GEOMATICS AND ENVIRONMENTAL ENGINEERING • Volume 20 • Number 4 • 2026

https://doi.org/10.7494/geom.2026.20.4.91

Twenty Years of Soil Organic Carbon Research in Ecuador: A Bibliometric and GIS-Based Assessment of Trends and Research Gaps

Lizardo Reyna-Bowen[1,2], Anna Klamerus-Iwan[2], María Isabel Delgado-Moreira[2]*

[1] Escuela Superior Politécnica Agropecuaria de Manabí Manuel Félix López, Campus Politécnico El Limón, Manabí, Ecuador
[2] University of Agriculture in Krakow, Faculty of Forestry, Krakow, Poland
* Corresponding author

Abstract: The study assesses the evolution of soil organic carbon (SOC) research in Ecuador between 2003 and 2023 using a bibliometric approach. The search was conducted in the Scopus, Web of Science, and SciELO databases, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. This protocol enabled the systematic identification and evaluation of the literature, resulting in a final selection of 60 peer-reviewed documents focused on SOC in Ecuador. These documents were analysed using RStudio (Bibliometrix), VOSviewer, and QGIS to map research output, collaboration networks, and thematic evolution. The main findings highlight that research on SOC in Ecuador has increased since 2003, largely due to international collaboration, primarily with institutions in Germany, Spain, and the United States. Early studies primarily focused on land-use change (deforestation and agriculture), whereas recent research emphasises remote-sensing applications, carbon stabilisation mechanisms, and nature-based solutions. Most research focuses on high-altitude provinces and protected areas, such as Loja and Chimborazo. The results also indicate that in volcanic ash soils (Andosols), altitude and land-use intensity are the main drivers of variation in SOC stocks. Key gaps include a lack of studies in the Amazon basin and coastal lowlands, as well as the absence of long-term SOC monitoring, both of which limit the development of national SOC inventories. While research output has increased steadily over time, addressing the identified gaps is necessary to establish a comprehensive scientific basis for climate change adaptation and sustainable soil management across the country's diverse ecosystems.

Keywords: SOC research trends, land-use change, climate change, sustainable soil management, bibliometric analysis

Received: December 8, 2025; accepted: April 14, 2026

© 2026 Author(s). This is an open-access publication that can be used, distributed, and reproduced in any medium according to the Creative Commons Attribution 4.0 International License (CC BY 4.0).

E-mails & ORCID iDs: jlreyna@espam.edu.ec, https://orcid.org/0000-0003-0352-4005 (L.R.-B.); anna.klamerus-iwan@urk.edu.pl, https://orcid.org/0000-0003-1303-6726 (A.K.-I.); isazamar92@gmail.com, https://orcid.org/0000-0002-3368-7481 (M.I.D.-M.).

1. Introduction

Global food security, ecosystem function, and climate change mitigation are highly interlinked to soil organic carbon (SOC) [1, 2]. This property of soil boosts its fertility, thereby improving aggregation, water retention, and nutrient cycling [3]. Furthermore, SOC stabilisation is regulated by protection within aggregates and by interactions with mineral surfaces, which constitute complex physicochemical processes [4] and contribute to nature-based climate solutions [5]. Although it has been determined that environmental drivers such as climate, vegetation, and land use control SOC dynamics [6, 7], issues such as the spatial and temporal variability of SOC still pose a challenge, and data on SOC stocks at national and regional levels are often inconsistent and uneven [8, 9].

As for SOC stocks in Latin America and the Caribbean, regional estimates are often based on direct field measurements and local soil maps, providing more accurate data that reflect the current impact of land-use changes and specific degradation processes [8, 9]. Ecuador's extensive biodiversity and the presence of sensitive ecosystems in its distinct regions (Coast, Highlands, Amazon, and Galápagos) reflect extreme edaphic diversity, ranging from Andosols [10] (soils derived from volcanic ash) to highly weathered soils such as Ferralsols and Acrisols in the Amazon [10]. The combination of all these soil types and threats, such as deforestation and land-use change, reinforces the premise that research on SOC in Ecuador is critical for the conservation of its edaphic resources. Research on SOC in developing countries such as Ecuador has garnered interest; however, there are no studies analysing the evolution of scientific production on this topic.

Under this approach, modern bibliometric analyses use tools such as VOSviewer and R-based workflows [11], enabling the identification of temporal trends, collaboration networks, and thematic clusters, thereby providing an objective, evidence-based view of any topic under analysis. When integrated with a Geographic Information System (GIS), these tools also enable the spatial assessment of research distribution and knowledge gaps. Therefore, this study assesses the evolution of SOC research in Ecuador between 2003 and 2023 using a bibliometric approach, presenting a roadmap to support decision-making in land management and strengthen Ecuador's contributions to climate change mitigation policies and global climate resilience.

2. Methodology

The methodology applied is based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, which provides a systematic structure for identifying and evaluating scientific literature [12, 13]. Under this approach, in addition to a quantitative evaluation, a structural and thematic analysis of the field of research on SOC in Ecuador was developed, thereby identifying gaps in this area. Figure 1 presents the details of the analysis performed.

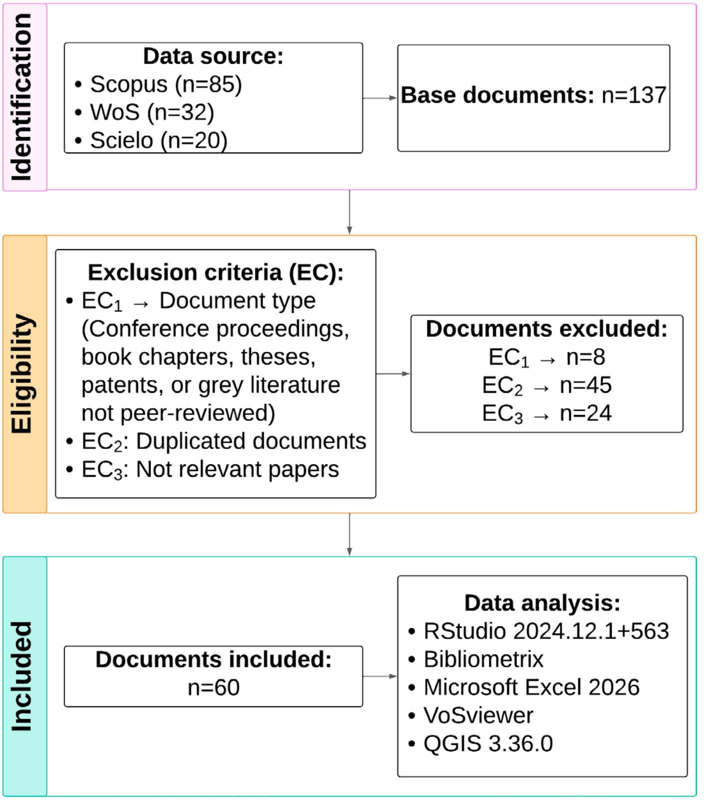

Fig. 1. PRISMA flow diagram of the document selection process

2.1. Data Search Strategy

The bibliometric search was conducted during the first week of September 2025 in the following databases: Scopus[1], Web of Science (WoS)[2], and SciELO[3], to include both international and regional scientific outputs. The search equation applied to the title, abstract, and keywords fields (TITLE-ABS-KEY) was: ('soil organic carbon' OR 'SOC' OR 'soil carbon stocks') AND Ecuador. A total of 137 documents were identified (85 from Scopus, 32 from WoS, and 20 from SciELO).

The screening and selection of articles were carried out by two researchers, who reviewed titles, abstracts, and full texts. Database management included the manual identification and removal of duplicate records after the downloaded records had been consolidated. The literature search was completed on 19 August 2025, the date that marks the final cutoff for inclusion in this analysis.

1 Elsevier. Scopus database. https://www.scopus.com.
2 Clarivate™ (Web of Science™). © 2025 Clarivate.
3 SciELO – Scientific Electronic Library Online. www.scielo.org.

2.2. Dataset Eligibility Criteria

After identifying the documents, the exclusion process was conducted according to the criteria defined in Table 1. Following this step, 60 documents met the inclusion criteria and formed the final dataset for analysis.

Table 1. Exclusion criteria applied to the documents identified for analysis

Criteria	Description
Exclusion (EC_1)	Document type: conference proceedings, book chapters, theses, patents, or non-peer-reviewed grey literature
Exclusion (EC_2)	Duplicated records
Exclusion (EC_3)	Relevance: documents that do not directly address SOC or SOC stock variables in Ecuador published before 2003

Note: 77 documents were excluded for not meeting these pre-established criteria. Of this group, 45 were duplicates (EC2), and the remaining 32 were excluded due to lack of thematic relevance (EC3) or insufficient methodological quality / transparency (EC4).

To ensure the reliability of the synthesis and assess the strength of the evidence, the final selection underwent a quality assessment. Only studies that provided transparent reports on soil sampling designs, standardised laboratory protocols for SOC analysis, or clear spatial validation for GIS models were retained. The complete list of the 60 validated articles and their specific evidence characteristics is detailed in "Appendix" (Table A1). The 'Study type' field in Table A1 was classified according to the standardised categories of [14] or based on the explicit methodology declared by the authors. Meanwhile, the 'evidential strength and focus' field was completed by synthesising the most relevant findings and constraints presented in the text of each document.

The final dataset of 60 peer-reviewed papers reflects the active body of internationally visible science in Ecuador. However, it is important to recognise that in developing countries like Ecuador, a significant volume of local scientific production remains as unpublished grey literature, particularly in the form of undergraduate and graduate theses (bachelor's and master's dissertations). While these documents contain valuable localised data, they were excluded from this dataset to maintain comparability, traceability, and international peer-reviewed standards. Consequently, the 60 selected papers represent the most rigorous and globally accessible tier of SOC research in the country.

2.3. Data Analysis Tools

A set of specialised software was used to obtain a multidimensional interpretation of the data: RStudio version 4.4.3 [15] with the Bibliometrix package [16] for generating descriptive statistics (counting publications, authors, affiliations and main journals) and visualising temporal productivity. VOSviewer 1.7.18 [17] was used to analyse co-occurrence and collaboration networks using a full-counting method, with a minimum threshold of 10 keyword occurrences established to ensure statistical robustness while minimising noise from low-frequency terms. This software was also used to perform an international collaboration analysis, examining country-level co-authorship and restricting the dataset to countries with at least two publications.

The thematic evolution and conceptual structure were analysed using a strategic diagram (thematic map) based on keyword [18] analysis. This mapping is defined by two dimensions: centrality and density. Centrality (X-axis) measures the extent to which a network interacts with other networks, representing the relevance of a topic in the overall development of SOC research in Ecuador. Density (Y-axis) measures the network's internal strength, reflecting its level of development or technical maturity.

The geographical locations of the primary studies across the 60 documents were extracted manually and processed with QGIS 3.36.0 [18] to generate a spatial visualisation of the research, highlighting the provinces or regions with the highest concentration of studies and thus revealing geographical research gaps. In this way, SOC research trends in Ecuador were established, identifying both established topics and emerging research frontiers.

3. Results and Discussion

While our final dataset of 60 papers represents the complete population of peer-reviewed SOC research in Ecuador identified through our systematic search, we acknowledge that this sample size is at the lower bound for robust quantitative bibliometric indicators (REFs). Consequently, our analysis emphasises the qualitative synthesis of thematic evolution and the identification of research gaps, which are appropriate goals for a dataset of this scope and provide a comprehensive overview of the field's development.

3.1. Evolution and Scientific Productivity

When analysing scientific production on SOC in Ecuador, considerable growth has been observed since 2003, as detailed in Figure 2. The coefficient of determination (R^2 = 0.44) indicates a moderately upward trend. The evolution of approaches (Fig. 3) shows a transition from land-use change studies (2003–2010) to in-depth analyses of Andean moorlands and forests (2011–2017), and finally to the adoption of sophisticated methodologies, including remote sensing and nature-based solutions (2018–2025). This chronological sequence demonstrates that Ecuadorian research has progressed from descriptive inventory studies to a more complex and holistic view of SOC.

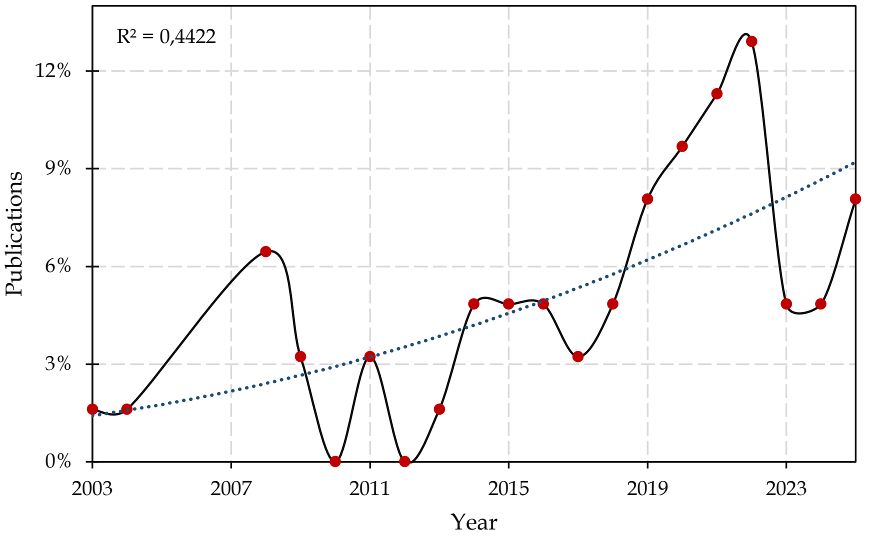

Fig. 2. Annual evolution of scientific production on SOC in Ecuador (2003–2025)

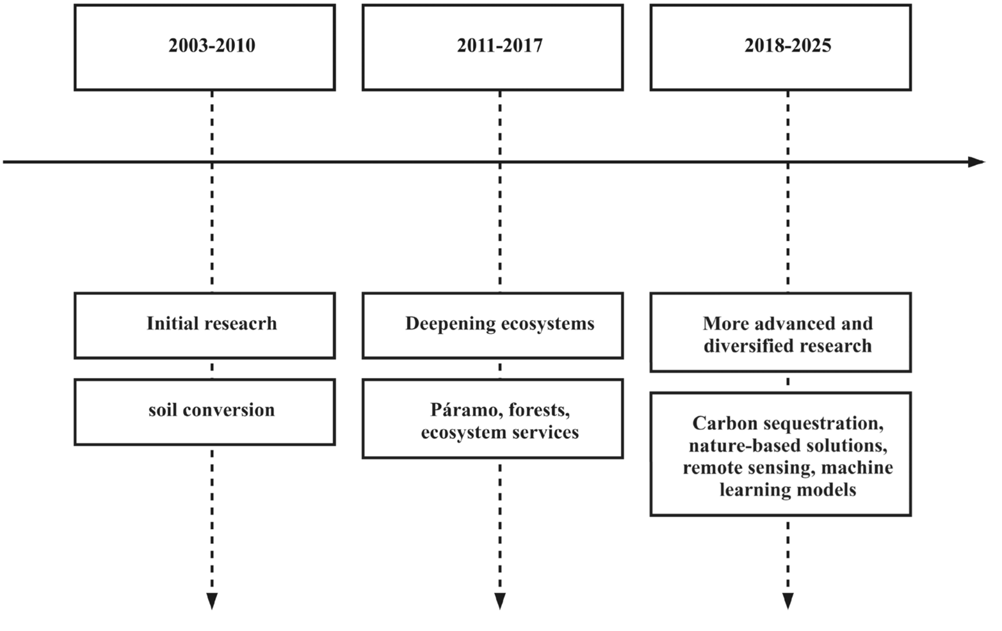

Fig. 3. Timeline of SOC research in Ecuador

Ecuadorian SOC research follows trends similar to those observed globally. The number of meta-analyses of SOC has steadily risen since 2001, with a marked increase from 2017 onwards. Most of this research focuses on how land management and land-use changes affect SOC in croplands; studies focusing on forests, grasslands, and, particularly, wetlands remain limited [19]. In Europe, similar bibliometric trajectories indicate a strengthening of soil monitoring networks and open-access databases for SOC-related policies and climate action [20].

3.2. Collaborative Networks and Institutional Structure

Based on the analysis conducted using Blibliometrix it was determined that there is strong international collaboration between Ecuador and 26 countries (Fig. 4). Among the most notable are Germany, with 33 publications (607 citations), indicating substantial intellectual influence; Spain, with 31 publications; and the United States, with 25 publications, among others.

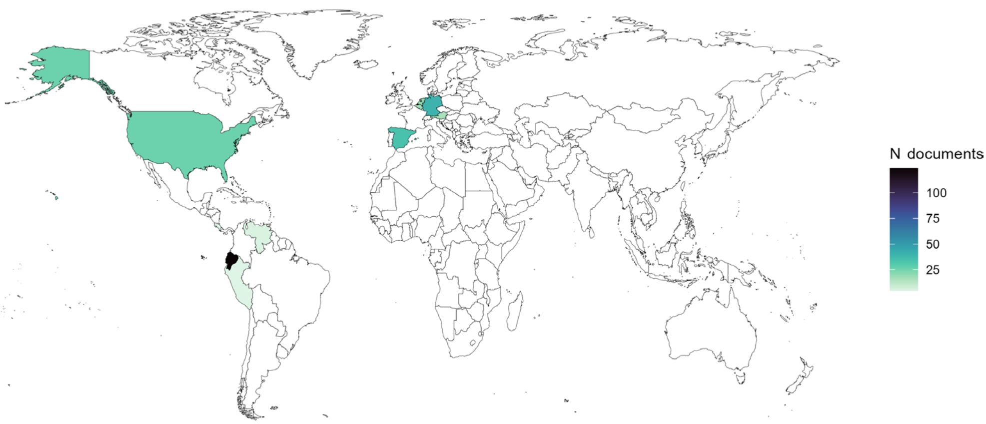

Fig. 4. Countries' scientific production in SOC research in Ecuador
Source: own elaboration based on Scopus data

In the context of global SOC research, SOC is considered a fundamental component of functional ecosystems worldwide, due to its role in ensuring food, soil, water, and energy security [1]. Despite a growing body of studies, the geographical coverage of SOC research remains uneven. While countries such as the United States and China dominate the total volume of SOC studies, many regions, including Oceania and numerous African countries, are significantly underrepresented [19].

With regard to institutional analysis, as shown in Figure 5, the Universidad Técnica Particular de Loja is the leading producer of scientific knowledge on SOC at the national level and is linked to key international partners, including BOKU University and the University of Göttingen. Knowledge from this network is disseminated in high-impact journals such as *Geoderma, Biogeochemistry*, and *Global Change Biology*.

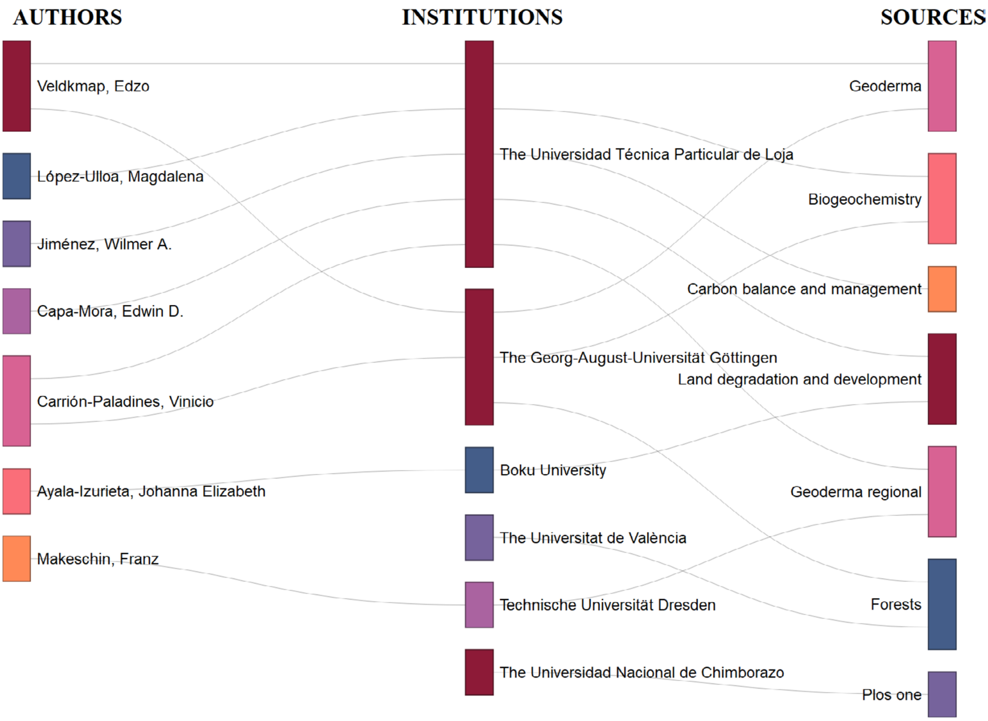

Fig. 5. Sankey diagram of author–institution–source linkages in SOC research in Ecuador

As institutions generate knowledge, their role in maintaining soil health and agricultural productivity is crucial. Similarly, SOC research depends on institutional research capacity. To cite a historical example, the Dust Bowl of the 1930s demonstrates how inappropriate agricultural practices, which are often linked to institutional deficiencies, can lead to severe environmental degradation [1]. In this regard, the role of institutions in ensuring long-term soil productivity and health is noteworthy, emphasising sustained academic collaboration as a determining factor in the national research agenda on SOC.

3.3. Thematic Mapping and Keyword Evolution

The thematic network analysis core cluster consists of 22 keywords, with 'Ecuador,' 'organic carbon,' and 'carbon sequestration' as the most prominent terms. The temporal gradient reflects an increase in these core topics between 2015 and 2019, while terms such as 'ecosystem' and 'biodiversity' have gained importance more recently, signalling a broadening of the research scope beyond carbon measurement itself (Fig. 6a).

Using a similar approach, the dendrogram shown in Figure 6b groups these keywords into four clusters, including: land-use change, specifically the conversion of native forests and páramo ecosystems into new pasture land for cattle ranching (blue); soil carbon dynamics with a geographical emphasis on the Andes and Ecuador (green); carbon cycles in relation to land use and climate change (purple); and finally, a broader group connecting various terms associated with SOC and the broader context of carbon (orange).

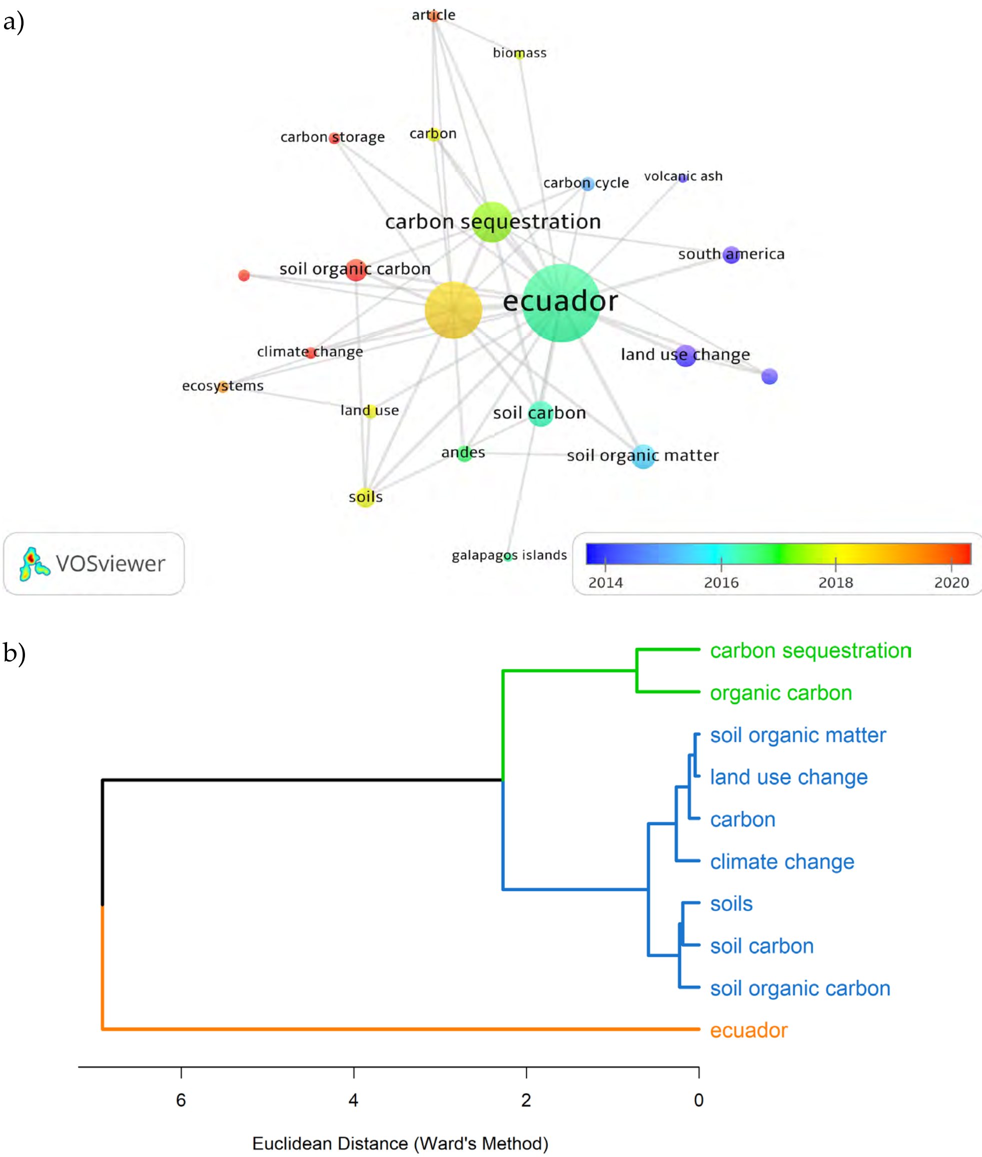

Fig. 6. Trends in SOC research in Ecuador (2003–2025):
a) thematic map of key words; b) hierarchical cluster analysis

When analysing the degree of development versus the degree of relevance, a thematic evolution emerges with the following patterns: the cluster including 'soil organic matter,' 'land use change,' and 'pasture' represents a mature and impactful research area. Similarly, the grouping of 'Ecuador,' 'organic carbon,' and 'carbon sequestration' indicates that this topic is central and well established in the national context. In contrast, niches such as 'topsoil,' 'tropical forest,' and 'carbon emission' are well-developed but have lower overall relevance. Emerging or declining themes with low relevance and limited development include: 'soil profile' and the cluster of 'Pacific Ocean,' 'GIS,' and 'rural areas.' Finally, basic themes with high relevance but still underdeveloped include clusters like 'andosol,' 'andosols,' and 'degradation,' as well as 'South America,' 'volcanic ash,' 'analysis,' 'Galapagos Islands,' 'soil property,' and 'tephra' (Fig. 7).

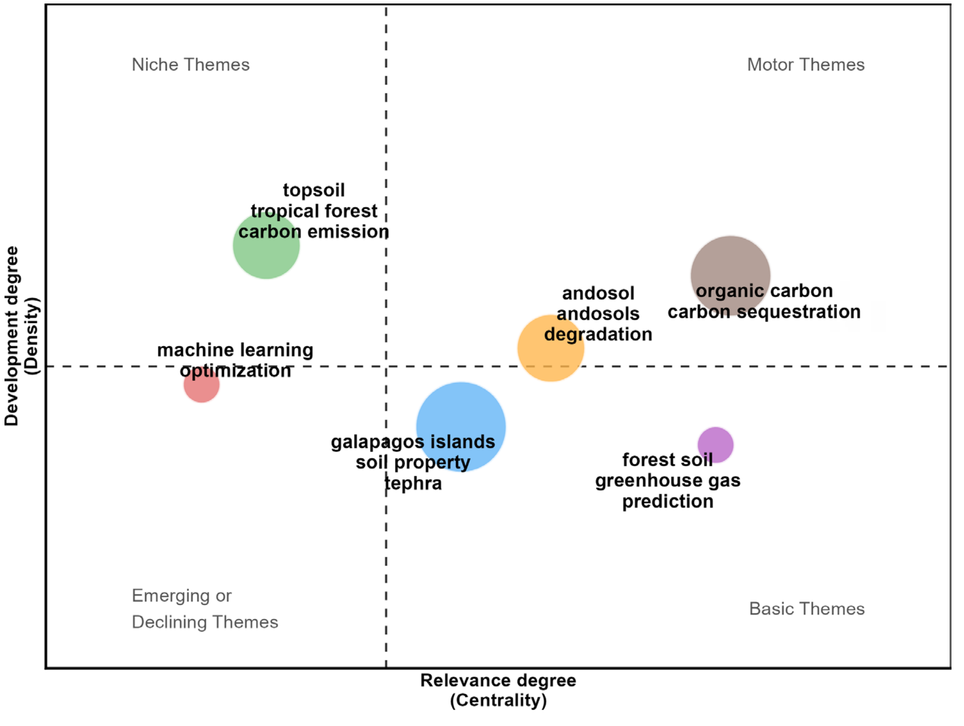

Fig. 7. Tracking thematic changes in SOC research in Ecuador

3.4. Drivers and Major Contributions of SOC Research in Ecuador

As reflected in the thematic mapping (Fig. 7), the dynamics of SOC research in Ecuador are predominantly driven by land use, soil type, and altitude, and research indicates that changes in land use are the main factors affecting SOC stocks. A notable result is that reforestation of grasslands can significantly increase soil organic carbon (SOC) stocks. For example, a cumulative SOC gain of 18.8 $Mg{\cdot}C{\cdot}ha^{-1}$ was observed over a period of 20 to 30 years following the conversion of grasslands to forests [21]. Grassland sites that exclude burning also show high soil carbon storage (172.8–201.9 $Mg{\cdot}C{\cdot}ha^{-1}$) [22]. However, other studies found no link between grassland age or stem density and SOC pools [23]. Furthermore, the conversion of Andean montane forests to exotic plantations can reduce SOC, causing losses ranging from 1.9% to 37.8% [24]. This reduction in SOC levels subsequently impairs the soil's physical structure, leading to decreased water retention capacity in the upper soil layers [25].

Sustainable agroforestry systems can store up to 42% more carbon than cocoa monocultures [26], with differences in SOC related to cocoa species [27], while unsustainable annual cultivation reduces SOC to approximately 85% of original forest levels [28]. The crop type, such as pitahaya (*Selenicereus* sp.), also affects soil carbon concentration and sequestration [29, 30]. 'Analogue' forest systems and teak plantations store more total carbon (178 and 141 $Mg{\cdot}C{\cdot}ha^{-1}$, respectively) than degraded pastures (124 $Mg{\cdot}C{\cdot}ha^{-1}$) [31].

Likewise, soil type and geology strongly influence SOC content [32, 33]. It has been confirmed that volcanic ash soils (Andosols) contain more carbon than sedimentary soils [34] and are also essential in the global carbon cycle [35]. In terms of edaphic processes, enzymatic activity, physicochemical properties, and total iron content also affect SOC availability, with greater dependence on soil characteristics and depth than on altitude or vegetation cover [36].

It has also been found that SOC increases with elevation in the Andes due to higher precipitation and lower temperatures [37–39]. As a result, páramo ecosystems are the largest carbon reservoirs in the Andean region (120 $Mg{\cdot}C{\cdot}ha^{-1}$) [40], with stocks two to three times greater than those of grasslands and crops at similar altitudes [41–45]. Natural and restored mangroves also have significant stocks [46], with tall mangroves storing 419.4 $Mg{\cdot}C{\cdot}ha^{-1}$ [47]. Lower landscape positions with clay soils retain more SOC compared to sandy or loamy soils in upper positions [48].

Furthermore, methodological advances have diversified the study of soil carbon. Specifically, recent research has implemented biomolecular markers to track SOC degradation [49], validated the reliability of the FAO volumetric method for large-scale estimation [50], and incorporated satellite-derived variables to improve SOC prediction [41]. These local efforts align with global mapping initiatives, such as the Global Soil Organic Carbon Map (GSOCmap) [51] and the SoilGrids system by ISRIC [52], which provide high-resolution spatial frameworks for contrasting and validating regional findings in Ecuador's Andean and coastal ecosystems.

3.5. Geographical Distribution and Critical Research Gaps

There is a disparity in the distribution of research on SOC in Ecuador, with concentrations in Loja (n = 10; 16%) and Chimborazo (n = 9; 15%), as well as in specific protected areas located in high-altitude and island regions. These include the

Galápagos Islands (Galápagos, n = 8; 13%), Podocarpus National Park (Loja and Zamora Chinchipe, n = 5; 8%), El Ángel Ecological Reserve (Carchi, n = 3; 5%), and Sangay National Park (Morona Santiago, Chimborazo, and Tungurahua, n = 2; 3%). Meanwhile, no SOC research was found in six provinces (Fig. 8).

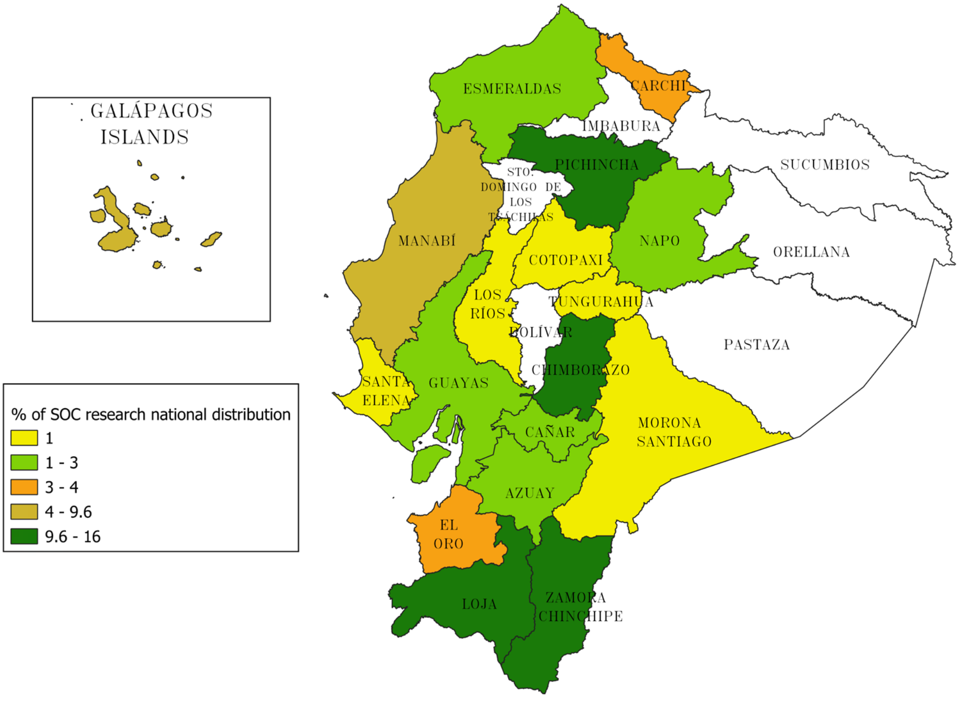

Fig. 8. Spatial analysis of scientific production on SOC research in Ecuador

The absence of records on the SOC in six provinces of Ecuador reflects a gap in information within the high-impact databases consulted (Scopus, Web of Science, and SciELO). While this result may be associated with limited research resources in a developing country, it is acknowledged that this absence is confined to indexed literature and does not rule out the possible existence of data in local repositories or grey literature not captured by the inclusion criteria of this study.

This heterogeneous distribution and gaps in low-altitude regions, such as the Amazon and coastal lowlands, limit the country's ability to develop a complete national inventory and design regionally adapted climate mitigation strategies. In addition to analysing the relationships between soil organic matter storage and soil quality characteristics, it is important to measure and monitor management-driven changes in soil carbon storage at the farm, landscape, or watershed scale [53]. Moreover, recognising the spatial distribution of SOC not only reflects ecosystem health but also plays an essential role in maintaining key soil functions, such as soil fertility and carbon sequestration [54].

A key gap is the absence of longitudinal studies evaluating the stabilisation of SOC stocks [55]. Although research has revealed variability in SOC among ecosystems, more detailed information is needed. Studies on tephra stratification [56, 57] and geology [32] are indispensable for understanding long-term carbon storage. Similarly, further research is needed on the role of biological soil crusts in regulating SOC [58] and on how volcanic eruptions act as carbon sinks [59, 60].

Although most reports provide information on total carbon [61], organic carbon, and inorganic carbon, characterising the labile and stable fractions would provide a deeper understanding of carbon turnover [62]. However, this data is rarely reported in the Ecuadorian context due to high analytical costs and technical complexity [41]. Regarding digital soil mapping, recent studies in Ecuador have begun using remote sensing models to estimate SOC [41, 44]. Nevertheless, validation is necessary for each soil type in Ecuador.

In socio-economic terms, the disconnect between farmers' traditional knowledge and formal scientific knowledge about soil management practices has recently begun to be addressed [63, 64]. In addition, it is essential to conduct cost-benefit analyses and economic feasibility studies of SOC improvement practices [65]. Addressing these gaps through coordinated and interdisciplinary monitoring efforts will enable Ecuadorian SOC research to align with global frameworks for soil health and climate resilience.

4. Conclusions

Ecuadorian research on SOC has evolved continuously from basic studies of land-use change to perspectives integrating remote sensing and nature-based solutions. This insight is based on strong international collaboration networks and the consolidation of leading national institutions, which are responsible for disseminating knowledge in high-impact journals.

There is a geographic disparity in SOC, with the Andean provinces and protected areas accounting for the highest percentage. Meanwhile, in six provinces of the coastal lowlands and the Amazon, there is not a single study. Beyond this scientific limitation, this poses environmental and financial risks to climate policy. For example, without baseline data on soil organic carbon in the Amazon, national carbon credit programmes and REDD+ initiatives are forced to operate with scant scientific evidence. This uncertainty threatens the verification of actual emission reductions and complicates the fair valuation of carbon stocks in international markets.

In future research, it is important to consider both the temporality and the chemical and pedological distribution of SOC to verify the stability of carbon gains in restored systems. A shift in focus from total carbon to SOC fractions is also needed to understand the mechanisms of organo-mineral stabilisation.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CRediT Author Contribution

L.R.-B.: conceptualization, investigation, methodology, validation, visualization, writing – review & editing.

A.K.-I.: supervision.

M.I.D.-M.: data curation, formal analysis, software, visualization, writing – original draft, writing – review & editing.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The raw data and source materials used to generate the results are accessible via the DOIs or external links provided in the References section of the paper.

Use of Generative AI and AI-Assisted Technologies

The Google Gemini large language model (LLM) was utilized. Specifically, the model was employed to improve the clarity, grammar, and idiomatic flow of the manuscript's English translation from its original source language.

Appendix

Table A1. Final dataset of peer-reviewed articles (n = 60) on SOC in Ecuador, detailing their study type and evidence characteristics

No.	Reference	Title	Study type	Evidential strength / focus
1	[59]	Explosive volcanic eruptions can act as carbon sinks	Regional modelling (Atacazo-ninahuilca)	First estimate of tephra-buried SOC. Approx. 1.1 Pg of organic C has accumulated in this soils from Holocene eruptions (predictive modelling framework)
2	[61]	Farmers' indigenous knowledge of soil management in an altitudinal gradient in southern Ecuador	Socio-ecological and field survey	Validates 368 farmer perceptions against empirical field measurements of SOC, texture, and climate variables
3	[42]	Driving variables to explain soil organic carbon dynamics: Páramo highlands of the Ecuadorian Real mountain range	GIS / Spatial Modelling (CART)	Robust spatial prediction validated with localised field datasets (0–30 cm horizon) and machine learning

Table A1. cont.

4	[50]	Advancing carbon quantification: A comparative evaluation of gravimetric and volumetric methods for soil carbon assessment in tropical ecosystems	Empirical field and methodological evaluation / observational (tropical dry forests)	Standardised evaluation of SOC / SIC quantification methods (gravimetric vs. volumetric). High methodological transparency (declared small sample size and shallow soil layers)
5	[66]	Assessment of soil erosion by RUSLE in the Ecuadorian basins (2001–2020) based on GIS and high-resolution satellite data: Main drivers and changes on soil erosion	GIS / spatial modelling (regional basin scale)	Standardised use of high-resolution global web servers (SoilGrids, MODIS, SRTM) to map SOC as a driver of soil erodibility across multi-decadal timeframes (2001–2020) at a national basin scale
6	[27]	Assessment of soil organic carbon: The influence of Ecuadorian cocoa varieties	Experimental field study (agricultural / plot scale)	High-quality empirical data with standardised stratified sampling
7	[67]	Evaluation of nature-based climate solutions for agricultural landscapes in the Galápagos Islands	Observational field research and monitoring (long-term plots with high-tech sensors)	High-quality empirical data with 30 months of continuous high-resolution microclimatic and pedological monitoring (replicated designs)
8	[68]	Bioindicators for assessing soil quality in Ecuador's Jun Jun micro-watershed	Observational field research (altitudinal gradients and soil quality indexing)	Quantitative assessment of soil quality using physical, chemical, and biological indicators (OC, OM, TN, pH, earthworms) across 24 sampling points and multiple altitudes
9	[69]	Ecosystem function associated with soil organic carbon declines with tropical dry forest degradation	Observational field research	Standardised laboratory protocols for total carbon, enzymatic activity, and carbon fractions (POC / MAOC). Uses a space-for-time substitution gradient with seasonal validation (dry vs. rainy)
10	[70]	Exploring ethnopedology in the Ecuadorian Andean highlands: A local farmer perspective of soil indicators and management	Mixed-methods study: ethnopedology / social survey and geospatial analysis (scale 1:25,000)	Integration of local farmer knowledge (N = 555 surveys) with national physicochemical soil datasets (SOC, pH, texture) for the Andean Highlands

Table A1. cont.

No.	Reference	Title	Study type	Evidential strength / focus
11	[58]	Biological crust diversity related to elevation and soil properties at local scale in a montane scrub of Ecuador	Observational field research (ecology / soil-plant interactions)	High replication ($N = 180$ subplots) and standardised composite soil sampling (0–10 cm) evaluating physicochemical drivers of SOC and biota across an altitudinal gradient
12	[71]	Improving the remote estimation of soil organic carbon in complex ecosystems with Sentinel-2 and GIS using Gaussian processes regression	GIS / remote sensing modelling	High-quality spatial prediction validated with a large field dataset ($N \approx 500$ points per horizon) and Sentinel-2 satellite data, achieving high accuracy ($R^2 \approx 0.85$) for two soil depths (0–30 cm and 30–60 cm) in complex Páramo ecosystems
13	[72]	Vegetation effects on soil pore structure and hydraulic properties in volcanic ash soils of the high Andes	Observational field research and laboratory study (High Andean Páramo)	High-quality empirical data analysing the relationship between vegetation types, topography, and SOC content across eight detailed soil profiles
14	[73]	Urban soil management in the strategies for adaptation to climate change of cities in the Tropical Andes	Digital soil mapping and spatial modelling	Spatial modelling validated with city-wide field sampling ($N = 300$) with explicit use of standardised laboratory protocols for bulk density (BD) and organic carbon (OC), combined with rigorous machine learning (Random Forest) and multiple regression comparisons
15	[74]	Soil organic carbon and fine particle stocks along a volcanic chrono- and elevation-sequence on the Galápagos archipelago/Ecuador	Observational field research (chronosequence / altitudinal sequence)	High-quality dataset evaluating the entire soil profile, establishing a direct relationship between soil age, climate gradients, and deep subsoil (>20 cm) SOC stocks using standardised physical fractionation
16	[75]	Mangrove sediment organic carbon storage and sources in relation to forest age and position along a deltaic salinity gradient	Observational field research	Depth profiles (0.64 m) including elemental analysis (OC%, C:N ratios), and stable carbon isotopes ($\delta^{13}C$) in sediment and vegetation. Quantifies SOC stocks in young (46–55 $Mg \cdot C \cdot ha^{-1}$) versus old mangroves (78–92 $Mg \cdot C \cdot ha^{-1}$), demonstrating that young sites are dominated by imported (allochthonous) carbon

Table A1. cont.

17	[64]	Rediscovering the edaphic knowledge of smallholder farmers in southern Ecuador	Mixed-methods study (social surveys and GIS mapping)	Validates local farmers' perceptions of soil fertility against scientific SOC stock and texture maps, using large-scale survey data ($N = 610$)
18	[24]	Conversion of Andean montane forest to exotic forest plantation modifies soil physicochemical properties in the buffer zone of Ecuador's Podocarpus National Park	Observational field research / comparative	Empirical field data analysing the impact of land-use change (Andean forest to exotic plantations) on SOC and physical soil properties
19	[41]	Multi-predictor mapping of soil organic carbon in the alpine tundra: a case study for the central Ecuadorian páramo	GIS / machine learning (random forest modelling)	High-quality regional spatial prediction, validated using a large *in situ* dataset ($N = 500$ samples) combining remote sensing (Landsat-8), topographic, climatic, and geological predictors with high accuracy ($R^2 = 0.82$)
20	[45]	Impacts of pine plantations on carbon stocks of páramo sites in southern Ecuador	Observational field research (elevational gradient and allometry)	High-quality empirical data using standardised local allometric equations and site-specific comparisons across a wide elevational gradient (2780–3760 m a.s.l.)
21	[44]	Identification of a set of variables for the classification of páramo soils using a nonparametric model, remote sensing, and organic carbon	Spatial modelling and machine learning (GIS)	Validation of non-parametric predictive models (CDT, MARS) for land-use and SOC monitoring at a sub-basin scale
22	[47]	Impact of shrimp ponds on mangrove blue carbon stocks in Ecuador	Observational field research and carbon stock assessment	High-quality ecological stratification (medium vs. tall mangroves) with standardised deep-soil sampling (1 m) across land-use gradients (mangroves vs. shrimp farms)
23	[31]	The carbon sequestration potential of 'analog' forestry in Ecuador: An alternative strategy for reforestation of degraded pastures	Experimental field study / comparative	Long-term (17-year) assessment of surface and subsurface carbon sinks using biomass and soil data

Table A1. cont.

No.	Reference	Title	Study type	Evidential strength / focus
24	[77]	Inter-community and on-farm asymmetric organic matter allocation patterns drive soil fertility gradients in a rural Andean landscape	Empirical field and social study (agroecology)	High-quality data integrating quantitative soil sampling (SOC, N, P, K) with farmer perceptions and spatial management (distance to the homestead)
25	[37]	Agroecosystem patterns and land management co-develop through environment, management, and land-use interactions	Observational field research (landscape scale)	High quality: explores elevation and slope gradients affecting SOC dynamics, coupled with farmer land-use management interactions
26	[38]	Trade-offs among aboveground, belowground, and soil organic carbon stocks along altitudinal gradients in Andean Tropical montane forests	Observational field research (ecological gradients)	High-quality regional field data. Standardised plot-based sampling (*N* = 60 plots of 0.1 ha) comparing altitudinal gradients in Ecuador (Podocarpus) and Peru. It explicitly links SOC with above / belowground biomass and climatic drivers
27	[40]	Digital mapping of organic carbon in Ecuador soils	Digital soil mapping / GIS spatial modelling	High-quality national-scale digital soil mapping using robust geostatistical models (regression-kriging) with large legacy datasets (*N* > 12,000) and external validation
28	[36]	Differences in the ratio of soil microbial biomass carbon (MBC) and soil organic carbon (SOC) at various altitudes of Hyperalic Alisol in the Amazon region of Ecuador	Observational field research / altitudinal gradient	Standardised empirical data measuring altitude-driven changes in SOC and microbial carbon
29	[43]	Carbon sequestration rates indicate ecosystem recovery following human disturbance in the equatorial Andes	Observational field research (ecosystem recovery and chronosequence)	Analyses changes over time (2012 vs. 2014) and calculates carbon sequestration rates associated with environmental variables (elevation, plant diversity, and disturbances). Quantifies SOC to a depth of 36 cm

Table A1. cont.

30	[78]	Mapping ecosystem services in a rural landscape dominated by cacao crop: A case study for Los Rios province, Ecuador	GIS-based spatial modelling (ECOSER protocol) / regional scale	Validated spatial mapping of SOC stocks across agricultural and forest land-use classes
31	[79]	Optimisation in machine learning: An application to topsoil organic stocks prediction in a dry forest ecosystem	GIS / spatial modelling (machine learning)	High-quality spatial modelling using 118 samples and robust machine learning validation (BRT models and *k*-fold cross-validation). It focuses on regional SOC prediction in hard-to-reach dry forest ecosystems
32	[56]	Weathering and soil formation in rhyolitic tephra along a moisture gradient on Alcedo Volcano, Galápagos	Observational field research (gradient / transect)	Standardised sampling along a climatic / elevation gradient (377–872 m a.s.l.) with clear pedological classification (Andosols / Regosols) and precise laboratory metrics (pH, water/phosphate retention, and SOC stocks)
33	[80]	Agriculture changes soil properties on the Galápagos Islands-two case studies	Observational field research (land-use change)	Paired-site comparison (forest vs. arable land) across two islands (Santa Cruz and San Cristóbal) and different soil types (Leptosol and Ferralsol). Includes synchronised analysis of SOC stocks (Mg·ha^{-1}), microbial biomass, and nutrient dynamics
34	[81]	Soil-organic-carbon concentration and storage under different land uses in the Carrizal-Chone Valley in Ecuador	Observational field research (stratified by land use)	High-quality empirical data with standardised lab protocols (Walkley–Black) and deep-profile sampling (*N* = 63, up to 150 cm)
35	[39]	Quantification of organic carbon stored in the soil in the paramo of Igualata, Chimborazo province-Ecuador	Observational field research (factorial random sampling)	High-quality empirical data with statistical validation (ANOVA) and standard laboratory protocols (Walkley–Black)
36	[82]	Soil organic carbon stocks in Santa Cruz Island, Galapagos, under different climate change scenarios	Legacy data and digital soil mapping (GIS)	Quantitative spatial modelling of SOC stocks using historic soil surveys (706 Gg SOC in the top 10 cm). High-quality regional assessment driven by clear bioclimatic variables (altitude / rainfall)

Table A1. cont.

No.	Reference	Title	Study type	Evidential strength / focus
37	[83]	Analytical methods comparison for soil organic carbon determination in Andean Forest of Sangay National Park-Ecuador	Methodological / lab-based calibration	High laboratory precision (DUMAS vs. LOI comparison) with robust local sampling ($N = 15$ plots, multiple depths, $R^2 = 0.99$)
38	[22]	Changes in carbon storage with land management promoted by payment for ecosystem services	Observational field research (comparative land-use)	Reporting of statistically significant carbon stocks for both aboveground biomass and soil (0–20 cm) over a 45-year period
39	[84]	Improving the spatial prediction of soil organic carbon stocks in a complex tropical mountain landscape by methodological specifications in machine learning approaches	GIS-based spatial modelling / machine learning	Spatial predictions using 5 machine learning algorithms validated via repeated 10-fold cross-validation. High methodological transparency in predictor selection and model tuning
40	[85]	An integer programming model to determine land use trajectories for optimizing regionally integrated ecosystem services delivery	Optimisation modelling (integer programming / GIS)	Uses linear programming (BIOLP) to simulate 30-year land-use trajectories and optimise trade-offs between economic income and ecosystem services (runoff, sediment, and SOC)
41	[23]	Carbon stocks in silvopastoral systems: A study from four communities in southeastern Ecuador	Observational field research / silvopastoral systems	Standardised sampling (20 cm topsoil) across a large regional sample (100 pastures) with quantitative correlation of biomass and SOC
42	[48]	Erosion and sedimentation effects on soil organic carbon redistribution in a complex landscape in Western Ecuador	Spatial and erosion modelling (GIS / model-based)	A landscape-scale study ($N = 36$ sites) that combines standardised field sampling with statistically validated linear predictive models ($P < 0.01$ and $P < 0.05$). It assesses the impact of topography and land-use change on carbon stocks
43	[28]	Modeling of soil nutrient balances, flows and stocks revealed effects of management on soil fertility in south Ecuadorian smallholder farming systems	Observational field research and modelling study	High-quality empirical data combined with standardised nutrient balance modelling (Nutmon). Standardised lab protocols for soil stocks and explicit land-use comparisons

Table A1. cont.

44	[86]	Soil nutrient stock dynamics and land-use management of annuals, perennials, and pastures after slash-and-burn in the Southern Ecuadorian Andes	Farming systems / modelling and observational field research	High-quality empirical and modelled data on SOC and nutrient stocks across different agricultural land-use systems
45	[46]	Organic carbon inventories in natural and restored Ecuadorian mangrove forests	Observational field research (comparative)	High-quality empirical field data (*N* = 72 soil cores) using standardised LOI protocols to compare natural and restored mangrove carbon stock
46	[87]	Nutrient stocks and phosphorus fractions in mountain soils of Southern Ecuador after conversion of forest to pasture	Observational field research (land-use gradient)	High-quality empirical data on SOC and nutrient stocks using standardised biogeochemical and microbial biomass protocols
47	[88]	Elevation effects on the carbon budget of tropical mountain forests (S Ecuador): The role of the belowground compartment	Observational field research (altitudinal transect)	High-quality empirical data along an elevation gradient (1,050–3,060 m a.s.l.), combining above / belowground biomass, NPP, and SOC stocks with standardised protocols
48	[35]	Selective extraction methods for aluminium, iron, and organic carbon from montane volcanic ash soils	Experimental laboratory analysis of SOM stabilisation mechanisms	High-quality geochemical assessment of carbon-mineral complexes using standardised sequential extraction protocols
49	[89]	Urea fertilisation affected soil organic matter dynamics and microbial community structure in pasture soils of Southern Ecuador	Laboratory Incubation (experimental)	High-quality experimental data using isotopic tracers (^{14}C) and PLFA biomarkers to track SOC priming effects
50	[49]	Methyl ketones in high altitude Ecuadorian Andosols confirm excellent conservation of plant-specific n-alkane patterns	Observational field research and lab study (biomarkers / paleopedology)	High-quality molecular evidence. Validates the preservation of SOC biomarkers (n-alkanes) along an altitudinal transect (3,500–3,860 m a.s.l.) and across soil depth, using robust proxy ratios (CPI and n-methyl ketones) to verify low degradation rates

Table A1. cont.

No.	Reference	Title	Study type	Evidential strength / focus
51	[34]	Differential response of mineral-associated organic matter in tropical soils formed in volcanic ashes and marine Tertiary sediment to treatment with HCl, NaOCl, and $Na_4P_2O_7$	Experimental laboratory and observational field research (fractionation and isotopes)	High-quality empirical evidence using ^{13}C isotopes and chemical fractionation (acid hydrolysis, NaOCl, $Na_4P_2O_7$) to test SOC stability across volcanic vs. smectite soils
52	[90]	Soil organic carbon in density fractions of tropical soils under forest – pasture – secondary forest land use changes	Observational field research and laboratory study (density fractionation and isotopes $\delta^{13}C$)	Evaluates the storage of SOC in physical fractions (<1.6 $g \cdot cm^{-3}$) and the stability of microaggregates. Applies standardised laboratory protocols and data dispersion measurements (reports means ±standard error, e.g. 7.6 ± 0.6 $Mg \cdot C \cdot ha^{-1}$)
53	[57]	Tephra stratification of volcanic ash soils in Northern Ecuador	Observational field research / stratigraphic soil profile	High-quality pedological data combining SOC high-resolution vertical profiling with radiocarbon dating (^{14}C) and mineral tracers
54	[91]	Stabilization of recent soil carbon in the humid tropics following land use changes: Evidence from aggregate fractionation and stable isotope analyses	Experimental and isotopic (fractionation ^{13}C)	High-quality data using isotopic tracing to measure SOC stability and mean residence time (MRT) across different soil mineralogies
55	[25]	Soil organic carbon and water retention after conversion of grasslands to pine plantations in the Ecuadorian Andes	Observational field research (chronosequence / land-use change)	High-quality empirical data analysing SOC stocks (kg/m^2) and soil physical properties across soil horizons (0–10 cm, A, AC, C), with standardised lab incubations and nutrient stoichiometry (C:N, C:P)
56	[21]	Quantification of carbon sequestration in soils following pasture to forest conversion in northwestern Ecuador	Observational field research / paired plots	High-quality regional field data ($N = 40$ sites) evaluating SOC stocks across two soil depths and mineralogies with high predictive power ($R^2 > 0.90$)
57	[33]	Reservas de carbono orgánico en suelos de la llanura fluvial Calceta-Tosagua, Manabí, Ecuador	Observational field research (soil profile assessment)	Regional baseline data of SOC stocks (0–30 cm) differentiated by soil reference groups (Mollisols, Inceptisols, etc.)

Table A1. cont.

58	[32]	Secuestro de carbono orgánico del suelo en pastizales de la provincia El Oro, Ecuador	Observational field research / empirical study (plot scale)	Clear sampling design (replicated plots, 3.0 ha), multi-depth standard protocols (0–0.30 m), and integration of physical, chemical, and biological soil indicators
59	[76]	Secuestro de carbono por el suelo y sus fracciones en agroecosistemas tropicales de la región costa ecuatoriana	Observational field research / land-use comparison	Standardised evaluation of total SOC and physical fractions (light and heavy) using the Walkley–Black method across tropical land-use gradients
60	[92]	Variaciones en algunas propiedades del suelo por el cambio de uso de la tierra, en las partes media y baja de la microcuenca Membrillo, Manabí, Ecuador	Observational field research / soil profile characterization	Empirical evidence of SOC losses and physical soil degradation (bulk density, horizon thickness) caused by land-use change in Feozems, Cambisols, and Fluvisols

References

[1] Stockmann U., Padarian J., McBratney A., Minasny B., de Brogniez D., Montanarella L., Hong S.Y., Rawlins B.G., Field D.J.: *Global soil organic carbon assessment*. Global Food Security, vol. 6, 2015, pp. 9–16. https://doi.org/10.1016/j.gfs.2015.07.001.

[2] Yigini Y., Panagos P.: *Assessment of soil organic carbon stocks under future climate and land cover changes in Europe*. Science of The Total Environment, vol. 557–558, 2016, pp. 838–850. https://doi.org/10.1016/j.scitotenv.2016.03.085.

[3] Patoine G., Eisenhauer N., Cesarz S., Phillips H.R.P., Xu X., Zhang L., Guerra C.A.: *Drivers and trends of global soil microbial carbon over two decades*. Nature Communications, vol. 13(1), 2022, 4195. https://doi.org/10.1038/s41467-022-31833-z.

[4] Hartemink A.E., McSweeney K. (eds.): *Soil Carbon*. Springer International Publishing, Cham 2014. https://doi.org/10.1007/978-3-319-04084-4.

[5] Beillouin D., Corbeels M., Demenois J., Berre D., Boyer A., Fallot A., Feder F., Cardinael R.: *A global meta-analysis of soil organic carbon in the Anthropocene*. Nature Communications, vol. 14(1), 2023, 3700. https://doi.org/10.1038/s41467-023-39338-z.

[6] Fujisaki K., Perrin A., Desjardins T., Bernoux M., Balbino L.C., Brossard M.: *From forest to cropland and pasture systems: A critical review of soil organic carbon stocks changes in Amazonia*. Global Change Biology, vol. 21(7), 2015, pp. 2773–2786. https://doi.org/10.1111/gcb.12906.

[7] Yang R.-M., Huang L.-M., Zhang X., Zhu C.-M., Xu L.: *Mapping the distribution, trends, and drivers of soil organic carbon in China from 1982 to 2019*. Geoderma, vol. 429, 2023, 116232. https://doi.org/10.1016/j.geoderma.2022.116232.

[8] Guevara M., Olmedo G.F., Stell E., Yigini Y., Duarte Y.A., Hernández C.A., Arévalo G.E., Arroyo-Cruz C.E., Bolivar A., Bunning S., Cañas N.B., Cruz-Gaistardo C.O., Davila F., Acqua M.D., Encina A., Tacona H.F., Fontes F., Herrera J.A.H., Navarro A.R.I., ..., Vargas R.: *No silver bullet for digital soil mapping: country-specific soil organic carbon estimates across Latin America*. SOIL, vol. 4(3), 2018, pp. 173–193. https://doi.org/10.5194/soil-4-173-2018.

[9] Jandl R., Rodeghiero M., Martinez C., Cotrufo M.F., Bampa F., van Wesemael B., Harrison R.B., Guerrini I.A., Richter Jr. D.deB., Rustad L., Lorenz K., Chabbi A., Miglietta F.: *Current status, uncertainty and future needs in soil organic carbon monitoring*. Science of The Total Environment, vol. 468–469, 2014, pp. 376–383.

[10] Quesada C.A., Paz C., Mendoza E.O., Phillips O.L., Saiz G., Lloyd J.: *Variations in soil chemical and physical properties explain basin-wide Amazon forest soil carbon concentrations*. SOIL, vol. 6(1), 2020, pp. 53–88. https://doi.org/10.5194/soil-6-53-2020.

[11] Khan M.O., Keesstra S.D., Słowik-Opoka E., Klamerus-Iwan A., Liaqat W.: *Determining the role of urban greenery in soil hydrology: a bibliometric analysis of nature-based solutions in urban ecosystem*. Water, vol. 17(3), 2025, 322. https://doi.org/10.3390/w17030322.

[12] Sarkis-Onofre R., Catalá-López F., Aromataris E., Lockwood C.: *How to properly use the PRISMA Statement*. Systematic Reviews, vol. 10(1), 2021, 117. https://doi.org/10.1186/s13643-021-01671-z.

[13] Torres B., Herrera-Feijoo R., Torres Y., García A.: *Global evolution of research on silvopastoral systems through bibliometric analysis: Insights from Ecuador*. Agronomy, vol. 13(2), 2023, 479. https://doi.org/10.3390/agronomy13020479.

[14] Gray P., Williamson J., Karp D., Dalphin J.: *The Research Imagination: An Introduction to Qualitative and Quantitative Methods*. Cambridge University Press, 2007.

[15] R Core Team: *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2024. www.R-project.org

[16] Aria M., Cuccurullo C.: *Bibliometrix: An R-tool for comprehensive science mapping analysis*. Journal of Informetrics, vol. 11(4), 2017, pp. 959–975. https://doi.org/10.1016/j.joi.2017.08.007.

[17] van Eck N., Waltman L.: *VOSviewer version 1.6.20*. Leiden University, The Netherlands, 2023. https://www.vosviewer.com.

[18] QGIS Development Team: *QGIS Geographic Information System*. QGIS Association, 2024. https://www.qgis.org.

[19] Beillouin D., Cardinael R., Berre D., Boyer A., Corbeels M., Fallot A., Feder F., Demenois J.: *A global overview of studies about land management, land-use change, and climate change effects on soil organic carbon*. Global Change Biology, vol. 28(4), 2022, pp. 1690–1702. https://doi.org/10.1111/gcb.15998.

[20] Panagos P., van Liedekerke M., Borrelli P., Köninger J., Ballabio C., Orgiazzi A., Lugato E., Liakos L., Hervas J., Jones A., Montanarella L.: *European soil data centre 2.0: Soil data and knowledge in support of the EU policies*. European Journal of Soil Science, vol. 73(6), 2022, e13315. https://doi.org/10.1111/ejss.13315.

[21] de Koning G.H.J., Veldkamp E., López-Ulloa M.: *Quantification of carbon sequestration in soils following pasture to forest conversion in northwestern Ecuador*. Global Biogeochemical Cycles, vol. 17(4), 2003, 2003GB002099. https://doi.org/10.1029/2003GB002099.

[22] Bremer L.L., Farley K.A., Chadwick O.A., Harden C.P.: *Changes in carbon storage with land management promoted by payment for ecosystem services*. Environmental Conservation, vol. 43(4), 2016, pp. 397–406. https://doi.org/10.1017/S0376892916000199.

[23] McGroddy M.E., Lerner A.M., Burbano D.V., Schneider L.C., Rudel T.K.: *Carbon stocks in silvopastoral systems: A study from four communities in southeastern Ecuador*. Biotropica, vol. 47(4), 2015, pp. 407–415. https://doi.org/10.1111/btp.12225.

[24] Carrión-Paladines V., Benítez Á., García-Ruíz R.: *Conversion of Andean montane forest to exotic forest plantation modifies soil physicochemical properties in the buffer zone of Ecuador's Podocarpus National Park*. Forest Ecosystems, vol. 9, 2022, 100076. https://doi.org/10.1016/j.fecs.2022.100076.

[25] Farley K.A., Kelly E.F., Hofstede R.G.M.: *Soil organic carbon and water retention after conversion of grasslands to pine plantations in the Ecuadorian Andes*. Ecosystems, vol. 7(7), 2004, pp. 729–739. https://doi.org/10.1007/s10021-004-0047-5.

[26] Avadí A.: *Environmental assessment of the Ecuadorian cocoa value chain with statistics-based LCA*. International Journal of Life Cycle Assessment, vol. 28(11), 2023, pp. 1495–1515. https://doi.org/10.1007/s11367-023-02142-4.

[27] Reyna-Bowen J.L., López Álava G.A., Ormaza Cedeño K.P., Delgado-Moreira M.I., Gullén Mendoza S.V.: *Assessment of soil organic carbon: The influence of Ecuadorian cocoa varieties*. Journal of Ecological Engineering, vol. 26(9), 2025, pp. 9–19. https://doi.org/10.12911/22998993/204503.

[28] Bahr E., Chamba-Zaragocin D., Fierro-Jaramillo N., Witt A., Makeschin F.: *Modeling of soil nutrient balances, flows and stocks revealed effects of management on soil fertility in south Ecuadorian smallholder farming systems*. Nutrient Cycling in Agroecosystems, vol. 101(1), 2015, pp. 55–82. https://doi.org/10.1007/s10705-014-9662-5.

[29] Reyna-Bowen J.L., Ormaza Cedeño K.P., Delgado-Moreira M.I., Guillén Mendoza S.V.: *Enhanced soil carbon storage in Hylocereus spp. systems: The role of cover crops.* Journal of Ecological Engineering, vol. 27(5), 2026, pp. 120–127. https://doi.org/10.12911/22998993/215793.

[30] Guillen S., López G., Ormaza P., Mesias F., Błońska E., Reyna-Bowen L.: *Soil health and dragon fruit cultivation: assessing the impact on soil organic carbon*. Scientia Agropecuaria, vol. 14(4), 2023, pp. 519–528. https://doi.org/10.17268/sci.agropecu.2023.043.

[31] Ramos R.A., MacFarlane D., Cooper L.: *The carbon sequestration potential of 'analog' forestry in Ecuador: An alternative strategy for reforestation of degraded pastures*. Forestry: An International Journal of Forest Research, vol. 94(1), 2021, pp. 102–114. https://doi.org/10.1093/forestry/cpaa017.

[32] Barrezueta-Unda S., Velepucha-Cuenca K., Solano M., Hurtado-Flores L.: *Secuestro de carbono orgánico del suelo en pastizales de la provincia El Oro, Ecuador*. Ciencia UNEMI, vol. 13(32), 2019, pp. 14–26. https://www.redalyc.org/journal/5826/582661898002/html/.

[33] Mesías Gallo F.W., Hernández Jiménez A., Vera Macías L.R., Guzmán Cedeño Á.M., Cedeño Sacón Á.F., Ormaza Cedeño K.P., López Alava G.A.: *Reservas de carbono orgánico en suelos de la llanura fluvial Calceta-Tosagua, Manabí, Ecuador*. Cultivos Tropicales, vol. 39(4), 2018, pp. 27–33. http://scielo.sld.cu/pdf/ctr/v39n4/ctr04418.pdf [access: June 10, 2025].

[34] Paul S., Veldkamp E., Flessa H.: *Differential response of mineral-associated organic matter in tropical soils formed in volcanic ashes and marine Tertiary sediment to treatment with HCl, NaOCl, and* $Na_4P_2O_7$. Soil Biology and Biochemistry, vol. 40(7), 2008, pp. 1846–1855. https://doi.org/10.1016/j.soilbio.2008.03.008.

[35] Jansen B., Tonneijck F.H., Verstraten J.M.: *Selective extraction methods for aluminium, iron and organic carbon from montane volcanic ash soils*. Pedosphere, vol. 21(5), 2011, pp. 549–565. https://doi.org/10.1016/S1002-0160(11)60157-4.

[36] Mendoza B., Béjar J., Luna D., Osorio M., Jimenez M., Melendez J.R.: *Differences in the ratio of soil microbial biomass carbon (MBC) and soil organic carbon (SOC) at various altitudes of Hyperalic Alisol in the Amazon region of Ecuador*. F1000Research, vol. 9, 2020, 443. https://doi.org/10.12688/f1000research.22922.1.

[37] Caulfield M.E., Fonte S.J., Groot J.C.J., Vanek S.J., Sherwood S., Oyarzun P., Borja R.M., Dumble S., Tittonell P.: *Agroecosystem patterns and land management co-develop through environment, management, and land-use interactions*. Ecosphere, vol. 11(4), 2020, e03113. https://doi.org/10.1002/ecs2.3113.

[38] de la Cruz-Amo L., Bañares-de-Dios G., Cala V., Granzow-de la Cerda Í., Espinosa C.I., Ledo A., Salinas N., Macía M.J., Cayuela L.: *Trade-offs among aboveground, belowground, and soil organic carbon stocks along altitudinal gradients in Andean tropical montane forests*. Frontiers in Plant Science, vol. 11, 2020, 106. https://doi.org/10.3389/fpls.2020.00106.

[39] Echeverría M., Mur R.J., Lindao V., Erazo N., Logroño W., Córdova R.: *Quantification of organic carbon stored in the soil in the paramo of Igualata, Chimborazo Province-Ecuador*. AIP Conference Proceedings, vol. 2003(1), 2018, 020004. https://doi.org/10.1063/1.5050356.

[40] Loayza V., Sevilla V., Olivera C., Guevara M., Olmedo G., Vargas R., Oyonarte C., Jiménez W.: *Digital mapping of organic carbon in Ecuador soils*. Ecosistemas, vol. 29(1), 2020, 1852. https://doi.org/10.7818/ECOS.1852.

[41] Ayala Izurieta J.E., Márquez C.O., García V.J., Jara Santillán C.A., Sisti J.M., Pasqualotto N., Van Wittenberghe S., Delegido J.: *Multi-predictor mapping of soil organic carbon in the alpine tundra: a case study for the central Ecuadorian páramo*. Carbon Balance and Management, vol. 16(1), 2021, 32. https://doi.org/10.1186/s13021-021-00195-2.

[42] Beltrán-Dávalos A.A., Ayala Izurieta J.E., Echeverría M., Jara Santillán C.A., Verrelst J., Delegido J., Merino A., Otero X.L.: *Driving variables to explain soil organic carbon dynamics: Páramo highlands of the Ecuadorian Real mountain range*. Journal of Soils and Sediments, vol. 25(5), 2025, 1578–1597. https://doi.org/10.1007/s11368-025-04017-7.

[43] Calderón-Loor M., Cuesta F., Pinto E., Gosling W.D.: *Carbon sequestration rates indicate ecosystem recovery following human disturbance in the equatorial Andes*. PLoS ONE, vol. 15(3), 2020, e0230612. https://doi.org/10.1371/journal.pone.0230612.

[44] Pazmiño Y., de Felipe J.J., Vallbé M., Cargua F., Quevedo L.: *Identification of a set of variables for the classification of páramo soils using a nonparametric model, remote sensing, and organic carbon*. Sustainability, vol. 13(16), 2021, 9462. https://doi.org/10.3390/su13169462.

[45] Quiroz Dahik C., Crespo P., Stimm B., Mosandl R., Cueva J., Hildebrandt P., Weber M.: *Impacts of pine plantations on carbon stocks of páramo sites in southern Ecuador*. Carbon Balance and Management, vol. 16(1), 2021, 5. https://doi.org/10.1186/s13021-021-00168-5.

[46] DelVecchia A.G., Bruno J.F., Benninger L., Alperin M., Banerjee O., de Dios Morales J.: *Organic carbon inventories in natural and restored Ecuadorian mangrove forests*. PeerJ, vol. 2, 2014, e388. https://doi.org/10.7717/peerj.388.

[47] Merecí-Guamán J., Casanoves F., Delgado-Rodríguez D., Ochoa P., Cifuentes-Jara M.: *Impact of shrimp ponds on mangrove blue carbon stocks in Ecuador*. Forests, vol. 12(7), 2021, 816. https://doi.org/10.3390/f12070816.

[48] Corre M.D., Schoorl J.M., Koning F.D., López-Ulloa M., Veldkamp E.: *Erosion and sedimentation effects on soil organic carbon redistribution in a complex landscape in western Ecuador*, [in:] Brearley F.Q., Thomas A.D. (eds.), *Land-Use Change Impacts on Soil Processes: Tropical and Savannah Ecosystems*, CABI, UK, 2015, pp. 108–121. https://doi.org/10.1079/9781780642109.0108.

[49] Jansen B., Nierop K.G.J.: *Methyl ketones in high altitude Ecuadorian Andosols confirm excellent conservation of plant-specific n-alkane patterns*. Organic Geochemistry, vol. 40(1), 2009, pp. 61–69. https://doi.org/10.1016/j.orggeochem.2008.09.006.

[50] Zamora-Ledezma E., Macías Pro M., Jarre Castro E., Vera Vélez J., Briones Saltos R., Vélez Velásquez J., Loor Dueñas R., Salas Macias C., Pacheco Gil H.: *Advancing carbon quantification: A comparative evaluation of gravimetric and volumetric methods for soil carbon assessment in tropical ecosystems*. Results in Engineering, vol. 25, 2025, 104141. https://doi.org/10.1016/j.rineng.2025.104141.

[51] FAO: *Global soil organic carbon map – GSOCmap v.1.6*. *Technical Report*. Food and Agriculture Organization of the United Nations, Rome 2022. https://doi.org/10.4060/cb9015en.

[52] Poggio L., de Sousa L.M., Batjes N.H., Heuvelink G.B.M., Kempen B., Ribeiro E., Rossiter D.: *SoilGrids 2.0: Producing soil information for the globe with quantified spatial uncertainty*. SOIL, vol. 7(1), 2021, pp. 217–240. https://doi.org/10.5194/soil-7-217-2021.

[53] Lal R.: *Challenges and opportunities in soil organic matter research*. European Journal of Soil Science, vol. 60(2), 2009, pp. 158–169. https://doi.org/10.1111/j.1365-2389.2008.01114.x.

[54] Rainford S., Martín-López J.M., Da Silva M.: *Approximating soil organic carbon stock in the Eastern Plains of Colombia*. Frontiers in Environmental Science, vol. 9, 2021, 685819. https://doi.org/10.3389/fenvs.2021.685819.

[55] Paul S., Veldkamp E., Flessa H.: *Soil organic carbon in density fractions of tropical soils under forest – pasture – secondary forest land use changes*. European Journal of Soil Science, vol. 59(2), 2008, pp. 359–371. https://doi.org/10.1111/j.1365-2389.2007.01010.x.

[56] Candra I.N., Gerzabek M.H., Ottner F., Tintner J., Wriessnig K., Zehetner F.: *Weathering and soil formation in rhyolitic tephra along a moisture gradient on Alcedo Volcano, Galápagos*. Geoderma, vol. 343, 2019, pp. 215–225. https://doi.org/10.1016/j.geoderma.2019.01.051.

[57] Tonneijck F.H., Hageman J.A., Sevink J., Verstraten J.M.: *Tephra stratification of volcanic ash soils in northern Ecuador*. Geoderma, vol. 144(1–2), 2008, pp. 231–247. https://doi.org/10.1016/j.geoderma.2007.11.009.

[58] Ruiz L., Carrión-Paladines V., Vega M., López F., Benítez Á.: *Biological crust diversity related to elevation and soil properties at local scale in a montane scrub of Ecuador*. Journal of Fungi, vol. 9(3), 2023, 386. https://doi.org/10.3390/jof9030386.

[59] Delmelle P., Biass S., Paque M., Lobet B.: *Explosive volcanic eruptions can act as carbon sinks*. Nature Communications, vol. 16(1), 2025, 4306. https://doi.org/10.1038/s41467-025-59692-4.

[60] Zehetner F., Jäger H., Keiblinger K.M., Dinter T.C., Candra I.N., Bajraktarevic A., Puschenreiter M., Gerzabek M.H.: *Soil formation, nutrient supply and ecosystem productivity on basaltic lava vs rhyolitic pumice on Alcedo Volcano, Galápagos*. Soil Research, vol. 60(2), 2021, pp. 173–186. https://doi.org/10.1071/sr21148.

[61] Hualpa G., Carrión-Paladines V., Jiménez W., Capa-Mora D., Quichimbo P., Fierro N., Jiménez L.: *Farmers' indigenous knowledge of soil management in an altitudinal gradient in southern Ecuador*. Sustainability, vol. 17(11), 2025, 4983. https://doi.org/10.3390/su17114983.

[62] Vos C., Jaconi A., Jacobs A., Don A.: *Hot regions of labile and stable soil organic carbon in Germany – spatial variability and driving factors*. SOIL, vol. 4(2), 2018, pp. 153–167. https://doi.org/10.5194/soil-4-153-2018.

[63] Caulfield M.E., Fonte S.J., Tittonell P., Vanek S.J., Sherwood S., Oyarzun P., Borja R.M., Dumble S., Groot J.C.J.: *Inter-community and on-farm asymmetric organic matter allocation patterns drive soil fertility gradients in a rural Andean landscape*. Land Degradation and Development, vol. 31(18), 2020, pp. 2973–2985. https://doi.org/10.1002/ldr.3635.

[64] Jiménez L., Jiménez W., Felicito D., Fierro N., Quichimbo P., Sánchez D., Capa-Mora D.: *Rediscovering the edaphic knowledge of smallholder farmers in southern Ecuador*. Geoderma, vol. 406, 2022, 115468. https://doi.org/10.1016/j.geoderma.2021.115468.

[65] Pérez H., Rodríguez I., Garcia R.: *Secuestro de carbono por el suelo y sus fracciones en agroecosistemas tropicales de la región costa ecuatoriana*. Revista Universidad y Sociedad, vol. 13(2), 2021, pp. 141–149. http://ref.scielo.org/vh2d7s.

[66] Delgado D., Sadaoui M., Ludwig W., Méndez W., Ortiz-Hernández E., Farfán-Intriago P.: *Assessment of soil erosion by RUSLE in the Ecuadorian basins (2001–2020) based on GIS and high-resolution satellite data: Main drivers and changes on soil erosion.* Geomorphology, vol. 469, 2025, 109515. https://doi.org/10.1016/j.geomorph.2024.109515.

[67] Alomía Herrera I., Molina A., Montes Y., Dixon J. L., Vanacker V.: *Evaluation of nature-based climate solutions for agricultural landscapes in the Galápagos Islands.* Global and Planetary Change, vol. 243, 2024, 104598. https://doi.org/10.1016/j.gloplacha.2024.104598.

[68] Meneses Quelal O., Yánez Yánez W., Aranguren Carrera J.: *Bioindicators for assessing soil quality in Ecuador's Jun Jun micro-watershed.* Agronomy, vol. 14(7), 2024, 1436. https://doi.org/10.3390/agronomy14071436.

[69] de Sosa L.L., Carmona I., Panettieri M., Griffith D.M., Espinosa C.I., Jara-Guerrero A., Plaza C., Madejón E.: *Ecosystem function associated with soil organic carbon declines with tropical dry forest degradation*. Land Degradation & Development, vol. 35(6), 2024, pp. 2109–2121. https://doi.org/10.1002/ldr.5047.

[70] Jiménez L., Jiménez W., Ayala N., Quichimbo P., Fierro N., Capa-Mora D.: *Exploring ethnopedology in the Ecuadorian Andean highlands: A local farmer perspective of soil indicators and management*. Geoderma Regional, vol. 36, 2024, e00755. https://doi.org/10.1016/j.geodrs.2024.e00755.

[71] Ayala Izurieta J.E., Jara Santillán C.A., Márquez C.O., García V.J., Rivera-Caicedo J.P., Van Wittenberghe S., Delegido J., Verrelst J.: *Improving the remote estimation of soil organic carbon in complex ecosystems with Sentinel-2 and GIS using Gaussian processes regression*. Plant and Soil, vol. 479(1–2), 2022, pp. 159–183. https://doi.org/10.1007/s11104-022-05506-1.

[72] Páez-Bimos S., Villacís M., Morales O., Calispa M., Molina A., Salgado S., de Bievre B., Delmelle P., Muñoz T., Vanacker V.: *Vegetation effects on soil pore structure and hydraulic properties in volcanic ash soils of the high Andes.* Hydrological Processes, vol. 36(9), 2022, e14678. https://doi.org/10.1002/hyp.14678.

[73] Bonilla-Bedoya S. Herrera M.Á., Vaca A., Salazar L., Zalakeviciute R., Mejia D., López-Ulloa M.: *Urban soil management in the strategies for adaptation to climate change of cities in the Tropical Andes*. Geoderma, vol. 417, 2022, 115840. https://doi.org/10.1016/j.geoderma.2022.115840.

[74] Gerzabek M.H., Rechberger M.V., Schmidt G., Wriessnig K., Zehetner F.: *Soil organic carbon and fine particle stocks along a volcanic chrono- and elevation-sequence on the Galápagos archipelago/Ecuador*. Geoderma Regional, vol. 29(A), 2022, e00508. https://doi.org/10.1016/j.geodrs.2022.e00508.

[75] Suello R.H., Hernandez S.L., Bouillon S., Belliard J.-P., Dominguez-Granda L., Van de Broek M., Rosado Moncayo A.M., Ramos Veliz J., Ramirez K.P., Govers G., Temmerman S.: *Mangrove sediment organic carbon storage and sources in relation to forest age and position along a deltaic salinity gradient.* Biogeosciences, vol. 19(5), 2022, pp. 1571–1585. https://doi.org/10.5194/bg-19-1571-2022.

[76] Pérez Iglesias H.I., Rodríguez Delgado I., García Batista R.M.: *Secuestro de carbono por el suelo y sus fracciones en agroecosistemas tropicales de la región costa ecuatoriana.* Revista Universidad y Sociedad, vol. 13(2), 2021, pp. 141–149. http://scielo.sld.cu/pdf/rus/v13n2/2218-3620-rus-13-02-141.pdf.

[77] Caulfield M.E., Fonte S.J., Tittonell P., Vanek S.J., Sherwood S., Oyarzun P., Borja R.M., Dumble S., Groot J.C.J.: *Inter-community and on-farm asymmetric organic matter allocation patterns drive soil fertility gradients in a rural Andean landscape.* Land Degradation & Development, vol. 31(18), 2020, pp. 2973–2985. https://doi.org/10.1002/ldr.3635.

[78] Portalanza D., Barral M.P., Villa-Cox G., Ferreira-Estafanous S., Herrera P., Durigon A., Ferraz S.: *Mapping ecosystem services in a rural landscape dominated by cacao crop: A case study for Los Rios province, Ecuador*. Ecological Indicators, vol. 107, 2019, 105593. https://doi.org/10.1016/j.ecolind.2019.105593.

[79] Gebauer A., Brito Gómez V.M., Ließ M.: *Optimisation in machine learning: An application to topsoil organic stocks prediction in a dry forest ecosystem.* Geoderma, vol. 354, 2019, 113846. https://doi.org/10.1016/j.geoderma.2019.07.004.

[80] Gerzabek M.H., Bajraktarevic A., Keiblinger K., Mentler A., Rechberger M., Tintner J., Wriessnig K., Gartner M., Valenzuela X., Troya A., Couenberg P.M., Jäger H., Carrión J.E., Zehetner F.: *Agriculture changes soil properties on the Galápagos Islands – two case studies.* Soil Research vol. 57(3), 2019, pp. 201–214. https://doi.org/10.1071/SR18331.

[81] Reyna-Bowen L., Vera-Montenegro L., Reyna L.: *Soil-organic-carbon concentration and storage under different land uses in the Carrizal-Chone Valley in Ecuador*. Applied Sciences, vol. 9(1), 2018, 45. https://doi.org/10.3390/app9010045.

[82] Rial M., Martínez Cortizas A., Taboada T., Rodríguez-Lado L.: *Soil organic carbon stocks in Santa Cruz Island, Galapagos, under different climate change scenarios.* CATENA, vol. 156, 2017, pp. 74–81. https://doi.org/10.1016/j.catena.2017.03.020.

[83] Cargua Catagña F.E., Rodríguez Llerena M.V., Carrión D.A.D., Recalde Moreno C.G., Santillán Lima G.P.: *Analytical methods comparison for soil organic carbon determination in Andean Forest of Sangay National Park-Ecuador.* Acta Agronómica, vol. 66(3), 2017. https://doi.org/10.15446/acag.v66n3.52467.

[84] Ließ M., Schmidt J., Glaser B.: *Improving the spatial prediction of soil organic carbon stocks in a complex tropical mountain landscape by methodological specifications in machine learning approaches.* PLoS ONE, vol. 11(4), 2016, e0153673. https://doi.org/10.1371/journal.pone.0153673.

[85] Estrella R., Cattrysse D., Van Orshoven J.: *An integer programming model to determine land use trajectories for optimizing regionally integrated ecosystem services delivery.* Forests, vol. 7(2), 2016, 33. https://doi.org/10.3390/f7020033.

[86] Bahr E., Chamba Zaragocin D., Makeschin F.: *Soil nutrient stock dynamics and land-use management of annuals, perennials and pastures after slash-and-burn in the Southern Ecuadorian Andes.* Agriculture, Ecosystems & Environment, vol. 188, 2014, pp. 275–288. https://doi.org/10.1016/j.agee.2014.03.005.

[87] Hamer U., Potthast K., Burneo J.I., Makeschin F.: *Nutrient stocks and phosphorus fractions in mountain soils of Southern Ecuador after conversion of forest to pasture.* Biogeochemistry, vol. 112(1–3), 2013, pp. 495–510. https://doi.org/10.1007/s10533-012-9742-z.

[88] Moser G., Leuschner C., Hertel D., Graefe S., Soethe N., Iost S.: *Elevation effects on the carbon budget of tropical mountain forests (S Ecuador): the role of the belowground compartment.* Global Change Biology, vol. 17(6), 2011, pp. 2211–2226. https://doi.org/10.1111/j.1365-2486.2010.02367.x.

[89] Hamer U., Potthast K., Makeschin F.: *Urea fertilisation affected soil organic matter dynamics and microbial community structure in pasture soils of Southern Ecuador.* Applied Soil Ecology, vol. 43(2–3), 2009, pp. 226–233. https://doi.org/10.1016/j.apsoil.2009.08.001.

[90] Paul S., Veldkamp E., Flessa H.: *Soil organic carbon in density fractions of tropical soils under forest – pasture – secondary forest land use changes.* European Journal of Soil Science, vol. 59(2), 2008, pp. 359–371. https://doi.org/10.1111/j.1365-2389.2007.01010.x.

[91] Paul S., Flessa H., Veldkamp E., López-Ulloa M.: *Stabilization of recent soil carbon in the humid tropics following land use changes: Evidence from aggregate fractionation and stable isotope analyses.* Biogeochemistry, vol. 87(3), 2008, pp. 247–263. https://doi.org/10.1007/s10533-008-9182-y.

[92] Hernández Jiménez A., Vera Macías L., Naveda Basurto C.A., Guzmán Cedeño Á.M., Vivar Arrieta M., Zambrano T.R., Mesías Gallo F., Ormanza K., León Aguilar R.V., López Alava G.A.: *Variaciones en algunas propiedades del suelo por el cambio de uso de la tierra, en las partes media y baja de la microcuenca Membrillo, Manabí, Ecuador.* Cultivos Tropicales, vol. 38(1), 2017, pp. 50–56. https://ediciones.inca.edu.cu/index.php/ediciones/article/view/1335.