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Estimation of Biomass and Carbon in Urban Forests: Methodological Advances and Implications for Climate Change Mitigation

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Abstract

Urban forests play an important role in mitigating climate change by acting as carbon reservoirs and providing essential ecosystem services in environments with heavy human impacts. This review article synthesizes and critically analyzes the main methods used to estimate biomass and carbon in urban forests, with emphasis on field inventories, allometric equations, remote sensing, and integrated spatial modeling. The review was conducted based on national and international scientific literature, including studies carried out in urban parks, forest fragments, and green areas embedded within urban matrices. The results indicate that forest inventories based on measurements of diameter at breast height and total tree height remain a fundamental reference for carbon quantification, particularly because they provide empirical data for model calibration and validation. However, reported aboveground carbon stocks showed wide variation, with values below 50 Mg C ha^{-1} in highly disturbed urban fragments and above 100 Mg C ha^{-1} in urban parks and protected areas with greater structural complexity. The use of geotechnologies, especially LiDAR and synthetic aperture radar (SAR), has expanded the scale and accuracy of estimates, allowing the spatial representation of carbon stocks in heterogeneous urban landscapes. The integration of field inventories, remote sensing, and spatial modeling proved to be the most robust approach for estimating biomass and carbon in urban forests, as it incorporates variables related to vegetation fragmentation and connectivity. We conclude that methodological advances in this field pro-vide relevant technical support for municipal emissions inventories, urban planning, and climate change mitigation strategies, highlighting the need for protocol standardization and the strengthening of long-term databases.

Keywords: Remote sensing; Climate change mitigation; Amazon forest.

1. Introduction

The accelerated growth of cities in recent decades has intensified pressure on natural ecosystems, resulting in forest fragmentation, structural simplification of vegetation, and increased greenhouse gas (GHG) emissions. This process is particularly pronounced in tropical countries, where urban expansion often occurs in a disorderly manner over areas that were originally forested, compromising essential ecological functions (Grimm et al., 2008; Seto et al., 2012). In this context, urban forests—understood as the set of isolated trees, parks, forest fragments, green corridors, and other tree-covered areas embedded within the urban matrix—play a strategic role in mitigating environmental impacts associated with urbanization.

Urban forests contribute to the provision of multiple ecosystem services, including microclimate regulation, mitigation of urban heat islands, retention of atmospheric pollutants, biodiversity conservation, and the provision of spaces for recreation and human well-being (Nowak et al., 2010; Escobedo et al., 2011). Among these services are carbon sequestration and storage in plant biomass and soils, conferring increasing relevance to urban green areas in local and regional climate change mitigation strategies (McPherson et al., 2013).

Although carbon stocks in urban forests are almost always lower than those observed in continuous natural forests, their relative importance is enhanced when considering the high population density of cities and the potential integration of these areas into public policies for urban planning (Churkina et al., 2015). In addition, the maintenance and expansion of urban forests can indirectly contribute to reducing emissions associated with energy consumption by promoting shading, thermal comfort, and decreased demand for artificial cooling (Akbari et al., 2001).

Estimating biomass and carbon in urban forests, however, presents specific methodological challenges. High structural and floristic heterogeneity, the coexistence of native and exotic species, wide variation in tree age, and intensive management distinguish these environments from natural forests and hinder the direct application of traditional methods developed for continuous ecosystems (Strohbach & Haase, 2012). Furthermore, spatial fragmentation and the frequent presence of isolated trees impose limitations on the extrapolation of data obtained from conventional sampling plots.

Historically, forest inventories based on measurements of diameter at breast height (DBH), total tree height, and the application of allometric equations have constituted the main approach for estimating biomass and carbon, including in urban areas (Brown, 1997; Soares et al., 2005). These methods remain fundamental for obtaining reference data and for model calibration; however, they require substantial sampling effort and present operational constraints in densely occupied urban environments.

In response to these limitations, the use of geotechnologies has expanded significantly. Remote sensing techniques such as airborne LiDAR, synthetic aperture radar (SAR), and high-resolution optical imagery enable three-dimensional characterization of urban vegetation and spatially explicit biomass estimation, expanding the scale of analysis and reducing operational costs (Wulder et al., 2012; Santana et al., 2024). More recently, approaches based on artificial intelligence and machine learning have been incorporated to integrate field and remote sensing data, increasing the accuracy of estimates.

Despite these advances, gaps remain related to methodological standardization, the availability of wood density data for urban species, and the integration of field inventories, geotechnologies, and spatial models. A critical synthesis is required to evaluate the advances, limitations, and potential of available methods, and the present article aims to review the main methods used to estimate biomass and carbon in urban forests, analyzing methodological advances, applications in national and international case studies, and implications for urban planning and climate change mitigation.

2. **Review Methodology**

This review was conducted based on a systematized bibliographic approach, with the objective of identifying, analyzing, and synthesizing scientific studies that address the estimation of biomass and carbon in urban forests. The methodological strategy adopted sought to ensure thematic breadth, technical rigor, and representativeness of both national and international scientific production, in accordance with recommendations for critical reviews in forest and environmental sciences (Grant & Booth, 2009; Snyder, 2019).

Bibliographic searches were carried out in the SciELO, Web of Science (Clarivate Analytics), Scopus (Elsevier) databases, as these include relevant journals in the fields of forest sciences, ecology, remote sensing, and environmental planning. In addition, technical publications and institutional reference documents were consulted, particularly those produced by forest and environmental research institutions, such as the Brazilian Enterprise for Agriculture and Ranching research (Embrapa), when directly related to the topic of this study.

Combinations of keywords in Portuguese and English were used, including the terms *florestas urbanas*, *urban forests*, *biomassa*, *aboveground biomass*, *carbono*, *carbon stock*, *carbon sequestration*, *remote sensing*, *LiDAR*, and *SAR*. The terms were combined using Boolean operators ("AND", "OR") and adapted to the specificities of each database in order to broaden the retrieval of relevant studies and reduce biases associated with selective indexing.

The inclusion criteria comprised peer-reviewed scientific articles that explicitly addressed the estimation of biomass and/or carbon in urban areas, urban parks, forest fragments embedded within urbanized matrices, green corridors, or urban green spaces. Studies that applied comparative methods between field inventories and remote sensing techniques in urban environments were also included. Preference was given to studies published from the 2000s onward, a period marked by the intensification of research on urban forests and climate change.

Studies conducted exclusively in rural environments or in continuous natural forests without an urban interface were excluded from the analysis, as were publications that mentioned urban areas only incidentally, without a direct focus on biomass or carbon quantification. Publications of a strictly conceptual or opinion-based nature, lacking clear methodological procedures, were also not considered.

After the selection stage, the included studies were organized according to the main method employed for biomass and carbon estimation and grouped into three categories: (i) field inventories and allometric equations; (ii) remote sensing and geotechnologies; and (iii) integrated approaches involving spatial modeling and hybrid techniques. For each group, the methodological procedures adopted, the spatial and temporal scales considered, the types of data used, and the main limitations reported by the authors were analyzed (Figure 1).

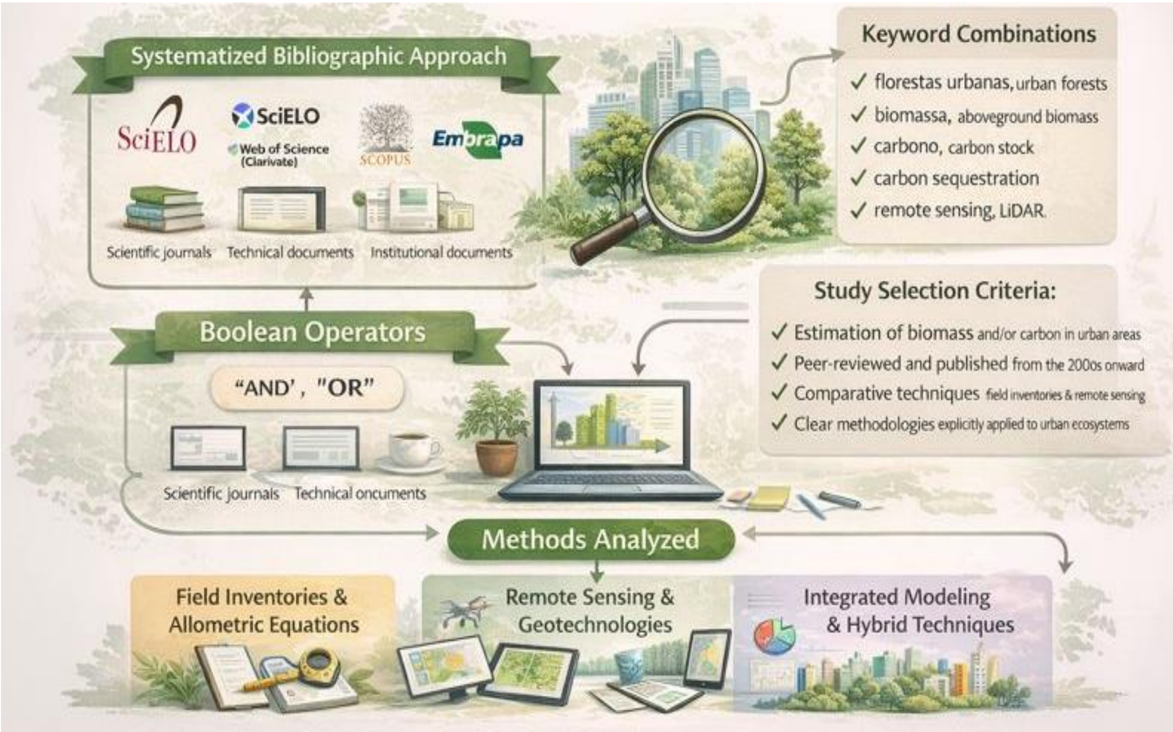

Figure 1. Review Methodology for Biomass and Carbon Estimation in Urban Forests: Processes involved in identifying and synthesizing scientific publications on biomass and carbon estimation in urban forests.

The analysis of the studies prioritized a comparative and critical approach, seeking to identify methodological convergences, technical advances, recurring gaps, and specific challenges associated with carbon estimation in urban forests. This strategy allowed discussion of the applicability of the reviewed methods for sustainable urban planning and for providing technical support to public policies aimed at mitigating greenhouse gas emissions.

3. Results

3.1 Methods for Estimating Biomass and Carbon in Urban Forests

The analysis of the literature indicated that biomass and carbon estimation in urban forests is predominantly based on field inventories associated with allometric equations, a method employed in most of the studies reviewed in Brazil and internationally (Soares et al., 2005; Guimarães et al., 2022). This approach has been applied mainly in urban parks, urban protected areas, and forest fragments embedded within metropolitan regions, where it is possible to establish permanent or temporary sample plots (Table 1).

In Brazilian studies, field inventories generally considered tree individuals with a diameter at breast height (DBH) ≥ 5 or 10 cm, using allometric equations developed for humid tropical or secondary forests. Aboveground biomass was subsequently converted into carbon stock using average conversion factors ranging from 0.47 to 0.50 of dry biomass (Soares et al., 2005; Moraes et al., 2025).

Reported aboveground carbon stock values showed wide variation among studies, reflecting differences in floristic composition, structural characteristics, soil conditions, and management practices. In highly disturbed urban fragments, carbon stocks below 50 Mg C ha^{-1} were recorded, whereas urban parks with more structurally complex vegetation exhibited values exceeding 100 Mg C ha^{-1}, approaching those observed in mature secondary forests (Guimarães et al., 2022; Santana et al., 2024).

Table 1. Examples of carbon stocks estimated by field inventories in urban forests

Study location	Type of urban area	Main method	Carbon stock (Mg C ha^{-1})	Reference
Belém (PA)	Urban fragment	Inventory + allometry	24–62	Castro et al. (2024)
Recife (PE)	Urban park	Inventory + allometry	74–108	Santana et al. (2024)
Belo Horizonte (MG)	Urban green area	Inventory + allometry	65–95	Guimarães et al. (2022)
Carajás (PA)*	Dense ombrophilous forest	Inventory + allometry	>120	Moraes et al. (2025)

*Study used as a comparative methodological reference.

3.2 Application of Geotechnologies in Urban Environments

More recent studies have shown a marked increase in the use of geotechnologies—especially airborne LiDAR, synthetic aperture radar (SAR), and high-resolution optical imagery—for estimating biomass and carbon in urban environments (Table 2). These techniques have been applied mainly at municipal or metropolitan scales, allowing spatial extrapolation of field-based estimates.

The integration of LiDAR data with forest inventories resulted in a significant increase in the accuracy of aboveground biomass estimates, with coefficients of determination frequently exceeding $R^2 = 0.70$ in Brazilian and international studies (Santana et al., 2024). LiDAR enabled the derivation of structural metrics such as mean canopy height and vertical vegetation density, reducing uncertainties associated with the heterogeneity typical of urban forests.

SAR-based approaches proved particularly useful in regions with high cloud cover, such as tropical areas, allowing indirect biomass estimation even under cloudy conditions. However, these studies indicated a greater dependence on local calibration, especially in areas with high biomass, due to signal saturation effects (Santana et al., 2024).

Table 2. Geotechnologies applied to biomass and carbon estimation in urban forests

Technology	Application scale	Main estimated variables	Advantages	Limitations
LiDAR	Local to metropolitan	Canopy height, volume, biomass	High structural accuracy	High cost
SAR	Regional	Aboveground biomass	Operates under cloud cover	Saturation at high biomass
Optical imagery	Local to regional	Vegetation cover, indices	Wide availability	Sensitive to cloud cover

3.3 Spatial Modeling and Data Integration

The integration of field inventories, remote sensing and spatial modelling has been consistently identified as a central methodological advance in studies assessing biomass and carbon stocks in urban and peri-urban forests. Field-based inventories provide high-accuracy measurements of tree structure and biomass, while remote sensing data enable spatial continuity and regional-scale extrapolation, overcoming the inherent limitations of plot-based approaches (Ometto et al., 2024; IPCC, 2019).

Recent studies demonstrate that spatial models incorporating land-use and land-cover data, forest fragmentation indices and landscape connectivity metrics significantly improve the representation of carbon stocks in heterogeneous urban environments. In Brazil, Guimarães et al. (2022) showed that including fragmentation and connectivity variables enhances the spatial accuracy of carbon estimates, particularly in cities characterized by strong contrasts between built-up areas, green spaces and forest remnants. Such approaches allow for the identification of urban zones with higher carbon sequestration potential, directly supporting conservation, restoration and green infrastructure planning.

Evidence from other countries further confirms that integrating multi-source remote sensing data—such as optical imagery, radar and LiDAR—with field inventories reduces uncertainty in biomass estimation and improves model transferability across different urban contexts. According to Harmon et al. (2023) and Ometto et al. (2024), these integrative frameworks are essential for generating spatially explicit carbon maps that are robust enough to inform national greenhouse gas inventories and urban climate mitigation strategies. Overall, spatial modelling combined with data integration emerges as a key methodological pathway for advancing urban carbon accounting and supporting evidence-based policy decisions.

3.4 Case Studies from Brazil and Other Countries

The analyzed case studies reveal substantial variability in carbon stocks and sequestration rates within urban forests, reflecting differences in vegetation structure, management practices and urbanization intensity. In Brazil, studies conducted in the North, Northeast and Southeast regions demonstrate that urban parks, forest fragments and protected areas embedded within metropolitan landscapes can play a significant role in local and regional carbon balances when they maintain complex forest structure and ecological integrity (Santana et al., 2024; Silva et al., 2024). These findings highlight the relevance of urban green spaces not only for carbon sequestration, but also for broader ecosystem services, including climate regulation and biodiversity conservation.

Case studies from other countries reinforce these conclusions. Research from the United States, Europe and Asia reports aboveground carbon stocks in urban forests ranging from 30 to 150 Mg C ha^{-1}, depending on vegetation type, tree age and degree of urban development (Nowak et al., 2013; Davies et al., 2017; Bluestein-Livnon et al., 2023). Despite regional differences, a common methodological pattern emerges: the most consistent and comparable estimates are achieved through the combination of detailed field inventories and geotechnological tools, including spatial modelling and remote sensing.

Collectively, these case studies demonstrate that methodological integration enhances the reliability of carbon stock assessments and facilitates cross-city and cross-country comparisons. Such evidence supports the adoption of harmonized approaches for urban carbon monitoring, contributing to climate mitigation planning and urban land management at multiple scales.

4. Discussion

The results of this review confirm that biomass and carbon estimation in urban forests has advanced consistently over recent decades, driven both by improvements in classical forest inventory methods and by the progressive incorporation of geotechnologies and integrated approaches. The predominance of field inventories associated with allometric equations observed in the literature reinforces the position of these methods as the primary reference for carbon quantification, especially because they provide essential empirical data for the calibration, validation, and interpretation of models applied in urban environments (Brown, 1997; Soares et al., 2005; Guimarães et al., 2022).

The wide variation in reported aboveground carbon stocks among the reviewed studies largely reflects the structural and floristic heterogeneity that characterizes urban forests. Forest fragments subjected to a high degree of disturbance, with a history of intensive use, low species diversity, and simplified structure, exhibited reduced aboveground carbon stocks, often below 50 Mg C ha^{-1}. In contrast, urban parks and protected areas embedded within metropolitan regions, which maintain greater structural complexity and continuity of tree cover, reached values exceeding 100 Mg C ha^{-1}, approaching those observed in mature secondary forests (Guimarães et al., 2022; Santana et al., 2024).

This pattern indicates that the potential of urban forests as carbon reservoirs is directly associated with the degree of vegetation conservation, tree age, and management practices adopted. Similar results have been reported from other countries, where older and structurally more complex urban green areas exhibited higher carbon stocks compared to recently established or intensively managed areas (Strohbach & Haase, 2012; McPherson et al., 2013). Thus, the mere presence of tree-covered areas in urban spaces does not guarantee high climate mitigation potential, making it essential to consider the ecological quality and management of these areas.

The growing use of geotechnologies, particularly LiDAR and synthetic aperture radar (SAR), represents a relevant methodological advance for carbon estimation in complex urban landscapes. The ability of these techniques to capture the three-dimensional structure of vegetation helps overcome operational limitations of field inventories, especially in extensive, fragmented, or hard-to-access areas (Wulder et al., 2012). The reviewed studies demonstrate that integrating field data with remote sensing results in a significant increase in the accuracy of biomass estimates, with coefficients of determination often exceeding those obtained by methods based solely on sample plots (Santana et al., 2024).

Nevertheless, the application of these technologies in urban environments still faces important challenges. The high diversity of native and exotic species, the frequent presence of isolated trees, and variability in crown architecture hinder the parameterization of generalized biomass models. In addition, the scarcity of reliable wood density data for species widely used in urban arborization introduces additional uncertainty into estimates, particularly when allometric equations developed for continuous natural forests are applied (Brown, 1997; Guimarães et al., 2022).

In the specific case of SAR-based approaches, signal saturation in areas with high biomass limits the ability to discriminate structural differences in denser urban forests, reinforcing the need for local calibration and integration with field and LiDAR data (Santana et al., 2024). These methodological challenges indicate that, although geotechnologies expand the scale and efficiency of estimates, their isolated application does not replace the need for well-designed forest inventories.

Integrated spatial modeling emerged in the analyzed studies as a promising approach to extrapolate point-based biomass and carbon estimates and to identify spatial patterns in urban areas. The incorporation of variables related to land use and land cover, forest fragmentation, and ecological connectivity allows a more realistic representation of carbon stock distribution in highly heterogeneous urban landscapes (Guimarães et al., 2022). These findings reinforce the conclusion that the spatial configuration of urban vegetation directly influences its carbon storage capacity and that analyses based solely on total vegetation cover area may underestimate or overestimate this potential.

From a conceptual perspective, these results are consistent with studies that emphasize the importance of ecological connectivity and structural continuity of vegetation for maintaining ecosystem functions, even in environments highly altered by human activity (Grimm et al., 2008; Churkina et al., 2015). In urban forests, fragmentation not only reduces total biomass but can also

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compromise ecological processes related to growth, regeneration, and vegetation stability, with direct implications for the carbon balance.

From the perspective of urban management and public policies, the results of this review indicate that urban forests can play a relevant role in local carbon balances, provided they are adequately planned, conserved, and managed. Consistent quantification of carbon stored in urban green areas provides essential technical support for the development of municipal greenhouse gas emissions inventories, climate change adaptation plans, and urban ecological restoration strategies (McPherson et al., 2013; Guimarães et al., 2022).

Moreover, incorporating biomass and carbon information into territorial planning instruments can contribute to prioritizing strategic green areas, defining urban ecological corridors, and maximizing the environmental benefits associated with urban tree cover. The integration of forest science, urban planning, and climate policies emerges as a central element for enhancing the effectiveness of urban forests as nature-based solutions.

Overall, the methodological advances observed in this review indicate that the combination of field inventories, geotechnologies, and spatial modeling constitutes the most robust approach for carbon estimation in urban forests. However, the consolidation of these methodologies depends on strengthening local databases, standardizing protocols, and expanding long-term studies capable of capturing the temporal dynamics of carbon in urban environments. Addressing these gaps is essential to increase the reliability of estimates and to strengthen the application of results in the context of climate change mitigation and urban planning.

5. Conclusion

This review demonstrates that urban forests constitute relevant components for climate change mitigation by acting as carbon reservoirs and providing essential ecosystem services in environments highly altered by human activity. The methodological advances observed in the estimation of biomass and carbon in urban areas show that, although traditional forest inventories remain fundamental, the incorporation of geotechnologies and integrated approaches has significantly expanded analytical capacity across different spatial scales.

Field inventories associated with allometric equations continue to be the basis for reliable biomass and carbon estimates, mainly because they provide indispensable empirical data for model calibration and validation. However, in urban environments characterized by high structural heterogeneity, fragmentation, and the presence of isolated trees, these methods present operational and spatial extrapolation limitations. The use of technologies such as LiDAR, synthetic aperture radar (SAR), and high-resolution imagery has proven to be an effective alternative for expanding the spatial coverage of estimates and reducing uncertainties associated with the complexity of urban landscapes.

The integration of field inventories, remote sensing, and spatial modeling has emerged as the most robust approach for carbon estimation in urban forests. Studies incorporating fragmentation and ecological connectivity metrics have demonstrated a greater ability to represent the spatial distribution of carbon stocks, reinforcing the conclusion that the configuration of urban vegetation is as relevant as its total extent. These results indicate that urban planning strategies should prioritize not only increasing tree cover but also conserving the structure and connectivity of existing green areas.

From an applied perspective, the consistent quantification of carbon stored in urban forests provides essential technical support for the development of municipal greenhouse gas emissions inventories, climate change adaptation plans, and urban tree management policies. Incorporating this information into territorial planning instruments can support the identification of priority areas for conservation and restoration, as well as guide public investments in nature-based solutions.

Despite the advances identified, important challenges remain, such as the scarcity of wood density data for urban species, the lack of methodological standardization among studies, and the limited availability of long-term time series. Overcoming these gaps requires strengthening local databases, enhancing integration between research institutions and management agencies, and adopting standardized protocols that allow comparability across different urban contexts.

In summary, consolidating integrated approaches for biomass and carbon estimation in urban forests represents a strategic step toward expanding the role of these areas in climate change mitigation. Progress in this direction depends on articulation between forest science, urban planning, and public policies, in order to transform technical knowledge into effective actions for more sustainable and resilient cities.

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