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Systematic evidence map of coffee agroecosystem management and biodiversity linkages in producing countries

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ABSTRACT

Coffee is one of the most important agricultural products globally, and its production has been boosted to fulfill the rising global demand. Despite being predominantly consumed in western countries, coffee is cultivated in many of the world's most biodiverse tropical regions, leading to tropical deforestation and biodiversity loss with further environmental and social implications. Despite extensive studies on the impacts of coffee farm management on biodiversity, the trends in research on this issue over the last two decades remain unclear. Therefore, this work was initiated with the aim of conducting a systematic evidence map study concerning the impacts of coffee production on biodiversity throughout tropical coffee-producing countries. After conducting a search of the literature in peer-reviewed journal databases and gray literature, we screened the identified papers using machine learning-related software, identifying a total of 292 studies for inclusion in the systematic map database and synthesis. We found that there was a trend for an increase in the number of publications examining the relationship between coffee cultivation and tropical biodiversity, with the majority of studies being conducted in Latin America. Among coffee management interventions, studies on the effects of land-use gradients driven by coffee cultivation and shade management on invertebrate biodiversity were identified as dominant topics. Meanwhile, there were fewer studies measuring the impacts of water management on tropical biodiversity. We suggest that these gaps become the focus of future research as such work might be essential to support more sustainable, cleaner and biodiversity-friendly forms of coffee production.

1. Introduction

The consumption of coffee, one of the world's most important and high-value agricultural products, has been rising over the last three decades, as indicated by the increasing yield, production, and export (ICO, 2020). These increasing trends are expected to continue as the demand for coffee is projected to grow by between 50 % and 163 % by 2050 (Killeen and Harper, 2016). This growth in demand will come not only from Europe and North America, but also from the Asia Pacific countries (ICO, 2020). In terms of economic value, globally, it has been estimated that coffee production is a source of income for 25 million farmer households (FAO, 2021). Around 70 % of these farmers cultivate coffee as smallholders and depend on coffee as the only major source of household income (Fridell et al., 2008). Moreover, the entire supply chain of coffee was reported to be worth more than US$173 billion in 2012 (ICO, 2014). Despite being predominantly consumed in western countries (FAO, 2021), coffee is cultivated in many of the world's most biodiverse tropical regions, such as Brazil, Indonesia, Colombia, and Vietnam (Myers et al., 2000). This is because coffee plants are very sensitive to climatic conditions and can only grow within a particular temperature and rainfall range (DaMatta and Ramalho, 2006; Tavares et al., 2018).

Similar to the case for other food crops (e.g., oil palm, soy, and cacao), coffee agriculture has also historically contributed directly and indirectly to deforestation, which has further environmental and social implications (Meyfroidt et al., 2014; Gibbs et al., 2010, for an overview of the social impacts of coffee commodity production and trade see a systematic literature review by Schaafsma et al., 2023). The growing demand for coffee worldwide will most likely lead farmers in coffee-producing countries to increase their yields either by expanding

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the cultivated land, which would result in more forest loss, or by intensifying their farming practices (FAO, 2014). Although coffee plantation has now been replacing other crops instead of forests, the impact of coffee production on the biodiversity loss remains an issue (Adams and Ghaly, 2007). Furthermore, the increasing temperature due to climate change will also likely exacerbate coffee production-driven deforestation as it is necessary to plant coffee on land with a suitable temperature (Magrach and Ghazoul, 2015).

Besides issues related to deforestation, coffee farming intensification through the addition of chemical fertilizer and pesticide, especially at excessive levels, has negative environmental impacts on soil quality and nontargeted species (Manson et al., 2022). A study by Coltro et al. (2006) showed that, to produce 1000 kg of coffee beans in Brazil, 270 kg of NPK, 900 kg of fertilizers, 620 kg of limestone, and 10 kg of pesticides were needed. Farmers' reliance on agrochemical inputs to boost yield is arguably unsustainable as it makes the soil more acidic and disrupts the balance of nutrients, which ultimately results in the poor growth of coffee plants (Manson et al., 2022). The use of fertilizer and pesticide also increases the carbon footprint of coffee cultivation as the production and application of these substances are associated with greenhouse gas emissions.

Ever since coffee agroecosystems were first identified as potential habitats and refuges for biodiversity (Perfecto et al., 1996; Philpott and Armbrecht, 2006; Vandermeer and Perfecto, 2007), there have been extensive studies on the impacts of coffee plantations on biodiversity. Such studies have involved measuring the biodiversity of particular taxonomic groups across spatial land-use gradients (e.g., forest coffee, agroforestry, monoculture, etc.) against biodiversity in the natural ecosystems as a baseline (Armbrecht et al., 2005; Perfecto et al., 2003). Planting coffee in agroforestry with a high shade level, polyculture with other types of crops, organic farming, and less intensive farming systems often mimic natural ecosystems and are considered to have a minimal impact on biodiversity (Moguel and Toledo, 1999). These farming systems provide tree diversity and density (Lozada et al., 2007), which are favorable for certain species and also create a suitable microclimate (i.e., temperature and humidity) required for optimal coffee production (Teodoro et al., 2008). Besides investigating coffee farm systems, the impacts of various treatments such as pest control, soil, and shade management in coffee plantations on biodiversity outcomes have also been studied (Manson et al., 2022; Venzon, 2021; Leite et al., 2020, 2021; Campera et al., 2021; Caudill et al., 2015).

To ensure that coffee production involves biodiversity-friendly farming, a coffee certification system has been applied to compensate farmers for their efforts in conserving biodiversity (Perfecto et al., 2004; Tscharntke, 2015). This voluntary, market-based approach emerged in the early 1990s and was introduced by several NGOs (Mas and Dietsch, 2004). Several empirical studies investigating the impact of coffee certification on forest and biodiversity conservation have been performed. Most of these studies revealed that such certification programs were successful at preventing deforestation (Takahashi and Todo, 2017) and maintaining the forest-like habitat quality needed by avifauna and insects (Gove et al., 2008; Mas and Dietsch, 2004).

Despite extensive studies on the impacts of coffee farm management on biodiversity, the trends in the number of studies performed on this issue over the last two decades remain unclear. Understanding the patterns of research, including the geographical distribution and quantity of studies, could help fill knowledge gaps, revealing which connections between coffee agriculture and biodiversity have been most extensively studied or have been relatively overlooked. Against this background, this work was initiated with the aim of conducting a systematic evidence map study on the impacts of coffee production on biodiversity throughout the tropical coffee-producing countries. Given that coffee plantations are mainly situated in tropical regions, we will be using the Tropical Agroecosystems and Biodiversity Framework (TABF), a framework consisting of important indicators that explain the relationship between agricultural production and biodiversity in a tropical context (Apriyani et al., 2021). Several indicators that are important to the agricultural context of coffee cultivation were applied to construct the map and guide this systematic study. Therefore, the primary overarching research question in this systematic map study is "what is the relationship between coffee agroecosystem management and biodiversity in the tropics?"

2. Methods

2.1. Search strategies (design review)

This systematic map study modified the Tropical Agriculture-Biodiversity Framework (Apriyani et al., 2021) to map the current state of research on the impacts of coffee agroecosystems on biodiversity. The coffee-related elements in the framework were selected through a consultative process with coffee experts from academia and research institutions. These selected elements guided us in establishing this systematic map outlined in the study inclusion criteria section.

2.2. Search source (literature database, search database, websites)

The literature search was performed between February and March 2021. The search included literature databases, internet search engines, and websites of specialist organizations. We considered all sources that had been published in the last 20 years (2001–2021). To cover references that were published between March and December 2021, we conducted a second literature search in February 2022 that focused only on the references published in 2021. The references identified in the first and second searches were combined.

The full list of sources searched is as follows:

Literature databases

- Web of Sciences
- Scopus
- Directory of Open Access Journals

Internet search engines

- Google: www.google.com
- Google Scholar: www.scholar.google.com

Websites of specialist organizations

- Biodiversity International https://www.bioversityinternational.org/
- CABI Agriculture and Bioscience http://www.cabdirect.org/
- Center for International Forestry Research https://www.cifor.org
- Climate Change Agriculture and Food Security https://ccafs.cgiar.org/publications/
- Consultative Group for International Agricultural Research https://ciat.cgiar.org/publications/ciat-library-resources/
- Conservation Evidence https://www.conservationevidence.com/
- Ecoagriculture Partners https://ecoagriculture.org/resources/publications/
- Fairtrade International https://www.fairtrade.net
- Food and Agricultural Organization https://www.fao.org
- Food and Land-Use Coalition https://www.foodandlandusecoalition.org/knowledge-hub/
- French Agricultural Research and International Cooperation Organization for the Sustainable Development of Tropical and Mediterranean Regions https://www.cirad.fr
- International Coffee Organization https://ico.org
- International Development Research Center https://www.idrc.ca/en
- International Food Policy Research Institute Library http://library.ifpri.info/
- International Institute of Tropical Agriculture https://www.iita.org/knowledge/publications/

- International Impact Initiative (3ie) https://www.3ieimpact.org/evidence-hub/publications
- International Institute for Environment and Development https://pubs.iied.org/
- Nestle AAA https://nestle-nespresso.com/
- Rainforest Alliance https://www.rainforest-alliance.org/
- Smithsonian Bird-Friendly Coffee https://nationalzoo.si.edu/migratory-birds/bird-friendly-coffee
- South Asian Network for Development and Environmental Economics http://www.sandeeonline.org/publicationdisp_main.php
- Sustainable Food Lab http://www.sustainablefoodlab.org
- The Economics of Ecosystems and Biodiversity http://teebweb.org/publications/
- TROPENBOS sustainable land use https://www.tropenbos.org/resources/publications?theme_title=Sustainable+land+use
- Tropical Agricultural Research and Higher Education Center (CATIE) http://www.catie.ac.cr/en/
- United Nations Environment Program https://wedocs.unep.org/
- UTZ https://utz.org/
- World Agroforestry Center (ICRAF) https://www.worldagroforestry.org/publications-all
- World Coffee Research https://worldcoffeeresearch.org/
- World Resources Institute (WRI) https://www.wri.org/publication
- 4C Certification https://www.4c-services.org/

2.3. Search terms and language

Search strings were created using two categories (population and outcome) with the Boolean operators “AND” to separate terms between categories and “OR” to distinguish terms within the same category.

Population: coffee plantation

Outcome: biodiversity of various taxonomic groups

To specify the exposure and to target more related search results on the management of coffee agroecosystems, operator W/3 was used within the exposure category. A wildcard character was used to include alternative word endings (i.e., function* to cover related terms, such as “functioning”, “functionality”, and “functions”). The word “species” was not used in the outcome since we aimed to cover taxonomic groups of various hierarchical levels. We focused on the articles published in the last two decades, from 2001 to 2021, by using the PUBYEAR AFT 2000 operator. The searches were conducted using search terms solely in English. Multiple trials of the reference search were performed by comparing the coverage of references yielded from different Boolean operators, in order to identify search terms and strings that produce the most comprehensive coverage of the relevant literature.

For example, Boolean operators used in the Scopus database search were as follows:

Population: (coffee OR *Coffea*) AND (plantation OR agri* OR agro* OR farm*)

Outcome: (heterogen* OR homogen* OR variety OR variati* OR density OR richness OR abundance OR similarity OR composition OR function* OR "ecosystem service" OR divers* OR (diversity w/3 (species OR bio OR plant OR animal OR insect OR crop OR micro* OR organ* OR tree OR fung* OR inverte* OR verte* OR genetic))))

2.4. Article screening and study inclusion criteria

A screening of collected citations was performed in two steps, as recommended by Pullin and Stewart (2006). The first step involved screening at the title and abstract levels, while the second step involved screening of the full text. A trained team of eight members consisting of researchers and research assistants was involved in this process. Given the large number of citations that we collected in the search stage (~3735), in the first screening stage, one title and abstract was screened by one individual. Eligible citations that passed the screening of title and abstract were subsequently screened at the full-text level. In this step, each paper was screened by two individuals to maintain consistency. All of the screening processes were performed against a set of inclusion criteria and were executed in Colandr. Colandr is a free software tool developed by Cheng et al. (2018), which is intended to make the process of screening in systematic review studies more time efficient.

The inclusion criteria that define the scope of this systematic map study and guide its implementation are as follows:

- Geographical location: Global, especially regions categorized into tropical climatic zone, a zone where coffee is commonly grown.
- Relevant subjects: Plants, animals (vertebrates and invertebrates), and microorganisms; including pests and weeds in coffee plantations.
- Type of exposure: Management of coffee agroecosystems. We clustered the exposure types into practices of managing biotic and abiotic factors in coffee farms (soil, pest, shade, and water), farming practices (agroforestry, polyculture, organic farming, and farm intensity), land-use and distance gradients, and coffee farms with and without sustainable coffee certification.
- Type of comparator: Site comparison, either spatially or temporally (i.e., between agroecosystem and natural tropical forest or plantations with different farming managements or practices). Comparator types vary depending on each exposure type.
- Type of outcome: Number of studies and changes in species richness and abundance, alpha diversity, beta diversity, and coverage. The outcome type covers flora, fauna, and microorganisms.
- Type of study: Qualitative and quantitative primary studies as well as descriptive studies and reports.

Given the large number of articles collected, we did not evaluate the quality of the papers included in this study. In systematic evidence map studies, quality assessment is often omitted (Bilotta, 2018). However, the absence of such assessment may limit the quality of evidence map produced here, so we recommend that this issue be addressed in future similar studies in order to provide more robust mapping results.

2.5. Data extraction and mapping presentation strategy

After conducting screening of the title/abstract and full text, we extracted data of the included articles and coded them in an extraction form. This extraction form contained several categories of information, including the name of the coder, bibliographic information, location and country of the study, forest type, confounding variables, type of intervention, comparator, outcome, study subject, and study design. One researcher was assigned to extract and compile information from one article.

Finally, a map showing evidence distribution of the relationship between coffee agriculture and biodiversity was generated. It consisted of rows reflecting the intervention types in coffee agroecosystem management and columns reflecting the biodiversity outcome in coffee agroecosystems. If an individual article was associated with more than one type of linkage, it was mapped into several relevant cells. The cells are colored according to the distribution of evidence collated in this study. A dark color indicates an abundance of related evidence studies, while a lighter color indicates a dearth of such studies (Fig. 1).

3. Results

3.1. Number and types of articles

As shown in the Fig. 2, the database search generated 3384 citations, while gray literature sources produced 478, which finally resulted in 3735 unique citations after the removal of duplicates. Of these 3735 citations, 2900 were excluded as they did not meet the inclusion criteria upon screening of the title and abstract. Next, the full-text papers of 811 references were retrieved and underwent full-text screening. These papers were screened against inclusion and exclusion criteria, which

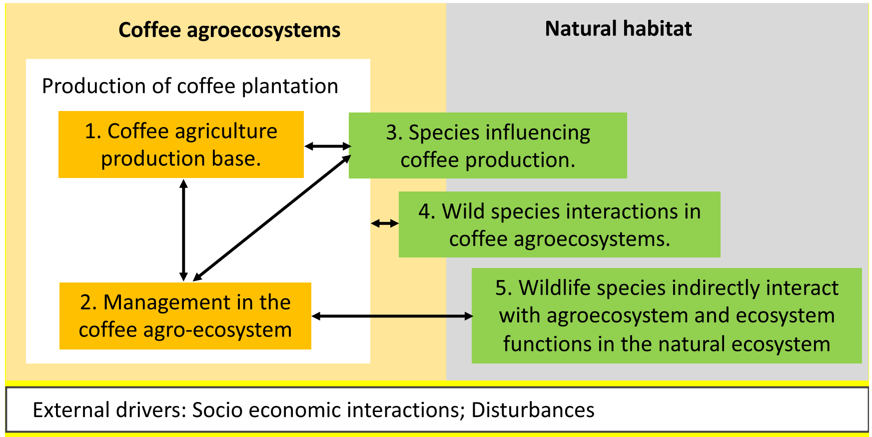

Fig. 1. Schematic diagram of the coffee production and biodiversity framework (Modified from TABF in Apriyani et al., 2021). This figure illustrates the five proposed indicators and the external drivers that influence coffee production and biodiversity. The indicators are distinguished by colors; orange boxes refer to components of coffee agroecosystems, and green boxes refer to the components of biodiversity. These components are affected by external drivers of socioeconomic interaction and disturbances.

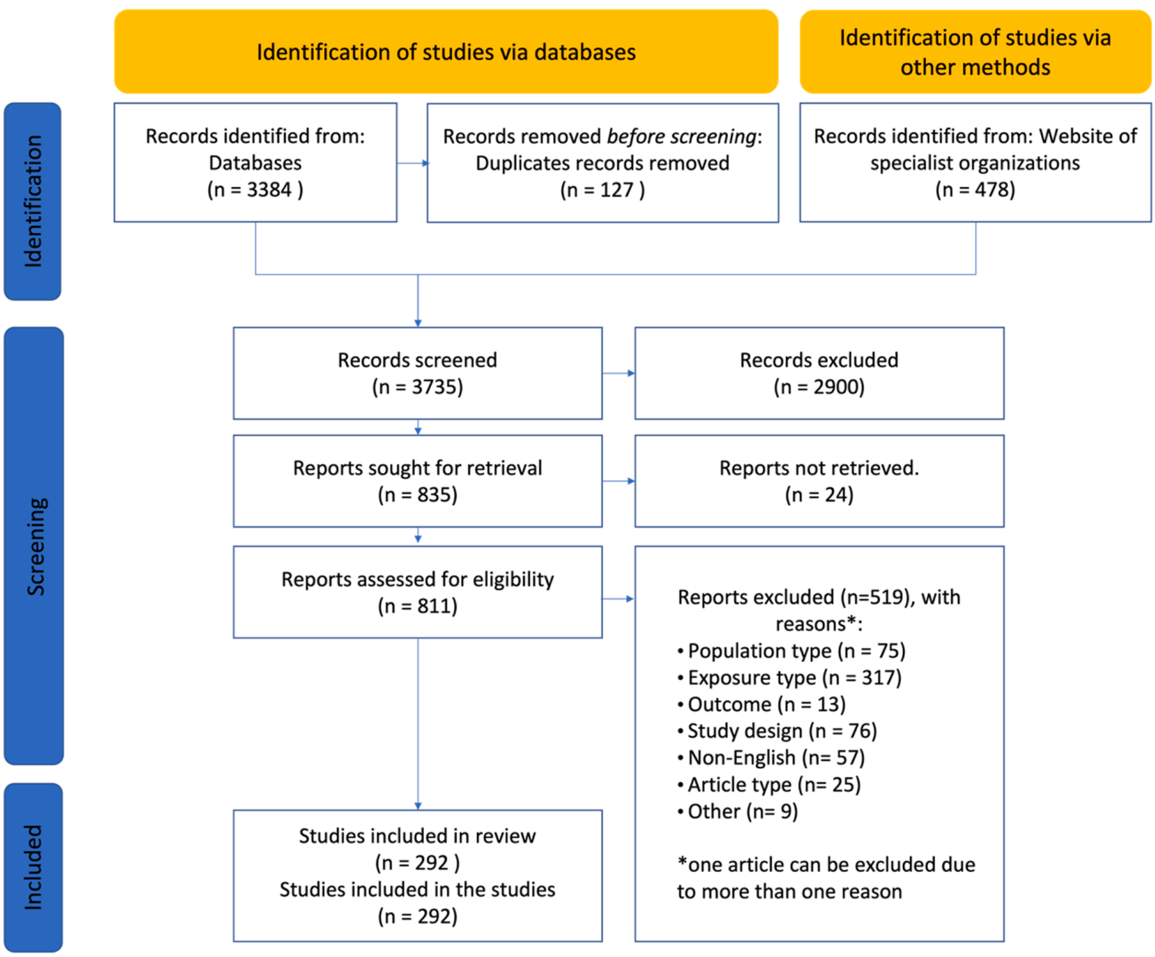

Fig. 2. PRISMA flow diagram undertaken for the identification and screening of articles that meet the eligibility criteria.

ultimately resulted in 292 articles being included in the synthesis and narrative report.

Over time, there was a trend for an increase in the number of reports examining the relationship between coffee management and tropical biodiversity (Fig. 3). The number of published reports in the first decade (2001–2011) was lower than that in the second decade (2012–2021). The greatest number of reports were published in the year 2020 and 2021 ($n = 27$). In general, both global annual coffee production (FAO, 2024) and the number of studies on the relationship between coffee management and biodiversity increased over time.

As displayed on the Fig. 4, studies in Latin America dominated the extracted literatures in terms of the geographical distribution of the identified studies. This aligns with the fact that >50 % of coffee produced globally is from these countries (Pham et al., 2019).

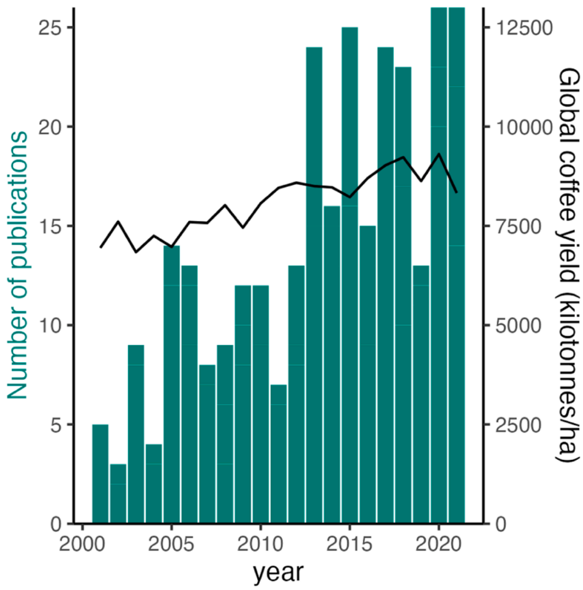

Fig. 3. Number of included articles published in different years within the range of 2001–2021 (n = 292). The overlying gray lines show global annual coffee bean production in 1 kilotonnes between 2001 and 2021 (FAO, 2024).

Approximately 25 % of all of the identified reports involved research sites in Mexico ($n = 73$), which was double the numbers from Costa Rica and Brazil ($n = 31$). Of the 73 studies performed in Mexico, 30 studies alone were conducted in the state of Chiapas. This is understandable given that Chiapas is the largest coffee-producing region in the country (accounting for 35.4 % of national production), with a total area devoted to coffee cultivation of 253,986 hectares (Folch and Planas, 2019). Besides Mexico, other countries in which large numbers of studies were performed were Brazil ($n = 31$), India ($n = 28$), and Ethiopia ($n = 25$).

Compared with the research performed in Latin America, research into the connections between coffee and biodiversity in Africa and Asia was lacking. Exceptions to this included Indonesia, Uganda, and Ethiopia. Note that several studies involved research performed in more than one country, which explains the difference between the total number of articles based on the country distribution and the total number of included full-text citations.

3.2. Intersection of coffee agroecosystem management and biodiversity outcomes

The distribution and frequency of studies that examined the connections between coffee agroecosystem management and biodiversity were displayed in a heatmap (Fig. 5). Among the coffee management interventions most commonly examined in the identified studies were the effects of land-use gradient driven by coffee plantations on the biodiversity of invertebrates ($n = 73$), vertebrates ($n = 64$), and plants ($n = 51$). Another common study topic was the impact of shade

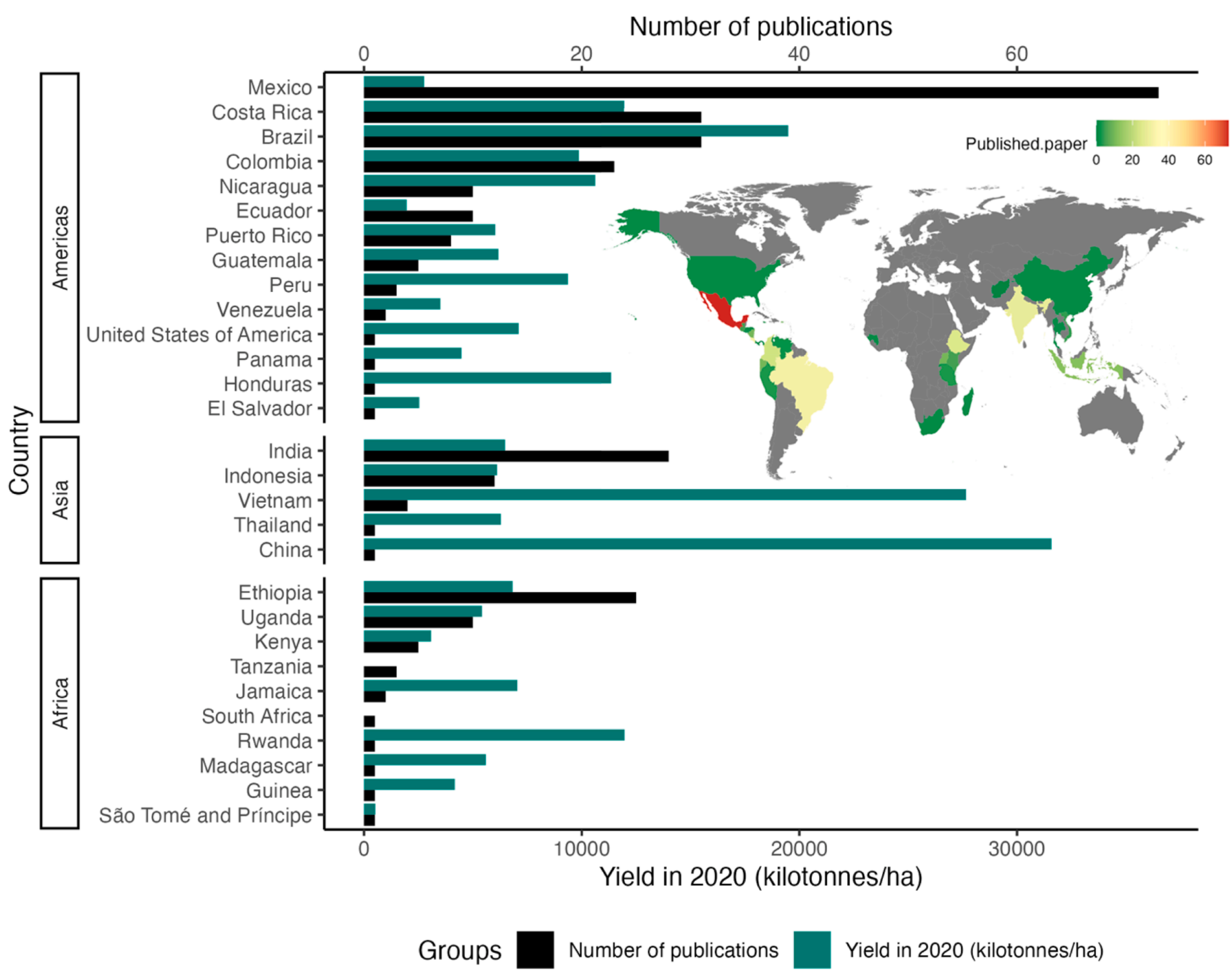

Fig. 4. Number of included studies from different countries (n = 296) in comparison with coffee yield in 2020.

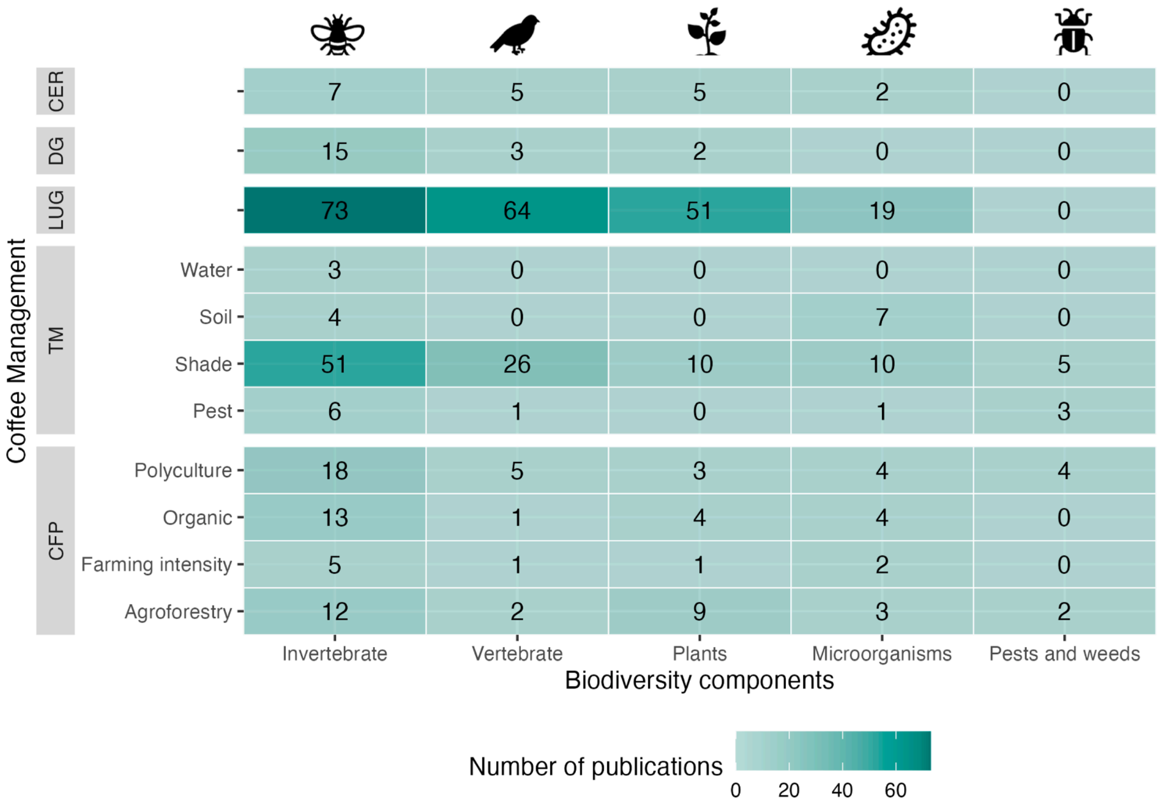

Fig. 5. Heatmap of the distribution and frequency of evidence of coffee agroecosystem management interventions (CFP: coffee farming practice; TM: type of management; LUG: land-use gradient; DG: distance gradient; TM: type of management; CER: certification;) and biodiversity outcomes. Articles incorporated into this map can fall into more than one cell.

management on invertebrate biodiversity ($n = 51$). The map shows that there was a dearth of studies on the outcomes regarding the biodiversity of vertebrates, plants, microorganisms, and pests and weeds for interventions associated with water and soil management, and the intensity of farming practices.

3.3. *Number of studies clustered by intervention types*

As indicated in the Fig. 6, the management of coffee agroecosystems in different land-use gradients (LUG) was the most studied topic, which was focused on in 158 studies (41 %), followed by the type of management (TM) (28 %, 108 studies), coffee farming practices (CFP) (22 %, 86 studies), distance gradient (DG) (5 %, 20 studies), and coffee certification (CER) (4 %, 13 studies). Within the TM sub-topics, shade management was the most studied (87 studies). Meanwhile, within the studies on coffee farming practices, the screened papers examined the following four sub-topics, in decreasing order of frequency: polyculture (31 studies), organic farming (26 studies), agroforestry (20 studies), and

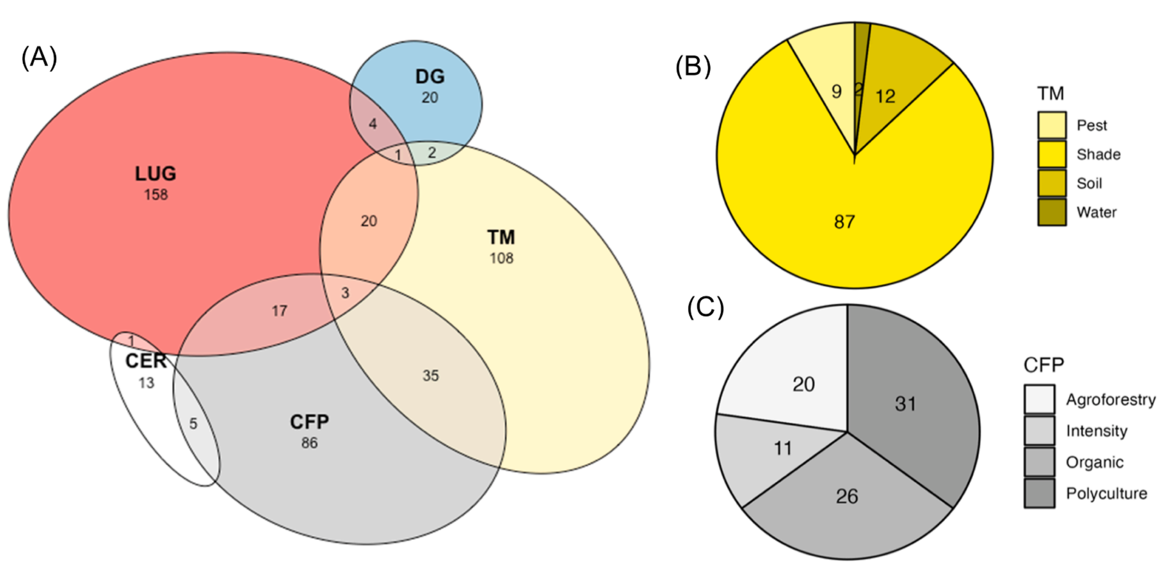

Fig. 6. Number of studies per intervention ($n = 354$), clustered by intervention types (A) and by sub-topics of type of management (TM) (B) and coffee farming practice (CFP) (C). LUG: land-use gradient; DG: distance gradient; TM: type of management; CER: certification; CFP: coffee farming practice.

intensity gradient (11 studies).

Some individual articles covered multiple interventions, for example, by comparing organic and intensive farming practices at various input levels and different shade-tree levels. Land-use gradient was the most studied topic to understand the impacts of coffee agro-ecosystems on biodiversity. The research compared biodiversity indicators in different coffee farm gradients ranging from coffee monoculture without trees as shade, shade-grown coffee, and rustic coffee, using primary or secondary forest as the baseline.

Besides land-use gradient, the research efforts were skewed toward examining the impacts of various practices for managing biotic (pest) and abiotic factors (soil, shade, and water) on biodiversity. Shade and pest management have key influences on coffee yield since these two elements affect each other to some extent. Specifically, a reduction of trees as shade, which also provides a habitat for natural enemies of pests, can lead to an increase of pest infestations (Perfecto et al., 1996). Finally, despite the emergence of certification systems in the early 1990s, only a few studies have investigated the impacts of voluntary coffee certification on biodiversity.

3.4. Number of articles by study subjects

Invertebrates were the most studied taxon (157 studies), followed by vertebrates (87 studies) and plants (70 studies). The most studied invertebrate, vertebrate, and plant taxa were ants (32 studies), birds (40 studies), and trees (27 studies), respectively. We also counted pests and weeds (12 studies) that have negative impacts on coffee agroecosystems as components of the biodiversity. Finally, we categorized plants according to their life forms, not taxonomic groups, because plant species exhibiting the same life forms share similar morphological characteristics and responses towards environmental changes (Fig. 7).

Empirical studies were dominated by taxonomic groups that have either positive or no impact on agriculture, while those with negative impacts such as pests were relatively scarce.

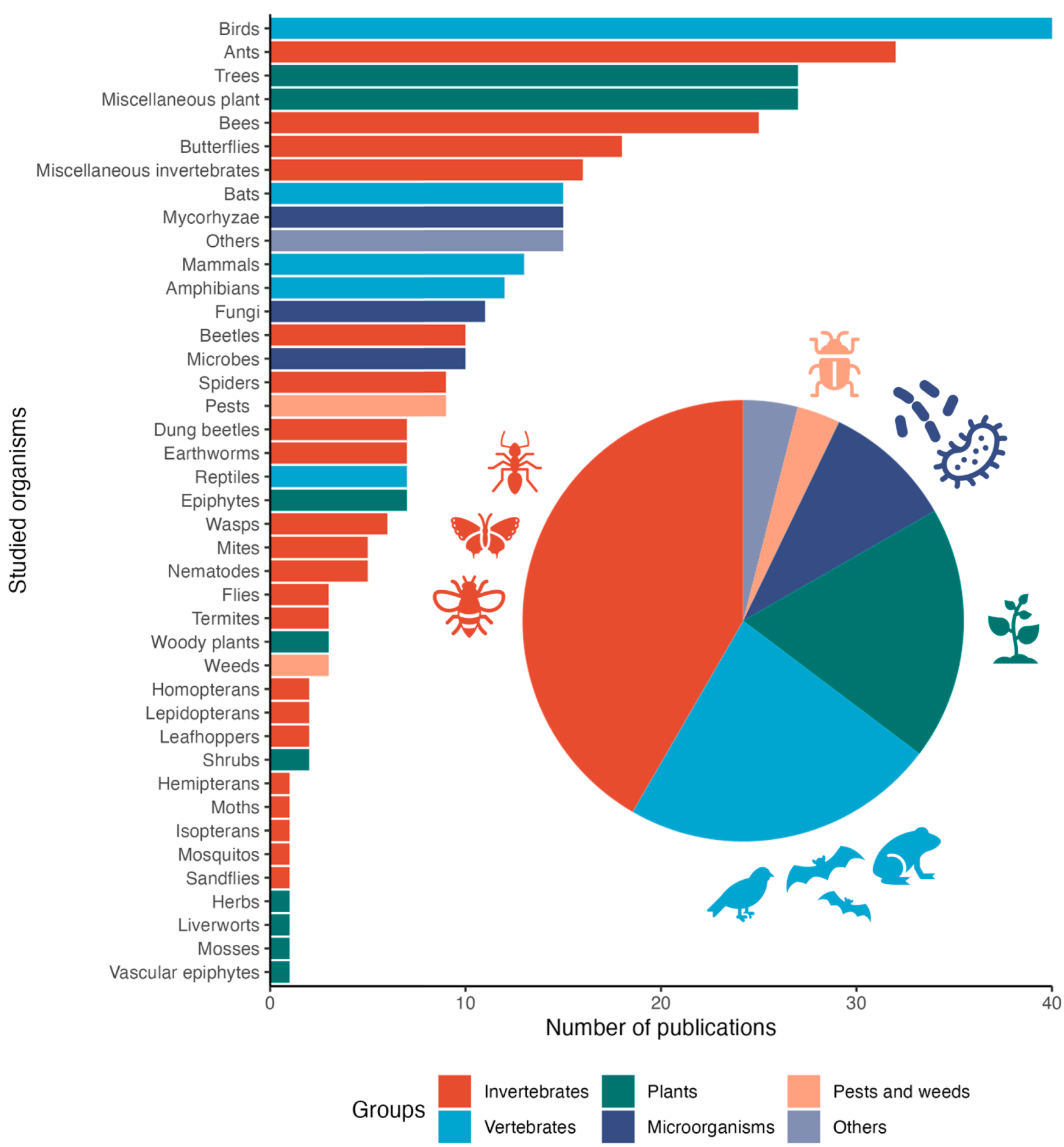

Fig. 7. Organisms categorized into different taxonomic groups studied in the 377 data points on biodiversity, as shown in the bar chart. The pie chart shows the general groupings of study subjects (Invertebrates, vertebrates, plants, microorganisms, pest and weeds, and others).

4. Discussion

4.1. Distribution and geographical trends of research on coffee farm management and biodiversity over time

Our work provides an overview of recent studies on the relationship between coffee farm management and biodiversity worldwide. We identified that the number of publications on this topic continually increased over time. Studies on coffee management and biodiversity are demand-driven, as indicated by the rising trend of the studies in association with the elevation in coffee production. The slight decline noted in 2021 might have been associated with the Covid-19 pandemic, which limited the ability of researchers to conduct field studies (Raynaud et al., 2021).

We observed that the studies on coffee agriculture management and biodiversity conducted in the Americas started earlier than those in other regions. Meanwhile, studies of the relationship between coffee farming and biodiversity in Africa have started to grow in number since 2006. Moreover, coffee production per continent was higher in the Americas than that in Asia and Africa, 56.8 %, 29.5 % and 13 % of global coffee production respectively, indicating that the more coffee is produced, the earlier and the more studies being conducted. Most of the countries where studies were performed are leading coffee producers, including Brazil, Colombia, Ethiopia, and Indonesia. However, Vietnam and Honduras were exceptions to this rule. Despite Vietnam and Honduras becoming the second and seventh largest coffee producers globally (ICO, 2019; FAO, 2024), there were fewer articles investigating coffee farming in these countries than for the other top coffee-producing countries. This illustrates a lack of research efforts targeting individual coffee-producing countries to evaluate how their coffee plantation management affects biodiversity. Moreover, this may indicate a language bias, as our search strategy was conducted in English and we excluded non-English articles, even though most coffee-producing countries are not English-speaking. There is thus a clear need to fill this research gap in the less-studied regions and under-represented countries. This lack of studies might be due to financial constraints. Therefore, this issue might be resolved by providing sufficient funding for research in relatively overlooked countries. Encouraging research in less-studied regions is particularly important because some of these regions are global biodiversity hotspots with unique taxonomy and environmental conditions.

Furthermore, the large number of publications on the relationship between coffee production and biodiversity in Mexico, Colombia, and Costa Rica is in line with the trend of coffee farming intensification in these Latin American countries. Since the late 1980s, such intensification has been particularly evident in Colombia and Costa Rica, where >40 % of each country's coffee plantations have been intensified by reducing the levels of shade trees and converting highly diverse coffee farms to monocultures (Perfecto et al., 1996). Therefore, it was considered important to examine the effects of intensification on biodiversity in these regions, especially with the emergence of the first World carbon-neutral coffee certifications in Latin America (Birkenberg and Birner, 2018).

4.2. Gap in research on biodiversity-related outcomes of coffee agroecosystem management interventions

In terms of the outcomes of interventions, the effects of coffee LUG on invertebrates were the most intensively studied, followed by their impacts on vertebrates. Intensive study on the land-use change is expected because the transformation of natural habitats to the agricultural land demonstrates the main driver of biodiversity loss (e.g. Crenna et al., 2019). In addition, similar to the findings in a previous systematic mapping study on oil palm plantations (Reiss-Woolever et al., 2021), invertebrates have been the most commonly studied taxonomic group when investigating biodiversity because of their widely known ecological roles in agroecosystems. Invertebrates have high diversity and a wide range of habitats, play both positive roles including as pollinators, pest predators, and soil engineers in agroecosystems and negative roles as pests. Ants, bees, and butterflies were found to be among the most studied invertebrate taxa. In coffee agroecosystems, ants play important roles as natural pest predators (Morris et al., 2018), bees provide pollination services (Jha and Vandermeer, 2010), and butterflies act as pollinators and biological indicators of habitat disturbance (Munyuli, 2013). Meanwhile, birds represent the vertebrate group on which the greatest number of studies have been performed, especially birds that benefit from shaded coffee plantations. In winter, shade trees provide habitats for migratory birds and become foraging sites in the dry season as they offer fruit and nectar (Perfecto et. al., 1996). We suggest that, in the future, less focus could be placed on invertebrate biodiversity as this issue has already been extensively studied.

Research on the taxonomic groups most studied as a reflection of biodiversity has been extensively conducted by measuring the diversity, abundance, and other biodiversity indicators in different gradients of coffee farms. This research primarily took place in multiple sites and in habitats of relatively high quality, such as those adjacent to primary or secondary forest, those with low-level disturbance of forest patches, and those with a high level of shade and floristically diverse coffee agroecosystems. The components of biodiversity in these habitats were then compared with those in low-quality habitats ranging from sun-grown coffee plantations, farms with a low level of shade, and sites with highly intensified coffee farming systems (Geeraert et al., 2019; Ibarra-Isassi et al., 2021; Perfecto et al., 2003; Philpott et al., 2006, 2008)

The types of practices for managing biotic (pest) and abiotic factors (soil, shade, and water) were the second most investigated topic. In its natural habitat and in traditional cultivation, coffee is grown under a canopy of shade trees. Important ecological services provided by the shade trees include the provision of organic matter and soil nitrogen (Romero-Alvarado et al., 2002), weed suppression, and microclimatic regulation (Staver et al., 2001; Lin 2007; Lin et al., 2008; Bael et al., 2008; Vandermeer et al., 2010). Shade management is essential in coffee agroecosystems as it determines the coffee yield and helps control pest infestations (Piato et al., 2020).

Finally, there was a dearth of studies measuring the impacts of water management on biodiversity. We found no research on the relationship between water management and vertebrates, plants, microorganisms, pests, and weeds. The huge gap in the literature regarding evidence of the linkages between water and biodiversity in coffee agroecosystems might be due to the fact that most coffee plantations rely on rainwater as the main source of water, considering that the majority of the landscape in coffee farms features steep slopes. However, coffee plantation is contributing to the sedimentation and eutrophication of the water resources (Adams and Ghaly, 2007) while water accessibility and sanitation are ignored even in the coffee plantation with certification scheme (Partzsch, 2021).

Despite being grown in the tropical region that is known for receiving sufficient rainfall throughout the year, rainfall only supplies 25 % of the coffee production water demand (Amarasinghe et al., 2015). Coffee plantation heavily relies on approximately 57 to 95 % of the ground water reserves to irrigate coffee farms (Tran et al., 2021). As coffee production is water-intensive (Luong and Tauer, 2006) and sensitive to the water supply (López et al., 2021), supplying water, such as establishment of irrigation, in the coffee plantation has become essential for coffee production, especially in places where water is not always available and during the dry period. The conventional irrigation system using micro-basin system is cheap but often wasting due to over-irrigation, making this method having a low water efficiency compared to other irrigation technologies (Ho et al., 2022). Moreover, coffee has a comparatively larger total water footprint than other major crops cultivated in coffee-producing countries and compared to the globally most grown commodities (Sporchia et al., 2023). Drip irrigation has been considered as one of the most common methods to improve coffee yield and water use efficiency, but the initial costs often become the barrier of its application. Therefore, the establishment of irrigation systems, that is water-efficient and affordable, is essential to improve the sustainability of the coffee plantation, so the negative impact of modified waterbodies on biodiversity is minimal (Krishnan, 2017).

4.3. Limitations of the map

Although we attempted to design the literature review and analytical methods to make them as robust as possible, the results presented here may not fully represent the extent of evidence on the linkages between coffee agroecosystem management and biodiversity. We recognized several risks that may have biased the collected evidence and synthesis results of this study, and recommend further improvements for future systematic reviews. First, since we only focused on collating articles written in English, this evidence map may have a language-related bias (Nuñez and Amano, 2021). We acknowledge that many articles investigating the impacts of coffee agroecosystem management on biodiversity might have been published in languages other than English in non-English-speaking tropical countries (e.g., Indonesian, Vietnamese, Spanish, etc.,). However, although this study was limited to the English language, it represents the most extensive evidence mapping exercise of the literature on coffee plantation management and biodiversity performed to date and is a valuable resource for directing future research. We recommend that future studies include articles written in the language of the respective country, especially for countries with high coffee production.

Second, we executed our search strategy using literature databases and gray literature. As we found that articles from the gray literature did not appropriately report the methods used or results obtained based on scientific standards, and did not undergo peer review, we excluded most of them. Moreover, only peer-reviewed articles were finally included in the synthesis stage because the gray literature, reports, and articles describing qualitative or descriptive studies did not meet our inclusion criteria. Finally, there were limitations regarding the search terms used. Although we attempted to broaden the search terms and the search strings to capture as many relevant citations as possible, this evidence map might still not be comprehensive. There are several reasons for this, including the linguistic diversity of reports on research of coffee agroecosystems and biodiversity and the differences in search functions between literature databases and gray literature sources that we explored in this study.

5. Conclusion

This systematic map study provides among the first descriptive characterizations of the evidence base regarding the effects of coffee agroecosystem management on biodiversity. The distribution, trends, and frequency of the studies performed, and reports published were presented according to the year of publication, country where the study was performed, type of coffee farm intervention, biodiversity outcome, and studied organisms. The occurrence of studies examining the impacts of coffee management interventions on biodiversity was presented in a heatmap. The impacts of coffee-forest LUG as determined by comparing the biodiversity outcomes for invertebrates, vertebrates, and plants at different LUG from natural forest to shaded coffee plantation and coffee monoculture were the most frequent evidence identified in this study. Conversely, there was a dearth of studies investigating the effects of water and soil management on all biodiversity groups in coffee agroecosystems.

The data synthesized from this systematic map highlight the knowledge clusters and gaps in this field of study, which should help researchers and policymakers in their selection of which research topics to address, what evidence gap to highlight to inform policy formulation and assessment, and where investment should be prioritized. This study is not intended to inform and draw conclusions about which kind of coffee farm management or practice contributes to positive or negative impacts to biodiversity. Such information could possibly be obtained through a systematic review designed with a significant test method to examine the validity and measure the magnitude of such effects (Qiu et al. 2018). This follow-up review study is important given the projected increase in coffee consumption and production globally, accompanied by the global trend of declining biodiversity. The synthesized data could enable sound evidence-based decision-making on coffee farm management that supports biodiversity conservation, especially in the tropics.

CRediT authorship contribution statement

Mukhlish Jamal Musa Holle: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Via Apriyani:** Writing – review & editing, Writing – original draft, Validation, Project administration, Formal analysis, Data curation, Conceptualization. **Sonny Mumbunan:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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.

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Data availability

Data will be made available on request.

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