Carbon storage in coffee agroforestry systems: A bibliometric analysis and meta-analysis

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Research Article

Keywords: climate change mitigation, environmental services, soil organic carbon, above-ground carbon

Posted Date: May 18th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-6559555/v1

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Agroforestry Systems on November 20th, 2025. See the published version at https://doi.org/10.1007/s10457-025-01389-0.

Abstract

Coffee is grown in some 75 countries, in which about 25 million people depend directly on coffee production for their livelihoods, with 70% of the labor being performed by women. Coffee cultivation systems based on agroforestry systems (CAFS) provide ecosystem services, such as carbon (C) storage. To identify the potential and opportunities for sequestration and storage of C in different coffee production systems, we selected 84 publications from indexed journals (Scopus and Web of Science) for the period 2006–2022 and applied a bibliometric analysis and meta-analysis. During the period 2006–2022, a total of 1,694 citations were recorded. We counted the countries of the corresponding authors, finding that the United States of America, Brazil, and Mexico are identified as the three nationalities with the highest number of publications. A mean total carbon content, considering both biomass and soil, of 178.9 ± 36.6 MgC ha^{-1} is recorded, with soil organic carbon (SOC) being the component with the highest C content, at 105.4 ± 48.0 MgC ha^{-1}, followed by aboveground C in trees with 45.2 ± 35.3 MgC ha^{-1}. We found 156 multipurpose perennial species used in the shade layer, with the genera *Albizia, Cordia, Erythrina, Ficus, Inga, Musa, Persea*, and *Terminalia* as the most representative in CAFS. Information about this ecosystem service offered by CAFS could be considered not only to improve the sustainability of the crop, but also to obtain competitive advantages in the marketing of coffee that may contribute to the development of coffee producers around the world.

INTRODUCTION

Implications of agricultural management in global change and development

Agriculture faces significant challenges under the current global need for food insurance and maintenance of environmental services (Webb et al. 2017). The current world population is 8.04 billion people and is estimated to rise to 9.7 billion by the year 2050, which leads to a greater demand for food and ecosystem services to meet the needs of human communities (McFarlane 2023). These goods and services come mainly from croplands and forests; however, it is estimated that 52% of global croplands are degraded. Moreover, agricultural activities are responsible for 80% of global deforestation and 29% of total greenhouse gas emissions (Augustinus and Alexander, 2022). In addition, 12 million hectares of land become unproductive annually due to land degradation, threatening the livelihoods of more than one million people in nearly 100 countries (Sena 2019). These degradative processes derive from increased greenhouse gas emissions and adverse climate change events such as droughts, floods, and wildfires (Augustinus and Alexander, 2022; Intergovernmental Panel on Climate 2022; Singh et al. 2020).

Land degradation feedback loops could be counteracted by implementing sustainable land management strategies, such as agroforestry (AF). AF is considered important for meeting the Sustainable Development Goals (SDG), which include no poverty, zero hunger, clean water and sanitation, decent work and economic growth, sustainable cities and communities, climate action, and life on land

(Andersson 2018). Agroforestry is also considered a strategy within the Millennium Ecosystem Assessment (MEA) to maintain and improve the ecosystem services of agroecosystems, especially those included in the categories of provisioning and regulating. In the 2016 Paris Agreement, AF is considered as an option to store and capture atmospheric carbon dioxide and reduce greenhouse gas (GHG) emissions (Jhariya et al. 2019).

Coffee agroforestry systems in the world and environmental quality (including carbon cycle)

Coffee is an important agricultural product consumed worldwide and grown in nearly 75 countries (of which 20% rank low on the human development index). Some 25 million people depend directly on coffee production for their livelihoods, and 70% of the labor is performed by women (ICO 2023). Many coffee plantations are grown unshaded where land degradation processes such as soil erosion, GHG emissions, and biodiversity loss are present; however, in several developing countries coffee plantations are managed on the basis of agroforestry systems (Bianco 2020; Perfecto et al. 2019; Perfecto et al. 2014). CAFS are multifunctional, providing ecological benefits such as biodiversity conservation, climate change mitigation, water infiltration, preservation of local knowledge, employment, economic growth, and food security, among others (Reyes González et al. 2016; Soto-Pinto et al. 2022; Toledo and Moguel 2012). Coffee certifications (organic, fair trade, bird friendly, rainforest alliance, common code for the coffee community, deforestation-free) provide a premium price to farmers who grow coffee under sustainable systems that improve the economic well-being of local communities (Donovan et al. 2019; Faure et al. 2012; Jurjonas et al. 2016; Sayekti and Prihandono 2023). Coffee-growing systems and their ecological services are vulnerable due to climate change (Pham et al. 2019); by 2050 the area suitable for coffee production (arabica and robusta) could be 50% less due to the increase in temperature and extreme dry periods (Bunn et al. 2015). Magrach and Ghazoul (2015) state that the impact of pests and diseases due to warmer conditions will increase and may reduce the quality of coffee beans as well.

In 2022–2023, world coffee production was 170 million 60-kg bags, with Brazil (36.8%), Vietnam (17.5%) and Colombia (6.6%) being the largest producing countries. The main coffee species grown worldwide are *Coffea arabica* L. (arabica coffee) and *Coffea canephora* (Pierre) ex Froehner (robusta coffee) (ICO 2023). World coffee production systems are diverse in structure and composition and can be classified into four general categories (Fig. 1): rustic, polyculture, specialized shade plantation, and unshaded, of which the first three are agroforestry systems. Rustic (also known as “mountain system”) is a system in which the original underground vegetation is removed to grow coffee, and the tree layer maintains its natural structure and composition. In polyculture systems (traditional or commercial), also known as coffee garden, the tree layer is a combination of native and/or introduced species, used mainly to shade the coffee plants, but they provide other benefits (food, fiber, wood, etc.) some of whose products are sold in local or regional markets. The specialized shade plantation (also known as “shaded monoculture”) is a system in which the tree stratum consists of a few species whose main use is providing shade to coffee plants. The specific design of coffee-growing systems is determined by the farmers, based on empirical and scientific knowledge as well as market and self-consumption needs (Toledo and Moguel 2012).

The structure of CAFS promotes carbon (C) storage, unlike unshaded systems (Nair 2011). There are seven C reservoirs in CAFS, which can be grouped into aboveground carbon (AGC) reservoirs (shade species, coffee plants, groundcover, litter, and deadwood) and belowground carbon (BGC) reservoirs (roots and soil) (Cristóbal-Acevedo et al. 2019; Espinoza-Domínguez et al. 2012; Negash & Starr 2015; Valdés-Velarde et al. 2022). These reservoirs are complex and dynamic in time and space, and they are interdependent according to the flux of matter in the system such as pruning, harvest, and coffee plant replacement, as well as environmental factors such as climate and soil characteristics (Schmitt and Perfecto 2021; Vandermeer et al. 2010). Farmers can receive a premium price from C storage in CAFS through climate change mitigation certifications or selling carbon credits on international carbon markets (Solér et al. 2016; Soto-Pinto and Jiménez-Ferrer 2018).

Despite the worldwide importance of coffee, there is a lack of information about C storage in global coffee agroforestry systems and the attributes related to each reservoir. We therefore carried out a global bibliometric analysis and meta-analysis on the role of coffee agroforestry systems in C storage, using databases of indexed journals. Our main objectives were to (i) assess the temporal evolution of publications, identify the more active authors, institutions, and countries, and their contributions to the advancement of the subject, (ii) assess the C storage potential in reservoirs of the main coffee-growing systems; and (iii) identify central points, research gaps and future trends. Our results may serve as guidance for policies and strategies.

METHODS

The methodology employed in this study followed three steps: data collection, bibliometric analysis, and meta-analysis.

Data collection

A literature survey of peer-reviewed publications was carried out using Web of Science and Scopus databases for the period 2000–2022. We limited the search parameters to papers whose title, abstract, or keywords included "carbon fluxes," "carbon stocks," "carbon storage," "soil organic carbon," or "carbon sequestration" in combination with "coffee" and "agroforestry" or "shade." This systematic review was conducted by following the reporting checklist of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis, known as PRISMA (Fig. 2) (Fragomeli et al. 2024). The search yielded 124 publications in Web of Science and 122 in Scopus. We removed duplicates and reviewed each one to clean the database. We selected 84 publications to use for the bibliometric analysis and meta-analysis processes.

The aim of the quantitative systematic review was to carry out a qualitative evaluation and interpretation (assembling, arranging, and assessing) of the knowledge of C storage in coffee agroforestry systems based on the literature survey (Donthu et al. 2021; Paul and Barari 2022). The main attributes identified in the review of publications were type of coffee growing systems, carbon reservoirs, methods used, amount of carbon obtained per hectare, and relationships between these attributes.

Bibliometric analysis

Once we had selected the papers, we proceeded with the bibliometric analysis. This focused on detecting the intellectual structure and emerging trends in C storage in coffee agroforestry systems. We collected the following quantitative data: citation-related metrics (total citations, publications by year, average citations), publication-related metrics (total publications, number of contributing authors, number of active years of publications), citation analysis (most influential publications), co-authorship analysis (author affiliations), network analysis (co-word network visualization), Bradford's law (source clustering), research directions, and thematic distribution (Donthu et al. 2021). The research areas of the papers were determined in accordance with the classification system of the Web of Science platform. For the document analysis we used the Bibliometrix R tool (Aria and Cuccurullo 2017) and the VOSviewer software tool (Van Eck and Waltman 2010) for network analysis.

Meta-analysis

The bibliometric analysis enabled us to quantitatively evaluate the bibliographic information. The meta-analysis provided a quantitative evaluation that integrated the results of C storage in coffee agroforestry systems reported in publications to provide a synthesized summary (Paul and Barari 2022). Per publication we extracted the data on C content in each reservoir evaluated (shaded species, coffee shrubs, groundcover, deadwood, litter, and SOC) and calculated descriptive statistics parameters (mean, minimum, maximum, standard deviation) using Excel. The standard deviation was estimated as:

$$SD = SE\sqrt{n}$$

where SE is the standard error and n the sample size. The information was described by country, coffee growing system, shade species, soils, and C reservoir. We grouped the publications into the five categories listed in Fig. 1; rustic (R), traditional polyculture (POL-T), commercial polyculture (POL-C), specialized shade plantation (SSP), and unshaded (US), since the information recorded in the papers does not identify the types of coffee production systems evaluated.

RESULTS

The results are organized in two steps. First, we show the results of the bibliometric analysis, describing the main bibliographic features of the publications, and second, the meta-analysis giving a statistical description of the C content in reservoirs, presence of species, and soils of coffee systems reported in publications.

1. Bibliometric analysis

Time evolution of publications

A total of 84 publications from 2006 to 2022 were retrieved, an average of five documents per year. The publications showed an exponential growth trend. An increase of 1 (2006) to 13 publications (2022) per year was observed. There was a significant increase in publications over the last eight years, reaching its peak in 2020 (15 publications). In the period 2006–2022, a total of 1,694 citations were recorded (Fig. 3).

More productive and prolific researchers

The most cited and influential publications on C storage in coffee agroforestry systems are presented in Table 1. The most cited article was published by Soto-Pinto et al. (2010) with 167 citations, followed by the research of Dossa et al. (2008) with 84 citations. The most prolific authors by number of documents are shown in Table 2; the authors with the most published articles on the topic are M. Negash from Hawassa University in Ethiopia with seven publications, and M. Noponen from Bangor University in the United Kingdom with four publications. Regarding the output of the authors over time, it is observed that the two authors previously mentioned, along with J. Haggar from the University of Greenwich in the United Kingdom, are among the authors with the most publications in the period 2012 to 2022.

Main journals

The journals in which 45% of the publications used for the analysis are found are *Agroforestry Systems* (n = 18), *Agriculture Ecosystems & Environment* (n = 14), *Agroecology and Sustainable Food Systems* (n = 3), and *Journal of Agricultural Science* (n = 3). The most significant journals can be identified more accurately through the total number of citations. The top 10 journals are listed in Table 3 along with their total citations (TC), number of publications (NP), debut publication year, and impact factor (IF_{2022}). Main source journals were *Agroforestry Systems*, *Agriculture Ecosystems & Environment*, and *Conservation Biology* with 580, 416, and 113 citations, respectively.

Table 1
Most cited publications on carbon cycle/sequestration/storage and management, according to the data from publications on carbon storage in coffee agroforestry systems from 2006 to 2022

Rank	Title	Authors	Source	Publication Year	Total Citations	Country
1	Carbon sequestration through agroforestry in indigenous communities of Chiapas, Mexico	Soto-Pinto, Lorena; Anzueto, Manuel; Mendoza, Jorge; Jimenez Ferrer, Guillermo; de Jong, Ben	Agroforestry Systems	2010	167	Mexico
2	Above- and belowground biomass, nutrient and carbon stocks contrasting an open-grown and a shaded coffee plantation	Dossa, E. L.; Fernandes, E. C. M.; Reid, W. S.; Ezui, K.	Agroforestry Systems	2008	84	Togo
3	Litter layer residence time in forest and coffee agroforestry systems in Sumberjaya, West Lampung	Hairiah, K; Sulistyani, H; Suprayogo, D; Widianto; Pumomosidhi, P; Widodo, RH; Van Noordwijk, M	Forest Ecology and Management	2006	83	Indonesia
4	Impacts of climate and land use on N2O and CH4 fluxes from tropical ecosystems in the Mt. Kilimanjaro region, Tanzania	Guetlein, Adrian; Gerschlauer, Friederike; Kikoti, Imani; Kiese, Ralf	Global Change Biology	2018	68	Tanzania
5	Changes in carbon stock and greenhouse gas balance in a coffee (Coffea arabica) monoculture versus an	Hergoualc'h, Kristell; Blanchart, Eric; Skiba, Ute; Henault, Catherine; Harmand, Jean-Michel	Agriculture Ecosystems & Environment	2012	65	Costa Rica

Rank	Title	Authors	Source	Publication Year	Total Citations	Country
	agroforestry system with Inga densiflora, in Costa Rica					
6	Climate change adaptation, mitigation and livelihood benefits in coffee production: where are the synergies?	Rahn, Eric; Laederach, Peter; Baca, Maria; Cressy, Charlotte; Schroth, Goetz; Malin, Daniella; van Rikxoort, Henk; Shriver, Jefferson	Mitigation and Adaptation Strategies for Global Change	2014	60	Nicaragua
7	Environmental-economic benefits and trade-offs on sustainably certified coffee farms	Haggar, Jeremy; Soto, Gabriela; Casanoves, Fernando; Virginio, Elias de Melo	Ecological Indicators	2017	44	Nicaragua
8	Carbon footprints and carbon stocks reveal climate-friendly coffee production	van Rikxoort, Henk; Schroth, Gotz; Laederach, Peter; Rodriguez-Sanchez, Beatriz	Agronomy for Sustainable Development	2014	42	Mexico, Guatemala, Nicaragua, El Salvador, Colombia
9	The effects of management and plant diversity on carbon storage in coffee agroforestry systems in Costa Rica	Haeger, Achim	Agroforestry Systems	2012	41	Costa Rica
10	Carbon stocks in coffee agroforests and mixed dry tropical forests in the western highlands of Guatemala	Schmitt-Harsh, Mikaela; Evans, Tom P.; Castellanos, Edwin; Randolph, J. C.	Agroforestry Systems	2012	41	Guatemala

Rank	Title	Authors	Source	Publication Year	Total Citations	Country
11	Soil organic carbon stocks under coffee agroforestry systems and coffee monoculture in Uganda	Tumwebaze, Susan Balaba; Byakagaba, Patrick	Agriculture Ecosystems & Environment	2016	40	Uganda
12	Tree pruning mulch increases soil C and N in a shaded coffee agroecosystem in Hawaii	Youkhana, Adel; Idol, Travis	Soil Biology & Biochemistry	2009	40	United States
13	Biodiversity and carbon storage co-benefits of coffee agroforestry across a gradient of increasing management intensity in the SW Ethiopian highlands	De Beenhouwer, Matthias; Geeraert, Lore; Mertens, Jan; Van Geel, Maarten; Aerts, Raf; Vanderhaegen, Koen; Honnay, Olivier	Agriculture Ecosystems & Environment	2016	39	Ethiopia
14	On the rebound: soil organic carbon stocks can bounce back to near forest levels when agroforests replace agriculture in southern India	Hombegowda, H. C.; van Straaten, O.; Koehler, M.; Hoelscher, D.	Soil	2016	38	India
15	Allometric equations for estimating aboveground biomass of Coffea arabica L. grown in the Rift Valley escarpment of Ethiopia	Negash, Mesele; Starr, Mike; Kanninen, Markku; Berhe, Leakemaraiam	Agroforestry Systems	2013	37	Ethiopia

Table 2
Top 5 most relevant authors, according to the data from publications on carbon storage in coffee agroforestry systems from 2006 to 2022

Rank	Author	NP	TC	h-index	Affiliation/Country
1	Negash, M.	7	127	5	Hawassa University/Ethiopia
2	Noponen, M.	4	104	4	Bangor University/United Kingdom
3	Haggar, J.	3	100	3	University of Greenwich/United Kingdom
4	Healey, J.	3	100	3	Bangor University/United Kingdom
5	Albrecht, A.	3	48	3	International Centre for Research in Agroforestry/Kenya

NP: Number of publications, TC: Total citations

Table 3
Top 10 most contributive journals based on total citations, according to the data from publications on carbon storage in coffee agroforestry systems from 2006 to 2022

Rank	Source	TC	NP	Initial year	IF_{2022}
1	Agroforestry Systems	580	18	2006	2.419
2	Agriculture Ecosystems & Environment	416	14	2012	6.576
3	Conservation Biology	113	2	2013	7.563
4	Forest Ecology and Management	83	1	2006	4.384
5	Plant and Soil	79	2	2015	4.993
6	Ecological Indicators	78	2	2017	6.263
7	Global Change Biology	68	1	2018	13.211
8	Agronomy For Sustainable Development	65	2	2014	7.832
9	Mitigation and Adaptation Strategies for Global Change	60	1	2014	3.926
10	Ecological Economics	59	1	2010	6.536

TC: Total citations, NP: Number of publications, IF_{2022}: Impact factor 2022

Most productive and prolific countries and institutions

Authors from a total of 25 countries have published studies on carbon sequestration in coffee agroforestry systems. Of these, the USA was the most productive, with 22 papers (19.6%). This country was also the most cited, generating 508 citations. Next were Mexico (*n* = 10, 8.9%), Brazil (*n* = 10, 8.9%), Ethiopia (*n* = 8, 7.1%), and Colombia (*n* = 6, 5.4%) with 202, 166, 108 and 42 citations, respectively. Authors from a total of 175 institutions have published studies on carbon sequestration in coffee agroforestry systems. The French Agricultural Research Centre for International Development (CIRAD) was the institution with the most publications (*n* = 22; 5.6%). The Consultative Group on International Agricultural Research (CGIAR) also stood out, with 10 publications (2.5%), as did the Universidad Autónoma Chapingo (UACh) with nine publications (2.3%). Research on carbon in coffee agroforestry systems is usually carried out through collaboration between institutions. The institutional collaboration network is shown in Fig. 4, where the most prominent cluster positions CIRAD as the central node and shows its relationship with other institutions; CGIAR, the World Agroforestry Center (ICRAF), the State University System of Florida (USF), and the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE).

Research areas

We found 23 research areas covered by our set of publications, of which the 10 most representative are presented in Table 4. Publications on the topic of carbon sequestration in coffee agroforestry systems are included in environmental themes as well as in agronomy and ecology. The area with the highest number of publications was Environmental Sciences, with 40 papers, corresponding to 18.9%. Other important areas were Forestry (16%) and Ecology (15.6%), which presented 34 and 33 records, respectively.

Keyword cluster map

The analysis of networks of keyword co-occurrence and the keyword cloud (Fig. 5) revealed that the most frequent terms in these publications are biomass (*n* = 29), management (*n* = 28) and biodiversity (*n* = 28). We do not include in our analysis the keywords directly related to the terms agroforestry, agroforestry systems and carbon sequestration, since they were our search terms, and therefore occur naturally more often in the papers. The keywords were organized into five clusters of distinct colors representing different research directions. The red cluster indicates studies on plant diversity of CAFS and allometry equations to estimate C storage in biomass. The blue cluster contains studies of the dynamics of agroecosystems related to C storage. The green cluster represents studies on climate change mitigation and agroecology. The yellow cluster consisted of studies on ecosystem services and biodiversity conservation. The purple cluster contains studies of soil organic carbon and greenhouse gas emissions.

Table 4
Top 10 research areas, according to the data from publications on carbon storage in coffee agroforestry systems from 2006 to 2022

Rank	Research areas	Number of records
1	Environmental Sciences	40
2	Forestry	34
3	Ecology	33
4	Agronomy	31
5	Agriculture Multidisciplinary	29
6	Soil Science	14
7	Environmental Studies	10
8	Green Sustainable Science Technology	9
9	Biodiversity Conservation	7
10	Plant Sciences	7

2. Meta-analysis

Locations of the research

Figure 6 shows the locations where studies included in the meta-analysis on C storage in coffee agroforestry systems were carried out. These span 19 countries across three continents: Americas (United States of America, Mexico, Costa Rica, Colombia, Nicaragua, Brazil, Guatemala, Peru, El Salvador, and Puerto Rico), Africa (Ethiopia, Uganda, Tanzania, Togo, and Kenya), and Asia (China, India, Indonesia, and Vietnam). Costa Rica, Ethiopia, and Mexico stand out for their number of studies, accounting for 42.2% of the total, followed by Colombia, Nicaragua, and Brazil, which together account for 23.3%.

Coffee growing systems, shade species and soils

Within the 84 publications analyzed, there is one record of a rustic system, and there are 73 of traditional polyculture, 17 of commercial polyculture, 43 of specialized shade plantation systems, and 21 of unshaded systems. For the shade stratum in all coffee-growing systems, 156 species are mentioned. The genera *Albizia, Cordia, Erythrina, Ficus, Inga, Musa, Persea*, and *Terminalia* are the most representative (Table 5), as well as *Grevillea robusta* and *Mangifera indica*. Of the 15 soils recorded, the most mentioned are andisols (10–200 cm depth), nitisols (30–60 cm depth), and ferralsols (60 cm depth).

The only study dealing with a rustic system is from Ethiopia within the Jimma zone; the soils are nitisols and the species in the shade stratum are *Olea capensis, Pouteria adolfi-friederici*, and *Syzigium guineense*. The POL-T systems studied were located in 15 countries, mainly in Mexico, Ethiopia, Nicaragua, Colombia, Costa Rica, and Brazil. The soils are mainly andisols, nitisols, luvisols, and ferralsols. A total of 130 shade species are recorded in these systems, of which the most notable are *Inga* spp, *P. americana, M. indica, Albizia gummifera, Cordia alliodora, Croton macrostachyus, G. robusta*, and *Cedrela odorata*. The POL-C systems are recorded in 11 countries, of which the majority were conducted in Mexico, Brazil, Peru, and Indonesia. The dominant soils are andisols, ferralsols, and hapludox. The species associated with the shade layer in these systems are *Euphoria longan, G. robusta, Hevea brasiliensis, Inga* spp, *Junglans* spp, *Macadamia ternifolia, Musa paradisiaca, P, americana, Pinus merkusii*, and *Toona sureni*.

Table 5
Main shade species in coffee agroforestry systems, according to the data from publications on carbon storage in coffee agroforestry systems from 2006 to 2022

Genus	Species
Albizia	*A. schimperi, A. adianthifolia, A. chinensis, A. coriaria, A. gummifera*, A. lebbeck, A. schimperiana*
Cordia	*C. africana*, C. alliodora*, C. collococca*
Erythrina	*E. abyssinica, E. brucei, E. fusca, E. poeppigiana*, E. sububrams*
Ficus	*F. insipida, F. nantalensis, F. ovata, F. racemosa, F. sur, F. vasta**
Inga	*I. densiflora, I. edulis*, I. jinicuil, I. laurina, I. longiflora, I. micheliana, I. oerstediana, I. punctata, I. ruiziana, I. spectabilis, I. spuria, I. vera*
Musa	*M. acuminata, M. paradisiaca**
Persea	*P. americana*, P. schiedeana*
Terminalia	*T. amazonia*, T. laxiflora, T. oblonga, T. paniculata*
*: most mentioned	

The SSP systems are found in 13 countries, mostly in Costa Rica, Ethiopia, the United States, Mexico, and India. The associated soils are andisols, haplustolls, inceptisols, nitisols, and ultisols. There are 30 shade species, of which the most frequent are *Cordia africana, Erythrina poeppigiana, Ficus* spp, *Leucaena leucocephala, Millettia ferruginea*, and *Terminalia amazonia*. US systems are located in 14 countries, of which Costa Rica, Brazil, Peru, and the United States have most of the records. The types of soils reported in these systems are haplustolls, humitropept, and inceptisols.

C stocks in coffee agroforestry systems

Average C storage in coffee-growing systems per reservoir is presented in Table 6. Mean total carbon in all reservoirs was 178.9 ± 36.6 MgC ha^{-1}. SOC is the reservoir with the highest C content (105.4 ± 48.0 MgC ha^{-1}), followed by aboveground carbon in trees (45.2 ± 35.3 MgC ha^{-1}). Figure 7 shows the C content in coffee-growing systems for each reservoir. In tree components, POL-T has the highest C content with a mean of 47.7 MgC ha^{-1} in AGC and 11.1 MgC ha^{-1} in BGC. The site with the highest C recorded in AGC from trees is a traditional polyculture in Ethiopia with shade species of genera *Milletia, Albizia*, and *Cordia*. In the coffee reservoir, the POL-C system records the highest C content with 7.9 MgC ha^{-1}. The system with highest C content in AGC of coffee plants is a traditional polyculture in Ethiopia in the Nono Sale district.

Table 6
Mean carbon content per reservoir, according to the data from publications on carbon storage in coffee agroforestry systems from 2006 to 2022

Reservoir	Carbon Stock (MgC ha^{-1})
Tree AGC	45.2 ± 35.3
Tree BGC	10.7 ± 6.4
Coffee AGC	6.8 ± 7.0
Coffee BGC	2.9 ± 2.5
Groundcover	1.0 ± 1.2
Deadwood	4.2 ± 6.5
Litter	2.8 ± 2.9
Soil organic carbon	105.4 ± 48.0
Mean total carbon	178.9 ± 36.6

AGC: Aboveground carbon, BGC: belowground carbon

The US and POL-T systems show the highest C content in groundcover reservoirs with an average of 2.0 MgC ha^{-1} and 1.39 MgC ha^{-1}, respectively. The same coffee cultivation systems also record the highest C content in deadwood reservoirs, with an average of 5.15 MgC ha^{-1} for POL-T and 3.69 MgC ha^{-1} for SSP. In the litter reservoir, the POL-T and SSP systems have the highest C content with averages of 2.73 MgC ha^{-1} and 2.83 MgC ha^{-1}, respectively. The site with the highest amount of litter (19 MgC ha^{-1}) is a rustic system in Ethiopia with shade trees of *Olea capensis, Pouteria adolfi-friederici*, and *Syzigium guineense*. In the SOC reservoir, SSP systems record the highest C content with 115.14 MgC ha^{-1}, followed by POL-C with 106.28 MgC ha^{-1}. The site with the highest SOC content (249.69 MgC ha^{-1}) is a SSP system in Ethiopia with leptosol and a shade layer composed of *Cordia africana*.

DISCUSSION

C stocks in coffee agroforestry systems: Bibliometric analysis

We conducted a bibliometric analysis of the global literature (2006–2022) on carbon storage in coffee agroforestry systems. Research related to C storage in CAFS shows an increasing trend from 2006 to the present that is reaffirmed for the specific case of Mexico by Ayala-Montejo et al. (2020). This trend may be related to growing international interest in technologies for climate change mitigation influenced by international policies such as the Paris Agreement and the 2030 Agenda, both adopted in 2015 (Jhariya et al. 2019). The 2030 Agenda consists of 17 Sustainable Development Goals (SDG) and 169 associated targets adopted by the United Nations to be met by 2030 (Sharma et al. 2022). Coffee agroforestry systems are considered a viable option to fulfill the Paris Agreement and the SDG 13 and SDG 15 by reducing atmospheric CO_2 and greenhouse gas emissions due to the incorporation of woody plants into the components of the agroecosystems (Poncet et al. 2024).

The top ten most productive countries consist of 60% developing countries (Mexico, Brazil, Ethiopia, Colombia, Indonesia, and China) and 40% developed countries (USA, Germany, Netherlands and Austria), which is related to world coffee-growing regions. Coffee is grown in nearly 75 countries, of which Latin America (Brazil, Colombia, Honduras, Mexico, Peru), Africa (Ethiopia, Uganda), and Asia (Vietnam, Indonesia, India) are the main producing regions and countries (ICO 2023). The interest in publishing about carbon sequestration in coffee agroforestry systems by developing countries may stem from national policy on mitigation strategies such as NAMA (Nationally Appropriate Mitigation Actions). NAMA are a set of policies and actions that countries take to reduce greenhouse gas emissions, and in the specific case of coffee, they include the potential of C storage in the productive regions. There are three NAMA-coffee countries registered in the United Nations Framework Convention on Climate Change (UNFCCC): Costa Rica, Dominican Republic, and Rwanda. In addition, Colombia, Peru, and Mexico have designed their NAMA-coffee but they are not yet registered (Melo et al. 2021). The top five most prolific and important organizations include research centers and universities located in France, Mexico, and Costa Rica. CIRAD and INRAE (France’s National Research Institute for Agriculture, Food and Environment) are French institutions that have collaborated with agencies in African and Latin American countries to evaluate the carbon storage potential in coffee-growing systems (Notaro et al. 2022). The Universidad Autónoma Chapingo (Mexico) and CATIE (Costa Rica) are the main prolific academic institutions. We observed that institutions located in high and middle-income countries have invested in coffee agroforestry research, and the low-income countries (in Africa, Central America, and Asia) usually require international support to finance the research through worldwide collaboration networks (Rahn et al. 2014).

Coffee-growing systems and their C storage potential are vulnerable to climate change. By 2050, the suitable area for worldwide coffee production (arabica and robusta) could be 50% less due to increased temperature and extreme dry periods (Bunn et al. 2015). Over half of the current coffee area in Central America will experience a decline in its suitability for coffee production under RCP 2.6 (less severe climate scenarios) by 2050; under the more extreme RCP 8.5, most coffee areas would have marginal and moderate suitability (Lara-Estrada et al. 2021). The impact of pests and diseases, resulting from warmer conditions, will increase and may reduce the quality of coffee beans as well (Magrach and Ghazoul 2015).

Despite the increasing scientific attention to carbon sequestration in coffee agroforestry systems, we identified some gaps that need to be covered to advance knowledge on the subject. First, a few studies have analyzed the impact of climate change on C reserves in coffee plantations. Ruíz-García et al. (2022) found decreases (0.77 to 8.75 MgC ha^{-1}) in C stocks through a simulation of aboveground biomass and SOC in coffee plantations in Veracruz, Mexico, applying climate change scenarios using the CO2Fix model. This topic is important in the context of REDD+ (Reducing Emissions from Deforestation and Degradation), in which the CAFS play an important role in climate change mitigation but at the same time are vulnerable to the impacts of global warming (Noponen et al. 2013). In addition, recent regulations such as Deforestation-Free Products (DFPs), which entered into force in the European Union (EU), promote avoiding buying, using, and consuming products that contribute to deforestation and forest degradation (coffee, oil palm, soy, cocoa, beef, and wood) (Berning and Sotirov 2024; Conte Grand et al. 2023). Second, there is a lack of studies regarding the economic advantages and markets of C storage in coffee agroforestry systems. In our literature review, not many publications were found referring to this topic. One of the few is the work by Goncalves et al. (2021) who carried out simulations of economic indicators (net present value, internal rate of return, and payback period) examining the effect on the profitability of coffee production gained by adding the sale of C in biomass.

C stocks in coffee agroforestry systems: a meta-analysis

Our results showed that Costa Rica, Ethiopia, and Mexico are the countries with the most studies on carbon storage in coffee agroforestry systems. Traditional polyculture and shade specialized plantation are the systems with the most studies. Traditional polyculture is the most common system in many countries, and in regions such as Mexico and Central America (Guatemala, Honduras), Africa (Ethiopia, Uganda), and Asia (Indonesia, India) (Poncet et al. 2024; Toledo and Moguel 2012). In this coffee agroforestry system, the tree layer is a combination of native and/or introduced species, used mainly to shade coffee plants, but they have another benefit which may include food, fiber, wood, or environmental services (Nair 2021). Unshaded coffee-growing systems are more usual in Brazil and Vietnam, where coffee production is more intense to increase yield but biodiversity and environmental services are lower (Poncet et al. 2024; Perfecto et al. 2019).

According to our findings, coffee agroforestry systems store higher C stocks than unshaded systems due to the presence of multipurpose perennial species in the shade layer. However, there is a broad variation in total C stocks in CAFS (25.64 to 439 MgC ha^{-1}) according to the density of tree and coffee plants, diameter, and age and type of trees, as well as climate conditions, management of the plot, and soil properties (França et al. 2022; Latifah et al. 2022; Niguse et al. 2022; Segnini et al. 2011; Segura et al. 2006; Soto-Pinto et al. 2010; Tesfay et al. 2022). Our results showed that rustic systems store more total C stock (439 MgC ha^{-1}). In these systems, the high amount of AGC (274 MgC ha^{-1}) is due to the presence of thick native trees in the shade layer (*Olea capensis*, *Pouteria adolfi-friederici* and *Syzigium guineense*) (De Beenhouwer et al. 2016). In rustic systems, the original shrub layer is removed to plant coffee and the tree layer maintains its natural structure and composition (Toledo and Moguel 2012). This allows the wild trees to be conserved (Wright et al. 2024) and AGC to accumulate since pruning and thinning do not take place (Escamilla and Díaz 2016).

Our results showed that trees are the reservoir in AGC with the greatest potential to store C in CAFS, and that many factors influence this characteristic. Trees with high wood density can store more C compared to species with lower wood density; however, high-density wood species generally require a longer growth period than those with lower density (Petrea et al. 2024; Guo et al. 2024; Mo et al. 2024). Tree management in CAFS is another factor that influences AGC accumulation, mainly in traditional polycultures, commercial polycultures, and shade specialized plantations. Optimal growth of wood species is favored through pest and disease management and thinning to reduce interspecific and intraspecific competition (Torrez et al. 2023; Harvey et al. 2021). Tree renewal with species highly adapted to climate change conditions enables C accumulation in the tree reservoir (Ruíz-García et al. 2022; Magrach and Ghazoul 2015). Coffee varieties are diverse in phenology, height, and biomass, which influence C storage in the coffee plant reservoir. Typica and Bourbon lineages were the first domesticated coffee (*Coffea arabica*) varieties, which had taken place by the late 1600s in Yemen. Since then, through selection and combination, a wide range of varieties has appeared, some of them crossed with *C. canephora*, such as the Catimor and Sarchimor groups. In general, the trees of Catimor and Sarchimor groups are of low height and contain less biomass compared with those of the Typica and Bourbon groups (WCR 2023). Litterfall by shade trees and management influence the C storage potential in herbaceous and litter reservoirs. Deciduous trees (e.g., *Albizia gummifera*, *Cordia alliodora*) contribute more to litterfall stock than do evergreen trees; moreover, coarse leaves (e.g., macadamia, oaks) decompose slowly and so remain longer on the forest floor (Chatterjee et al. 2019; Dossa et al. 2008). Tree layer and litterfall in CAFS also reduce the sunlight reaching the forest floor, decreasing herbaceous growth (Nair 2021). Furthermore, farmers usually prune weeds in coffee agroecosystems to reduce competition with coffee plants (Teixeira et al. 2021; Tadesse et al. 2014).

In this study, soil is the reservoir with the highest amount of C in CAFS (Cristóbal-Acevedo et al. 2019; Espinoza-Domínguez et al. 2012; Negash and Kanninen 2015; Valdés-Velarde et al. 2022), with andisols, nitosols, and leptosols being the soils reported to have the most SOC content. Our results show that the highest amount of SOC (249.69 MgC ha^{-1}) is reported by Toru and Kibret (2019) in an SSP system of Ethiopia with leptosols as the dominant soil and *Cordia africana* as the shade tree. In Yunnan, China, Xiao et al. (2021) report similar SOC content in traditional polyculture (90 MgC ha^{-1}) and unshaded coffee plantations (87.5 MgC ha^{-1}). The shade species in POL-C were rubber (*Hevea brasiliensis*), macadamia (*Macadamia ternifolia*) and longan (*Euphoria longan*). SOC stock in coffee plantations is influenced by environmental and management conditions. França et al. (2022) found a difference of 30 MgC ha^{-1} in coffee plantations at high elevations (1,260 masl) compared to those at low elevations (940 masl). This is because SOC is more stable in areas with lower temperatures (high elevation) where the soil microbiota is less active, in contrast to low areas where the temperature is higher and the microorganisms are more active and degrade soil organic matter (SOM) more quickly (Eldor and Serita 2023). The relationship between temperature and SOC dynamics is an important issue in the context of climate change (Xiao et al. 2020). Management also affects the SOC in terms of soil quality and functionality. Agronomic practices that alter soil structure decrease soil aggregates and promote SOC mineralization; in addition, soil loss due to water erosion reduces SOC content in the upper horizons (Cerretelli et al. 2023; Lal 2016). A constant supply of SOM favors the accumulation of SOC, especially by recalcitrant materials that allow the accumulation of SOC for longer periods. Litterfall, and compost in many CAFS, are the main organic materials that supply SOM pools in coffee agroecosystems where their decomposition rates are influenced by the soil microbiome (Notaro et al. 2014; Latifah et al. 2022). Organic and shaded coffee-growing systems increase the soil microbial biomass compared to conventional systems, where the use of inorganic fertilizers and pesticides decreases the presence of soil microorganisms (Paolini 2018).

Our study contributes to the knowledge of C storage potential in coffee agroforestry systems in a comparison with unshaded systems. Nevertheless, we identified a lack of studies about the relationship of C storage with soil microbiota as well as with the quality of soil organic matter. We also observed the need to develop carbon flux models in CAFS to simulate their dynamics within the reservoirs and correlate these with biophysical and management characteristics.

CONCLUSIONS

Bibliometric analysis and meta-analysis enabled a systematic quantitative analysis of C storage in coffee agroforestry systems. Costa Rica, Ethiopia, and Mexico are the countries with the most publications referring to C quantification in coffee plantations. It is necessary to promote international finance and collaboration to improve research in low-income countries with coffee-growing systems. Environmental science, forestry and ecology are the main research areas where publications on these topics are grouped, but socioeconomic studies also seem necessary to evaluate the potential of CAFS in carbon markets. CAFS store more C compared to unshaded systems; however, there is considerable variability in C content due to density, diameter, age, and type of trees; climate conditions; management; and soil properties. We found 156 multipurpose perennial species in the shade layer, the genera *Albizia, Cordia, Erythrina, Ficus, Inga, Musa, Persea*, and *Terminalia* being the most representative in CAFS. Generally, the species used in each coffee agroforestry system are a mixture of native and introduced species. It is observed that selecting native species promotes the resilience of the system, as these are adapted to the environmental conditions of the region. Soil is the reservoir with the highest amount of C in CAFS, of which andisols, nitosols, and leptosols are the soils with the most SOC content. We observed gaps in research related to the economic advantages and markets of C storage in coffee agroforestry systems, as well as in the evaluation of deforestation and land use change to identify the implications for C reserves in coffee plantations. Further studies are required to identify the impact of climate change on C stocks in CAFS.

Declarations

ACKNOWLEDGMENTS

We gratefully acknowledge the work carried out by the researchers whose published data was used for this study. We thank the Universidad de Santiago de Compostela and the Universidad Autónoma Chapingo for access to bibliographic databases.

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Funding Declaration: No funding was received for conducting this study.

Author Contribution Declaration: Juan Angel Tinoco and Agustín Merino wrote the main manuscript text. Eduardo Valdés-Velarde prepared all figures. Esteban Escamilla-Prado prepared all tables. All authors reviewed the manuscript.

References

1. Andersson L (2018) Achieving the Global Goals through agroforestry. Agroforestry Network and Vi-Skogen, Stockholm.
2. Aria M, Cuccurullo C (2017). Bibliometrix: An R-tool for comprehensive science mapping analysis. Journal of Informetrics 11(4):959-975. https://doi.org/10.1016/J.JOI.2017.08.007
3. Augustinus C, Alexander S (2022) Global land outlook. United Nations Convention to Combat Desertification, Bonn.
4. Ayala-Montejo D, Monterroso-Rivas AI, Baca-Del Moral J, Escamilla-Prado E, Sánchez-Hernández R, Pérez-Nieto J, Rajagopal I, Alegre-Orihuela J. C, Valdes-Velarde E (2020) Identifying research areas on carbon and nitrogen dinamyc in coffee agroforestry systems in Mexico. Tropical and Subtropical Agroecosystems 23 (2020): #99. https://www.revista.ccba.uady.mx/ojs/index.php/TSA/article/view/3403
5. Berning L, Sotirov M (2024) The coalitional politics of the European Union Regulation on deforestation-free products. Forest Policy and Economics 158(2024)103102. https://doi.org/10.1016/j.forpol.2023.103102
6. Bianco GB (2020) Climate change adaptation, coffee, and corporate social responsibility: challenges and opportunities. International Journal of Corporate Social Responsibility 5,3(2020). https://doi.org/10.1186/s40991-020-00048-0
7. Bunn C, Laderach P, Perez Jimenez JG, Montagnon C, Schilling T (2015) Multiclass classification of agro-ecological zones for arabica coffee: an improved understanding of the impacts of climate change. Plos One 10(10):e0140490. https://doi.org/10.1371/journal.pone.0140490

8. Cerretelli S, Castellanos E, González-Mollinedo S, Lopez E, Ospina A, Haggar J (2023) A scenario modelling approach to assess management impacts on soil erosion in coffee systems in Central America. CATENA 228 (2023):107182. https://doi.org/ARTN10718210.1016/j.catena.2023.107182
9. Chatterjee N, Nair PKR, Nair VD, Bhattacharjee A, Filho E, Muschler RG, Noponen MRA (2019) Do coffee agroforestry systems always improve soil carbon stocks deeper in the soil?—A case study from Turrialba, Costa Rica. Forests 11(1):49. https://doi.org/10.3390/f11010049
10. Conte Grand M, Schulz-Antipa P, Rozenberg J (2023) Potential exposure and vulnerability to broader climate-related trade regulations: an illustration for LAC countries. Environment, Development and Sustainability 26(3):6195-6220. https://doi.org/10.1007/s10668-023-02958-y
11. Cristóbal-Acevedo D, Tinoco-Rueda JA, Prado-Hernández JV, Hernández-Acosta E (2019) Soil carbon and nitrogen in tropical montane cloud forest, agroforestry and coffee monoculture systems. Revista Chapingo Serie Ciencias Forestales y del Ambiente 25(2):169-184. https://doi.org/10.5154/r.rchscfa.2018.09.070
12. De Beenhouwer M, Geeraert L, Mertens J, Van Geel M, Aerts R, Vanderhaegen K, Honnay O (2016) Biodiversity and carbon storage co-benefits of coffee agroforestry across a gradient of increasing management intensity in the SW Ethiopian highlands. Agriculture, Ecosystems & Environment 222:193-199. https://doi.org/10.1016/j.agee.2016.02.017
13. Donovan J, Blare T, Peña M (2019) Multiple certification uptake by coffee businesses: Evidence of functions and benefits from Central America. Business Strategy & Development 3(3):264-276. https://doi.org/10.1002/bsd2.93
14. Donthu N, Kumar S, Mukherjee D, Pandey N, Lim WM (2021) How to conduct a bibliometric analysis: An overview and guidelines. Journal of Business Research 133:285-296. https://doi.org/10.1016/j.jbusres.2021.04.070
15. Dossa E. L., Fernandes, E. C. M., Reid, W. S., & Ezui, K. (2007). Above- and belowground biomass, nutrient and carbon stocks contrasting an open-grown and a shaded coffee plantation. Agroforestry Systems 72(2):103-115. https://doi.org/10.1007/s10457-007-9075-4
16. Dossa E L, Fernandes ECM, Reid WS, Ezui K (2008) Above- and belowground biomass, nutrient and carbon stocks contrasting an open-grown and a shaded coffee plantation. Agroforestry Systems 72(2):103-115. https://doi.org/10.1007/s10457-007-9075-4
17. Eldor AP, Serita DF (2023) Soil microbiology, ecology and biochemistry (5th ed.). Elsevier. https://doi.org/10.1016/c2019-0-04976-x
18. Escamilla E, Díaz S (2016) Sistemas de cultivo de café en México. Centro Nacional de Investigación, Innovación y Desarrollo Tecnológico del Café. Mexico.
19. Espinoza-Domínguez W, Krishnamurthy L, Vázquez-Alarcón A, Torres- Rivera A (2012) Almacén de carbono en sistemas agroforestales con café. Revistas Chapingo Seria Ciencias Forestales y del Ambiente XVIII(1):57-70. https://doi.org/10.5154/r.rchscfa.2011.04.030
20. Faure G, Coq JFL, Vagneron I, Hocdé H, Muñoz GS, Kessari M (2012) Stratégies des organisations de producteurs de café au Costa Rica vis-à-vis des certifications environnementales et sociales.

Cahiers Agricultures 21(2-3):162–168. https://doi.org/10.1684/agr.2012.0545

21. Fragomeli R, Annunziata A, Punzo G, Fragomeli R, Annunziata A, Punzo G (2024) Promoting the transition towards agriculture 4.0: a systematic literature review on drivers and barriers. Sustainability 16, 2425. https://doi.org/10.3390/su16062425
22. França EM, Silva CA, Zinn YL, Lazcano C (2022) Coffee plantations can strongly sequester soil organic carbon at high altitudes in Brazil. Soil Research 61(2):198-207. https://doi.org/10.1071/sr22103
23. Goncalves N, Andrade D, Batista A, Cullen L, Souza A, Gomes H, Uezu A (2021) Potential economic impact of carbon sequestration in coffee agroforestry systems. Agroforestry Systems 95(2):419-430. https://doi.org/10.1007/s10457-020-00569-4
24. Guo P, Zhao X, Wang X, Feng Q, Li X, Tan Y (2024) Wood density and carbon concentration jointly drive wood carbon density of five rosaceae tree species. Forests 15:1102. https://doi.org/10.3390/f15071102
25. ICO (2023) Coffee report and outlook. International Coffee Organization, London.
26. Intergovernmental Panel on Climate Change (2022) Climate change and land. Cambridge University Press, New York. https://doi.org/10.1017/9781009157988
27. Jhariya MK, Yadav DK, Banerjee A (2019) Agroforestry and climate change: issues and challenges. Apple Academic-Press, Inc., Florida.
28. Jurjonas M, Crossman K, Solomon J, Baez WL (2016) Potential links between certified organic coffee and deforestation in a protected area in chiapas, Mexico. World Development 78:13-21. https://doi.org/10.1016/j.worlddev.2015.10.030
29. Lal R (2016) Soil health and carbon management. Food and Energy Security 5(4):212-222. https://doi.org/10.1002/fes3.96
30. Latifah S, Sani MA, Simorangkir AJF, Muhdi (2022) Species diversity and carbon storage of undergrowth and litter in the agroforestry system of north sumatera-indonesia. International Journal of Conservation Science 13(3):1003-1014
31. Magrach A, Ghazoul J (2015) Climate and pest-driven geographic shifts in global coffee production: implications for forest cover, biodiversity and carbon storage. Plos One 10(7):e0133071. https://doi.org/10.1371/journal.pone.0133071
32. McFarlane I (2023) State of world population report 2023. United Nations, New York. https://doi.org/https://doi.org/10.18356/9789210027137
33. Melo E, Medina B, León R, Vargas V, Jiménez G, Lennox J, Meléndez M, Chocooj ME (2021) El estado de las NAMA-café y lineamentos regionales para iniciativas sobre café y clima en América Central, República Dominicana y México. Agroforestería en las Américas (51):55-66.
34. Mo L, Crowther TW, Maynard DS, van den Hoogen J, Ma H, Bialic-Murphy L et al (2024) The global distribution and drivers of wood density and their impact on forest carbon stocks. Nat Ecol Evol 8(12):2195-2212. https://doi.org/10.1038/s41559-024-02564-9

35. Nair PKR (2011) Carbon sequestration studies in agroforestry systems: a reality-check. Agroforestry Systems 86(2): 243-253. https://10.1007/s10457-011-9434-z
36. Nair PKR, Kumar BM, Nair DV (2021) An introduction to agroforestry (2nd ed.). Springer, Cham. https://doi.org/https://doi.org/10.1007/978-3-030-75358-0
37. Negash M, Kanninen M (2015) Modeling biomass and soil carbon sequestration of indigenous agroforestry systems using CO2FIX approach. Agriculture, Ecosystems & Environment 203:147-155. https://doi.org/10.1016/j.agee.2015.02.004
38. Negash M, Starr M (2015) Biomass and soil carbon stocks of indigenous agroforestry systems on the south-eastern Rift Valley escarpment, Ethiopia. Plant and Soil 393(1-2):95-107. https://doi.org/10.1007/s11104-015-2469-6
39. Niguse G, Iticha B, Kebede G, Chimdi A (2022) Contribution of coffee plants to carbon sequestration in agroforestry systems of Southwestern Ethiopia. The Journal of Agricultural Science 160(6):440-447. https://doi.org/10.1017/S0021859622000624
40. Noponen MRA, Haggar JP, Edwards-Jones G, Healey JR (2013) Intensification of coffee systems can increase the effectiveness of REDD mechanisms. Agricultural Systems 119:1-9. https://doi.org/10.1016/j.agsy.2013.03.006
41. Notaro M, Gary C, Le Coq JF, Metay A, Rapidel B (2022) How to increase the joint provision of ecosystem services by agricultural systems. Evidence from coffee-based agroforestry systems. Agricultural Systems 196:103332. https://doi.org/10.1016/j.agsy.2021.103332
42. Paolini JE (2018) Microbial activity and microbial biomass in coffee soils of the Venezuelan Andes. Revista Terra Latinoamericana 36(1):13-22. https://doi.org/10.28940/terra.v36i1.257
43. Paul J, Barari M (2022) Meta-analysis and traditional systematic literature reviews—What, why, when, where, and how? Psychology and Marketing 39:1099-1115
44. Perfecto I, Jiménez-Soto ME, Vandermeer J (2019) Coffee landscapes shaping the anthropocene. Current Anthropology 60(S20):S236-S250. https://doi.org/10.1086/703413
45. Perfecto I, Vandermeer HJ, Philpott S (2014) Complex ecological interactions in the coffee agroecosystem. Annual Review of Ecology, Evolution, and Systematics 45(1): 21. https://doi.org/10.1146/annurev-ecolsys-120213-091923
46. Petrea S, Radu GR, Braga CI, Cucu AB, Serban T, Zaharia A et al (2024) The role of wood density variation and biomass allocation in accurate forest carbon stock estimation of european beech (Fagus sylvatica L.) mountain forests. Forests 15(3):404. https://doi.org/10.3390/f15030404
47. Pham Y, Reardon-Smith K, Mushtaq S, Cockfield G (2019) The impact of climate change and variability on coffee production: a systematic review. Climatic Change 156(4):609-630. https://doi.org/10.1007/s10584-019-02538-y
48. Poncet V, van Asten P, Millet CP, Vaast P, Allinne C (2024) Which diversification trajectories make coffee farming more sustainable? Current Opinion in Environmental Sustainability 68:101436. https://doi.org/10.1016/j.cosust.2024.101432

49. Rah E, Läderach P, Baca M, Cressy C, Schroth G, Malin D, van Rikxoort H, Shriver J (2013) Climate change adaptation, mitigation and livelihood benefits in coffee production: where are the synergies? Mitigation and Adaptation Strategies for Global Change 19(8):1119-1137. https://doi.org/10.1007/s11027-013-9467-x
50. Reyes-González F, Escamilla-Prado E, Pérez-Portilla E, Almaguer-Vargas G, Curiel-Rodríguez A, Hernández-Gómez JA (2016) Evaluación de productividad, calidad física y sensorial del grano del café (Coffea arabica L.), en cafetos injertados en el CRUO, Huatusco, Veracruz. Revista de Geografía Agrícola (56):45-53.
51. Ruíz-García P, Monterroso-Rivas AI, Valdés-Velarde E, Escamilla-Prado E, Gómez-Díaz JD (2022) Reservas de carbono en sistemas agroforestales con café (C. arabica L.) ante el cambio climático: caso México. Agronomía Mesoamericana 33(3):48671-48671. https://doi.org/10.15517/am.v33i3.48671
52. Sayekti C, Prihandono I (2023) Regulating sustainable coffee: an analysis of smallholder farmers' participation in certifications. World Journal of Entrepreneurship, Management and Sustainable Development 19(1-2):111-123. https://doi.org/10.47556/j.Wjemsd.19.1-2.2023.9
53. Schmitt L, Perfecto I (2021) Coffee leaf litter decomposition: Short term home-field advantage in shaded coffee agro-ecosystems. Applied Soil Ecology 161: 103854. https://doi.org/10.1016/j.apsoil.2020.103854
54. Segnini A, Posadas A, Quiroz R, Milori DMBP, Vaz CMP, Martin-Neto L (2011) Soil carbon stocks and stability across an altitudinal gradient in southern Peru. Journal of Soil and Water Conservation 66(4):213-220. https://doi.org/10.2489/jswc.66.4.213
55. Segura M, Kanninen M, Suárez D (2006) Allometric models for estimating aboveground biomass of shade trees and coffee bushes grown together. Agroforestry Systems 68(2):143-150. https://doi.org/10.1007/s10457-006-9005-x
56. Sena A (2019) Land under pressure – health under stress. United Nations Convention to Combat Desertification, Bonn.
57. Sharma R, Mina U, Kumar BM (2022) Homegarden agroforestry systems in achievement of sustainable development goals. A review. Agron Sustain Dev 42:44. https://doi.org/10.1007/s13593-022-00781-9
58. Singh RK, Sinha VSP, Joshi PK, Kumar M (2020) Modelling agriculture, forestry and other land use (AFOLU) in response to climate change scenarios for the SAARC nations. Environ Monit Assess 192(4): 236. https://doi.org/10.1007/s10661-020-8144-2
59. Solér C, Sandström C, Skoog H, Solér C, Sandström C, Skoog H (2016) How can high-biodiversity coffee make it to the mainstream market? the performativity of voluntary sustainability standards and outcomes for coffee diversification. Environmental Management 59:230-248. https://doi.org/10.1007/s00267-016-0786-z
60. Soto-Pinto L, Anzueto M, Mendoza J, Ferrer GJ, de Jong B (2010) Carbon sequestration through agroforestry in indigenous communities of Chiapas, Mexico. Agroforestry Systems 78(1):39-51.

https://doi.org/10.1007/s10457-009-9247-5

61. Soto-Pinto L, Colmenares SE, Kanter MB, Cruz AL, Lugo EE, Hernández BH, Jiménez-Soto E (2022) Contributions of agroforestry systems to food provisioning of peasant households: conflicts and synergies in Chiapas, Mexico. Frontiers in Sustainable Food Systems 5:756611. https://doi.org/10.3389/FSUFS.2021.756611/BIBTEX
62. Soto-Pinto L, Jiménez-Ferrer G (2018) Contradicciones socioambientales en los procesos de mitigación, asociados al ciclo del carbono en sistemas agroforestales. Madera Y Bosques 24. https://doi.org/10.21829/myb.2018.2401887
63. Tadesse G, Zavaleta E, Shennan C (2014) Effects of land-use changes on woody species distribution and above-ground carbon storage of forest-coffee systems. Agriculture, Ecosystems & Environment 197: 21-30. https://doi.org/10.1016/j.agee.2014.07.008
64. Teixeira HM, Bianchi FJJA, Cardoso IM, Tittonell P, Peña-Claros M (2021) Impact of agroecological management on plant diversity and soil-based ecosystem services in pasture and coffee systems in the Atlantic forest of Brazil. Agriculture, Ecosystems & Environment 305:107171-107171. https://doi.org/10.1016/j.agee.2020.107171
65. Tesfay HM, Negash M, Godbold DL, Hager H (2022) Assessing carbon pools of three indigenous agroforestry systems in the southeastern Rift-Valley landscapes, Ethiopia. Sustainability 14(8):4716. https://doi.org/10.3390/su14084716
66. Toledo V, Moguel P (2012) Coffee and sustainability: the multiple values of traditional shaded coffee. Journal of Sustainable Agriculture 36(3):353–377. https://doi.org/10.1080/10440046.2011.583719
67. Toru T, Kibret K (2019) Carbon stock under major land use/land cover types of Hades sub-watershed, eastern Ethiopia. Carbon Balance and Management 14, 7 (2019). https://doi.org/10.1186/s13021-019-0122-z
68. Valdés-Velarde E, Vázquez-Domínguez LP, Tinoco-Rueda JA, Sánchez-Hernández R, Salcedo-Pérez E, Lagunes-Fortiz E (2022) Servicio ecosistémico de carbono almacenado en cafetales bajo sombra en sistema agroforestal. Revista Mexicana de Ciencias Agrícolas 13(28):287-297. https://doi.org/10.29312/remexca.v13i28.3283
69. Van Eck NJ, Waltman L (2010) Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84(2):523-538. https://doi.org/10.1007/s11192-009-0146-3
70. Van Rikxoort H, Läderach P, Van Hal J (2013) The potential of latin american coffee production systems to mitigate climate change. In: Leal Filho, W. (eds) Climate change and disaster risk management. Springer, Berlin, pp 655-679 https://doi.org/10.1007/978-3-642-31110-9_43
71. Vandermeer J, Perfecto I, Philpott S (2010) Ecological complexity and pest control in organic coffee production: uncovering an autonomous ecosystem service. BioScience 60(7):527-537. https://doi.org/10.1525/bio.2010.60.7.8
72. WCR (2023) Arabica varieties, a global catalog of arabica coffee varieties from around the world. World Coffee Research. Portland.

73. Webb NP, Marshall NA, Stringer LC, Reed MS, Chappell A, Herrick JE (2017) Land degradation and climate change: building climate resilience in agriculture. Frontiers in Ecology and the Environment 15(8):450-459. https://doi.org/10.1002/fee.1530
74. Wright DR, Gordon A, Bennett RE, Selinske MJ, Lentini PE, Garrard GE, Rodewald AD, Bekessy SA (2024) Biodiverse coffee plantations provide co-benefits without compromising yield. Journal of Sustainable Agriculture and Environment 3(3):1-12. https://doi.org/10.1002/sae2.70005
75. Xiao Z, Bai X, Zhao M, Luo K, Zhou H, Ma G, Guo T, Su L, Li J (2021) Soil organic carbon storage by shaded and unshaded coffee systems and its implications for climate change mitigation in China. *The Journal of Agricultural Science 158*(8-9):687-694. https://doi.org/10.1017/s002185962100006x

Figures

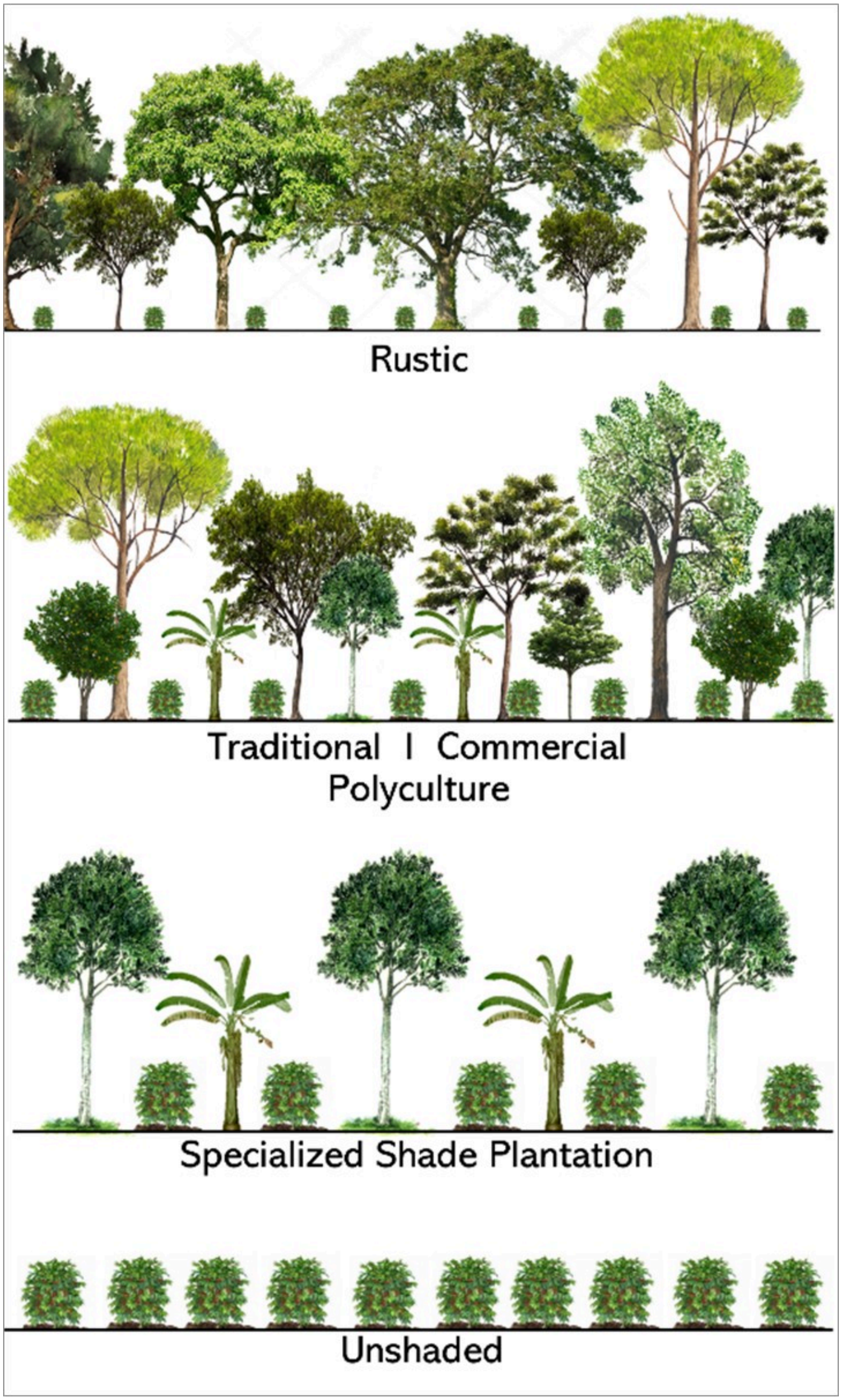

Figure 1

Main coffee-growing systems grouped by vegetation structure and composition

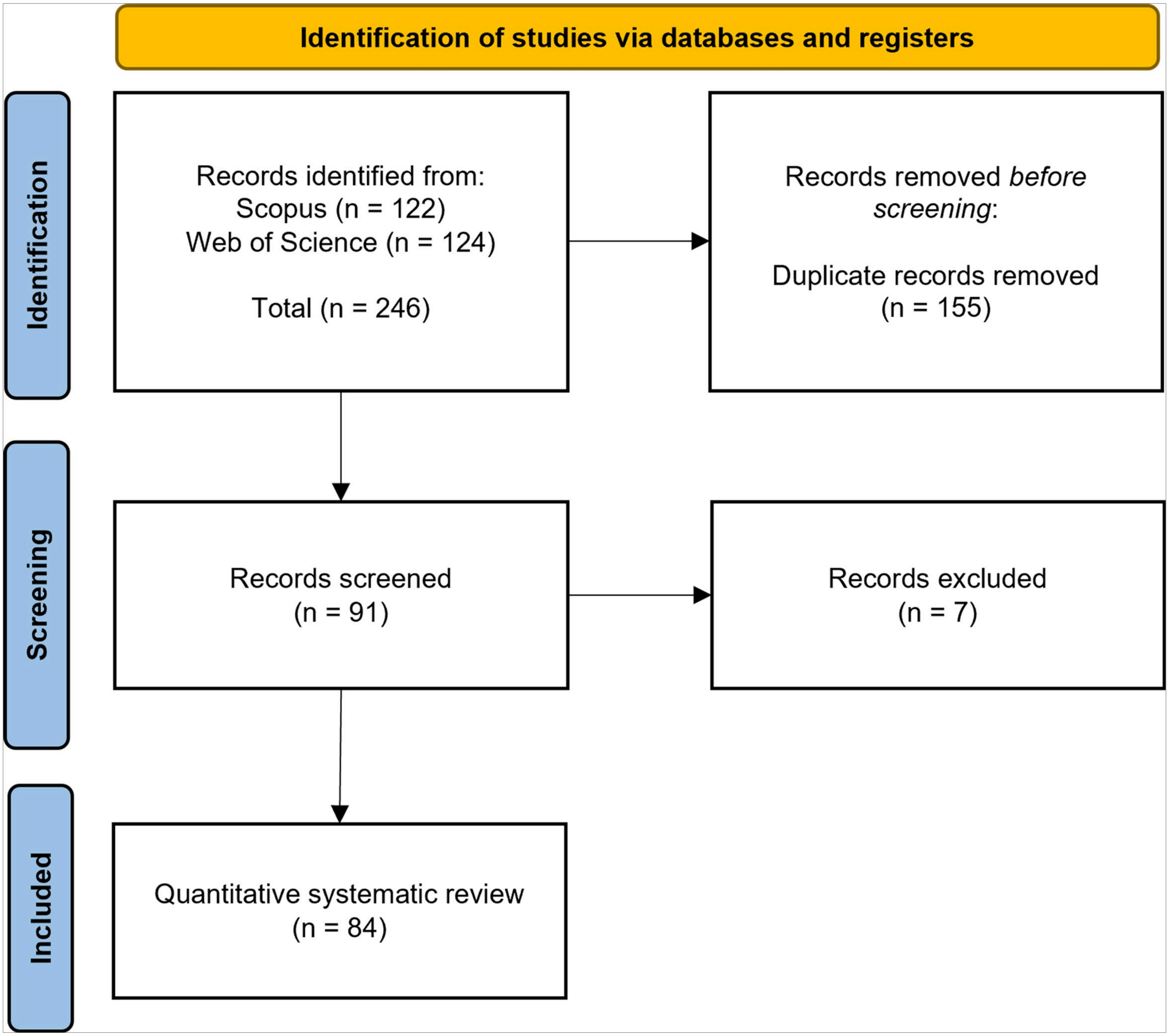

Figure 2

PRISMA flow diagram of the publication’s selection (Fragomeli et al. 2024)

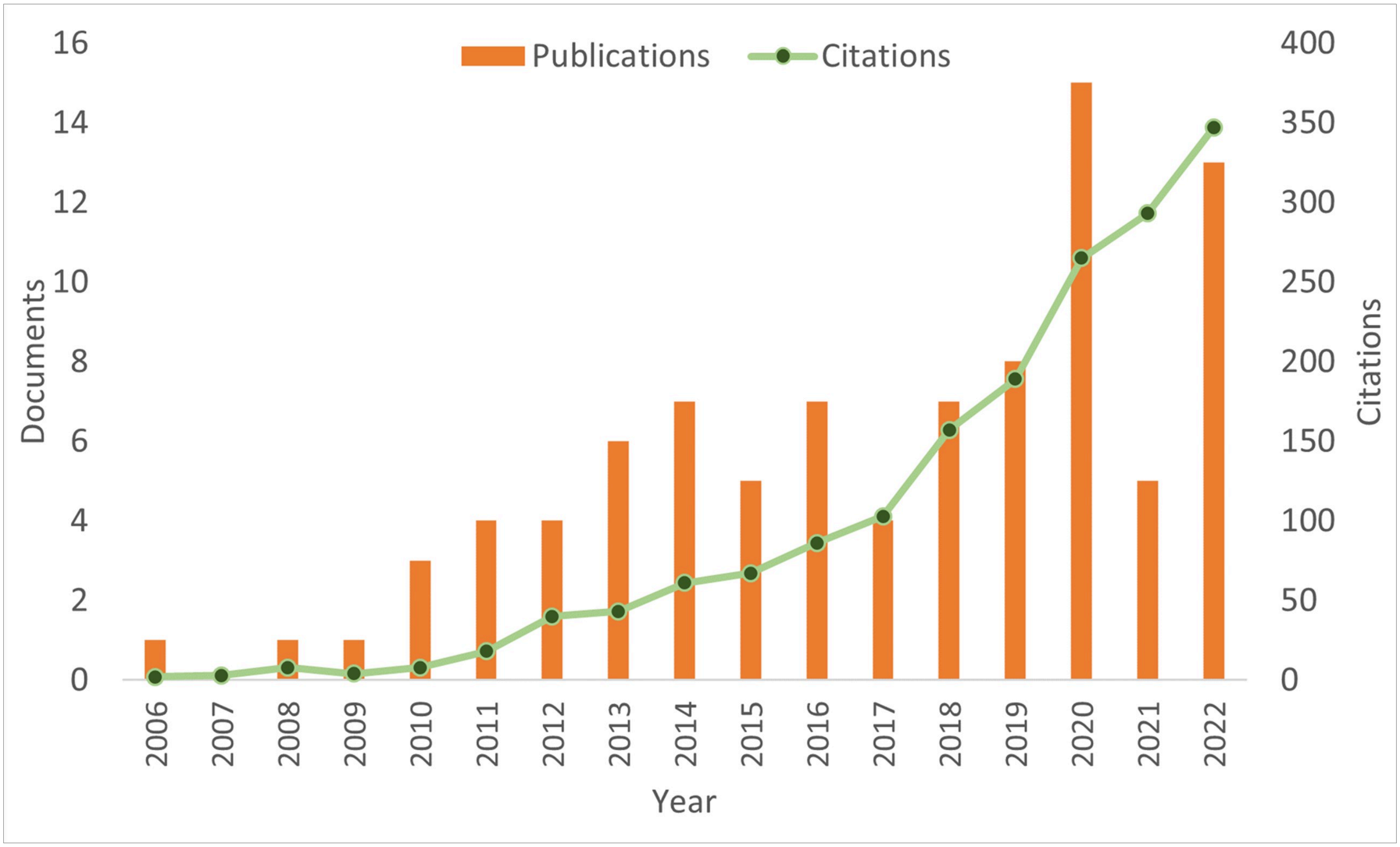

Figure 3

Temporal evolution of scientific publications on carbon storage in coffee agroforestry systems from 2006 to 2022

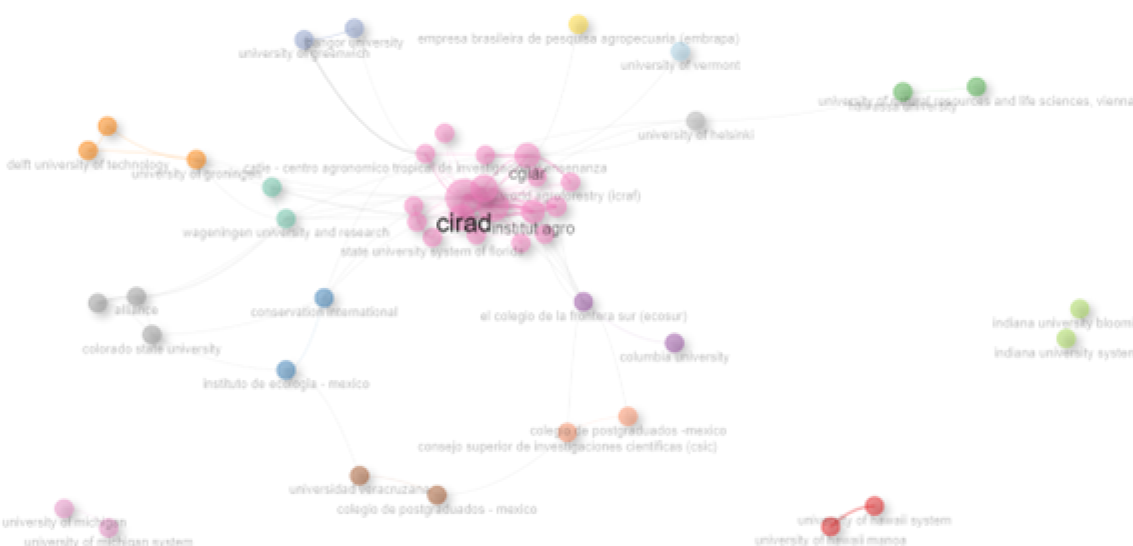

Figure 4

Institutional collaboration network obtained by R-tool Bibliometrix on carbon storage in coffee agroforestry systems from 2006 to 2022

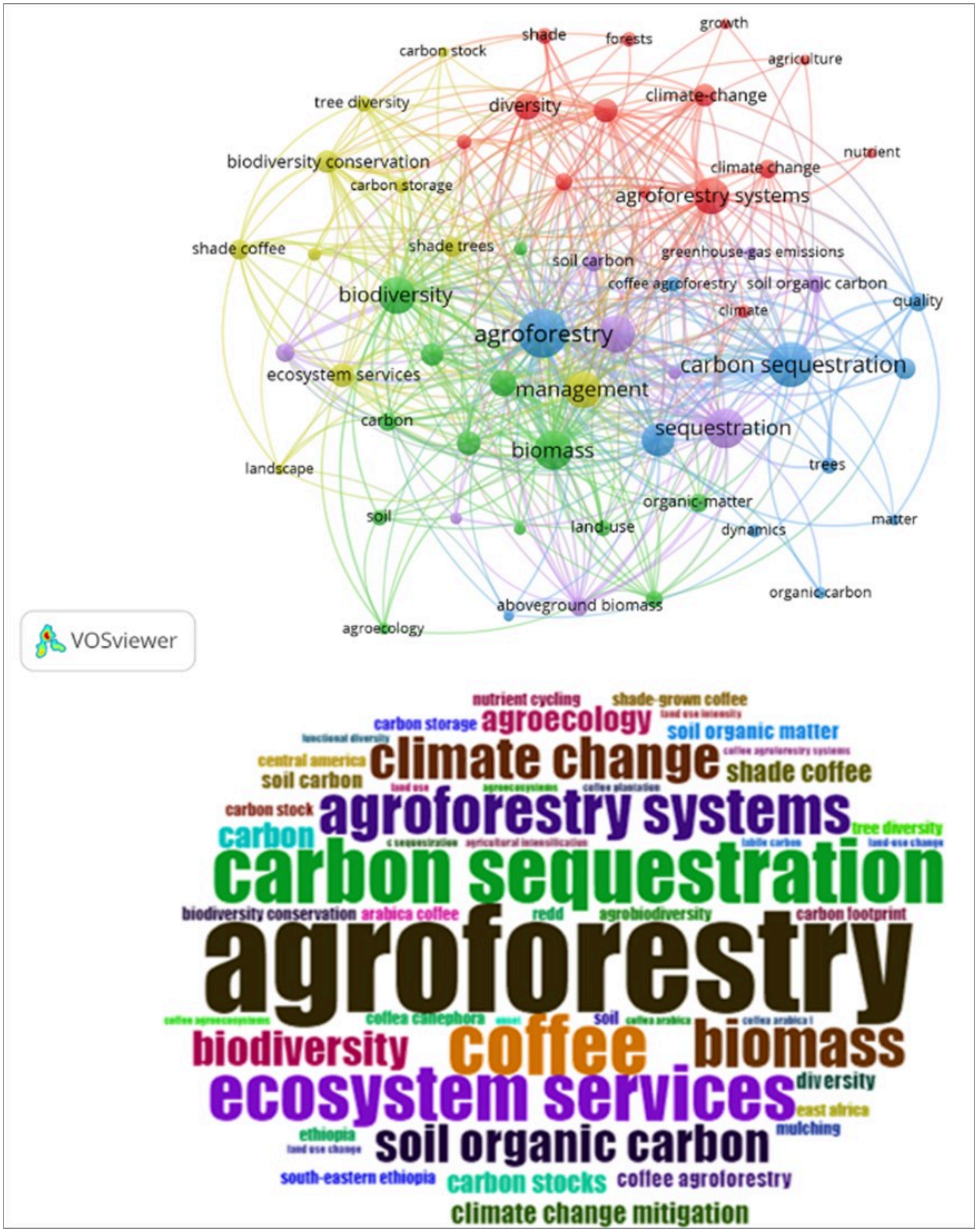

Figure 5

Map of most used keywords (top) and keywords cloud (bottom) in publications on carbon storage in coffee agroforestry systems from 2006 to 2022. Different colors represent the terms belonging to different clusters. The size of the circle and the letters is based on the number of occurrences of the term. The connecting lines indicate the 400 strongest co-occurrence links between the terms

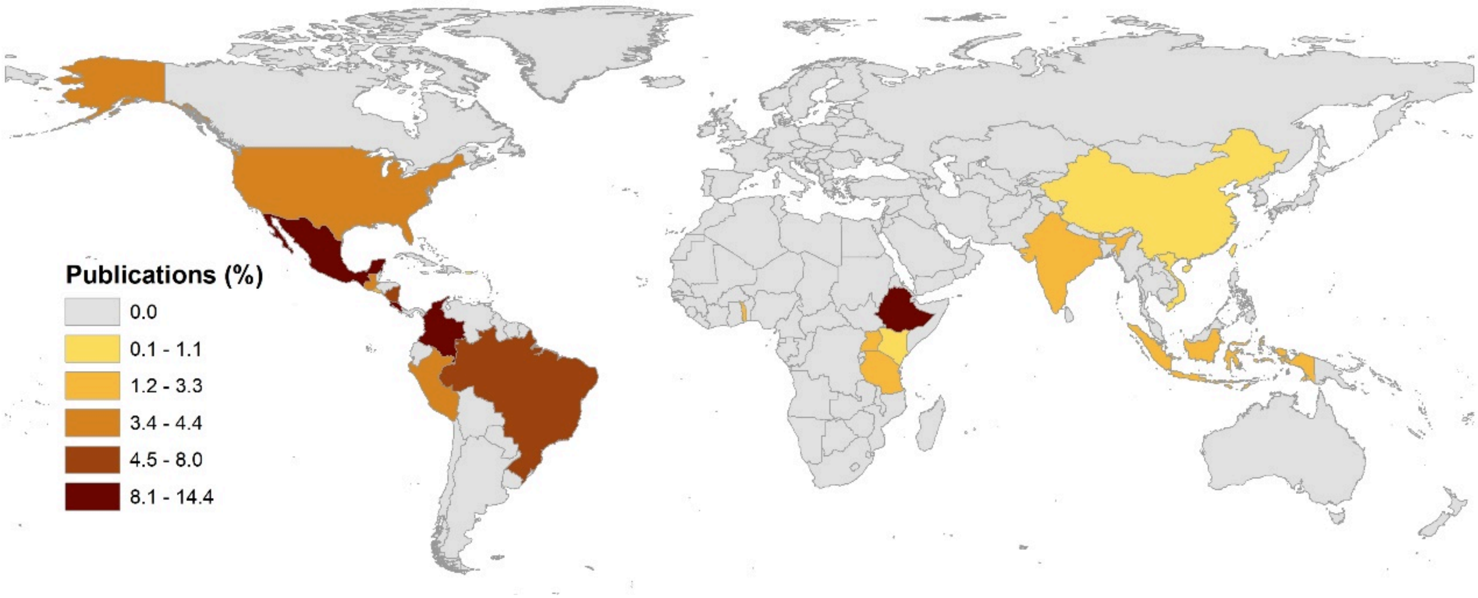

Figure 6

Map of the locations where studies included in the meta-analysis were carried out, according to the data from publications on carbon storage in coffee agroforestry systems from 2006 to 2022

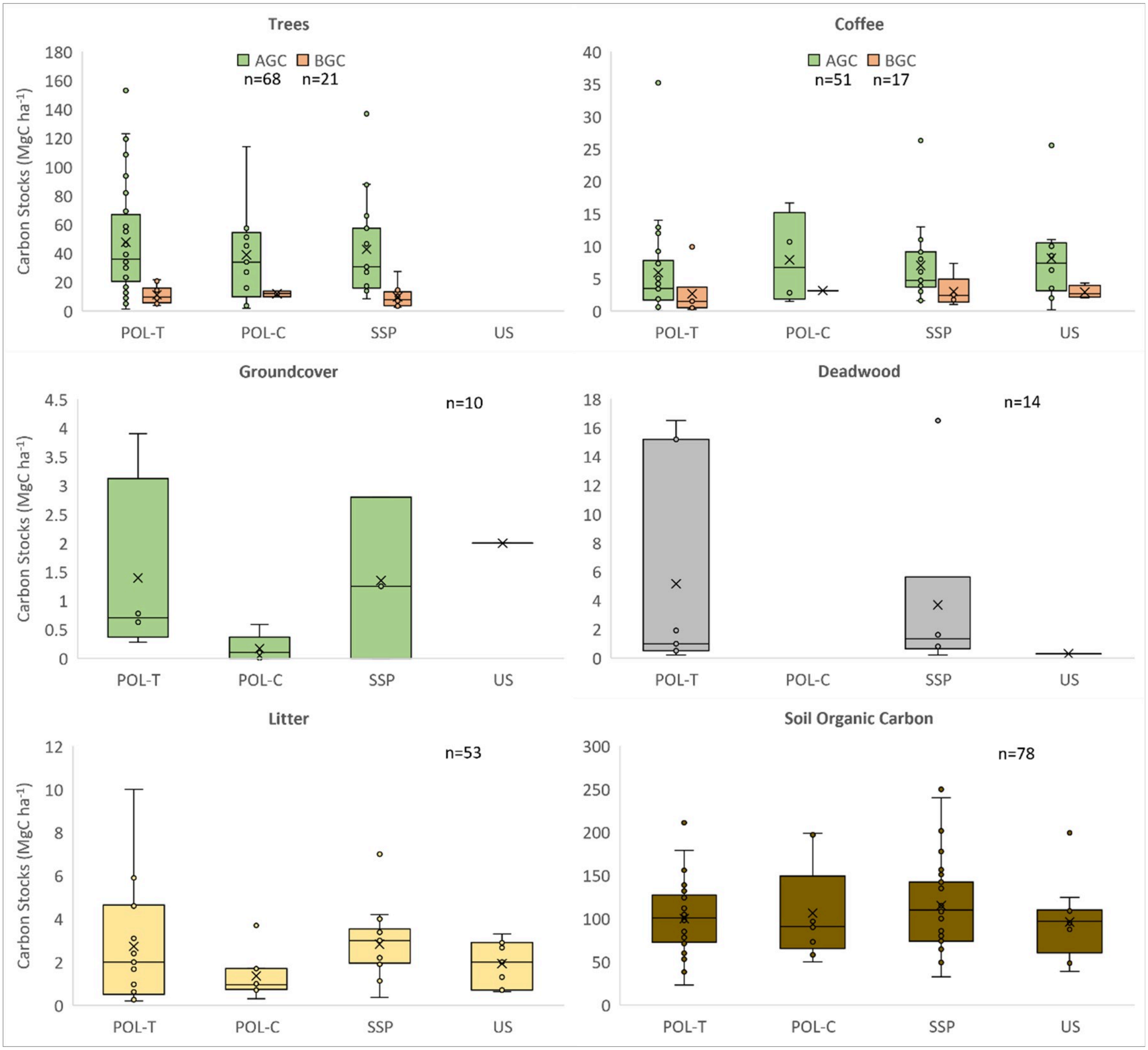

Figure 7

Carbon stocks per reservoir, distinguishing management systems (POL-C: Commercial Polyculture, POL-T: Traditional Polyculture, SSP: Specialized shade plantation, US: Unshaded). The data shown are mean values of 84 observations according to the data from publications on carbon storage in coffee agroforestry systems from 2006 to 2022