by chemical pollution [23]. Mature canopy structures further strengthen thermal regulation by decreasing the frequency and intensity of extreme heat events, a phenomenon well documented in urban forest studies [24].

Taken together, the urban forest represents not only represents a nature-based solution for climate mitigation, but also a sustainable alternative to energy-intensive cooling systems. However, certain limitations remain. i-Tree Canopy relies on user interpretation of remote sensing imagery, which may be influenced by subjectivity, and lacks field measurements for validation. Furthermore, the carbon storage estimates do not account for soil carbon or deadwood pools, potentially underestimating total urban forest carbon stocks. Future research could integrate field plot measurements and multiple data sources to improve the accuracy and comprehensiveness of carbon storage estimation.

V. Conclusion

This study demonstrates that the urban forest of the National Museum of Natural Science not only performs a stable carbon sequestration function but also exhibits significant potential for ecological services in terms of air pollutant removal and urban microclimate regulation. Specifically, tree-dominated green spaces contribute the most to carbon storage, whereas impervious surfaces and built-up areas provide virtually no sequestration benefits, underscoring the structural impact of land use planning on carbon dynamics. Additionally, the annual removal of more than 500 kilograms of air pollutants and its associated economic valuation confirm the tangible contributions of urban forests to the improvement of public health, the reduction of pollution control costs, and the advancement of climate justice.

These findings highlight that educational green spaces, such as those surrounding museums, should not only be appreciated for their environmental awareness-raising functions, but should also be recognized as strategically valuable assets for climate adaptation. Future urban planning should integrate urban forests into mainstream policy frameworks, positioning them as central components of urban carbon management and ecological sustainability. Through targeted monitoring and effective institutional design, the role and responsibilities of urban forests in national climate action can be substantially strengthened.

Although this study provides a quantitative analysis of carbon sequestration and pollutant removal using the i-Tree Canopy tool, the biomass parameters embedded within the model may present regional discrepancies that could affect the accuracy of the results. Future efforts should focus on developing locally calibrated biomass estimation models that incorporate the composition of tree species, the dynamics of carbon dynamics, and variations in the structure of the age. Furthermore, the role of urban forests in policy planning and carbon market mechanisms remains insufficiently defined. Future research is recommended to explore the impacts of different management strategies and policy integrations on the long-term ecological performance of urban forests. Furthermore, the feasibility of incorporating urban forests into carbon trading schemes and green infrastructure frameworks should be evaluated to further institutionalize their role in climate action.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

J.-C. C. conducted the research, performed the analyses, and prepared the original draft; Y.-M. C. was responsible for data curation and literature collection; and J.-Y. L. provided supervision; with all authors having read and approved the final version of the manuscript.

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