



Litter carbon stock in the Amazon: scientific panorama, spatial distribution, and methodological gaps

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ABSTRACT: Through carbon fixation and nutrient cycling, forests support global biogeochemical dynamics, and the Amazon, the largest continuous tropical forest, constitutes one of the world's most important carbon sinks. This study aimed to review the scientific literature on litter carbon stocks in the Amazon. For this purpose, a database was compiled from the Scopus and Web of Science platforms using a previously defined set of keywords, including publications up to 2023. Initially, 232 publications were identified and subsequently screened according to pre-established criteria, resulting in a final dataset of 32 studies. Brazil accounted for the highest number of studies on the subject, whereas no research was identified from Ecuador, Guyana, or Suriname. Within Brazil, a greater concentration of studies was observed in the state of Pará, while no scientific records were found for the states of Amapá, Roraima, and Tocantins. Fewer than half of the studies evaluated areas were subjected to changes in vegetation cover. Additionally, approximately 4% of the publications did not report the type of litter assessment conducted, and about 22% did not specify the method used to determine carbon content. The findings of this review underscore gaps in the scientific literature, particularly regarding the spatial distribution of studies across the Amazon and the lack of methodological detail in the assessment of litter carbon stocks.

Keywords: litter input; bibliometrics; biogeochemical cycles; carbon sink; land-use change.

Estoque de carbono da serapilheira na Amazônia: panorama científico, distribuição espacial e lacunas metodológicas

RESUMO: Por meio da fixação de carbono e da ciclagem de nutrientes, as florestas sustentam a dinâmica biogeoquímica global, e a Amazônia, a maior floresta tropical contínua do planeta, constitui um dos mais importantes sumidouros de carbono em escala mundial. Este estudo teve como objetivo revisar a literatura científica sobre os estoques de carbono da serapilheira na Amazônia. Para isso, foi compilado um banco de dados a partir das bases de dados Scopus e Web of Science, utilizando um conjunto de palavras-chave previamente definido, abrangendo publicações até 2023. Inicialmente, foram identificadas 232 publicações, que foram posteriormente triadas de acordo com critérios pré-estabelecidos, resultando em um conjunto final de 32 estudos. O Brasil concentrou o maior número de pesquisas sobre o tema, enquanto não foram identificados estudos provenientes do Equador, da Guiana ou do Suriname. No contexto brasileiro, observou-se maior concentração de estudos no estado do Pará, ao passo que não foram encontrados registros científicos nos estados do Amapá, Roraima e Tocantins. Menos da metade dos estudos avaliou áreas submetidas a mudanças na cobertura vegetal. Além disso, aproximadamente 4% das publicações não informaram o tipo de avaliação da serapilheira realizada, e cerca de 22% não especificaram o método utilizado para a determinação do teor de carbono. Os resultados desta revisão evidenciam lacunas na literatura científica, especialmente quanto à distribuição espacial dos estudos na Amazônia e à ausência de detalhamento metodológico na avaliação dos estoques de carbono da serapilheira.

Palavras-chave: ingresso de serapilheira; bibliometria; ciclos biogeoquímicos; sumidouro de carbono; mudança de uso da terra.

1. INTRODUCTION

Forest ecosystems store more than 80% of terrestrial aboveground carbon and therefore constitute a major

reservoir of this element (PAN et al., 2011; MA et al., 2018; GUERREIRO et al., 2021). The Amazon stands out as one of the most important carbon sinks on the planet, hosting the

largest tropical forests on Earth (HUBAU et al., 2020). The Intergovernmental Panel on Climate Change (IPCC) classifies aboveground biomass, roots, soil organic matter, and necromass as the principal carbon pools in forest ecosystems (IPCC, 2006).

Necromass consists of deposited organic material derived from leaves, reproductive structures (flowers and fruits), branches, and bark, and is classified into fine necromass (litter) and coarse necromass (VIVANCO et al., 2018; SILVA et al., 2023). The amount of litter deposited depends on both biotic and abiotic factors (JASINSKA et al., 2019; QU et al., 2021). Its quality, in turn, is influenced by vegetation cover and management practices, nutrient concentration, and the characteristics of the species present in the area (SOUZA et al., 2016; VILLA et al., 2016; RIBEIRO et al., 2022).

Litter decomposition releases elements that compose forest biomass, including carbon previously fixed through photosynthesis. Because of its role in reactivating nutrient cycles between plants and soil in anthropogenic areas, litter quantity and decomposition rates are widely used as environmental indicators in sites undergoing forest cover restoration (AQUINO et al., 2016; BELLO et al., 2022).

Given the high biomass and carbon stocks in the Amazon, identifying underexplored research areas is essential to guide and stimulate new research (ARAUJO et al., 2023). This requires a comprehensive understanding of existing studies on litter carbon stocks in the region, as well as the identification of major knowledge gaps to support conservation and sustainable management strategies.

Bibliometric analysis provides a quantitative approach to examine scientific production, enabling the identification of impacts, trends, and emerging themes, while state-of-the-art analysis provides a critical synthesis of existing knowledge, emphasizing gaps and prevailing methodological approaches (MIKHAIL et al., 2020; DONTU et al., 2021).

Unlike reviews limited to mapping scientific production, this study integrates bibliometric analysis with a critical assessment of the methods used to evaluate litter carbon stocks in the Amazon. By highlighting spatial and temporal gaps and recurring methodological weaknesses, such as the lack of standardization in carbon quantification, litter characterization, and carbon-to-nitrogen ratio assessment, this work contributes to refining the conceptual framework of this topic. It clarifies limitations that affect comparability among studies and the interpretation of litter's role in the carbon cycle under different land uses in the Amazon.

An integrated understanding of this body of literature can support actions related to sustainability, climate change mitigation, and forest ecosystem conservation. Accordingly, the present study aims to construct a comprehensive overview of scientific production and to identify the main knowledge gaps regarding litter carbon stocks in the Amazon.

2. MATERIAL AND METHODS

A bibliometric analysis was conducted to examine studies related to litter carbon stocks in the Amazon. The methodology adopted in the present work follows the approach proposed by Silva et al. (2020), with predefined search, screening, and eligibility criteria to ensure transparency and reproducibility. This approach is structured into six stages (Figure 1) and uses Scopus and Web of Science as data sources.

After defining the keywords and Boolean operators, the following search string was used: (TITLE-ABS-KEY (litterfall OR "litter fall" OR "leaf litter") AND TITLE-ABS-KEY (biomass OR "carbon stock" OR "stored carbon" OR "carbon sink" OR "carbon storage" OR "fixed carbon" OR "carbon sequestration")) AND TITLE-ABS-KEY (amazon*) AND PUBYEAR > 1979 AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE, "ar")).

Although Scopus and Web of Science do not cover all available literature, these platforms were selected because they are widely recognized multidisciplinary scientific databases and are commonly used in bibliometric analyses to assess the current scenario of various research fields (PRANCKUTÉ, 2021).

The database search was conducted in 2024, considering all publications indexed up to December 31, 2023, since the year 2024 was still in progress. Searches were performed in the titles, abstracts, and keywords using only English search terms. No restrictions were applied regarding the language of publication, allowing the retrieval of studies published in any language provided that they were indexed using the selected English terms. This review is not intended to provide an exhaustive census, but it provides a representative and robust sample of the available studies on the subject.

The search yielded 232 publications, of which 92 were indexed in Scopus and 140 in Web of Science. Of these, 66 articles were identified as duplicates and were therefore excluded. The remaining 166 articles were read in full and selected according to predefined criteria.

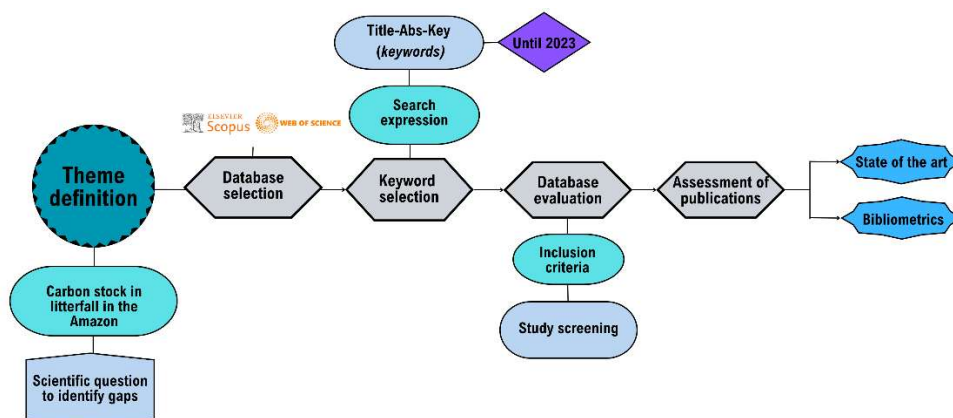


Figure 1. Simplified schematic outlining the stages used for publication screening in the bibliometric review and state-of-the-art analysis.

Figura 1. Esquema simplificado das etapas da revisão bibliométrica e da análise posterior do estado da arte.

Only original peer-reviewed scientific articles were considered. Review papers, conference proceedings, book chapters, books, theses, dissertations, technical reports, editorials, and other non-peer-reviewed publications were excluded. Duplicate records were removed before screening. Studies were included only when they simultaneously (i) evaluated litterfall, litter accumulation, and/or litter

decomposition, (ii) determined carbon content of the material, and (iii) were conducted within the Amazon. The quantitative flowchart of the aforementioned processes is outlined in Figure 2. Two reviewers independently performed the screening and eligibility assessment. Any disagreements regarding study inclusion were discussed until consensus was reached.

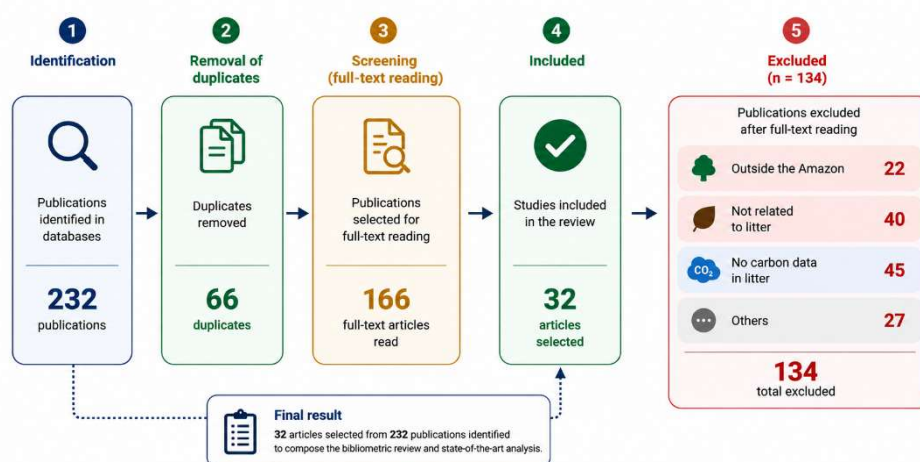


Figure 2. Simplified schematic outlining the stages used for publication screening in the bibliometric review and state-of-the-art analysis. Figura 2. Esquema simplificado das etapas da revisão bibliométrica e da análise posterior do estado da arte.

During the bibliometric analysis, the following parameters were assessed: (1) year of publication; (2) authors and collaboration networks; (3) authors' nationality and international interactions; (4) institutional affiliations; (5) keywords; (6) journals; and (7) funding agencies. For the state-of-the-art analysis, the selected papers were classified according to the following criteria: (1) study location; (2) land cover type; (3) type of litter assessment (input, accumulation, or decomposition); (4) method used to determine carbon in litter; and (5) litter carbon-to-nitrogen (C/N) ratio.

Land cover types were classified into the following categories: i) natural forests, including regenerating or mature forests; ii) plantations, including areas with tree species

planted for commercial or restoration purposes; iii) integrated systems, involving annual and/or perennial species; iv) crops; v) pastures, natural or managed.

Data were tabulated, and graphs were generated in R using the Bibliometrix package and the Biblioshiny interface (ARIA; CUCCURULLO, 2017; R Core Team, 2023).

3. RESULTS

After full-text reading, 32 papers met the previously established inclusion criteria. The first study on litter carbon content in the Amazon indexed in the selected databases was published in 1988, whereas the highest number of publications was recorded in 2018 (11.76%) (Figure 3).

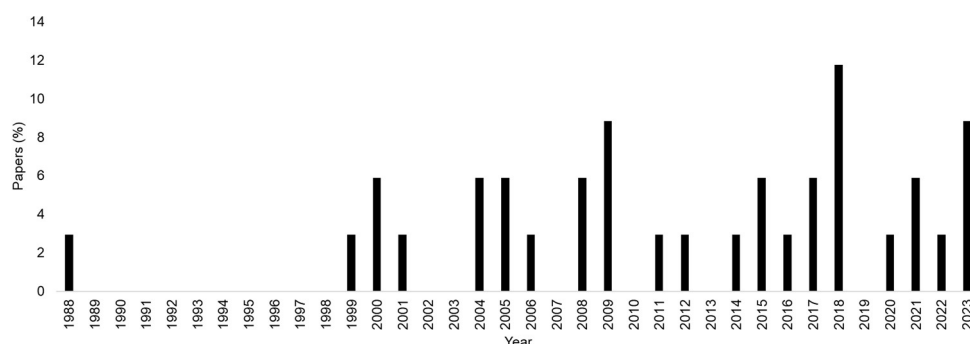


Figure 3. Percentage of publications indexed in Scopus and/or Web of Science databases up to 2023.

Figura 3. Percentual de publicações indexadas nas bases de dados Scopus e/ou Web of Science até 2023.

The analyzed studies demonstrate broad participation of researchers and collaboration networks, with a predominance of authors affiliated with Brazilian institutions (Figure 4).

The geographic distribution of authors indicates a predominance of researchers based in Brazil, along with international collaborations (Figure 5). Collaboration links were observed between Brazil and Colombia, Germany, Peru, and the United States. A high level of collaboration was

also observed between authors from Peru and Colombia. Institutional affiliations indicate that research is concentrated in universities and research centers with established activity in the Amazon (Figure 6).

Regarding the institutional affiliation of the authors, the University of São Paulo (USP – *Universidade de São Paulo*) stands out as one of the leading higher education institutions in Latin America. The National Institute for Amazonian

Research (INPA – *Instituto Nacional de Pesquisas da Amazônia*), founded in 1952 and headquartered in the Amazonian city of Manaus, is widely recognized for its research focused on the Amazon region. The University of Brasília (UnB – *Universidade de Brasília*), one of the most renowned Brazilian universities, is known for its tradition in environmental sciences. In turn, EMBRAPA (Brazilian Agricultural Research Corporation - *Empresa Brasileira de Pesquisa Agropecuária*) is a Brazilian governmental research institution

focused on developing new technologies, techniques, and solutions for forestry, agronomy, and sustainability through scientific research.

Figure 7 shows the most frequently used keywords in the analyzed articles. Word size is proportional to the frequency of occurrence, with larger words indicating higher frequency. The most frequent keywords were “Amazon”, “biomass”, “carbon”, “litter decomposition”, “soil respiration”, and “nutrient cycling”.

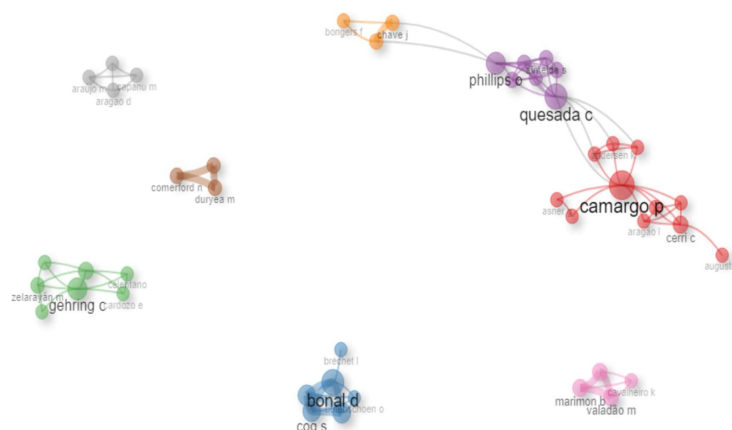


Figure 4. An author collaboration network based on articles indexed in Scopus and/or Web of Science on litter carbon stock in the Amazon up to 2023.

Figura 4. Teia de colaboração entre os autores das pesquisas indexadas nas bases de dados Scopus e/ou Web of Science relacionadas ao estoque de carbono em serapilheira na Amazônia até 2023.

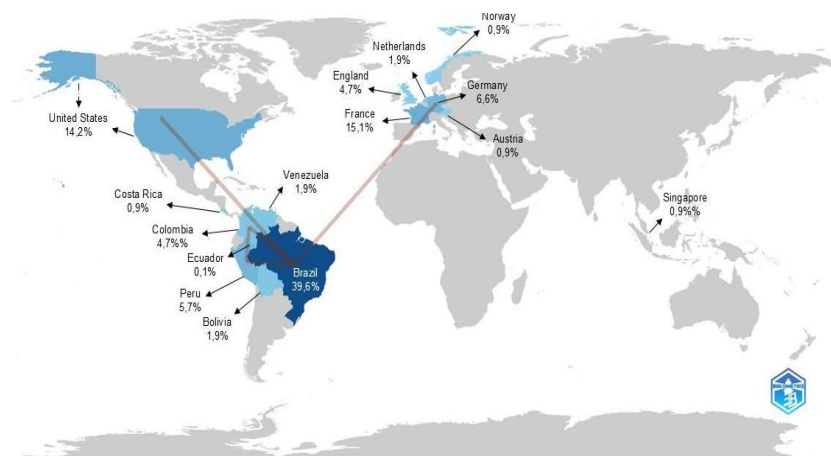


Figure 5. Geographical distribution of authors conducting studies on litter carbon stock in the Amazon based on publications indexed in Scopus and/or Web of Science up to 2023.

Figura 5. Mapa dos países de origem dos autores com estudos indexados nas bases de dados Scopus e/ou Web of Science sobre o estoque de carbono em serapilheira na Amazônia até 2023.

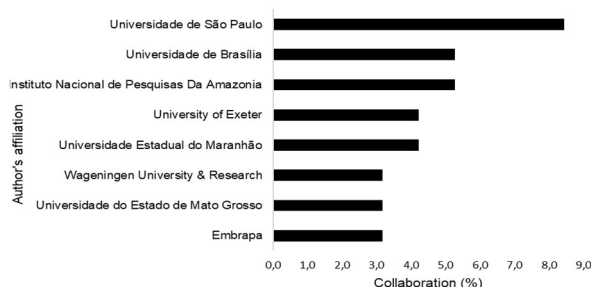


Figure 6. Main institutional affiliations of authors publishing on litter carbon stock in the Amazon indexed in Scopus and/or Web of Science up to 2023.

Figura 6. Principais afiliações dos autores, com estudos indexados nas bases de dados Scopus e/ou Web of Science sobre estoque de carbono em serapilheira na Amazônia até 2023.

Figura 7. Nuvem de palavras-chave mais utilizadas em estudos publicados e indexados nas bases de dados Scopus e/ou Web of Science sobre o estoque de carbono em serapilheira na Amazônia até 2023.

supporting 17.95% of the studies, followed by the Brazilian Ministry of Science, Technology and Innovation (MCTI – *Ministério da Ciência, Tecnologia e Inovação*) and the Natural Environment Research Council, each accounting for 12.82% of the publications, and UK Research and Innovation, which supported 10.26% of the studies (Figure 8).



Figura 8. Principais agências de financiamento de estudos publicados e indexados nas bases de dados Scopus e/ou Web of Science sobre o estoque de carbono em serapilheira na Amazônia, até 2023.

Most studies focused on litterfall evaluation, accounting for more than 40% of the articles (Figure 11), followed by studies on decomposition (31.91%) and accumulation (23.40%). About 4% of the studies did not specify the type of litter assessment. Among the methods used to determine litter carbon content, dry combustion was the most frequently employed, accounting for 44.4% of the studies (Figure 12). By contrast, 22.2% of the publications did not report the method used for carbon determination. Wet combustion, mass spectrometry, and conversion factors were also used, each representing 11.1% of the studies. A total of 41.67% of the studies evaluated the carbon-to-nitrogen ratio in litter. However, 58.33% of the articles did not include this type of assessment. This represents a significant gap in the literature, highlighting the importance of including the litter carbon-to-nitrogen ratio for a better understanding of ecological and biogeochemical processes.

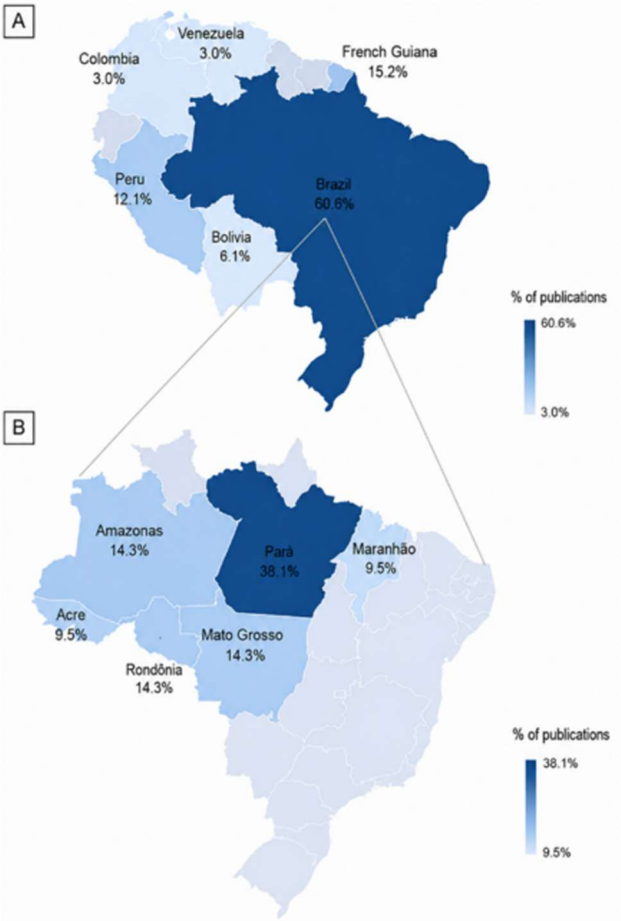


Figure 9. Countries (A) and Brazilian states (B) with studies on litter carbon stock in the Amazon indexed in Scopus and/or Web of Science up to 2023.

Figura 9. Países (A) e estados brasileiros (B) com estudos publicados e indexados nas bases de dados Scopus e Web of Science sobre o estoque de carbono em serapilheira na Amazônia até 2023.

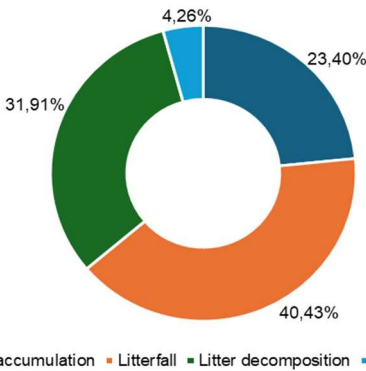


Figure 11. Types of litter assessment (input, accumulation, decomposition, and not reported) reported in studies on litter carbon stock in the Amazon indexed in Scopus and/or Web of Science up to 2023.

Figura 11. Tipos de avaliação da serapilheira (aporte, acúmulo, decomposição e não informado) com estudos publicados nas bases de dados Scopus e/ou Web of Science, relacionados ao estoque de carbono da serapilheira na Amazônia até 2023.

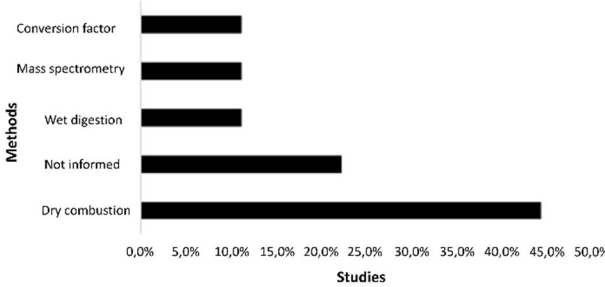


Figure 12. Methods used for carbon determination in studies on litter carbon stock in the Amazon indexed in Scopus and/or Web of Science up to 2023.

Figura 12. Métodos para determinação de carbono em estudos publicados e indexados nas bases de dados Scopus e/ou Web of Science, relacionados ao estoque de carbono em serapilheira na Amazônia.

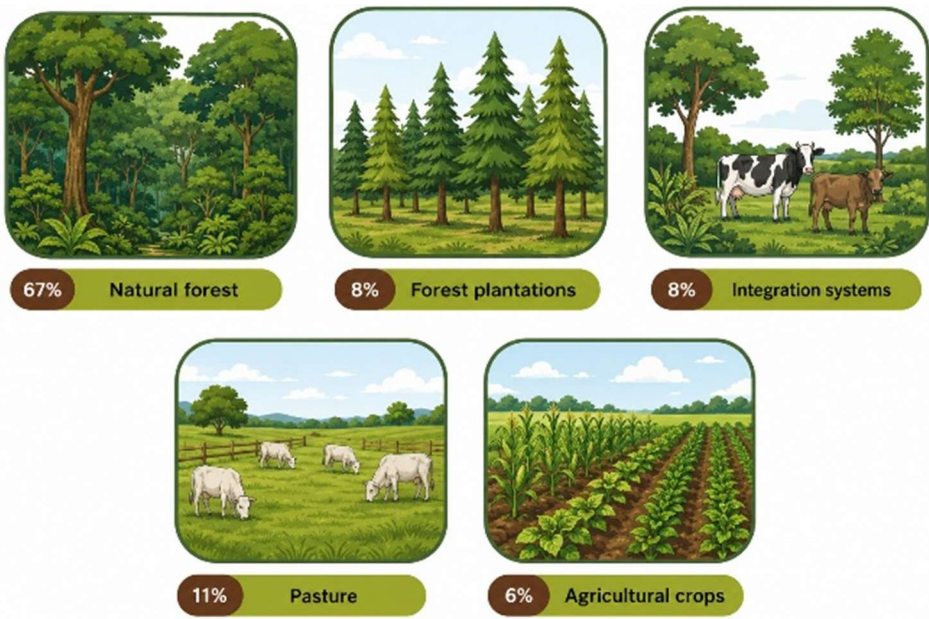


Figure 10. Vegetation types represented in studies on litter carbon stock in the Amazon indexed in Scopus and/or Web of Science up to 2023.

Figura 10. Tipos de vegetação com estudos indexados nas bases de dados Scopus e/ou Web of Science sobre o estoque de carbono da serapilheira na Amazônia até 2023.

4. DISCUSSION

The increase in the number of publications over recent decades reflects the growing scientific attention given to the importance of forest ecosystems in the global carbon cycle, particularly after litter was incorporated as a compartment/pool in carbon inventories. This trend is associated with the strengthening of research agendas on climate change and land use, in which litter has become recognized as an important component of carbon dynamics in Amazonian ecosystems. However, significant spatial and methodological gaps persist in the literature.

This expansion of scientific production is directly associated with international conferences on climate change, which have stimulated research focused on carbon fixation, vegetation cover, and land-use and land-management changes (ARAUJO et al., 2023). Within this context, the IPCC (2006) recommendation to include litter as a relevant carbon pool in carbon inventories contributed to increasing its visibility in research agendas.

The predominance of Brazilian authors is consistent with the fact that approximately 60% of the Amazon Forest is located in Brazil. Collaboration among researchers from Brazil, Peru, and Colombia reflects the shared distribution of the biome across these countries, which favors the development of joint studies and transnational scientific networks.

At the same time, the interest of foreign researchers in the Amazon is associated with the high biodiversity of the biome, which harbors a wide diversity of species with potential for investigation in different fields, such as medicine, agriculture, and technology (ELLWANGER et al., 2020). Furthermore, the relevance of the region as one of the major global carbon sinks reinforces its strategic importance in the context of climate change (RODRIGUES; CAETANO, 2023). Considering this, countries particularly vulnerable to climate change impacts have directed efforts toward understanding how the management of the Amazon may influence global climate balance and associated environmental conditions (NGUYEN et al., 2023).

Overall, universities and research institutions are central in consolidating these scientific agendas by knowledge production and dissemination as well as by supporting partnerships and exchanges among researchers from different fields and countries (DUSDAL; POWELL, 2021). These interactions strengthen scientific networks and expand the reach and impact of research conducted in the region.

“Litter decomposition,” “nutrient cycling,” and “soil respiration” were the most frequently used keywords, likely due to their strong interconnection. Litter decomposition and soil respiration are processes involved in nutrient cycling and directly influence carbon dynamics and the biogeochemical balance of ecosystems.

Biomass assessment and carbon stock estimation are directly related (Pechanec et al., 2022), as plant biomass constitutes the main carbon reservoir in terrestrial ecosystems (SPIKOUKIDIS et al., 2024). Therefore, biomass estimation allows a more accurate inference of accumulated carbon stocks. In this context, integrated approaches that simultaneously consider biomass and carbon are essential to support conservation strategies, sustainable management, and climate change mitigation, while also improving the understanding of biogeochemical dynamics in ecosystems.

Plant and Soil was the international journal with the highest number of publications on the subject, with particular

emphasis on studies in plant biology and soil science, particularly those related to mineral nutrition, plant–water relations, and soil biology. At the national level, *Acta Amazonica* also stood out; this journal was founded by INPA in 1971 and focuses on multidisciplinary research on the Amazon, ranging from botany to the social sciences.

The concentration of publications in these journals indicates that the topic is being addressed in well-established scientific outlets, which is an important factor for the academic consolidation of the field. Publishing in high-visibility journals influences career evaluation and funding opportunities, while also increasing the international reach of research and the recognition of authors (HYLAND, 2023).

The predominance of public funding agencies among the analyzed studies reinforces the strategic interest in understanding carbon dynamics in Amazonian ecosystems. This pattern indicates that the evaluation of litter carbon stocks has been conducted mainly within the scope of publicly funded research, highlighting the importance of greater methodological standardization to enable regional comparisons and support environmental planning (MCMANUS et al., 2020).

Although the Amazon extends across seven countries, Brazil holds the largest territorial portion of the biome and also has the largest territory and population among these nations. This context helps explain the observed results, in which the country stands out for having the highest number of publications, funding agencies, authors, and institutions dedicated to studies on litter carbon stocks in the Amazon region.

The state of Pará records the highest deforestation rates in the Amazon (Mapbiomas, 2023). It ranks among the major global emitters of greenhouse gases (seventh position) (Pará, 2024), which may explain its prominence as the state with the largest number of studies. This scenario is directly related to land-use change, which intensifies emissions and increases pressure on regional ecosystems. In response, the state government has sought alternatives to mitigate the impacts of deforestation and greenhouse gas emissions, establishing the *Amazônia Agora* State Plan (PEAA), which aims to reduce emissions from land-use change by at least 37% by 2030, in alignment with global climate commitments.

Most studies were conducted in natural environments, with relatively few evaluations in areas converted to other land uses, which are generally associated with higher levels of degradation and greater greenhouse gas emissions. Studies addressing land-use and land-management changes are essential for understanding how the removal of natural forests affects litter carbon stocks and overall carbon dynamics in the Amazon (COSTA et al., 2022).

The bibliometric patterns identified in this review help explain several of the methodological gaps observed in the state-of-the-art analysis. Research activity is concentrated, particularly in Pará and other Brazilian states, whereas extensive portions remain without published studies. This uneven spatial distribution restricts the diversity of environmental conditions evaluated and reduces opportunities to compare methodological approaches across different ecological and land-use contexts. Consequently, the current scientific evidence is insufficient to support broader methodological standardization for litter carbon assessments throughout the Amazon.

Likewise, the predominance of studies conducted in natural forests influences the type of information currently

available. Land-use systems associated with agricultural production, pasture, forest plantations, and integrated systems remain underrepresented, limiting the understanding of how methodological approaches perform under contrasting environmental conditions. This imbalance also contributes to the limited assessment of complementary variables, such as the litter carbon-to-nitrogen ratio, which is essential for interpreting decomposition processes and carbon dynamics across different land-use systems. Therefore, the bibliometric evidence indicates that the identified methodological gaps are not only related to reporting practices but are also associated with the uneven distribution of research efforts across the Amazon.

The predominance of dry combustion as the method for determining litter carbon content is likely explained by the lower variability it produces among samples, thereby reducing the number of sampling units required (SILVA et al., 2021; ARAUJO et al., 2023). In addition, this procedure results in lower environmental impact, as it does not require chemical digestion and generates fewer residues. Mass spectrometry also stands out as an employed method; however, due to its high sensitivity and specificity, it is more commonly recommended for detailed analyses (HALE, 2013). The use of conversion factors requires careful technical justification, as inappropriate values may lead to overestimation or underestimation of carbon stocks (ARAUJO et al., 2023).

The omission of methodological descriptions for litter carbon stock assessment, observed in 22% of the analyzed publications, represents an important gap in the literature. The absence of this information compromises methodological transparency and limits the reproducibility of studies, both of which are essential for scientific validation and for data comparability.

These findings indicate that bibliometric indicators and methodological quality should not be interpreted independently. The concentration of scientific production in specific regions and land-use contexts, combined with inconsistent methodological reporting, reinforces the need for future studies that integrate bibliometric mapping with quantitative assessments of methodological patterns, enabling a more comprehensive understanding of research biases and knowledge gaps across the Amazon.

In addition to quantifying litter carbon stocks, it is also necessary to understand how this compartment interacts with other ecosystem components and the outcomes of these interactions. In this regard, studies on the carbon-to-nitrogen ratio are essential for understanding decomposition dynamics and nutrient cycling and also serve as indicators of organic matter content, decomposition rate, and nutrient availability (JÍLKOVÁ et al., 2020). The C/N ratio is an important parameter for predicting carbon release, which in turn affects ecological processes such as carbon sequestration and nitrogen retention, both of which are essential for soil health and climate change mitigation.

Based on the results of this review, important spatial gaps and inconsistencies in methodological reporting were identified in studies addressing litter carbon stocks in the Amazon. From a broader conceptual perspective, these findings may have implications for environmental governance in Brazil, particularly by influencing the availability and comparability of scientific information used to support environmental planning and decision-making. Evidence-based environmental management requires robust,

territorially representative, and methodologically transparent scientific information, particularly in a region that is strategic for the global carbon balance.

Within the framework of national legislation, the relationship between litter dynamics and the objectives of the Brazilian Forest Code (Law No. 12.651/2012) is particularly relevant. The restoration of Permanent Preservation Areas (APPs – *Áreas de Proteção Permanente*) and Legal Reserves (*Reservas Legais*) is not limited to the structural recovery of vegetation cover but also involves the restoration of ecosystem functionality. Litter actively contributes to nutrient cycling, soil protection against erosion, and the maintenance of organic carbon, thus representing an important indicator of ecological quality in areas undergoing restoration. Based on the results of this review, no studies were identified for some Amazonian states. From a conceptual perspective, this uneven spatial distribution may limit the availability of scientific information for integrated evaluations of restoration actions, although this relationship was not directly assessed in the present study.

The need for a consistent scientific basis also extends to the National Policy on Climate Change (Law No. 12.187/2009) and to the commitments assumed by Brazil under the United Nations Framework Convention on Climate Change (UNFCCC). The preparation of greenhouse gas emission and removal inventories in the Land Use, Land-Use Change and Forestry (LULUCF) sector requires reliable estimates of the different carbon pools. Although aboveground biomass has received greater attention, litter represents a dynamic compartment that influences soil carbon and the stability of forest systems. The methodological inconsistencies and territorial asymmetries identified in this review suggest that uncertainties associated with regional carbon estimates may be greater, particularly where scientific evidence remains limited. Although this implication was not directly evaluated, it highlights the importance of expanding spatial coverage and improving methodological reporting.

Similarly, the National REDD+ Strategy (ENREDD+) and state-level climate mitigation plans depend on territorially distributed and technically consistent data to support actions aimed at reducing emissions associated with deforestation and forest degradation. The underrepresentation of certain Amazonian states identified in this review suggests the existence of informational asymmetries that may influence the development of evidence-informed public policies, particularly in a decentralized federal system such as Brazil, in which states have autonomy to implement environmental management instruments. However, the effects of these asymmetries on policy implementation were not evaluated in this study.

The interface between science and public policy is also evident in the agricultural sector, particularly within the framework of the ABC+ Plan (Low-Carbon Agriculture), which establishes mitigation targets through the adoption of sustainable practices such as integrated production systems, recovery of degraded pastures, and forest restoration. The current body of literature indicates that relatively few studies have investigated litter dynamics in Amazonian production systems. This limitation suggests that additional research is needed to better understand how these management practices influence litter carbon dynamics under different land-use conditions. Increasing research efforts in areas under agricultural use is therefore strategic for evaluating the

effectiveness of the measures proposed by the ABC+ Plan in the Amazonian context.

In a complementary manner, the National Policy for Payment for Environmental Services (Law No. 14.119/2021) recognizes carbon as an ecosystem service subject to economic valuation. The implementation of PES programs and initiatives associated with voluntary carbon markets requires reliable and transparent estimates of carbon stocks and fluxes.

In addition, the availability of territorially representative data is essential for environmental planning and for the Ecological-Economic Zoning (ZEE), which is a strategic instrument for territorial management in Brazil. The ZEE depends on consistent regional environmental information and detailed ecological characterization to guide land uses compatible with ecosystem carrying capacity. The absence of studies in certain Amazonian regions compromises the preparation of integrated environmental assessments and may weaken territorial zoning decisions.

These methodological and spatial limitations may also have implications for carbon market initiatives. The growing expansion of jurisdictional, compliance and voluntary carbon projects in the Amazon requires robust, comparable, and transparent estimates of carbon stocks and fluxes. From a broader policy perspective, the spatial gaps and methodological inconsistencies identified in this review may increase uncertainty in carbon quantification. Consequently, they have the potential to influence the technical basis of carbon quantification and carbon credit initiatives, as well as the reliability of contracts linked to these mechanisms. Assessing these broader implications was beyond the scope of the present study. In this sense, strengthening the scientific basis of litter, through methodologically consistent and spatially representative data, contributes not only to national inventories but also to the environmental integrity of market-based mechanisms by increasing technical credibility and reducing uncertainty in the quantification of environmental services.

Given these interfaces between science, legislation, and public policy instruments, the main implications of this study for environmental governance in Brazil lie in the expansion of the spatial coverage of research and harmonization of methodological reporting. This can be achieved by strengthening guidelines that standardize and systematically describe, in future studies, parameters such as sampling area, number of collectors, sampling frequency, criteria for litter fraction separation, analytical methods for carbon determination, justification for the use of conversion factors, and inclusion of the C/N ratio when appropriate.

Such standardization would reduce uncertainties, improve data comparability, and strengthen the integration of litter into carbon inventories and sustainable management strategies. Therefore, reducing territorial asymmetries and improving scientific transparency favors more consistent environmental governance, capable of supporting climate policies, territorial planning, and economic instruments with greater technical reliability and a stronger empirical basis.

5. CONCLUSIONS

The scientific production on litter carbon stocks in the Amazon has advanced in recent decades but still presents spatial gaps and methodological inconsistencies that limit comparability and the integrated understanding of regional

carbon dynamics. Limited integration between carbon stock quantification and the analysis of functional processes also persists, reinforcing the need to expand the spatial coverage of studies, improve methodological transparency, and more consistently include areas undergoing land-use change.

These advances are strategic for environmental management, as they contribute to reducing uncertainties in carbon inventories, strengthening the technical basis for public policies, improving territorial planning, and enhancing the monitoring of areas undergoing land-use conversion. As part of a future research agenda, integrated approaches involving biomass, litter, and soil carbon are recommended, as well as comparative studies among land-use systems and long-term investigations to assess carbon stability under anthropogenic and climatic pressures.

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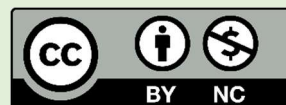
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Data availability: Data from this study can be obtained via email upon request to the corresponding author.

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