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Carbon Sequestration in Tropical Agroforestry Systems: A Bibliometric Analysis of Research Trends and Future Perspectives

Secuestro de carbono en sistemas agroforestales tropicales: un análisis bibliométrico de las tendencias de investigación y perspectivas futuras

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Highlights:

- This bibliometric study maps 788 Scopus-indexed publications on carbon sequestration in tropical agroforestry systems published between 1992 and 2026, using Bibliometrix, VOSviewer, and RPYS.
- Results indicate steady annual growth, a core group of journals, recurrent institutional and country-level participation patterns, and thematic clusters focused on agroforestry, soil carbon, ecosystem services, and land use.
- Findings provide a contextual basis for discussions on ecosystem-based mitigation, restoration of degraded tropical landscapes, and low-carbon rural development, while underscoring research gaps related to costs, equity, gender, indigenous peoples, and rural wellbeing.

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ABSTRACT

Introduction. The conversion of tropical forests to agricultural and pastoral land has reduced soil carbon stocks by 12 to 30% and removed more than 200 Mg C per hectare of aboveground biomass, which reinforces interest in agroforestry systems that can sequester carbon and restore degraded soils. **Objectives**: To describe and quantitatively analyse the evolution of research on carbon sequestration in tropical agroforestry systems, identifying temporal, geographical and thematic patterns to inform mitigation policies. **Materials and Methods**. A systematic bibliometric review of the Scopus database was conducted using a specific search string, with no language or time restrictions; after screening and metadata cleaning, 788 documents published between 1992 and 2026 in 283 sources were analysed with Bibliometrix and VOSviewer, with 2026 records treated as early access items. **Results.** The results show an annual growth rate of 4.16%, a mean article age of 7.25 years, 3,121 authors with an average of 5.36 co-authors per article and 43.78% international co-authorship, 5,580 references and 2,092 author keywords, a core of nine journals that concentrate 27% of publications, recurrent institutional and national participation patterns, and thematic clusters centred on agroforestry, soil carbon, ecosystem services and land use. **Conclusions.** The field is now well established and offers a contextual basis for discussions on ecosystem-based mitigation, restoration of degraded tropical landscapes and low carbon rural development, although important gaps remain regarding costs, equity, gender, indigenous peoples and rural wellbeing that future research agendas need to address.

Key words Agroforestry systems; Carbon sequestration; Bibliometric analysis; Tropical ecosystems; Climate change mitigation; Ecosystem services.

RESUMEN

Introducción. La conversión de bosques tropicales en tierras agrícolas y pastoriles ha reducido las reservas de carbono del suelo entre un 12 y un 30% y ha eliminado más de 200 Mg C por hectárea de biomasa aérea, lo que refuerza el interés en los sistemas agroforestales por su capacidad para secuestrar carbono y restaurar suelos degradados. **Objetivos.** Describir y analizar cuantitativamente la evolución de la investigación sobre el secuestro de carbono en sistemas agroforestales tropicales, identificando patrones temporales, geográficos y temáticos que contribuyan a orientar políticas de mitigación. **Materiales y métodos.** Se realizó una revisión bibliométrica sistemática en la base de datos Scopus utilizando una cadena de búsqueda específica, sin restricciones de idioma ni de periodo temporal. Después del proceso de cribado y depuración de metadatos, se analizaron 788 documentos publicados entre 1992 y 2026 en 283 fuentes, mediante Bibliometrix y VOSviewer. Los registros de 2026 fueron tratados como documentos de acceso anticipado. **Resultados**. Los resultados muestran una tasa de crecimiento anual del 4,16%, una edad media de los artículos de 7,25 años, 3.121 autores, un promedio de 5,36 coautores por artículo y un 43,78% de coautoría internacional. Además, se identificaron 5.580 referencias y 2.092 palabras clave de autor, un núcleo de nueve revistas que concentra el 27% de las publicaciones, patrones recurrentes de participación institucional y nacional, y conglomerados temáticos centrados en agroforestería, carbono del suelo, servicios ecosistémicos y uso del suelo. **Conclusiones.** El campo se encuentra actualmente bien consolidado y ofrece una base contextual para las discusiones sobre mitigación basada en ecosistemas, restauración de paisajes tropicales degradados y desarrollo rural bajo en carbono. Sin embargo, persisten vacíos importantes relacionados con costos, equidad, género, pueblos indígenas y bienestar rural, los cuales deben ser abordados en futuras agendas de investigación.

Palabras clave: sistemas agroforestales; secuestro de carbono; análisis bibliométrico; ecosistemas tropicales; mitigación del cambio climático; servicios ecosistémicos.

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INTRODUCTION

The increase in global mean temperature already exceeds 1.1 °C above pre-industrial levels and anthropogenic net emissions reached 59 ± 6.6 Gt CO2-eq in 2019, representing an approximate increase of 54% relative to 1990, yet they are projected to decline to 30 Gt CO2-eq yr^{-1} by 2050 [1-2]. The agriculture, forestry and other land use sector accounts for roughly 22% of these emissions, with 13 Gt CO2-eq yr^{-1} in 2019, and concentrates a substantial share of emissions from deforestation and ecosystem degradation, particularly in Latin America, Africa and South East Asia [3-4]. At the same time, managed and natural terrestrial systems act as a net sink and absorb nearly one third of anthropogenic CO2 emissions, which makes land use a key component of any mitigation strategy compatible with the goals of the Paris Agreement [5-6].

The conversion of tropical forests to agricultural and pastoral uses leads to substantial losses of soil and biomass carbon [7]. A global meta-analysis indicates that the conversion of forest to cropland reduces soil organic carbon stocks by around 25% on average, while conversion to perennial plantations produces reductions close to 30% and conversion to grasslands results in declines of almost 12% [8-9]. These losses add to the decline in aboveground biomass carbon, which can exceed 200 Mg C per hectare in humid tropical forests replaced by agricultural or livestock monocultures [10-11]. Scientific evidence consistently shows that the degradation of tropical soils reduces fertility, increases vulnerability to erosion and constrains agricultural productivity, which strengthens interest in production systems that maintain or enhance carbon stocks in tropical landscapes [12-13].

The Sustainable Development Goals (SDGs) framework provides direct normative support for the study of tropical agroforestry systems aimed at carbon sequestration [14]. SDG 13, target 13.2, calls on countries to integrate climate mitigation and adaptation measures into national policies and plans, including explicit strategies on land use and the management of terrestrial ecosystems [15]. SDG 15, targets 15.2 and 15.3, requires progress towards the sustainable management of all types of forests, halting deforestation, restoring degraded forest stands and achieving a balance between land degradation and restoration by 2030 [16]. At the same time, SDG 2, target 2.4, promotes food production systems that increase productivity and resilience, maintain ecosystem services and improve the quality of soils and agricultural land [17]. Within these targets, tropical agroforestry systems emerge as key interventions because they combine food production, increased carbon stocks in biomass and soils, and the restoration of degraded lands, which links them directly to the climate action, forest conservation and food security agendas articulated by SDGs 13, 15 and 2 [18-19].

In this context, tropical agroforestry systems are recognised as a strategic option to reconcile agricultural production, food security and climate mitigation [20]. Global estimates suggest that in 2022 the area under agroforestry practices was on the order of 1 023 million hectares, with significant coverage in Latin America, sub-Saharan Africa and Asia, where trees on agricultural land represent between 13 and 32% of regional agricultural area [21-22]. Several analyses concur that most of the potential for agroforestry expansion is concentrated in tropical and subtropical regions, in landscapes with high land-use change dynamics and large rural development gaps [23-24].

The carbon sequestration potential of tropical agroforestry is quantitatively relevant at the global scale [25]. It is estimated that the aboveground components of tropical agroforestry systems could store about 2.1×10^9 Mg C yr^{-1}, while temperate systems could reach around 1.9×10^9 Mg C yr^{-1} [26]. Studies focused on tropical systems indicate that total carbon stocks in agroforestry range from 12 to 228 Mg C ha^{-1}, with median values close to 95 Mg C ha^{-1}, and that the conversion of degraded agricultural land to agroforestry systems can increase soil carbon by about 10 to 30 Mg C ha^{-1} in the first decades of management [27-28]. Agroforestry also raises soil organic carbon by an average of 10.7%, with increases of up to 18.7% in arid zones, which confirms the importance of these systems for restoring degraded soils and strengthening resilience to drought [29].

The literature also shows variability among types of tropical agroforestry systems. Studies on coffee-shade tree systems, cocoa-native tree systems and silvopastoral arrangements report combined carbon stocks in biomass and soils ranging from 70 to more than 170 Mg C ha^{-1}, values that double or triple those of degraded pastures or treeless monocultures [30-31]. Moreover, the conversion from conventional agriculture to agroforestry increases soil carbon by 19 to 30 Mg C ha^{-1}, with sequestration rates close to 0.3 to 1.3 Mg C ha^{-1} yr^{-1} depending on climate, soil texture and system design [27,32]. These results support the consideration of agroforestry as an ecosystem-based mitigation measure in tropical countries [33].

Recent IPCC reports assign the agriculture, forestry and other land use sector a technical mitigation potential that accounts for 20 to 30% of the global emission reductions required for pathways compatible with 1.5 to 2 °C, with an important contribution from options that combine forest management, land restoration and agroforestry systems [34-35]. However, the available evidence on carbon sequestration in tropical agroforestry systems is dispersed across multiple regions, crop types, scales of analysis and quantification methodologies, which hampers an integrated view of research trends and knowledge gaps that affect their effective incorporation into climate and land use policies [35].

Along similar lines, Sharma et al. [36] conducted a global review combining systematic and bibliometric approaches to examine the evolution of agroforestry research using 8,090 Scopus-indexed publications from 1980 to 2024. Their findings show that agroforestry has gained scientific depth and strategic relevance through its links to climate change mitigation, biodiversity conservation and food security. This contribution is important because it confirms that agroforestry is no longer a peripheral topic, but an established field within environmental research and policy. Yet its broad global and thematic scope also leaves room for more focused analyses of specific ecosystem functions. Within this context, examining carbon sequestration in tropical agroforestry systems enables a more precise understanding of scientific trajectories, production patterns, impact structures and knowledge gaps surrounding one of agroforestry's most significant contributions to the contemporary climate agenda. Compared with previous broad reviews, the novelty of this manuscript lies in isolating the tropical agroforestry-carbon sequestration interface and in linking productivity, collaboration, source dispersion, historical citation peaks and thematic evolution within the same corpus. Understanding the scientific dynamics surrounding carbon sequestration in tropical agroforestry systems, with the aim of informing climate policies and land use decisions, first requires a broad reading of the theoretical, empirical and methodological developments of recent decades. This reading leads to the central research question: What is the level of scientific development on carbon sequestration in tropical agroforestry systems and how has it evolved over time? From this question, twelve specific sub-questions are formulated: i) How has scientific production on carbon sequestration in tropical agroforestry systems evolved over time? ii) What types of documents predominate and what is their relative weight in the period analysed? iii) Which subject areas within Scopus are most closely associated with this field and how are they distributed in relation to tropical agroforestry? iv) Which institutions and countries show the highest participation frequencies in the corpus? v) Who are the most productive authors in the field? vi) To what extent does author productivity follow Lotka's law and what does this reveal about productivity concentration in the field? vii) Which journals concentrate the dissemination of research on carbon sequestration in tropical agroforestry systems? viii) How is the core of journals organised according to Bradford's law and which zones of dissemination can be identified? ix) What is the level of international collaboration between countries and institutions working on tropical agroforestry and carbon sequestration? x) What does Reference Publication Year Spectroscopy (RPYS) reveal about the historical roots of the field and the years with greatest impact? xi) Which seminal publications, carbon quantification methods or climate regulatory frameworks are associated with the citation peaks detected in the RPYS?

and xii) What trends and emerging lines guide the future agenda according to the dynamics of keywords and the thematic map of research on carbon sequestration in tropical agroforestry systems?

Building on these questions, the general objective is to describe and quantitatively analyse the evolution of research on carbon sequestration in tropical agroforestry systems, identifying temporal, geographical and thematic patterns, recurrent participation patterns and influential sources, in order to inform discussion on policy-relevant scientific agendas related to ecosystem-based mitigation.

MATERIALS AND METHODS

This systematic bibliometric review was designed to characterise the scientific evolution of carbon sequestration in tropical agroforestry systems through quantitative mapping of Scopus metadata. Bibliometric mapping was applied as a quantitative approach based on mathematical and statistical models, focused on analysing scientific production and patterns of academic communication in this domain. This approach made it possible to synthesise trends, identify the most productive authors and the most recurrent institutions and countries, and detect research gaps and thematic trends, providing an integrated view of theoretical and methodological development on carbon sequestration in tropical agroforestry systems [37-38].

The application of the method followed the stages proposed by Luna-Morales et al. [39] i) formulation of the general and specific research questions, ii) selection of the reference database, iii) construction of a reproducible search equation, iv) definition of eligibility criteria, v) screening and cleaning of the corpus, vi) extraction of bibliometric variables, and vii) statistical analysis and visualisation of the retrieved metadata. The study adopted a quantitative approach of exploratory and descriptive scope, with a non-experimental, longitudinal and retrospective design, focused on tracing and interpreting the historical trajectory of the literature on carbon sequestration in tropical agroforestry from the earliest records up to 2026, and on identifying its growth patterns, intellectual structure and areas of specialisation [40-41].

The review protocol defined the population as scientific records on tropical or subtropical agroforestry systems, the conceptual focus as carbon sequestration, carbon storage, soil organic carbon, carbon stocks or related carbon-balance terms, and the source as Scopus-indexed publications [42-43]. Eligible documents were those retrieved by the search equation in title, abstract or keywords, with sufficient bibliographic metadata for bibliometric processing, and explicitly related to agroforestry systems in tropical or subtropical contexts. Records were considered ineligible when

they referred exclusively to non-agroforestry forests, treeless cropping systems, temperate agroforestry outside the target context, or land-use categories unrelated to the objective [44].

Based on the research question, the following search equation was developed, integrating the most representative terms of the thematic domain: (TITLE-ABS-KEY ("carbon sequestration" OR "C sequestration" OR "carbon storage" OR "carbon stock*" OR "carbon sink*" OR "soil organic carbon" OR soc OR "soil carbon" OR "terrestrial carbon" OR "biomass carbon" OR "belowground carbon" OR "aboveground carbon" OR "carbon pool*" OR "carbon budget" OR "carbon balance" OR "carbon flux*" OR "net ecosystem exchange" OR "greenhouse gas mitigation" OR "GHG mitigation" OR "climate change mitigation" OR "secuestro de carbono" OR "almacenamiento de carbono" OR "sumidero de carbono" OR "reservorio de carbono" OR "sequestro de carbono" OR "armazenamento de carbono" OR "sumidouro de carbono" OR "estoque de carbono") AND TITLE-ABS-KEY (agroforest* OR "agro forestry" OR "agro-forestry" OR "agroforestry system*" OR "agroforestry practice*" OR "agroforestry land use" OR "silvopastoral system*" OR silvopasture OR agrosilvopastoral OR "silvo pastoral" OR "agroforestry parkland*" OR parkland* OR "tree based farming" OR "tree based system*" OR "tree crop system*" OR "tree crop farming" OR "tree based agriculture" OR "shade coffee" OR "shade cocoa" OR "cocoa agroforest*" OR "coffee agroforest*" OR homegarden* OR "home garden*" OR "forest farming" OR taungya OR "alley cropping" OR "sistema agroforestal" OR "sistemas agroforestales" OR "sistema agroflorestal" OR "sistemas agroflorestais" OR "sistema silvopastoril" OR "sistemas silvopastoriles" OR "sistema silvipastoril" OR "sistemas silvipastoris") AND TITLE-ABS-KEY (tropic* OR subtropic* OR "humid tropics" OR "dry tropics" OR "tropical forest*" OR "tropical rainforest*" OR "tropical dry forest*" OR "tropical region*" OR "tropical area*" OR "tropical zone*" OR amazon* OR "Cerrado" OR "Congo Basin" OR "Southeast Asia" OR "Mekong Basin" OR "región tropical" OR "regiones tropicales" OR "regiao tropical" OR "regioes tropicais" OR tropicais OR trópico)).

The search was run on 24 November 2025 and initially identified 788 records, with no restriction on language or time period, in order to obtain the widest possible coverage of the field. Scopus was used as the reference database due to its multidisciplinary breadth, refined subject filters and high quality metadata, which facilitate the analysis of authors, affiliations, journals, countries and collaboration networks. The publication year assigned by Scopus was retained for descriptive purposes. Records labelled by Scopus as 2026 corresponded to early access or article-in-press items with active DOI and complete bibliographic metadata. These records were classified as early access items, retained to

capture the most recent direction of the field and interpreted as a partial series, not as evidence of complete annual production for 2026. The search equation was designed to focus the corpus on studies of carbon sequestration in tropical agroforestry systems and to exclude records centred on non-agroforestry forests, non-tree cropping systems or other land uses that do not match the aim of the study.

The records were exported in Comma Separated Values (CSV) format and processed statistically. The selection process followed four steps: identification of 788 Scopus records; screening of 788 records by title, abstract, keywords and metadata completeness; eligibility verification against the thematic scope; and inclusion of 788 records in the final corpus. During manual cleaning, no duplicate records and no out-of-scope records were removed, so the final corpus remained unchanged. The cleaning procedure corrected spelling variants and normalised author names, affiliations, countries, source titles and author keywords in Microsoft Excel spreadsheets for information normalisation and quality control [45].

The extracted variables included author, title, year, document type, source, affiliation, country, subject area, author keywords, index keywords, references, citations and DOI when available. The bibliometric analysis was carried out with Bibliometrix 5.1.1 in the R environment and with VOSviewer 1.6.20. Bibliometrix was used to calculate indicators of scientific productivity (authors, countries and journals) and collaboration (co-authorships and institutions), and to apply Lotka's and Bradford's laws to assess the distribution of author productivity and the core of journals [46]. VOSviewer was employed to construct and visualise co-occurrence networks of keywords through density and cluster maps based on association strength [47-48]. The analytical strategy combined descriptive productivity indicators, collaboration indicators, source-dispersion indicators, keyword co-occurrence, thematic mapping and Reference Publication Year Spectroscopy (RPYS), which was applied to identify the historical roots of the field and the citation peaks that mark milestones in the evolution of research on carbon sequestration in tropical agroforestry systems.

In this study, author productivity was operationalised as the frequency of author appearances in the cleaned dataset, regardless of authorship position. Accordingly, **Figure 3** identifies the most productive authors, not first, corresponding, or senior authors. Positional authorship was not used as a proxy for scientific leadership. Citation-based indicators, including total citations and the h, g and m indices, were treated separately as measures of scholarly impact. Likewise, institutional and country productivity were computed through whole counting of co-author affiliations and country affiliations in the cleaned corpus. Therefore, affiliation and country frequencies represent

participation counts rather than unique-document totals, and they should not be interpreted as direct shares of the total corpus.

Data Availability. The dataset supporting the findings of this study has been deposited in Mendeley Data and is publicly accessible under the title: Hoyos-Alayo, Walter Manuel (2025), "Bibliometric analysis of carbon sequestration in tropical agroforestry systems: trends and perspectives", Mendeley Data, V1, doi: http://doi.org/10.17632/rh5kpjbyn4

RESULTS

The analysed corpus spans the period from 1992 to 2026 and includes 788 documents published in 283 sources, with an annual growth rate of 4.16% and a mean age of 7.25 years, which indicates a sustained and current trajectory of research on carbon sequestration in tropical agroforestry systems. In total, 5 580 references and 2 092 author keywords are recorded, figures that point to broad thematic development and a dense bibliographic base in this field of study (**Figure 1**).

The results also show an extensive scientific community, with 3 121 authors and an average of 5.36 co-authors per document, together with an international co-authorship level of 43.78%, indicators that reflect strong cooperation between countries and interdisciplinary teams. Only 33 documents have single authorship, which confirms the predominance of collaborative networks in addressing this topic, while an average of 33.5 citations per document indicates high academic impact at the intersection between climate change mitigation and tropical agroforestry.

The annual production of articles on carbon sequestration in tropical agroforestry systems begins in 1992 with a single study and remains below ten documents until the mid 2000s, with values between 1 and 8 articles (**Figure 2**). From 2005 a gradual increase is observed, with 11 papers in 2005, 17 in 2007 and a range of 15 to 25 articles between 2009 and 2013. Between 2014 and 2016 activity stabilises at between 24 and 34 publications per year, while 2017 records a drop to 19 papers before the upward trend resumes.

Figure 1. General bibliometric indicators of the corpus

Growth accelerates from 2018, with 34 and 36 articles in 2018 and 2019, then 55 publications in 2020, 59 in 2021 and 65 in both 2022 and 2023, reaching a historical maximum of 104 documents in 2024, a figure that more than doubles the output of 2016. The apparent decline to 77 articles in 2025 and 4 in 2026 reflects the closure of the search in November 2025 and the partial inclusion of early access records, so those years represent still incomplete series. In this context, the data reveal a rapid expansion of research in this field over the past two decades, aligned with growing international attention to carbon sequestration in tropical agroforestry.

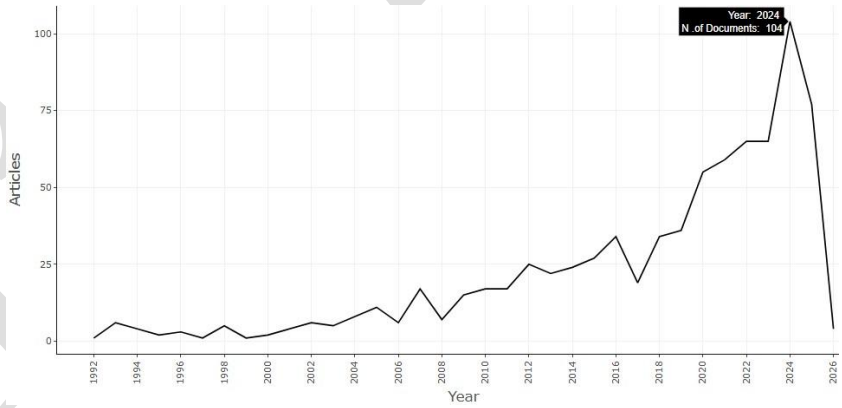

Figure 2. Annual scientific production

Scientific output is concentrated among a small group of the most productive authors. P. K. Ramachandran Nair heads the ranking with 18 documents, followed by Fernando Casanova Lugo with 16 and Gilberto Villanueva López

with 15 (**Figure 3**). Together, these three authors account for just over one third of the 135 author appearances accumulated by the ten most productive authors, indicating a marked concentration of productivity within the upper segment of the distribution. The remaining members of the group also display high productivity, with Deb Raj Aryal and Vimala D. Nair contributing 14 papers each, Leidivan Almeida Frazão 13, Arun Jyoti Nath 12, and Dietrich Hertel, Christoph Leuschner and B. Mohan Kumar 11 each. This structure reveals a concentration of output among specialists with established publication trajectories in different tropical contexts.

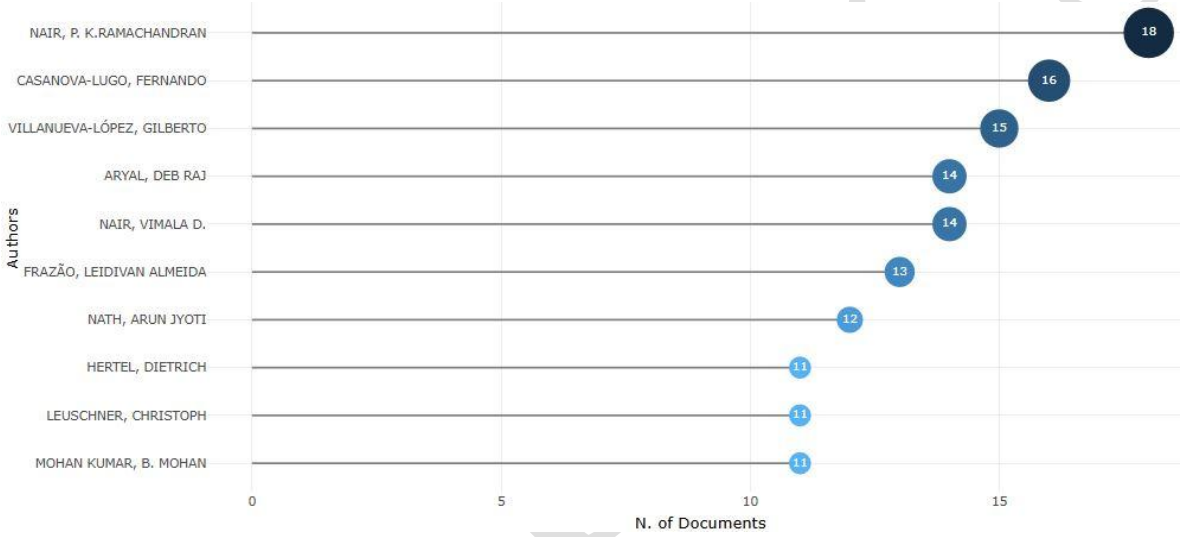

Figure 3. Most productive authors

The 82.3% of authors have published a single document, 10.9% have written two, and only 3.4% have contributed three articles (**Figure 4**). For four and five documents the percentages fall to 1.5% and 0.7%, while from six publications onwards the proportion of authors remains below 0.5%. As the number of published documents increases, the percentage of authors approaches zero, which reveals a long tail dominated by a small group of highly productive researchers.

The solid line representing the empirical data closely follows the theoretical Lotka distribution indicated by the dashed line. For authors with one document, the observed value is 82.3% compared with 63.0% predicted by the law, while for two and three documents the empirical values of 10.9% and 3.4% lie close to the expected 15.7% and 7.0%. This pattern confirms that author productivity in research on carbon sequestration in tropical agroforestry systems is

organised according to Lotka's law, with output concentrated in a limited number of highly productive specialists, consistent with the distribution shown in (**Figure 3**).

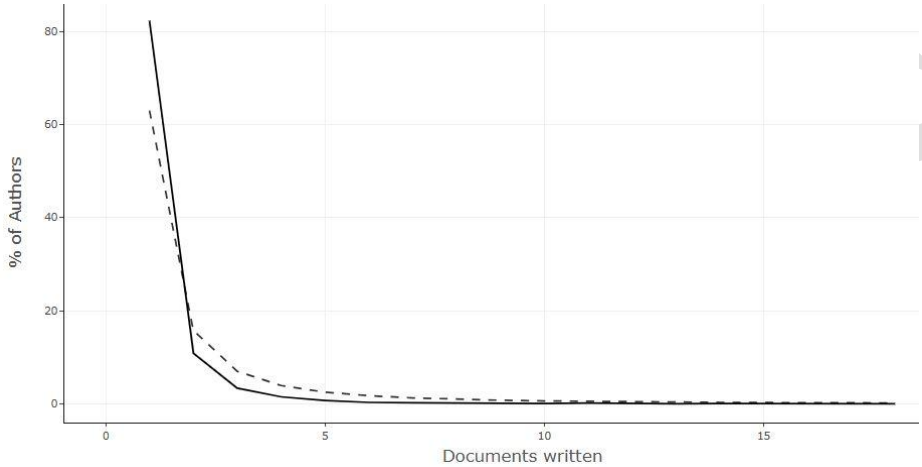

Figure 4. Distribution of authors by productivity – Lotka's Law

The dissemination of knowledge on carbon sequestration in tropical agroforestry systems is concentrated in a small set of specialised journal (**Figure 5**). Agroforestry Systems leads with 78 articles, followed by Agriculture, Ecosystems and Environment with 39 documents. At a second level are Forests with 20 publications and Science of the Total Environment with 17 papers, which reflects the important role of journals focused on agroforestry, ecosystem ecology and environmental sciences.

The group of leading sources is completed by Forest Ecology and Management, Plant and Soil and Sustainability, each with 13 articles, Geoderma with 12 and Journal of Environmental Management with 9 documents. Together, these nine journals account for 214 publications, close to 27% of the total corpus, which indicates the presence of a select core of high impact outlets where scientific discussion on carbon sequestration in tropical agroforestry is concentrated.

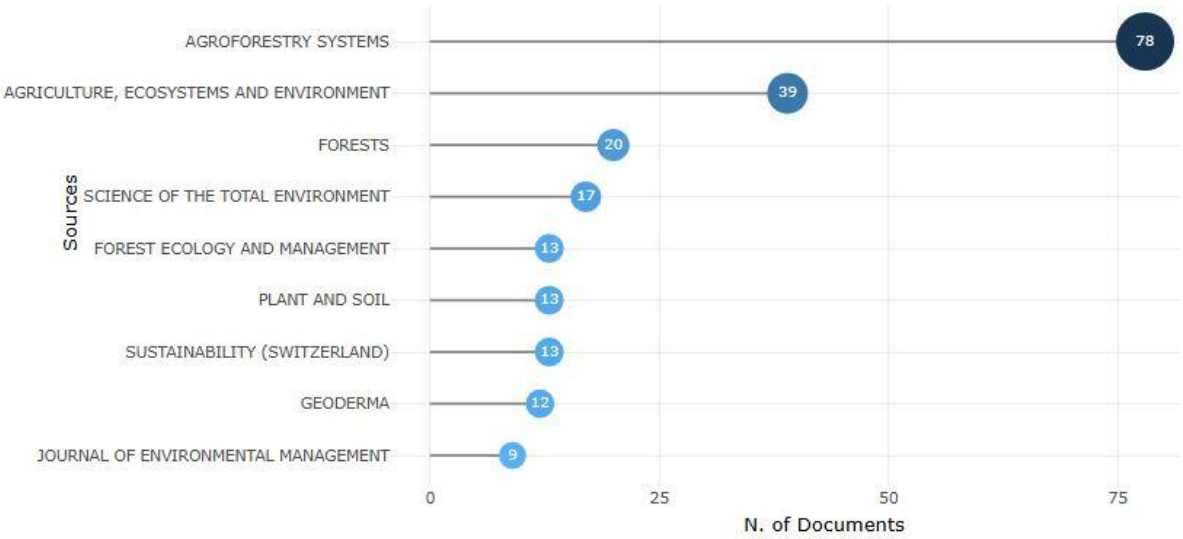

Figure 5. Leading journals

The application of Bradford's law identifies a small core of journals in which research on carbon sequestration in tropical agroforestry systems is concentrated (**Figure 6**). The six leading sources, headed by Agroforestry Systems and Agriculture, Ecosystems and Environment and including Forests, Science of the Total Environment, Forest Ecology and Management and Plant and Soil, account for 180 articles. This represents 22.8% of the 788 documents in the corpus, concentrated in only 2.1% of the 283 journals analysed, which clearly defines the "core sources" zone highlighted in the graph.

Beyond this core, there is a pronounced decline in the number of articles per source and a marked dispersion of the literature. The remaining 277 journals share 608 documents, with an average of about 2.2 articles per source and a predominance of titles that publish one or two papers on the topic. This pattern confirms that the dissemination of knowledge on carbon sequestration in tropical agroforestry is organised around a small group of highly productive specialised journals, followed by a broad band of peripheral publications with sporadic contributions.

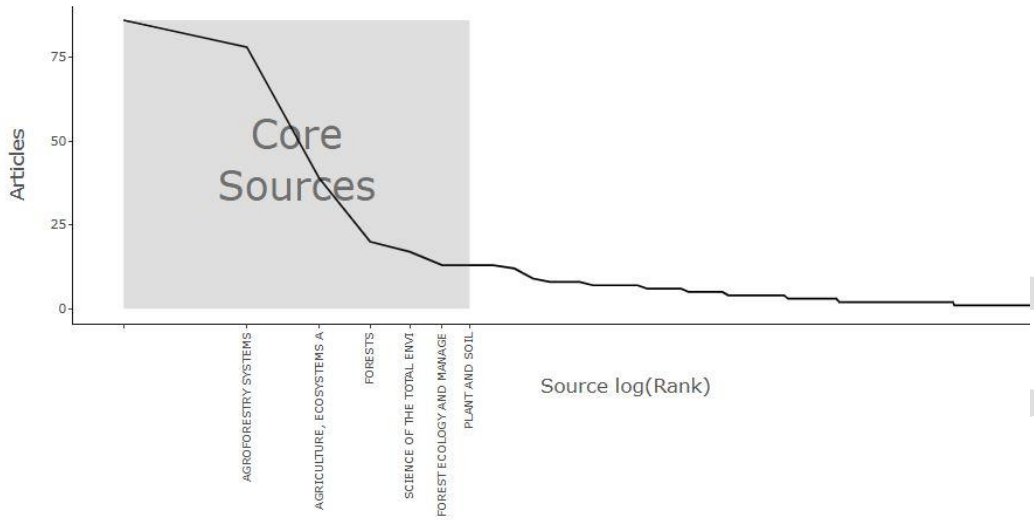

Figure 6. Article dispersion – Bradford's Law

Georg-August-Universität Göttingen records the highest affiliation frequency with 162 appearances in the cleaned dataset. It is followed by Universidade Federal de Minas Gerais with 90 appearances, Universidade de São Paulo with 67, and the Brazilian Agricultural Research Corporation EMBRAPA with 65 (**Figure 7**). The University of Florida and the World Agroforestry Centre contribute 51 and 50 affiliation appearances, respectively, which confirms the recurrent participation of universities and research centres with consolidated agendas on tropical agroforestry and carbon sequestration. The ten most frequent affiliations, which also include Universidad de la Amazonia, Universidad Autónoma de Chiapas, IPB University and Universidade Federal de Viçosa, sum 645 appearances. These values represent co-author affiliation frequencies rather than unique-document totals. Accordingly, the pattern should be interpreted as a concentration of institutional participation within the corpus, rather than as a direct measure of institutional leadership.

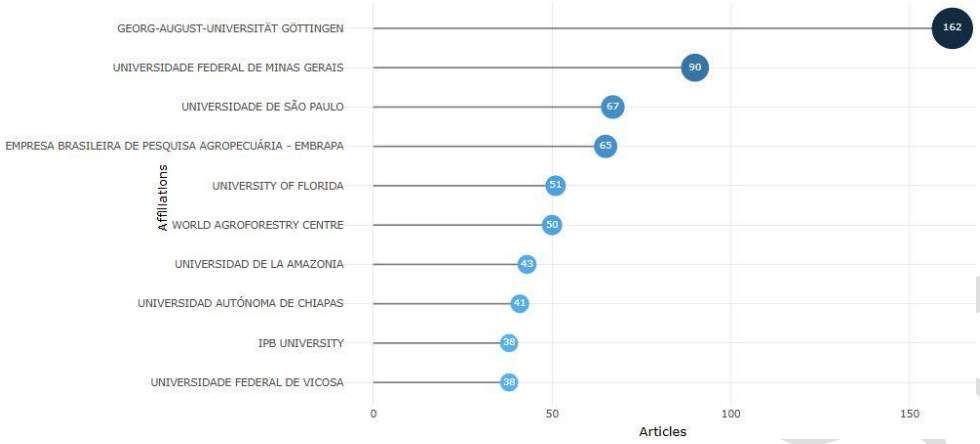

Figure 7. Institutional affiliations

The United States registers the highest country frequency, with about 175 country-affiliation appearances, followed by Brazil with about 160 and India with just over 100 (**Figure 8**). These values represent country-affiliation appearances in the authorship metadata and not unique articles, because one multi-country publication contributes to each participating country. The pattern therefore indicates recurrent participation of these countries within the corpus. A second group comprises Germany with around 80 appearances, Indonesia with about 65, Colombia with roughly 55 and China with approximately 50, while the United Kingdom, Mexico and Australia each register between 35 and 45. This distribution reflects participation from both high-income scientific systems and tropical countries with broad agroforestry relevance.

The keyword dynamics intensify from the mid-2000s onwards (**Figure 9**). The term agroforestry moves from values close to zero in the 1990s to about 10 cumulative occurrences by 2003, then reaches around 30 in 2010, approaches 60 in 2015 and exceeds 100 in 2021, reaching 160 occurrences in 2025. Carbon sequestration grows in parallel, with fewer than 5 cumulative appearances before 2005, about 20 in 2012, around 40 in 2017, roughly 70 in 2020 and about 115 occurrences in 2025. Climate change shows a somewhat later increase, with fewer than 5 appearances until 2010, about 15 in 2015, around 30 in 2020 and roughly 60 cumulative occurrences in 2025. Taken together, these three terms account for more than half of the cumulative appearances of the group of analysed keywords, which confirms their role as conceptual axes of the field.

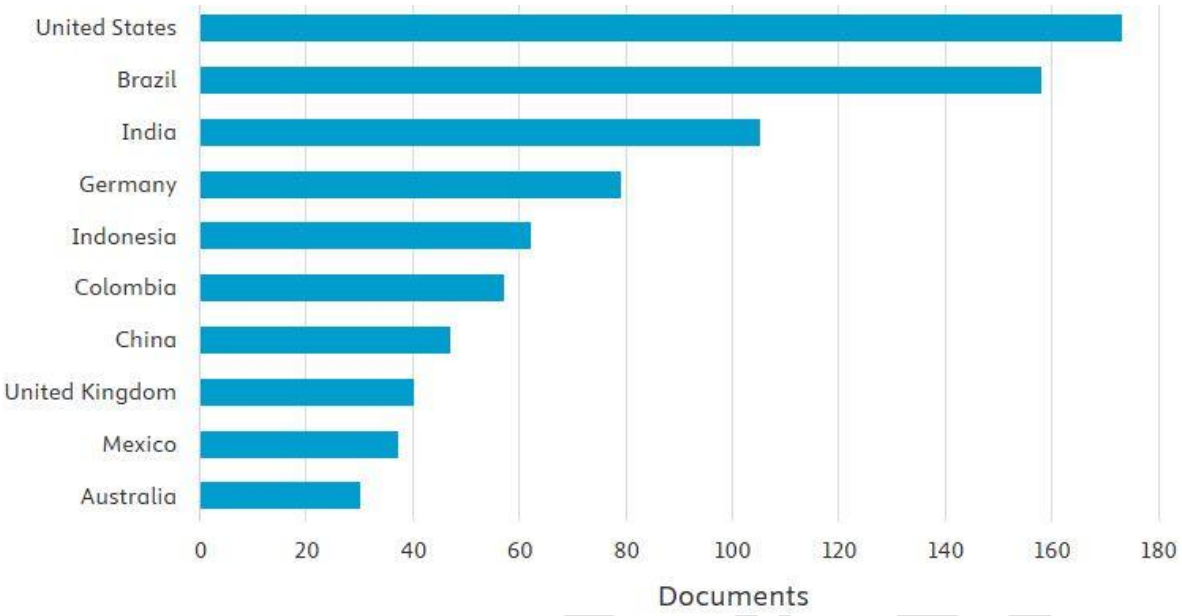

Figure 8. Production by country

.

At a second level, soil organic carbon reaches nearly 40 occurrences in 2025, while ecosystem services, soil organic matter and soil quality lie between 30 and 35, after having remained below 10 cumulative appearances for almost the entire period prior to 2015. The terms biomass, carbon and agroforestry systems display more moderate trajectories, with final values of around 25 to 30 occurrences. The almost simultaneous increase of these terms after 2015 indicates that the literature not only reinforces the association between agroforestry and carbon sequestration but also assigns greater weight to soil quality and ecosystem services as key dimensions of analysis.

The 42.0% of the publications are classified under Agricultural and Biological Sciences and 29.0% under Environmental Science, so nearly three quarters of the corpus fall within disciplines directly related to the management of agroecosystems, soils and environmental services (**Figure 10**).

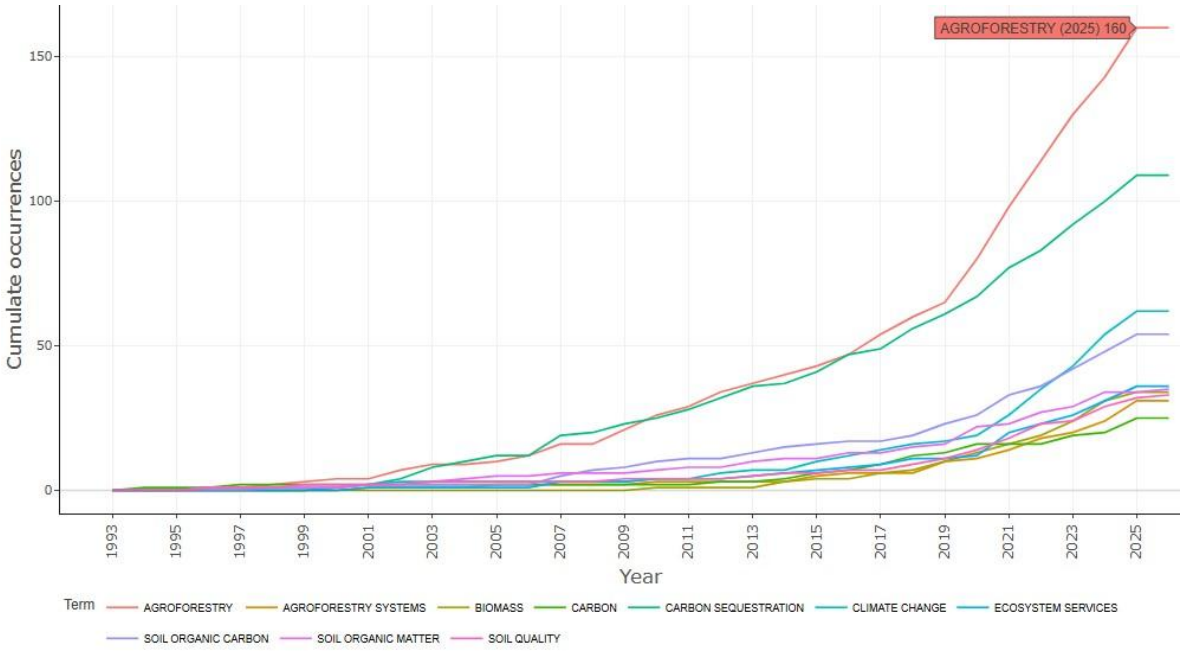

Figure 9. Frequency of terms over time

A second block comprises Earth and Planetary Sciences with 5.2%, Social Sciences with 5.0% and Engineering with 4.4%, reflecting an important contribution from approaches addressing Earth system dynamics, the social dimensions of agroforestry and technological solutions. The areas of Energy (2.9%), Biochemistry, Genetics and Molecular Biology (2.4%) and Computer Science (1.6%), together with Multidisciplinary and Economics, Econometrics and Finance (1.3% each), together account for around 14.5% of the publications, while the Other group represents 4.9%. In this context, the field shows a strongly agronomic and environmental base, enriched by contributions from Earth sciences, engineering, social sciences and economics, which results in a study area with a high degree of thematic integration around carbon sequestration in tropical agroforestry systems.

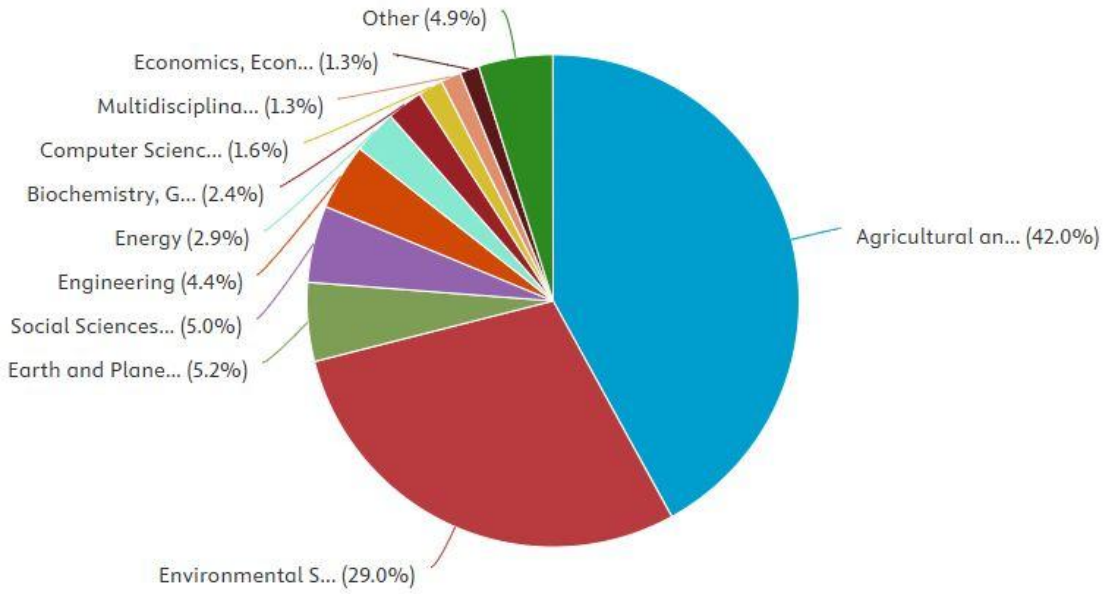

Figure 10. Publications by subject area

The keyword co-occurrence network is organised around a central core dominated by agroforestry and carbon sequestration, which display the largest node size and a high density of links to soil organic carbon, climate change, ecosystem services, biomass and soil organic matter (**Figure 11**). This structure indicates that the literature systematically connects tropical agroforestry with carbon sequestration, soil quality and ecosystem services, and that these terms concentrate most of the recorded co-occurrences.

The map also reveals thematic branches extending from this core towards three main areas. A first cluster groups terms related to soil properties and management, such as soil quality, soil health, soil management, soil degradation and tropical soils. A second cluster brings together concepts linked to land use and production systems, including shade trees, alley cropping, silvopastoral, pasture, cocoa, coffee, secondary forest and plantation. A third cluster connects with mitigation and conservation frameworks, highlighting greenhouse gases, environmental services, sustainable agriculture, biodiversity, restoration and REDD+. The colour gradient shows that terms such as soil health, ecosystem services, biodiversity, restoration and silvopastoral become more frequent in recent years, suggesting a research agenda that moves from merely quantifying carbon stocks to integrating soil restoration, ecosystem services and climate strategies based on tropical agroforestry.

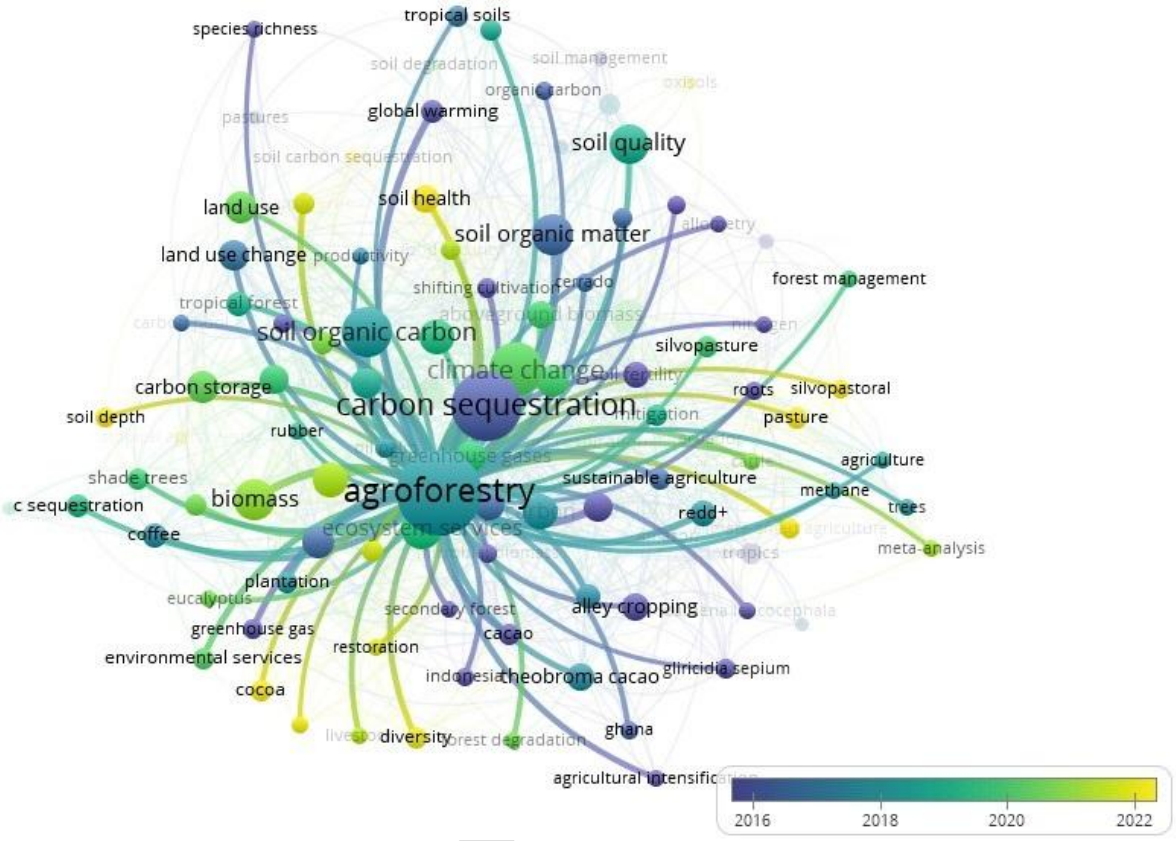

Figure 11. Keyword co-occurrence

The cited references are almost absent between 1929 and 1944, with values of 0 to 1 citation per year (**Figure 12**). From 1945 onwards, the first clear peak appears, with 10 cited references and a positive deviation of 9 units from the local median, associated with pioneering work on soil carbon analysis. The curve then remains low until 1960, a year with 5 citations, and later shows a new rise in 1965, with 12 references and a deviation of 10 units, indicating the consolidation of soil analysis manuals and methods that underpin subsequent studies.

Between 1970 and the early 1980s the signal intensifies. In 1973 there are 12 citations and in 1982 there are 39 references, with a deviation of 26 units, linked to studies on carbon storage and biomass assessment in tropical regions. The key phase begins in the early 1990s. In 1993 the references reach 104 citations, in 1996 they increase to 148 and in 1997 there is a peak of 220 citations with a deviation of 87 units, the highest relative value of the entire series in terms of impact on the median. These years mark the systematic incorporation of manuals on tropical soil fertility and methods for estimating biomass and carbon in humid forests.

The recent phase shows an even greater accumulation of references. In 2003 there are 276 citations, in 2010 and 2011 there are 272 and 296 respectively, while 2014 reaches 318 and 2017 reaches 295. The absolute maximum corresponds to 2018 with 344 cited references and a deviation of 49 units, followed by 2020 with 327 citations and a deviation of 59 units, indicating a strong concentration of the literature in articles published in that decade. After these peaks, the series gradually declines to 268 citations in 2019, 247 in 2021, 212 in 2022 and 131 in 2023. Overall, the data reveal a trajectory in which the years 1945, 1965, 1982, 1993, 1997, 2003, 2010, 2014, 2018 and 2020 act as historical nodes that bring together most of the seminal references for the study of carbon sequestration in tropical agroforestry systems.

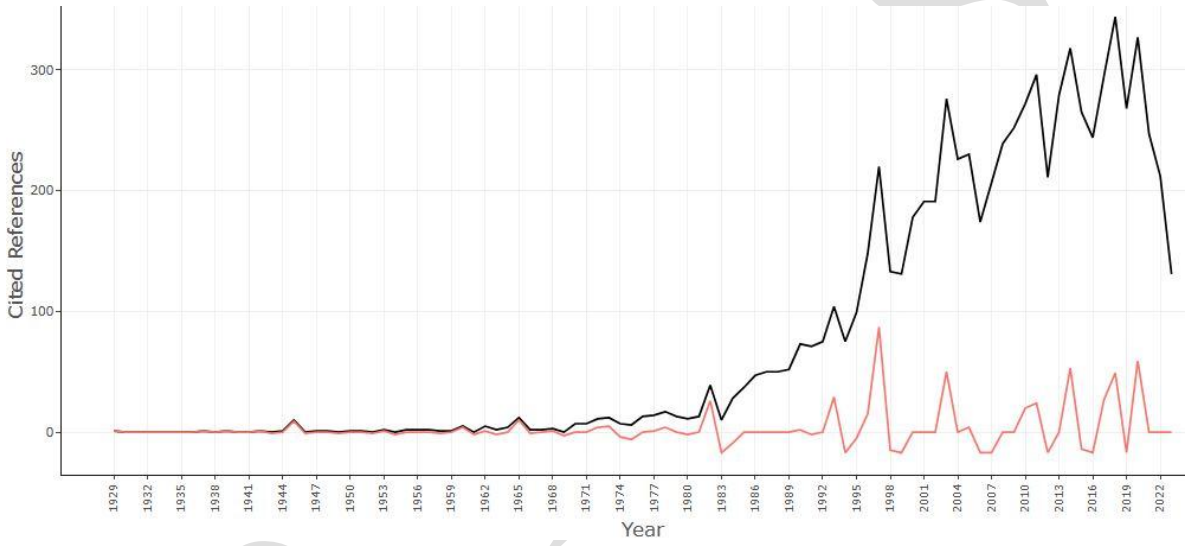

Figure 12. Annual distribution of cited references

The thematic map distinguishes three main sets of terms (**Figure 13**). The cluster formed by carbon, forestry and land use is located in the motor themes quadrant, with the highest centrality and density in the diagram, which indicates strong connections with the other concepts and an advanced degree of theoretical and methodological development. This core reflects that the debate on carbon sequestration in tropical agroforestry systems is directly integrated with discussions on forest management and land use planning.

In the lower right, the group agroforestry, carbon sequestration and climate change appears as a basic and highly relevant theme, with high centrality and moderate density. It functions as a transversal axis structuring the field, on which more specific lines depend. In turn, the cluster soil carbon, soil organic matter and organic carbon is positioned

in the niche themes quadrant, with high density but lower centrality, which indicates strong specialisation in soil processes that still maintains limited connections with other approaches. The absence of well defined clusters in the emerging or declining themes quadrant suggests a relatively consolidated domain, where efforts focus on deepening the links between land use, forest management, soil carbon and climate mitigation in tropical agroforestry.

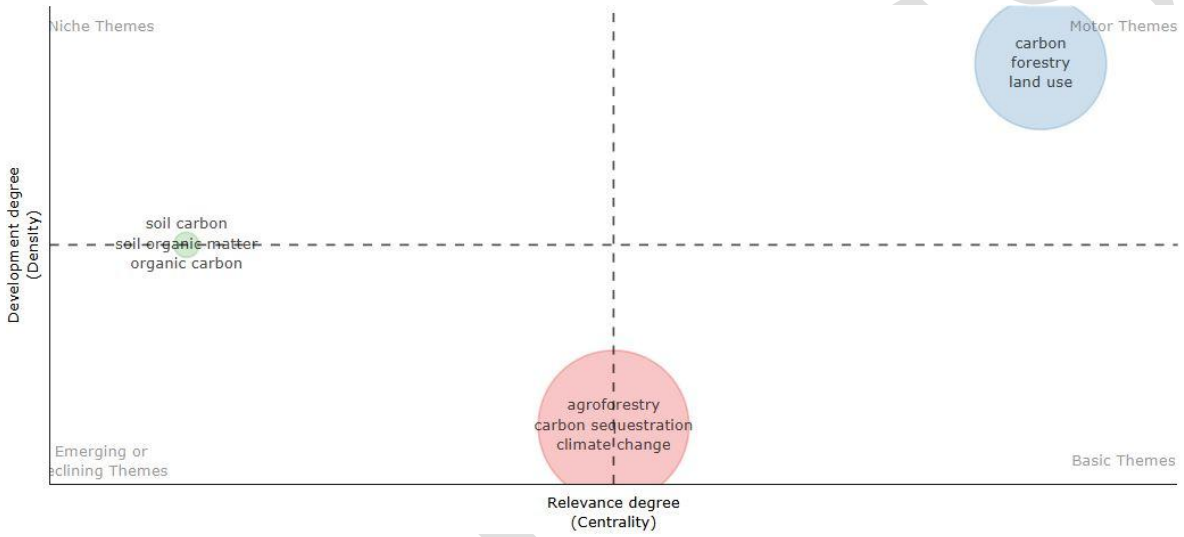

Figure 13. Thematic map.

DISCUSSION

The temporal dynamics of the field point to rapid maturation rather than a simple increase in publication numbers [17]. Figure 1 shows sustained growth supported by a broad author base, and **Figure 2** highlights a recent jump in annual output that coincides with the integration of land based solutions in IPCC reports and with the roll out of nationally determined contributions aligned with the Paris Agreement [49-50]. This convergence suggests that tropical agroforestry systems have moved from a peripheral position to become central components of mitigation and adaptation portfolios for a 1.5 to 2 °C world, which reinforces their relevance for SDG 13, especially target 13.2 on the incorporation of climate action into national policies and plans [51-52]. Compared with other forms of land use, the observed pattern indicates that agroforestry is increasingly recognised as an option that can combine carbon sequestration, soil stability and productive functions [53].

The journal structure reveals a specialised core that acts as a conceptual and methodological reference [35]. **Figure 5** shows the role of Agroforestry Systems and Agriculture, Ecosystems and Environment as main platforms for studies that integrate tree management, soil dynamics and ecosystem services, while Figure 6, based on Bradford's law, identifies a small group of core journals where a notable fraction of the corpus is concentrated [25,54]. The presence of Forests, Geoderma, Plant and Soil and Journal of Environmental Management within this core indicates that discussion on carbon sequestration in tropical agroforestry systems rests on a well consolidated interface between soil science, ecosystem ecology and environmental management [55-56]. This concentration facilitates the adoption of comparable protocols to measure carbon stocks and fluxes, design experiments and calibrate models, and it provides direct inputs for restoration policies and sustainable land management strategies aligned with SDG 15, particularly target 15.3 on land degradation neutrality [57-58].

Authorship and co-authorship indicators depict a highly collaborative field with a stable core of highly productive specialists and a broad peripheral base of occasional contributors [33]. **Figure 1** points to a high number of co-authors per article, a feature that suggests interdisciplinary teams in which soil scientists, foresters, remote sensing specialists and environmental economists converge [53]. **Figure 3** identifies a small group of highly productive authors with long trajectories in tropical agroforestry and carbon quantification in soils and biomass, while **Figure 4** shows a distribution consistent with Lotka's law, supported by a broad base of occasional authors [3,13]. This combination of a stable core and an expanding periphery indicates that the field is spreading into diverse biogeographical and socio-economic contexts [17]. Such a structure promotes the generation of local evidence for mitigation programmes in tropical countries and, at the same time, improves the potential quality of meta-analyses and global assessments that depend on comparable series from multiple regions [59-60].

The institutional and geographical dimension shows a heterogeneous distribution of participation across universities, research centres and countries. **Figure 7** records high affiliation frequencies for Georg-August-Universität Göttingen, Universidade Federal de Minas Gerais, Universidade de São Paulo and EMBRAPA, while Figure 8 identifies the United States, Brazil and India as the countries with the highest country-affiliation frequencies in the corpus. Because these indicators were computed through whole counting, they should be interpreted as participation frequencies rather than as direct measures of collaboration intensity, coordination capacity or leadership [25,31,55]. Even so, the pattern indicates that research activity is distributed across both consolidated scientific systems and tropical countries with strong agroforestry relevance [57]. This distribution is useful as contextual background for future discussion on capacity

building, data infrastructure and knowledge circulation, but it does not in itself demonstrate the structure or effectiveness of North South cooperation networks [15,56-57].

The analysis by subject area and keywords suggests a clear shift from approaches focused mainly on carbon stocks towards an integrated view of ecosystem services, soil health and productive resilience [64]. **Figure 10** indicates that most articles are classified under Agricultural and Biological Sciences and Environmental Science, with relevant contributions from Earth and Planetary Sciences, Engineering, Energy and the Social Sciences [65]. **Figure 9** shows that agroforestry and carbon sequestration occupy the core of the discourse, while terms such as soil organic carbon, ecosystem services, soil quality, biomass and climate change increase their presence in recent periods [23]. This pattern indicates that carbon sequestration is no longer treated as an isolated indicator and is instead interpreted within agroforestry systems that aim to reconcile production, soil restoration and yield stability [66]. This reading connects directly with SDG 2, in particular targets 2.3 and 2.4, which seek to raise the productivity of small scale producers and to consolidate resilient agricultural systems in the face of climate variability through practices such as agroforestry [57,67].

The structure of keyword co-occurrence and the thematic network deepen this conceptual transition and show how research foci are organised [33]. **Figure 11** presents a core structured around agroforestry and carbon sequestration, with dense connections to soil organic carbon, ecosystem services, climate change and soil organic matter. Around this core, branches appear that are linked to specific production systems, such as coffee, cocoa and silvopastoral arrangements, and to terms associated with biodiversity, restoration and REDD type programmes [68-69]. **Figure 13** places the group carbon, forestry and land use in the motor themes quadrant, which confirms the centrality of the link between forest management, land use planning and carbon sequestration [54]. The cluster agroforestry, carbon sequestration and climate change emerges as a basic theme that structures a large share of the literature, while the group soil carbon, soil organic matter and organic carbon appears as a niche theme, with strong internal development and weaker connections to socio-economic and governance dimensions [70-71]. This organisation indicates that the field has advanced solidly in biophysical metrics, although there is still scope to integrate analyses of cost effectiveness and impacts on equity and environmental justice within the same thematic networks [22,72].

The historical reading of key references helps to explain how the methodological and conceptual base that supports recent production has been constructed [17]. Figure 12, through Reference Publication Year Spectroscopy, identifies milestones linked to soil analysis manuals, developments in biomass models, global assessments of land use change

and synthesis studies on agroforestry [73]. The peaks in the 1980s and 1990s reflect efforts to quantify carbon stocks in tropical forests and to adapt forest inventory methods to agroforestry contexts [74]. Subsequent rises are associated with carbon accounting manuals, integrated mitigation assessments and studies that position agroforestry as an ecosystem-based measure [28]. This historical trajectory has consolidated a methodological backbone that prioritises soil sampling, biomass estimation and carbon balance models, and it shapes the current design of studies in tropical agroforestry by focusing attention on carbon stocks and fluxes over other indicators [61,75].

Taken together, the evidence synthesised in **Figures 1** to **13** shows a mature and expanding research domain, with sustained growth, a concentrated journal core, recurrent institutional and national participation, and a thematic structure centred on agroforestry, soil carbon, ecosystem services and land use [53,64]. These patterns offer a useful contextual basis for discussions on restoration planning and low-carbon rural development, but they should not be interpreted as direct evidence of policy convergence, cooperation performance, or implementation outcomes [1,60]. Within the empirical scope of this bibliometric study, the main contribution lies in identifying where the literature is concentrated and which themes have gained prominence [21,52,73]. The same evidence also reveals clear gaps, including limited integration of socio-economic outcomes, gender, indigenous peoples, rural wellbeing, and cost distribution [67,76].

The study has four limitations that frame the interpretation of the results. First, Scopus was used as the only source of bibliographic metadata, which may underrepresent regional journals and records indexed only in Web of Science, SciELO, CAB Abstracts or local databases. Second, the analysis depends on the quality of the metadata provided by the database, including affiliations, keywords, references and citation counts. Third, records in languages or journals with lower international visibility may be less represented, which introduces database and language bias. Fourth, early access records assigned to 2026 were retained to preserve topical currency, but they were treated as a partial series and were not interpreted as a complete publication year.

CONCLUSIONS

The bibliometric analysis shows that research on carbon sequestration in tropical agroforestry systems has consolidated as an expanding field, with 788 documents, marked growth since 2018, a specialised journal core and broad international co-authorship. The results reveal a concentrated productivity structure consistent with Lotka's and Bradford's laws, recurrent institutional and national participation patterns, and a set of historical reference peaks

identified through RPYS that underpin current work on biomass and soil carbon estimation. Keyword dynamics and the thematic map indicate a shift from carbon-centred metrics towards approaches that integrate soil health, ecosystem services and resilience. These findings are relevant to debates on restoration and low-carbon rural development as a contextual implication of the observed thematic structure, not as direct evidence of policy convergence or implementation outcomes. Significant gaps remain regarding socio-economic dimensions, gender, indigenous peoples and rural wellbeing. The findings must be read within the limits of a Scopus-based bibliometric review, because coverage, metadata quality, language visibility and early access records may affect the observed distribution of authors, institutions, countries, sources and themes.

ETHICAL CONSIDERATIONS

This study is a bibliometric analysis of publicly available bibliographic metadata and did not involve human participants, animals, biological samples, direct contact with individuals or collection of new primary data. Therefore, ethical approval and informed consent were not required.

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CONFLICT OF INTEREST

The authors declare no conflict of interest

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