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Quantifying ecosystem services of urban green spaces using I-Tree Canopy: Evidence from a rapidly urbanizing region in Indonesia

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ABSTRACT

Greater Cibinong, a buffer zone of Jakarta, has experienced rapid population growth leading to the conversion of green areas into built-up zones. This transformation affects ecological balance, reduces air quality, and worsens climate change. As land availability for green open spaces (GOS) becomes increasingly limited amid rapid urbanization, understanding the extent of GOS ecological functions in providing landscape services is crucial. Aims: This study aims to analyze the ecological functions of GOS in delivering landscape services, including carbon sequestration and storage, pollution absorption, and rainfall interception. Methodology and results: This study applies the i-Tree Canopy method using a random point sampling technique with 500 sampling points across six subdistricts in Greater Cibinong. The number of samples is set to achieve a 95% confidence level with a margin of error below 1.6%, meets this tolerance. Conclusion, significance and impact study: GOS play a vital role in maintaining ecological functions. Babakan Madang Subdistrict recorded the highest vegetation cover (tree/shrub) at 60.24%, with annual carbon storage of 16.99 kt (equivalent to IDR 134.46 billion), pollution removal of 491.19 tons per year (equivalent to IDR 23.62 billion), and runoff reduction of 183.86 ML (equivalent to IDR 7.19 billion). In contrast, Bojong Gede Subdistrict showed the highest impervious building cover at 43.80%. The most absorbed pollutants were ozone (O_3) and PM_{10}. The findings highlight the significant contribution of GOS to climate change mitigation, air quality improvement, and hydrological regulation, emphasizing the need for more effective policies on GOS protection and management.

Keywords: green open space, carbon sequestration, landscape services, i-Tree Canopy, climate change mitigation.

INTRODUCTION

Greater Cibinong, which consists of six subdistricts, is an area currently experiencing rapid population growth. The population of Greater Cibinong has reached approximately 2.7 million population and continues to increase annually at an average growth rate of 1.5% (Badan Pusat Statistik Kabupaten Bogor, 2023). The significant population increase has led to a greater demand for residential land. One of the direct consequences of this growth is land-use and land cover change (LUCC), where areas previously designated as green open spaces (GOS) have been transformed into built-up zones. Rapid urbanization in Indonesia has led to the reduction of vegetation formations and ecological functions of urban landscapes (Prastiyo et al., 2020). This condition requires serious attention because green infrastructure provides various benefits including urban microclimate cooling, improved air quality, biodiversity, as well as documented benefits for human health and well-being at both individual and community levels (Kumar et al., 2025)

This trend occurs globally; rapid urban growth has modified hydrological systems by substituting vegetation with impervious cover, producing faster and greater runoff quantities (Rahman et al., 2023). Similar patterns have been observed across cities in developing countries, where urban expansion often occurs at the expense of green infrastructure (Hanna and Comín, 2021). The GOS conversion to developed areas compromises landscape services while exacerbating urban heat, air pollution, and flood hazards (Naik et al., 2025). This phenomenon reduces the availability of GOS, which in turn potentially diminishes environmental quality and ecological functions.

Population increase exacerbates air pollution levels, which remains a major urban environmental challenge globally, with particulate matter ($PM_{2.5}$ and PM_{10}) and ground-level ozone (O_3) being among the most critical pollutants affecting human health (Sicard et al., 2023; Bui and Nghiem, 2025). The combined effects of population density, heavy traffic volume, and industrial activities contribute to poor air quality and elevated carbon dioxide emissions. Urban trees have been demonstrated to remove significant amounts of air pollutants through dry deposition processes, with annual removal rates varying substantially among cities depending on tree cover, species composition, and local pollution concentrations (Pace et al., 2021). Trees demonstrate the ability to assimilate gaseous contaminants – specifically O_3, NO_2, SO_2, and CO – through microscopic leaf pores, while airborne particles are captured and deposited on external plant structures including leaves and bark (Baumann and Grêt-Regamey, 2024; Corona et al., 2022). Plant coverage serves indispensable roles in maintaining climatic equilibrium, retaining atmospheric carbon reserves, and moderating hydrological processes (Sankey et al., 2021).

The GOS serve a vital function in maintaining urban ecosystem balance. They provide healthy public spaces, improve air quality, and deliver various landscape services that support environmental sustainability. GOS offer landscape services such as water reservoirs, biodiversity conservation habitats, carbon sequestration, microclimate regulation, agricultural and aquacultural production areas, and recreation spaces (Godoi et al., 2025; Aulia et al., 2023). Trees, as a major component of GOS, plays a critical role in mitigating climate change impacts and enhancing urban resilience to environmental stresses (Coleman et al., 2022). As a key element in urban spatial planning, GOS contributes significantly to the quality of life – physically, socially, and ecologically. However, with the limited land availability for GOS amid rapid urbanization, it becomes increasingly important to understand the ecological functions of GOS in providing landscape services to both the environment and society. According to Indonesian regulations, the proportion of GOS in a city should be at least 30% of the total urban area, ensuring the stability of urban ecosystems and the availability of clean air for residents (Dan & Soelistyari, 2021).

The objective of this research are analyze the ecological functions of GOS in Greater Cibinong and to analyze the functions of landscape services such as carbon sequestration and storage, pollution absorption, and rainfall interception. The research employs i-Tree Canopy, a software-based tool designed to estimate the proportions of various types of land cover such as grassland, built up area, artificial surfaces, paved roads, unvegetated land, woodland, water bodies and ecological functions of urban GOS. The i-Tree platform has become one of the most widely used tools globally for quantifying landscape services provided by urban forests, with applications demonstrated across diverse climatic and socio-economic contexts (Ghorbankhani et al., 2024; Hintural et al., 2024; Mosyaftiani et al., 2022; Aulia et al., 2023; G. Sharma et al., 2025). The random point sampling methodology employed by i-Tree Canopy has been validated against remote sensing methods and shown to provide reliable estimates with standard errors typically below 2% when sufficient sample points are used (Hwang and Eric Wiseman, 2020). Recent studies have established optimal sampling protocols, recommending 500–1000 points for large areas to achieve 95% confidence levels with acceptable margins of error (Selim et al., 2023). This approach provides a comprehensive understanding of the ecological contributions of GOS in Greater Cibinong and underscores the importance of proper protection and planning for their sustainable management in the future.

The findings of this study are expected to offer deeper insights into the significance of preserving and managing GOS effectively amid rapid urbanization. The results may serve as a scientific basis for policymakers in formulating environmental sustainability strategies in Greater Cibinong. Urban green infrastructure that provides landscape services is fundamental to ensuring sustainable urban development (Ghorbankhani et al., 2024).

The aim of this study is to quantitatively assess the ecosystem services provided by urban green open spaces in a rapidly urbanizing tropical region and to examine how variations in land cover influence carbon storage, air pollution removal, and hydrological regulation.

- H1: Subdistricts with higher tree canopy cover exhibit significantly greater ecosystem service provision (carbon storage, pollution removal, and hydrological regulation).
- H2: Increased impervious surface cover is negatively associated with ecosystem service capacity.
- H3: Ecosystem services follow an urban–peri-urban gradient, with higher values in less urbanized subdistricts.
- H4: The magnitude of ecosystem services derived from GOS is sufficient to provide policy-relevant environmental benefits in rapidly urbanizing regions.

MATERIALS AND METHODS

Study area

This study was conducted in Greater Cibinong region, located in Bogor Regency, West Java, Indonesia.

The study area comprises six subdistricts: Tajurhalang, Bojong Gede, Cibinong, Citeureup, Babakan Madang, and Sukaraja (Figure 1 and Data S1). Geographically, Greater Cibinong is situated between 106°41’39” – 106°58’37” E and 6°26’9” – 6°38’29” S. This region has

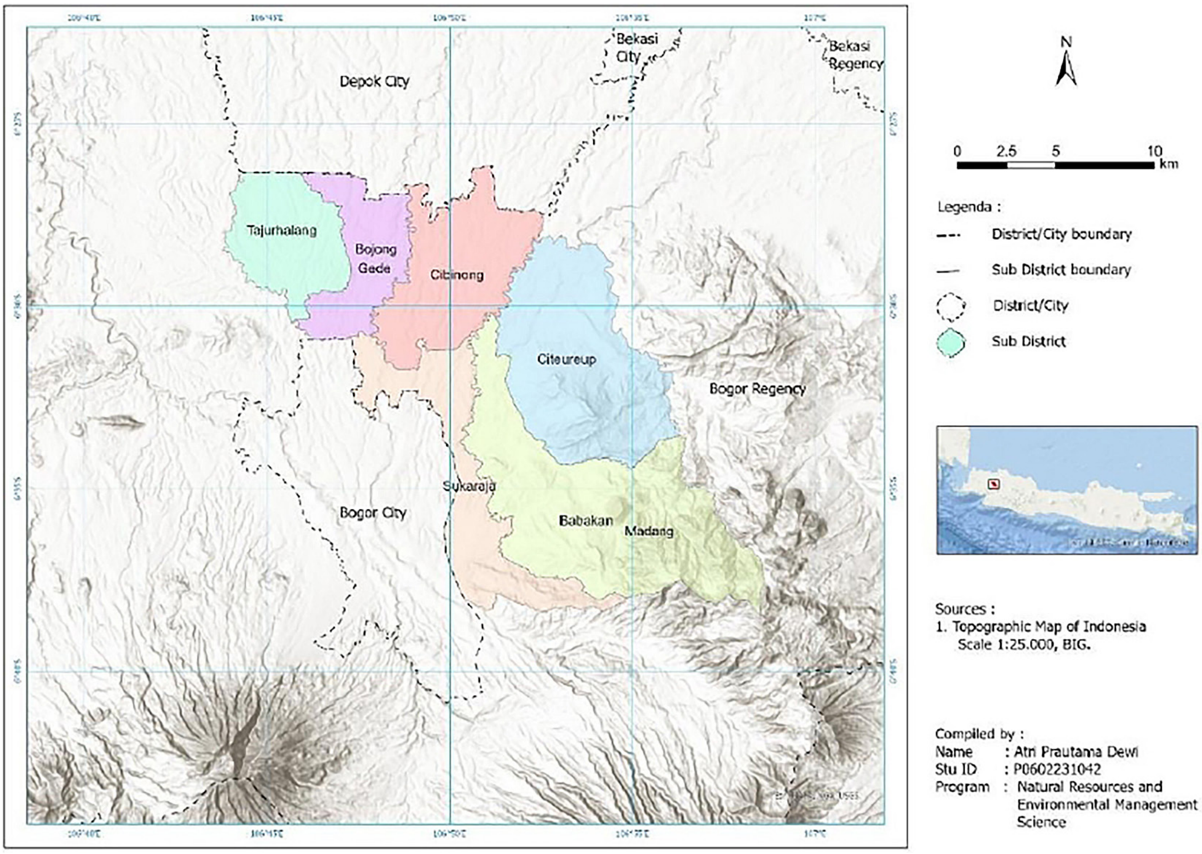

Figure 1. Research location map of greater cibinong

experienced rapid urbanization over the past decades, making it a suitable case study for assessing ecosystem services provided by urban GOS.

Data sources

High-resolution satellite imagery was used as the primary data source for land cover classification. Specifically, imagery from Google Earth acquired in 2025 with a spatial resolution of 0.5 m was employed and imagery 2026 airbus, CNES, maxar technologies. All imagery was accessed and interpreted within the i-Tree Canopy environment. In addition, the study adopted the standard i-Tree Canopy classification protocol (USDA Forest Service, 2020) and used the default biophysical parameters embedded in i-Tree Canopy were used in this study, as region-specific calibration data for Indonesia are currently limited.

Research methodology

The ecological functions of urban GOS were assessed using the i-Tree Canopy tool version 7.1, developed by the USDA Forest Service. This tool applies a point-based classification approach to estimate land cover distribution and quantify ecosystem services, including carbon storage, annual carbon sequestration, and air pollution removal (Ghorbankhani et al., 2024). i-Tree Canopy applies the random point sampling principle to estimate the type and proportion of land cover in the study area and to evaluate its ecological functions (Parmehr et al., 2016).

The study area was defined based on the administrative boundaries of the Greater Cibinong region. Spatial boundary data were obtained in the form of shapefiles (SHP) for each subdistrict, which were imported into the i-Tree Canopy platform for analysis. Each subdistrict (Tajurhalang, Bojong Gede, Cibinong, Citeureup, Babakan Madang, and Sukaraja) was analyzed independently to capture spatial variability. The results from all subdistricts were subsequently compiled to represent the overall ecological condition of the Greater Cibinong area.

A stratified random sampling design was implemented to ensure balanced representation across the study area. A total of 3.000 sampling points were generated, with 500 points allocated to each of the six subdistricts (Tajurhalang, Bojong Gede, Cibinong, Citeureup, Babakan Madang, and Sukaraja), each point classified according to its corresponding surface cover type (Selim et al., 2023). Within each subdistrict, sampling points were randomly distributed. This sampling intensity follows the recommendations of the USDA Forest Service (2020) for achieving a 95% confidence level and a standard error below 1.6%. Each sampling point was visually interpreted and classified into predefined land cover categories. The classification scheme included the following classes: tree canopy, grass/herbaceous cover, impervious surfaces, bare land, water bodies, and others. Classification was conducted by trained interpreers following a standardized interpretation protocol to ensure consistency across the dataset. Ambiguous points were carefully reviewed using high-resolution imagery to minimize misclassification.

To evaluate classification uncertainty, standard errors were calculated for each land cover category using the built-in statistical functions of i-Tree Canopy. Particular attention was given to the tree canopy class, as it plays a dominant role in ecosystem service estimation within the model. The standard error associated with tree cover was within an acceptable range, and generally comparable to those of other land cover categories, indicating a reliable level of classification precision. The accuracy and robustness of the point-based sampling approach have been widely validated in previous studies, demonstrating comparable performance to high-resolution pixel-based classification methods, with differences typically ranging from 1% to 4.5% (Parmehr et al., 2016; Hwang and Wiseman, 2020). The point-based sampling method is particularly advantageous for large-area assessments as it requires less processing time and technical expertise compared to pixel-based classification methods, while maintaining acceptable accuracy levels (Selim et al., 2023). These findings support the reliability of the approach used in this study for estimating land cover distribution and associated ecosystem services.

Land cover classification was conducted using a predefined classification scheme consisting of seven categories: (1) grassland, (2) built-up area, (3) artificial surfaces, (4) paved roads, (5) unvegetated land, (6) woodland, (7) water bodies. Each sampling point was visually interpreted and assigned to one of these categories based on visual characteristics such as color, texture, shape, and surrounding spatial context. Tree cover was defined as areas dominated by woody vegetation with visible canopy structure, while grass/shrub included low-lying vegetation without continuous canopy cover. Built-up areas were identified as permanent structures such as buildings and roads.

The classification process was performed manually by the researcher. To improve consistency, a classification guideline was established prior to analysis, and a subset of sampling points (10%) was re-evaluated by the same interpreter to ensure internal consistency and reduce interpretation bias.

The analysis was conducted using the default imagery provided within the i-Tree Canopy platform, which integrates web-based map services. The imagery used in this study was indicated as © 2025 Google within the platform interface. These images were used solely as a visual reference for manual classification of sampling points and were not directly processed or analyzed. While the imagery source can be identified, the exact acquisition date and spatial resolution were not controlled by the researcher. The analysis was conducted in October 2025. This represents an inherent limitation of the method, as variations in imagery quality and temporal differences may influence classification accuracy.

The proportion of each land cover class was calculated based on the frequency of classified sampling points. These proportions were subsequently used by i-Tree Canopy to estimate ecological functions, including carbon storage, annual carbon sequestration, and air pollution removal. It is important to note that these estimates are derived from generalized empirical models and not from direct field measurements.

Although the sampling intensity ensures a relatively low statistical error, the overall reliability of the results is influenced by the accuracy of visual classification, particularly for the tree cover category, which plays a central role in ecological function estimation (Hwang et al., 2020). Potential sources of uncertainty include visual interpretation bias, mixed land cover conditions, and limitations of the underlying imagery. The overall workflow of the analysis, including boundary delineation, point generation, land cover classification, and estimation of ecological functions, is presented in Figure 2.

RESULT AND DISCUSSIONS

Land cover classification in greater Cibinong

Greater Cibinong is a strategic area within Bogor Regency that has experienced rapid urbanization and population growth in recent years. This population increase has driven expansion in various sectors such as housing, industry, infrastructure, and public facilities to accommodate the growing needs of residents. This has accelerated land conversion, causing environmental damage and ecosystem decline. The development of urban physical infrastructure does not necessarily guarantee sustainable urban growth; therefore, continuous monitoring of urban development dynamics is essential. One effective approach is to analyze land use information through land cover classification maps generated using i-Tree Canopy. These maps provide spatial insight

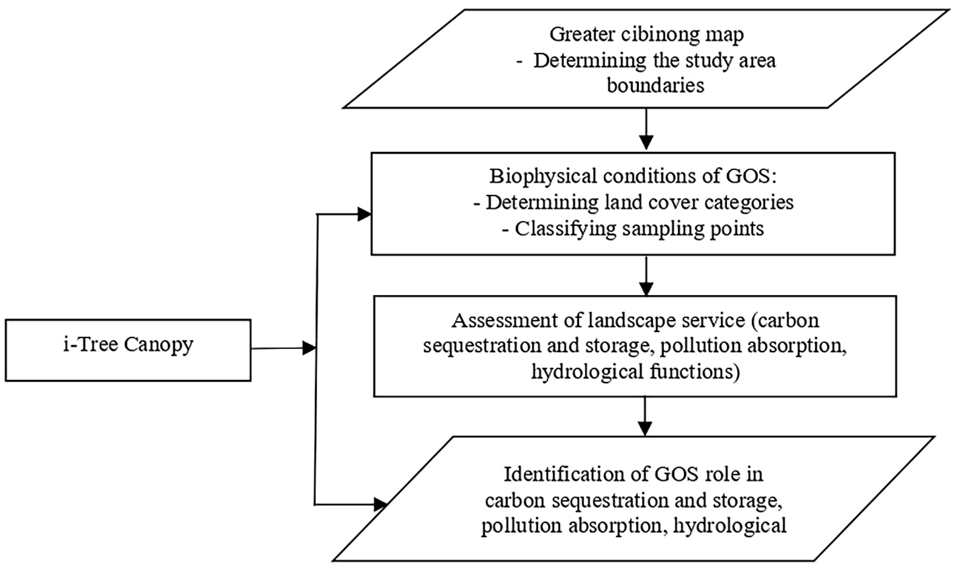

Figure 2. Research flowchart

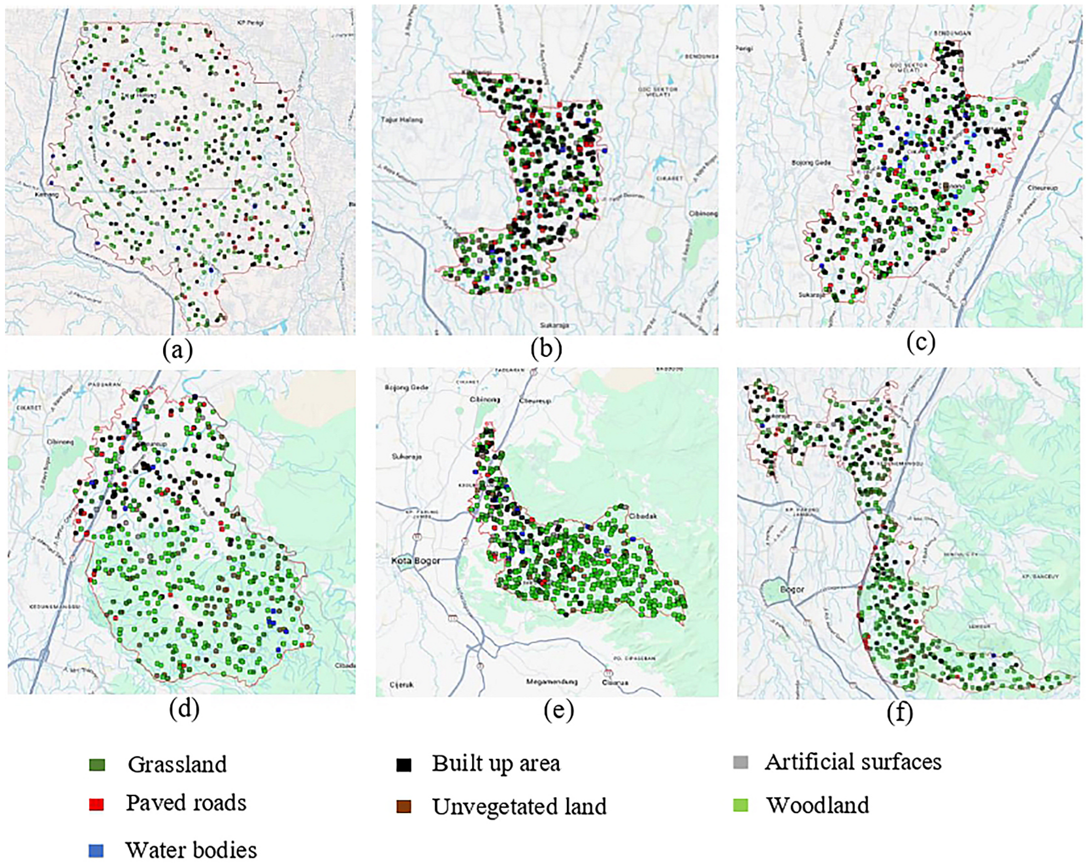

Figure 3. 500 Random sampling points using i-Tree Canopy across six subdistricts in greater cibinong: (a) tajurhalang, (b) bojong gede, (c) cibinong, (d) citeureup, (e) babakan madang, and (f) sukaraja

into how urban space is utilized and transformed. Figure 3 and Figure S3 presents the classification of 500 random sampling points distributed across the six subdistricts of Greater Cibinong.

The land cover analysis in the Greater Cibinong region revealed significant variations in land cover characteristics across six districts based on the dominance of cover classes and their respective areas (see Table 1 and Table S1). In Tajurhalang District, with a total area of 44.15 km², the highest land cover was dominated by Woodland covering 16.07 km² (36.40%), while the lowest cover was Water Bodies at only 0.18 km² (0.40%). A similar pattern was identified in Bojong Gede District (27.00 km²), where Built Up Area occupied the highest proportion at 12.11 km² (43.80%), whereas Water Bodies had the smallest coverage at 0.44 km² (1.60%). The high proportion of Impervious Buildings in Bojong Gede indicates intensive urbanization in this area, consistent with findings that impervious surface expansion serves as a primary indicator of land transformation due to urban development (Naikoo et al., 2020).

Cibinong subdistrict, as the administrative center of Bogor Regency with a total area of 46.95 km², exhibited the highest dominance of Built Up Area reaching 18.97 km² (40.40%), which represents the highest value among all districts examined. Conversely, the lowest cover was Water Bodies with an area of only 1.50 km² (3.20%). The high proportion of built-up land in Cibinong reflects the characteristics of an administrative and economic activity center that has undergone intensive land conversion from vegetated areas to impervious surfaces (Pravitasari et al., 2024). This condition warrants particular attention in spatial planning, given that areas with administrative functions should ideally serve as reference models for implementing the minimum 30% GOS standard mandated by Indonesian regulations (Dan and Soelistyari, 2021).

In Citereup subdistrict, which has the second-largest total area (69.77 km²), Woodland dominated with an area of 30.42 km² (43.60%), while Impervious Other occupied the lowest proportion at 0.98 km² (1.40%). The dominance of forest and shrub cover in Citereup demonstrates that this area still maintains peri-urban characteristics with relatively preserved vegetation (Hubert et al., 2023).

Babakan Madang subdistrict has the largest total area of 92.19 km², with Woodland dominating at 55.54 km² (60.24%), making it the district with the highest proportion of forest cover in the Greater Cibinong region. Water Bodies represented the lowest land cover with an area of 1.83 km² (1.99%). This condition indicates that Babakan Madang functions as a conservation zone and ecological buffer for the surrounding urban areas, providing essential landscape services for metropolitan sustainability (Aleha et al., 2024). Meanwhile, Sukaraja District with a total area of 44.15 km² showed dominance of Woodland at 16.07 km² (36.40%), while the lowest cover was Water Bodies with an area of only 0.18 km² (0.40%). Overall, the land cover distribution pattern in Greater Cibinong reflects an urban-peri-urban gradient, where districts in the southern part (Babakan Madang and Citereup) are still dominated by forest vegetation, while the northern parts (Cibinong and Bojong Gede) have undergone intensive transformation into built-up areas with high proportions of Impervious Buildings. These land cover variations have implications for the ecological balance of the region, given that increased impervious surfaces positively correlate with elevated surface temperatures and surface runoff risks (Bikis et al., 2025).

Although the land cover data generated in this study provide a cross-sectional snapshot of current conditions, a more comprehensive understanding of GOS dynamics in Greater Cibinong requires multi-temporal analysis. A study of 20 major US cities showed that tree cover was decreasing by an average of 0.9% per year due to development, with higher conversion rates in cities undergoing rapid growth phases (Nowak and Greenfield, 2012). If a similar pattern applies to Greater Cibinong – which records an average population growth rate of 1.5% per year (Badan Pusat Statistik Kabupaten Bogor, 2023), then multi-temporal land cover change analysis using satellite imagery is urgently needed to quantify the rate of GOS degradation and project future conditions. Historical land cover change data of this kind are essential as a foundation for evidence-based spatial planning scenarios.

The land cover distribution findings of this study also raise an important environmental justice concern. The subdistricts with the lowest GOS proportions – Bojong Gede (woodland: 24.20%) and Cibinong (woodland: 33.20%) – are simultaneously the areas with the highest population densities and most intensive economic activities, implying that the residents most in need of ecosystem services live in the subdistricts with the least available GOS. This condition aligns with the findings of (Pham et al., 2017), who identified the unequal spatial distribution of urban green spaces across sociodemographic factors in multiple cities worldwide. Therefore, GOS enhancement policies in Greater Cibinong must go beyond aggregate percentage targets to explicitly address the spatial equity of GOS distribution across subdistricts, ensuring that all population groups benefit equally from ecological services.

Methodological validation is a critical aspect of evaluating the reliability of results in this study. The random point sampling approach applied by i-Tree Canopy has demonstrated good consistency with remote sensing methods in several comparative studies (Parmehr et al., 2016; Hwang and Eric Wiseman, 2020), However, it is important to acknowledge that this tool was designed and calibrated using vegetation databases from temperate North American climates. Its application in tropical regions such as Greater Cibinong – characterized by highly distinct vegetation types, rainfall patterns, and species composition – requires caution in interpretation. Recent studies applying i-Tree in tropical and subtropical Asian settings (Aulia et al., 2023; Mosyaftiani et al., 2022; Hintural et al., 2024) suggest that i-Tree model outputs remain relevant as preliminary estimates, but ideally should be validated through direct field measurements using tree inventory plots. This limitation must be considered in the interpretation of all ecological analysis results presented in this study.

Carbon storage in Greater Cibinong

The GOS in Greater Cibinong play a crucial role in maintaining environmental sustainability, particularly by providing landscape services in the form of carbon storage and sequestration. Through vegetation growth, each subdistrict contributes to carbon sequestration and storage, which helps reduce greenhouse gas concentrations in the atmosphere, improve air quality, and stabilize the local climate (Huang et al., 2024).

The analysis of carbon storage was conducted using the i-Tree Canopy tool, which estimates the amount of carbon sequestered and stored annually (Dan and Soelistyari, 2021). As shown in Table 2,

Table 1. Land cover class values in greater cibinong

Abbr.	Cover class	Tajurhalang		Bojong gede	
		Area covered (km²)	% Cover	Area covered (km²)	% Cover
G	Grassland	12.36	28.00	4.37	15.80
BU	Built-up area	9.71	22.00	12.11	43.80
AS	Artificial surfaces	0.88	2.00	0.61	2.20
PR	Paved roads	2.12	4.80	2.16	7.80
UL	Unvegetated land	2.83	6.40	1.27	4.60
W	Woodland	16.07	36.40	6.69	24.20
WB	Water bodies	0.18	0.40	0.44	1.60
Total		44.15	100	27.00	100
Abbr,	Cover class	Cibinong		Citereup	
		Area covered (km²)	% Cover	Area covered (km²)	% Cover
G	Grassland	5.07	10.80	14.65	21.00
BU	Built-up area	18.97	40.40	11.58	16.60
AS	Artificial surfaces	0.85	1.80	0.98	1.40
PR	Paved roads	3.00	6.40	3.63	5.20
UL	Unvegetated land	1.97	4.20	7.26	10.40
W	Woodland	15.59	33.20	30.42	43.60
WB	Water bodies	1.50	3.20	1.26	1.80
Total		46.95	100	69.77	100
Abbr,	Cover class	Babakan madang		Sukaraja	
		Area covered (km²)	% Cover	Area covered (km²)	% Cover
G	Grassland	13.38	14.51	12.36	28.00
BU	Built-up area	8.08	9.54	9.71	22.00
AS	Artificial surfaces	3.30	3.58	0.88	2.00
PR	Paved roads	2.20	2.39	2.12	4.80
UL	Unvegetated land	7.15	7.75	2.83	6.40
W	Woodland	55.54	60.24	16.07	36.40
WB	Water bodies	1.83	1.99	0.18	0.40
Total		92.19	100	44.15	100

the results include annual carbon sequestration, carbon dioxide equivalents (CO_2-eq), and monetary value (in Million IDR) for each subdistrict.

Table 2 presents the results of the analysis of the estimated value of carbon stored annually in six sub-districts in Greater Cibinong. Based on the estimated annual carbon storage values, the subdistricts ranked from highest to lowest are as follows. Babakan Madang Subdistrict records the highest annual tree carbon storage, approximately 16.99 kt, with a carbon dioxide equivalent (CO_2-eq) of 62.31 kt, valued at IDR 134,462 million. In addition, the total carbon storage in trees, not calculated on an annual scale, is approximately 426.78 kt, with a CO_2-eq of 1,564.85 kt, equivalent to IDR 3,376,840.00 million. This exceptional carbon storage capacity in Babakan Madang is primarily attributable to its extensive tree canopy coverage (60.24%) and the presence of mature vegetation with high biomass accumulation. The relationship between vegetation cover and carbon storage is well-established in the literature, with studies consistently demonstrating that areas with higher tree density and larger individual tree sizes exhibit superior carbon sequestration rates (Zhang et al., 2024).

In Citeureup Subdistrict, the annual tree carbon storage is estimated at 9.31 kt, with a CO_2-eq of 34.13 kt, valued at IDR 73,650.61 million. The total (non-annual) carbon storage is approximately 233.76 kt, with a CO_2-eq of 857.13 kt, valued at IDR 1,849,640 million. The substantial carbon sequestration in Citeureup reflects its relatively high tree/shrub coverage (43.6%), which

Table 2. Annual carbon sequestration and storage estimates in greater cibinong

Sub district	Description	Carbon (Kt)	CO_2 ekuiv. (Kt)	Million (IDR)
Tajurhalang	Sequestered annually in trees	3.66	13.41	29,031.71
	Stored in trees (Note: this benefit is not an annual rate)	91.84	336.73	729,095.00
Bojong Gede	Sequestered annually in trees	2.05	7.51	16,179.52
	Stored in trees (Note: this benefit is not an annual rate)	51.43	188.56	406,329.00
Cibinong	Sequestered annually in trees	4.77	17.49	37,739.03
	Stored in trees (Note: this benefit is not an annual rate)	119.78	439.2	947,769.00
Citereup	Sequestered annually in trees	9.31	34.13	73,650.61
	Stored in trees (Note: this benefit is not an annual rate)	233.76	857.13	1,849,640.00
Babakan Madang	Sequestered annually in trees	16.99	62.31	134,462.00
	Stored in trees (Note: this benefit is not an annual rate)	426.78	1564.85	3,376,840.00
Sukaraja	Sequestered annually in trees	4.92	18.03	38,908.96
	Stored in trees (Note: this benefit is not an annual rate)	123.50	452.82	977,150.00

supports significant biomass development and photosynthetic activity (Zhang et al., 2024).

In Bojong Gede Subdistrict records the lowest annual tree carbon storage of 2.05 kt, with a CO_2-eq of 7.51 kt, valued at IDR 16,179.52 million. The total carbon storage (non-annual) in Bojong Gede is approximately 51.43 kt, with a CO_2-eq of 188.56 kt, equivalent to IDR 406,329.00 million. This substantially lower carbon sequestration capacity is directly linked to Bojong Gede's high proportion of Built Up Area cover (43.8%) and the lowest Woodland coverage (24.2%) among all subdistricts. The inverse relationship between urbanization intensity and carbon storage has been consistently documented in urban ecology literature (Huang et al., 2024).

Land cover type significantly influences the amount of carbon stored in urban ecosystems (Sharma et al., 2025). The highest carbon storage is typically found in areas with mature forest vegetation, including primary and secondary dryland forests, shrublands, and well-managed urban parks, while the lowest occurs in grasslands, savanna, and highly developed residential or commercial areas (Li et al., 2026).

The spatial distribution pattern of carbon values across subdistricts – from high in Babakan Madang to low in Bojong Gede – mirrors the urban–peri-urban gradient identified in the land cover analysis. This gradient underscores that the expansion of built-up areas in northern Greater Cibinong has resulted in substantial loss of carbon sequestration functions, while the southern subdistricts continue to retain their ecological capacity. Similar patterns have been reported by (Vijayalaxmi and Dnyanesh, 2021) in urban green spaces across major Chinese cities, and by (Nowak et al., 2013) who found that cities with tree canopy cover above 30% exhibit carbon sequestration capacities two to three times greater than cities with cover below 15%.

The economic values of carbon estimated in this study employ a monetary valuation approach integrated within the i-Tree platform. The total carbon storage value across all subdistricts of Greater Cibinong reaches a scale of significant policy relevance within the framework of Payment for Ecosystem Services (PES) mechanisms and carbon trading schemes. Under Presidential Regulation No. 98 of 2021 on the Economic Value of Carbon, Indonesia has established a regulatory framework for integrating the carbon value of forests and urban vegetation into regional fiscal instruments. Accordingly, the carbon sequestration data generated in this study can serve as a scientific basis for the Bogor Regency Government to pursue carbon credits or vegetation maintenance incentives, particularly for Babakan Madang, which holds the largest carbon reserve.

Pollution absorption in Greater Cibinong

The GOS provide substantial environmental benefits, particularly in improving air quality through pollution absorption. The analysis of air pollution removal using the i-Tree Canopy tool produces annual estimates of carbon absorption and related ecological values. This analysis demonstrates the effectiveness of GOS in reducing various types of pollutants, including carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), and particulate matter smaller than 2.5 microns ($PM_{2.5}$) as well as particulate matter between 2.5 and 10 microns (PM_{10}). In addition, i-Tree Canopy is capable of estimating the economic value of pollution removal, which is calculated in Indonesian Rupiah. The results of the estimated annual pollution removal and its economic valuation for the six subdistricts in Greater Cibinong are presented (Table 3 and Table 4)

Based on the estimated pollution removal analysis in Greater Cibinong, the highest estimated pollution removal value was found in Babakan Madang Subdistrict, with approximately 491.19 tons per year, equivalent to an economic value of IDR 23,624.33 million. The most absorbed pollutants were ozone (O_3), amounting to 282.92 tons with an economic value of IDR 3,017.36 million and particulate matter (PM_{10}), totaling 113.44 tons with an economic value of IDR 14,022.57 million.

In Citeureup Subdistrict, the total estimated pollution removal reached 269.04 tons per year, with an economic value of IDR 12,940.06 million. The most absorbed pollutants in this subdistrict were ozone (O_3) at 154.97 tons with an economic value of IDR 1,652,74 million and PM_{10} at 62.14 tons, valued at IDR 7,680.76 million.

Conversely, the lowest pollution removal estimate was found in Bojong Gede Subdistrict, with only 59.19 tons per year, equivalent to IDR 2,842.67 million The dominant pollutants absorbed in this subdistrict were ozone (O_3) at 34.09 tons, with an economic value of IDR 363.07 million and PM_{10} at 13.67 tons, valued at IDR 1,687.31 million.

Babakan Madang Subdistrict records the highest annual carbon storage value among the three subdistricts (Babakan Madang, Citeureup, and Bojong Gede), which is primarily due to its larger tree canopy coverage. Trees can absorb various harmful pollutants through the process of photosynthesis, including CO, NO_2, O_3, SO_2 and particulate matter smaller than 2.5 microns ($PM_{2.5}$) and between 2.5 and 10 microns (PM_{10}) (Afrizal et al., 2022).

Among all six subdistricts in Greater Cibinong, the most absorbed pollutants are ozone (O_3) and PM_{10}. This indicates that while ozone is one of the dominant pollutants, trees have limited effectiveness in mitigating it compared to particulate matter or other gaseous pollutants. PM_{10} is considered to have a greater impact on human health compared to other pollutants and is therefore often used as a primary indicator of air quality. These two pollutants contribute the most to both the environmental and economic benefits of trees within the study area (Neyns et al., 2024).

Another important pollutant to consider is fine particulate matter ($PM_{2.5}$). Although in Bojong Gede Subdistrict, trees only absorbed 1.78 tons of $PM_{2.5}$ per year, the corresponding economic value reached IDR 764.35 million highlighting the critical importance of $PM_{2.5}$ control. Due to its extremely small particle size, $PM_{2.5}$ can penetrate deep into the lung alveoli and enter the bloodstream, posing a high risk of respiratory diseases (Yuwanda et al., 2024).

The study sites also demonstrated the ability to absorb sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO). Babakan Madang Subdistrict recorded the highest SO_2 absorption at 50.64 tons, with an economic value of IDR 10.07 million while the lowest SO_2 absorption occurred in Bojong Gede Subdistrict, amounting to 6.10 tons, valued at IDR 1.21 million. For NO_2, Babakan Madang again exhibited

Table 3. Estimated pollution absorption value in Greater Cibinong

Subdistrict	Pollutans removed annualy/years (ton)						Total
	CO	NO_2	O_3	SO_2	$PM_{2.5}$	PM_{10}	
Tajurhalang	1.28	5.05	60.88	10,9	3.18	24.41	105.70
Bojong Gede	0.72	2.83	34.09	6,10	1.78	13.67	59.19
Cibinong	1.67	6.59	79.41	14.21	4.15	31.84	13.86
Citereup	3.25	12.86	154.97	27.74	8.09	62.14	269.04
Babakan Madang	5.94	23.47	282.92	50.64	14.77	113.44	491.19
Sukaraja	1.72	6.79	81.87	14.65	4.27	32.83	142.13

Table 4. Estimated air pollution removal values in greater Cibinong

Subdistrict	Estimated annual pollutant removal value (in million Rupiah)						Total
	CO	NO_2	O_3	SO_2	$PM_{2.5}$	PM_{10}	
Tajurhalang	33.38	14.58	651.48	2.17	1,371.51	3,027.62	5,100.73
Bojong gede	18.60	8.12	363.07	1.21	764.35	1,687.31	2,842.67
Cibinong	43.39	18.95	846.87	2.83	1,782.86	3,935.67	6,630.57
Citereup	84.68	36.98	1,652.74	5.52	3,479.39	7,680.76	12,940.06
Babakan madang	154.60	67.52	3,017.36	10.07	6,352.22	14,022.57	23,624.33
Sukaraja	44.74	19.54	873.13	2.91	1,838.13	4,057.68	6,836.12

the highest absorption rate of 23.47 tons, with an economic value of IDR 67.52 million, whereas Bojong Gede had the lowest value of 2.83 tons, equivalent to IDR 8.12 million. Regarding CO, Babakan Madang absorbed the highest amount at 5.94 tons, valued at IDR 154.60 million, while Bojong Gede showed the lowest absorption of 0.72 tons, corresponding to IDR 18.60 million. Although the economic values associated with SO_2, NO_2, and CO absorption are relatively lower compared to PM_{10} and $PM_{2.5}$, the absorption of these gaseous pollutants still contributes significantly to improving overall air quality within the study area.

Trees absorb gaseous pollutants through their stomata – microscopic pores on leaf surfaces that facilitate gas exchange during photosynthesis. The process occurs through: (1) diffusion through boundary layer, (2) stomatal uptake, and (3) internal conversion where gases react with water on mesophyll cell surfaces or are metabolized by plant tissues. Pollutants such as SO_2, NO_2, CO, and O_3 are permanently removed from the atmosphere through these reactions (Gong et al., 2023; Zhou et al., 2022; He et al., 2025)

The rate of gaseous pollutant removal depends on stomatal conductance, leaf area index (LAI), species-specific physiology, and ambient pollutant concentration (Gong et al., 2023; Lawson and Leakey, 2024). Among all six subdistricts in Greater Cibinong, ozone (O_3) constitutes the largest proportion of pollutants removed by mass, accounting for approximately 57–58% of total pollution removal. This pattern is consistent with pollution removal studies conducted globally using the i-Tree framework (Zhao et al., 2023).

Based on the air pollution standard index (ISPU) data from the Ministry of Environment and Forestry (KLHK) for the Bogor and surrounding area, annual mean PM10 concentrations range from 40–75 μg/m^3 – approaching or exceeding the national quality standard of 75 μg/m^3 (PP No. 22/2021). Peak-hour O_3 concentrations across the Jabodetabek region have been reported to reach 60–120 μg/m^3 during the dry season (Sicard et al., 2023), exceeding the WHO guideline value of 100 μg/m^3. In the context of such elevated ambient pollutant concentrations, the capacity of trees in Babakan Madang to absorb 282.92 tonnes of O_3 and 113.44 tonnes of PM10 per year represents an ecologically significant contribution. Nevertheless, it must be acknowledged that this contribution represents only a fraction of the total atmospheric pollutant burden, as trees are not the sole air purification mechanism and their capacity is substantially smaller than the volume of affected air. A more comprehensive approach to estimating the pollutant fraction actually reduced by vegetation would require integrated atmospheric dispersion modelling (Jeanjean et al., 2016).

Aulia et al. (2023) studying urban forests in Jakarta, reported PM10 absorption ranging from 2.1–8.7 tonnes/ha/year. (Zhao et al., 2023), applying i-Tree Eco in Changchun, China, found that O_3 also dominated pollutant absorption by mass (55–60% of total) – a pattern consistent with the present study's findings and suggesting that O3 dominance is a universal feature of i-Tree estimates across diverse climatic contexts. Studi (Hintural et al., 2024), conducting a study in South Korea, reported total pollutant absorption of approximately 3.2 tonnes/ha/year for areas with 35% tree cover – a value that, when scaled to Babakan Madang conditions (woodland 60.24%, area 55.54 km^2), yields a rough estimate of 1700–2000 tonnes/year, substantially higher than the i-Tree Canopy estimate of 491.19 tonnes/year in this study. This discrepancy likely reflects differences in method (i-Tree Eco vs. i-Tree Canopy), species composition, and climatic conditions, but suggests that the present study's estimates may represent conservative approximations of actual pollutant absorption capacity.

The substantial variation in pollutant absorption capacity across subdistricts – from 59.19 t/year in Bojong Gede to 491.19 t/year in Babakan Madang – carries direct implications for GOS spatial planning strategy in Greater Cibinong. Bojong Gede and Cibinong, which simultaneously have the highest population densities and lowest pollutant absorption capacities, represent the subdistricts most in need of vegetation enhancement interventions. (Abhijith et al., 2017) demonstrated that increasing tree cover along major urban road corridors can reduce local PM10 concentrations by 20–40% depending on vegetation spatial configuration. Implementation of planned urban greening strategies in Bojong Gede – such as expanding street tree planting, establishing green buffers along arterial roads, and adding small parks in dense residential areas – has the potential to significantly increase pollutant absorption capacity without requiring extensive land. This approach is consistent with the urban green infrastructure concept, which emphasizes the strategic spatial distribution of vegetation to maximize ecological benefits per unit of land (Hanna and Comín, 2021; Kumar et al., 2025).

Hydrology in greater Cibinong

One of the outcomes of the ecological function analysis of Green Open Spaces using i-Tree Canopy is the estimation of the hydrological benefits provided by vegetation. In this analysis, several key parameters are calculated, including avoided runoff, evaporation, water interception, transpiration, and potential evapotranspiration. By accounting for these factors, the analysis provides an overview of how effectively GOS manage the urban water cycle, helping to reduce flood risk, improve water quality, and enhance the microclimate in the surrounding areas (Table 5).

Based on the estimated hydrological benefits of trees across the six subdistricts of Greater Cibinong, the highest estimated values for avoided runoff, evaporation, water interception, transpiration, potential evaporation, and potential evapotranspiration were found in Babakan Madang Subdistrict, amounting to 183.86 ML, 3,239.50 ML, 3,261.11 ML, 3,836.87 ML, 20,003.49 ML, and 20,003.49 ML, respectively. The avoided runoff in Babakan Madang had the highest economic value, estimated at IDR 7,199.75 million, while the lowest value was recorded in Bojong Gede Subdistrict, amounting to IDR 866.33 million.

The high hydrological values in Babakan Madang Subdistrict are directly correlated with the highest vegetation cover (Woodland) at 60.24%, whereas the low values in Bojong Gede are attributed to the high percentage of impervious surfaces (Built Up Area) at 43.80% and vegetation cover (Woodland) of only 24.20%.

In the context of urban water systems, canopy interception of rainfall is one of the most relevant functions of vegetation, as it retains some of the precipitation before it reaches the surface and contributes to the reduction of surface runoff (Dowtin et al., 2023; Rahman et al., 2023). In general, canopy interception is reported to be in the range of 10–30%, but under certain conditions (e.g. dense canopy structure and certain rainfall characteristics) it can reach up to around 50% of total rainfall, especially in forest canopies (Liu et al., 2024 ; (Fischer et al., 2023). At the individual-tree scale, empirical evidence from urban environments indicates that standalone (open-grown) trees can also intercept a substantial proportion of rainfall. For example, approximately 25.6% for certain deciduous species (Alivio et al., 2023) and around 24–33% in some urban tree species

Table 5. Estimated annual hydrological benefits provided by trees in Greater Cibinong

Subdistrict	Avoided runoff	Evaporation	Interception	Transpiration	Potential evaporation	Potential evapotranspiration
Tajurhalang	39.56	697.09	701.75	825.64	4,304.48	4,304.48
Bojong Gede	22.16	390.36	392.96	462.34	2,410.41	2,410.41
Cibinong	51.60	909.22	915.29	1,076.88	5,614.32	5,614.32
Citereup	100.71	1,774.41	1,786.25	2,101.62	10,956.77	10,956.77
Babakan Madang	183.86	3,239.50	3,261.11	3,836.87	20,003.49	20,003.49
Sukaraja	53.20	937.41	943.66	1,110.27	5,788.37	5,788.37

Note: Unit = megaliters

(Howard et al., 2022), Thus, this supports using an approximate range of 15–28% as a practical estimate for rainfall interception by individual trees under a wide range of conditions

Citeureup Subdistrict ranked second highest with avoided runoff of 100.71 ML, evaporation of 1,774.41 ML, interception of 1,786.25 ML, and transpiration of 2,101.62 ML. This subdistrict has a Woodland cover of 43.60%. Sukaraja and Cibinong Subdistricts showed relatively similar values, where Sukaraja recorded avoided runoff of 53.20 ML with evaporation of 937.41 ML, while Cibinong recorded avoided runoff of 51.60 ML with evaporation of 909.22 ML. Tajurhalang Subdistrict ranked fourth with avoided runoff of 39.56 ML, evaporation of 697.09 ML, interception of 701.75 ML, and transpiration of 825.64 ML. Meanwhile, Bojong Gede Subdistrict recorded the lowest values across all hydrological parameters with avoided runoff of only 22.16 ML, evaporation of 390.36 ML, interception of 392.96 ML, transpiration of 462.34 ML, and potential evaporation and potential evapotranspiration of 2,410.41 ML each.

The pronounced variations among administrative territories exhibiting contrasting vegetation densities are attributable to interconnections between surface coverage patterns and runoff generation. Refined analytical platforms such as i-Tree have revealed that incremental 1% additions to impervious territory coverage correlate with mean runoff increases of 2.2%, while corresponding 1% enhancements in tree canopy extent yield average runoff reductions of only 0.067% (Selbig et al., 2022). This explains why intensive urbanization in Bojong Gede and Cibinong has resulted in a drastic decline in hydrological functions compared to Babakan Madang, which still maintains natural ecosystems.

Transpiration arguably dominates annual water partitioning processes. Trees provide cooling as water moves from roots through stems and evaporates via leaf stomata. This evaporative process consumes latent heat that would otherwise manifest as sensible heat raising air temperatures, instead cooling leaf surfaces and surrounding air through advection (Gobatti et al., 2025; Zhang et al., 2024) (Table 6).

Table 6. Estimated annual economic value of hydrological benefits provided by trees in Greater Cibinong

Subdistrict	Avoided runoff (in million IDR)
Tajurhalang	1,554.50
Bojong Gede	866.33
Cibinong	2,020.73
Citereup	3,943.61
Babakan Madang	7,199.75
Sukaraja	2,083.37

Based on data from the BMKG Dramaga Climatological Station – located within Bogor Regency – mean annual rainfall in this area ranges from 2.800–3.500 mm/year, with the highest monthly rainfall occurring in January–February, potentially reaching 400–600 mm/month. The maximum 24-hour rainfall intensity (R24) with a 25-year return period in the Bogor area has been estimated at 150–200 mm/day (Balai Besar Wilayah Sungai Ciliwung-Cisadane, 2019), an intensity that far exceeds the interception capacity of individual trees. In this context, the avoided runoff value of 183.86 ML/year in Babakan Madang – which when distributed uniformly throughout the year equates to approximately 0.50 ML/day – suggests that trees provide effective hydrological regulation primarily for low- to moderate-intensity rainfall events, while during extreme rainfall, canopy interception and retention capacity may be rapidly exceeded. This reinforces the argument that GOS must be integrated as a complementary component – not a substitute – for conventional drainage infrastructure within an integrated flood management system in Greater Cibinong.

Applying the quantitative relationship from (Selbig et al., 2022) in greater depth to the Greater Cibinong context provides a more concrete picture of the hydrological consequences of urbanization. A comparison between Bojong Gede (imperviousness: 43.80%, woodland: 24.20%) and a hypothetical scenario in which its woodland coverage equalled that of Babakan Madang (60.24%) illustrates the scale of potential benefit: a 36.04 percentage-point increase in tree cover, multiplied by the Selbig et al. coefficient (0.067 ML/ha/year per 1% increase in tree cover, converted to appropriate units), yields a significant estimated increase in avoided runoff. Although this rough estimate does not account for non-linear interactions between land cover and hydrological response, it demonstrates that investment in increasing tree cover in Bojong Gede has the potential to measurably reduce the runoff burden on the drainage system. Berland et al. (2017), in a review of urban trees' role in stormwater management, confirmed that increases in urban tree canopy cover in residential areas can reduce annual runoff volume by 1–7% depending on rainfall intensity, tree species, and soil conditions – a range that is directly relevant as a target in green action plans for high-imperviousness subdistricts in Greater Cibinong.

The hydrological findings of this study implicitly support the concept of integrating green-blue infrastructure in spatial planning for Greater Cibinong. Green-blue infrastructure combines vegetative elements (trees, shrubs, parks) with water management elements (bioswales, retention ponds, infiltration wells) to create a more holistic and adaptive stormwater management system (Hanna and Comín, 2021; Kumar et al., 2025). The GOS in Babakan Madang and Citeureup should be designated as hydrological protection areas. These areas currently function as natural water absorption zones. In Bojong Gede and Cibinong, open land is becoming increasingly limited. Design strategies should prioritize trees, porous drainage systems, rain gardens, and green roofs.

Gobatti et al. (2025) showed that trees help maintain soil moisture. This increases evapotranspiration capacity and improves urban cooling. These provide dual benefits under rising urban temperatures in the Jabodetabek area. Such an integrated approach requires synergy between spatial policy, building standards, and infrastructure investment, coordinated across subdistricts under the umbrella of holistic Greater Cibinong regional planning. While this study provides a robust baseline for ecosystem service assessment, some unresolved issues remain. Further refinement of pollutant removal estimates could improve through the use of i-Tree Eco or integrated atmospheric dispersion modeling. Carbon stock estimates could also benefit from field-based biomass measurements to validate values derived from remote sensing-assisted random point sampling. In addition, longitudinal monitoring of GOS cover across Greater Cibinong could help clarify whether ongoing urbanization may affect the ecological functions identified in this study.

CONCLUSIONS

This study successfully achieved its objective of quantifying the ecological functions of GOS in Greater Cibinong using i-Tree Canopy model. The research hypothesis that GOS ecological performance varies significantly among subdistricts in relation to land cover composition, and that subdistricts with higher woodland cover deliver measurably greater landscape services was fully confirmed. Subdistricts with greater woodland cover consistently delivered higher carbon sequestration, air pollutant removal, and runoff mitigation. Babakan Madang (60.24% woodland cover) stored 16.99 kt of carbon annually (IDR 134.46 billion), absorbed 491.19 tons of pollutants per year (IDR 23.62 billion), and reduced surface runoff by 183.86 ML/year (IDR 7.19 billion), while Bojong Gede (24.20% woodland, 43.80% impervious surface) recorded the lowest values across all three services categories.

A novel finding of this study is the quantification of the economic value of GOS landscape services at the subdistrict scale within a rapidly urbanizing peri-urban corridor in Indonesia a granularity of spatial analysis that had not previously beeb applied to the Greater Cibinong context. The study further established that O_3 and PM_{10} concistently dominate pollutant removal across all subdistricts, confirming that this pattern previously observed in studies from China and South Korea also holds in a tropical Southeast Asian urban context. This study fills the gap in the literature on tropical peri-urban GOS assessment, where most prior i-Tree Canopy applications have focused on temperate cities. Importantly, the subdistrict-level spatial resolution of the findings enables direct integration into local spatial planning instruments, a contribution that aggregate city-scale studies cannot provide.

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