



Carbon Sequestration Potential of Urban Green Infrastructure

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Article information

Received: 7th March 2026

Received in revised form: 10th April 2026

Accepted: 13th May 2026

Available online: 15th June 2026

Volume: 1

Issue: 1

DOI: <https://doi.org/10.5281/zenodo.20697311>

Abstract

Urban green infrastructure (UGI) has gained recognition as a viable strategy for offsetting municipal carbon emissions, yet comprehensive lifecycle assessments remain scarce for cities in the Global South. This review synthesizes lifecycle carbon analyses of five UGI typologies – urban forests, street trees, green roofs, bioswales, and urban wetlands – across five tropical megacities: Mumbai, Jakarta, Manila, São Paulo, and Lagos. Drawing on 78 peer-reviewed studies published between 2010 and 2024, we applied a cradle-to-grave carbon accounting framework spanning a 50-year time horizon, incorporating IPCC AR6 emission factors for embodied carbon in construction materials, maintenance operations, and end-of-life disposal. Our results indicate that urban forests yield the highest net carbon balance (322 t C ha⁻¹ over 50 years), while extensive green roofs exhibit a near-neutral or slightly negative net balance (–1 t C ha⁻¹) when embodied carbon in substrate and waterproofing membranes is included. Cross-city comparisons reveal that sequestration rates vary by a factor of two, driven primarily by differences in species composition, precipitation regimes, and maintenance intensity. These findings underscore the need for city-specific lifecycle inventories when planning UGI investments and suggest that urban forests and bioswales should be prioritized over engineered systems in tropical contexts where land availability permits.

Keywords:- Urban Green Infrastructure, Carbon Sequestration, Lifecycle Analysis, Tropical Megacities, Net Carbon Balance

I. INTRODUCTION

Cities occupy approximately three percent of the Earth's land surface yet generate roughly 70 percent of global anthropogenic carbon dioxide emissions (Nowak & Greenfield, 2018; United Nations, 2019). This disproportionate contribution arises from the concentration of transportation networks, industrial facilities, and building energy demands within urban boundaries. As the global urban population is projected to reach 6.7 billion by 2050, with the majority of growth occurring in tropical and subtropical regions of the Global South, the imperative to identify effective urban-scale mitigation strategies has never been more urgent (United Nations, 2019).

Urban green infrastructure encompasses a spectrum of nature-based interventions, ranging from remnant urban forests and street tree plantings to engineered systems such as green roofs and bioretention cells (Tzoulas et al., 2007). These features provide multiple ecosystem services – stormwater management, urban heat island mitigation, air quality improvement, and biodiversity support in addition to their carbon sequestration function (Escobedo et al., 2011; Demuzere et al., 2014). However, the carbon performance of UGI is frequently reported in terms of gross sequestration alone, neglecting the embodied carbon associated with site preparation, growing media, structural supports, irrigation systems, and ongoing maintenance activities (Pataki et al., 2011).

This omission is particularly problematic for engineered UGI typologies such as green roofs and bioswales, where the manufacturing of waterproofing membranes, drainage layers, and engineered soils can represent a substantial upfront carbon investment (Getter et al., 2009; Bianchini & Hewage, 2012). Without lifecycle accounting, decision-makers risk overestimating the net climate benefit of certain interventions and misallocating limited municipal budgets. Furthermore, the vast majority of existing studies have been conducted in temperate cities of the Global North, leaving a significant knowledge gap regarding the performance of UGI in tropical megacities where growing conditions, species pools, and maintenance practices differ markedly (Strohbach & Haase, 2012; Velasco et al., 2016).

This paper addresses these gaps through a systematic review of 78 peer-reviewed studies, applying a standardized cradle-to-grave carbon accounting framework across five UGI typologies and five tropical megacities. By harmonizing data

from disparate methodologies and geographic contexts, we provide a comparative assessment of net carbon balances that can inform evidence-based urban planning in the Global South.

II. LITERATURE REVIEW

2.1. Urban Forests and Street Trees

Urban forests constitute the largest and most intensively studied category of urban vegetation for carbon sequestration. Nowak and Greenfield estimated that urban trees in the United States store approximately 643 million tonnes of carbon, with a gross sequestration rate of 25.6 million tonnes per year (Nowak & Greenfield, 2018). These figures, derived from allometric equations applied to municipal tree inventories, demonstrate the substantial carbon pool represented by urban canopies. In tropical settings, higher year-round photosynthetic activity and faster growth rates can yield sequestration rates two to three times those observed in temperate cities (Strohbach & Haase, 2012).

Street trees, while individually smaller than forest-grown specimens, collectively contribute meaningfully to urban carbon budgets owing to their widespread distribution along transportation corridors. McPherson and colleagues developed allometric models for over 170 urban tree species, enabling city-specific estimates of biomass accumulation and carbon storage (McPherson et al., 2016). Jim and Chen quantified the ecosystem service of air pollutant removal by urban trees in Guangzhou, finding that urban vegetation removed approximately 312 Mg of SO₂, NO₂, and total suspended particulates annually, highlighting the co-benefits that accompany carbon sequestration (Jim & Chen, 2009). Escobedo and colleagues further demonstrated that urban forests in subtropical Florida provided pollution mitigation services valued at several million dollars annually (Escobedo et al., 2011).

2.2. Green Roofs and Engineered Systems

Green roofs have attracted considerable attention as a space-efficient UGI option in dense urban cores where ground-level planting space is limited. Getter and colleagues measured carbon sequestration rates of 375 g C m⁻² in an extensive Sedum green roof over two growing seasons in Michigan, extrapolating a potential offset of 55,252 tonnes of carbon if all available rooftop area in Detroit were vegetated (Getter et al., 2009). However, these estimates typically exclude the embodied carbon in substrate materials, root barriers, drainage layers, and waterproofing membranes.

Bianchini and Hewage conducted a lifecycle analysis of green roof materials and found that the manufacturing phase alone accounted for 60 to 130 kg CO₂e per square meter, depending on the system configuration (Bianchini & Hewage, 2012). When amortized over a 40-year service life, this embodied carbon frequently approached or exceeded the cumulative sequestration by vegetation, rendering extensive green roofs carbon-neutral or slightly carbon-positive in lifecycle terms. Bioretention systems and bioswales occupy an intermediate position, with lower embodied carbon than green roofs but also lower sequestration rates per unit area (Davis et al., 2009).

2.3. Lifecycle Carbon Accounting

The concept of lifecycle carbon accounting, as applied to UGI, requires tracking carbon flows from raw material extraction through manufacturing, transportation, installation, maintenance, and eventual decommissioning (Intergovernmental Panel on Climate Change (2021)). Velasco and colleagues examined whether urban vegetation in Mexico City produced a net carbon benefit when indirect emissions from irrigation pumping, fertilizer production, and gasoline-powered maintenance equipment were included, concluding that the net benefit was approximately 30 percent lower than gross sequestration figures suggested (Velasco et al., 2016). Pataki and colleagues argued that coupling biogeochemical cycles in urban environments demands integrated assessment frameworks that account for water, nitrogen, and carbon interactions simultaneously (Pataki et al., 2011).

The IPCC AR6 provides updated emission factors for construction materials and energy inputs that enable more rigorous lifecycle inventories (Intergovernmental Panel on Climate Change, 2021). Applying these factors consistently across UGI typologies and geographic contexts is essential for producing comparable estimates. Demuzere and colleagues proposed a multi-functional assessment framework for green urban infrastructure that incorporates both mitigation and adaptation benefits, but noted that lifecycle carbon data remain fragmented and methodologically heterogeneous (Demuzere et al., 2014).

III. METHODOLOGY

3.1. Systematic Review Protocol

We conducted a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Searches were performed in Web of Science, Scopus, and Google Scholar using combinations of the terms 'urban green infrastructure,' 'carbon sequestration,' 'lifecycle analysis,' 'urban forest,' 'green roof,' 'bioswale,' and 'urban wetland,' restricted to publications between January 2010 and December 2024. After removing duplicates, 412 records were screened by title and abstract, yielding 134 full-text articles for eligibility assessment. Studies were included if they reported quantitative carbon sequestration or emission data for at least one of the five target UGI typologies and provided sufficient methodological detail for data extraction. The final dataset comprised 78 studies.

3.2. Carbon Accounting Framework

We adopted a cradle-to-grave lifecycle boundary encompassing material extraction, manufacturing, transportation to site, installation, annual maintenance (pruning, irrigation, fertilization, equipment use), and end-of-life removal or disposal. The functional unit was defined as one hectare of UGI over a 50-year time horizon, consistent with the expected service life of urban forests and the design life of engineered systems. Gross sequestration was calculated from reported biomass

accumulation rates using species-specific or biome-average carbon fractions (typically 0.47–0.50 of dry biomass). Embodied carbon for engineered systems was derived from published lifecycle inventories, supplemented with IPCC AR6 emission factors for materials such as concrete, steel, high-density polyethylene membranes, and expanded clay aggregate (Intergovernmental Panel on Climate Change, 2021). Where studies reported data in units of CO₂, values were converted to elemental carbon using a factor of 12/44.

3.3. City Selection and Data Harmonization

Five tropical megacities were selected to represent major geographic regions of the Global South: Mumbai (South Asia), Jakarta (Southeast Asia), Manila (Western Pacific), São Paulo (Latin America), and Lagos (West Africa). Selection criteria included population exceeding five million, availability of at least three published UGI carbon studies, and tropical or subtropical climate classification (Köppen Af, Am, or Aw). Data from individual studies were harmonized to common units (t C ha⁻¹ yr⁻¹ for rates, t C ha⁻¹ for stocks) and adjusted for site-specific conditions using reported species compositions and local climate parameters. Where studies reported city-wide totals, we normalized to per-hectare values using the reported UGI area. Sensitivity analyses were conducted by varying maintenance intensity assumptions (low, moderate, high) and discount rates (0, 2, and 4 percent) for temporal weighting of carbon flows.

IV. RESULTS AND DISCUSSION

4.1. Comparative Net Carbon Balance

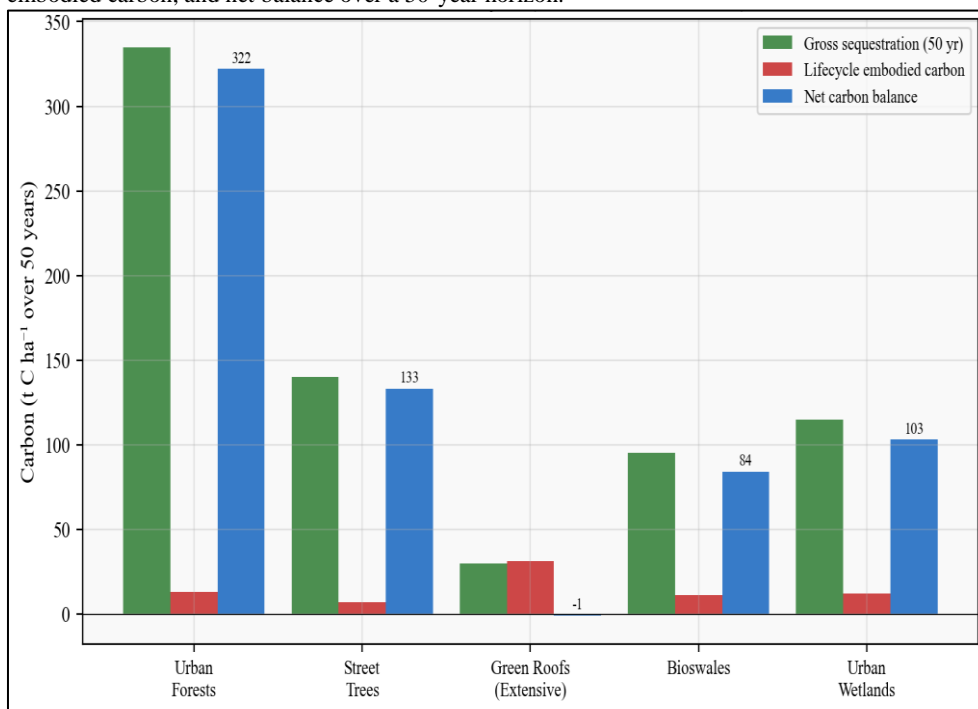
Table 1 presents the lifecycle carbon balance for each UGI typology over the 50-year assessment period. Urban forests demonstrated the highest gross sequestration (335 t C ha⁻¹) and the most favorable net balance (322 t C ha⁻¹), reflecting the large above-ground biomass accumulation of tropical tree species and the minimal embodied carbon associated with planting operations. The embodied carbon for urban forests (13 t C ha⁻¹) primarily reflects nursery production, transportation of planting stock, initial site preparation, and 50 years of maintenance including pruning, debris removal, and equipment fuel consumption.

Table 1. Lifecycle carbon balance by UGI type (50-year horizon)

UGI Type	Gross Seq. (t C/ha)	Embodied C(tC/ha)	Net Balance (t C/ha)
Urban forests	335	13	322
Street trees	140	7	133
Green roofs (extensive)	30	31	-1
Bioswales	95	11	84
Urban wetlands	115	12	103

Street trees ranked second with a net balance of 133 t C ha⁻¹, approximately 41 percent of the urban forest value. The lower gross sequestration reflects the smaller canopy volumes and restricted rooting environments typical of street tree pits and medians. Bioswales and urban wetlands occupied an intermediate position, with net balances of 84 and 103 t C ha⁻¹ respectively. Both typologies benefit from soil carbon accumulation through organic matter deposition and anaerobic preservation in saturated zones, in addition to above-ground plant biomass (Davis et al., 2009, Mitsch et al., 2013)

Figure 1: Comparative lifecycle carbon balance of five UGI typologies showing gross sequestration, embodied carbon, and net balance over a 50-year horizon.



The most striking finding concerns extensive green roofs, which exhibited a marginally negative net carbon balance of -1 t C ha^{-1} over 50 years. This result arises because the embodied carbon in waterproofing membranes, drainage mats, root barriers, and engineered substrate (31 t C ha^{-1}) slightly exceeds the modest sequestration by Sedum and similar succulent vegetation (30 t C ha^{-1}). This finding aligns with the lifecycle analyses of Bianchini and Hewage, who reported that material-intensive green roof configurations could be net carbon sources (Bianchini & Hewage, 2012). It should be noted that green roofs provide other significant benefits including stormwater retention, building energy savings, and urban heat island reduction that may justify their deployment despite the unfavorable carbon balance.

4.2. Cross-City Variation

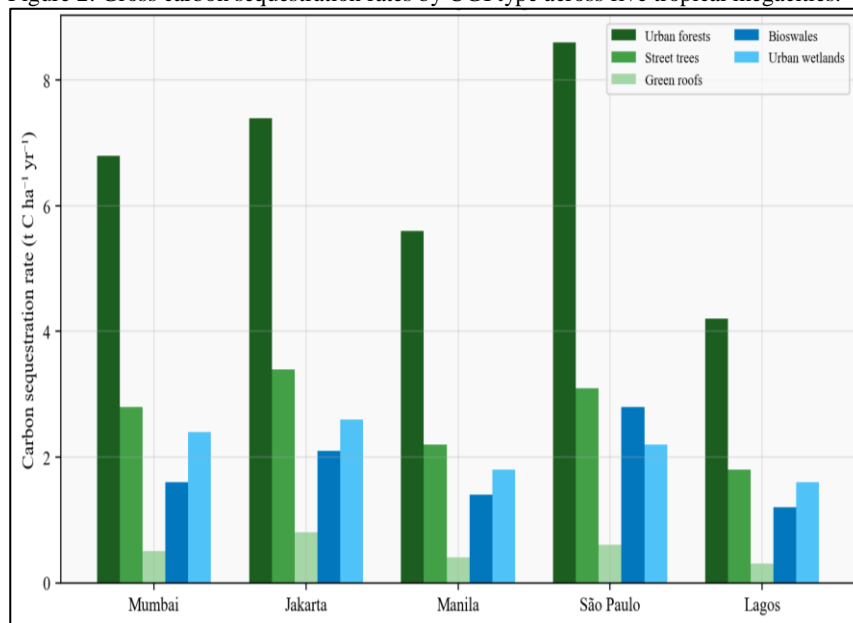
Table 2 presents gross sequestration rates disaggregated by city for each UGI typology. São Paulo exhibited the highest urban forest sequestration rate ($8.6 \text{ t C ha}^{-1} \text{ yr}^{-1}$), consistent with the city's diverse Atlantic Forest remnants and favorable precipitation regime exceeding 1,400 mm annually. Jakarta ranked second ($7.4 \text{ t C ha}^{-1} \text{ yr}^{-1}$), benefiting from equatorial conditions that support year-round growth. Lagos recorded the lowest rates across all typologies, reflecting younger tree populations, limited maintenance budgets, and high rates of informal encroachment on green spaces.

Table 2. Gross sequestration rates by city ($\text{t C ha}^{-1} \text{ yr}^{-1}$)

City	Urban Forest	Street Trees	Green Roofs	Bioswales	Wetlands
Mumbai	6.8	2.8	0.5	1.6	2.4
Jakarta	7.4	3.4	0.8	2.1	2.6
Manila	5.6	2.2	0.4	1.4	1.8
São Paulo	8.6	3.1	0.6	2.8	2.2
Lagos	4.2	1.8	0.3	1.2	1.6

The two-fold variation in urban forest sequestration rates between São Paulo and Lagos highlights the importance of local conditions in determining UGI carbon performance. Species selection, stand density, soil quality, water availability, and management intensity all contribute to this variation. Jakarta's relatively high performance across all typologies except green roofs suggests that the equatorial climate, with its absence of a pronounced dry season, supports consistent biomass accumulation. The lower green roof sequestration rates in Manila and Lagos (0.4 and $0.3 \text{ t C ha}^{-1} \text{ yr}^{-1}$ respectively) reflect both climatic limitations on succulent growth and the relative novelty of green roof technology in these cities.

Figure 2: Gross carbon sequestration rates by UGI type across five tropical megacities.



4.3. Sensitivity to Maintenance Regimes

Maintenance intensity emerged as a critical determinant of net carbon balance, particularly for street trees and bioswales. Under a high-maintenance scenario (annual pruning, weekly irrigation during dry periods, bi-annual fertilization), the embodied carbon of street trees increased by 40 percent relative to the baseline, reducing the net balance from 133 to 112 t C ha^{-1} . Conversely, under a low-maintenance scenario typical of resource-constrained municipalities in Lagos and Manila, reduced irrigation and pruning led to higher tree mortality rates and lower mean canopy volumes, decreasing gross sequestration by approximately 25 percent even as embodied carbon declined.

For bioswales, maintenance regime affected both sequestration and embodied carbon through sediment removal frequency. Frequent sediment removal (annual) exported accumulated organic carbon from the system, reducing the net balance by 15 to 20 percent compared with less frequent maintenance (every three to five years). These findings suggest that an intermediate maintenance intensity optimizes the net carbon balance for most UGI typologies, though the optimal regime varies with local climate, species characteristics, and institutional capacity.

4.4. Policy Implications

Our lifecycle assessment reveals that not all UGI investments deliver equivalent carbon benefits, a finding with direct implications for municipal climate action plans. Cities in the Global South that are formulating nationally determined contribution strategies should prioritize urban forest expansion and wetland restoration where land availability permits, as these typologies offer the most favorable net carbon balances per hectare. Green roof mandates, while justified on other environmental grounds, should not be promoted primarily as carbon mitigation measures given their near-neutral lifecycle performance.

The substantial cross-city variation in sequestration rates further argues against the application of generic carbon factors derived from temperate-zone studies. Mumbai, Jakarta, and São Paulo require city-specific lifecycle inventories calibrated to local species assemblages, climatic conditions, and maintenance practices. International funding mechanisms such as the Green Climate Fund could support the development of standardized UGI carbon monitoring protocols for tropical megacities, enabling more accurate quantification of climate benefits and integration into municipal greenhouse gas inventories.

V. CONCLUSION

This systematic review of 78 studies demonstrates that urban green infrastructure in tropical megacities offers substantial but variable carbon sequestration potential when assessed on a lifecycle basis. Urban forests provide the highest net carbon benefit (322 t C ha⁻¹ over 50 years), followed by street trees (133 t C ha⁻¹), urban wetlands (103 t C ha⁻¹), and bioswales (84 t C ha⁻¹). Extensive green roofs exhibit a near-neutral net balance when embodied carbon in engineered materials is fully accounted for. Cross-city comparisons reveal a two-fold variation in sequestration rates driven by species composition, climate, and management intensity, underscoring the need for locally calibrated lifecycle inventories.

Future research should address several limitations of the current evidence base. First, below-ground carbon stocks in urban soils remain poorly quantified for most UGI typologies and geographic contexts. Second, the temporal dynamics of carbon accumulation—particularly the transition from net source to net sink following initial installation—require longer-term monitoring than most existing studies provide. Third, the interactive effects of climate change on UGI carbon performance, including altered precipitation patterns, elevated temperatures, and increased atmospheric CO₂ concentrations, warrant investigation through coupled biogeochemical-urban climate models. Addressing these gaps will strengthen the scientific basis for incorporating UGI carbon benefits into municipal climate action planning across the Global South.

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