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The evidence base on the environmental, economic and social outcomes of agroforestry is patchy—An evidence review map

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Agroforestry is often seen as a panacea that offers multiple environmental, economic, and social benefits. However, the validity of generalized statements on agroforestry outcomes is doubtful because the evidence base is unclear. Systematic reviews and meta-analyses exist on the topic in addition to many case studies that address specific outcomes of individual agroforestry practices at different sites. However, the overall picture of available scientific evidence on agroforestry outcomes remains opaque due to the wide diversity of existing agroforestry practices, outcome indicators, and spatial locations. To clarify whether and in which areas the research landscape allows conclusions to be drawn about the potential benefits or drawbacks of agroforestry compared to other land uses, an evidence review map was created for the purpose of this study. Based on a systematic literature search and screening, 64 systematic review articles were finally identified that summarize ecological, economic, or social outcomes of at least one agroforestry practice compared to another land use as control. The thematic and spatial coverage of the systematic reviews on agroforestry outcomes is mapped to identify density and research gaps in the evidence base. Moreover, the comprehensibility of the study selection for each identified systematic review is critically assessed. The resulting evidence review map discloses a solid evidence base for environmental outcomes and productivity aspects of individual agrisilvicultural practices, as well as for agroforestry systems when considering an aggregate level. However, the outcomes of individual silvopastoral and agrosilvopastoral practices have been less studied in the literature. A global coverage at the level of individual agroforestry practices is only available for impacts on climate change mitigation. Major research gaps were identified for systematic analysis of social outcomes of all agroforestry types. The results of the evidence mapping highlight further research needs, but also urge for caution in making generalized statements about the benefits of agroforestry.

KEYWORDS

agroforestry, systematic review, evidence review map, evidence base, environmental economic and social outcomes

1 Introduction

Agroforestry, defined as the inclusion of woody perennials within farming systems, is widespread over the globe and estimated to comprise about 43% of agricultural land globally with an increasing trend in area and people involved (Zomer et al., 2014, observed between 2000 and 2010). Agroforestry comprises several systems and practices, which are based on combinations of trees or hedges with crops and/or animals. However, no standard definition exists. The FAO defines agroforestry as "the collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence" (FAO, 2015). Nair (1985) defines agroforestry as "an approach of integrated land-use that involves deliberate retention or admixture of trees and other woody perennials in crop/animal production fields to benefit from the resultant ecological and economic interactions". While former definitions clearly separated agroforestry from agriculture and forestry, the definitions evolved to describing interfaces among these land use systems as well as describing multifunctional landscapes (van Noordwijk et al., 2019). van Noordwijk et al. (2019) understands agroforestry today as all interactions, interfaces and synergies between agriculture and forestry.

Although agroforestry has a multi-faceted evolving definition, and encompasses a variety of very different practices, "agroforestry" is often talked about in generalized terms in policy and community contexts. Agroforestry has increasingly received recognition by governments, NGOs and donor agencies and is considered in national and international policy initiatives, programs, guidelines and frameworks (Santiago-Freijanes et al., 2018a; Santiago-Freijanes et al., 2018b; Miller et al., 2020). Examples are the "Agroforestry Strategic Framework for 2019–2024" published by the United States Department of Agriculture (USDA, 2019), the "Guidelines for Agroforestry Development" of the Association of Southeast Asian Nations (ASEAN) (ASEAN Secretariat, 2018), and the Common Agricultural Policy of the European Union, under which agroforestry in Europe can receive support (EU, 2013a; b). Several NGOs have been established to promote the adoption of agroforestry practices and research, such as the World Agroforestry Centre (ICRAF since 1978, merged 2019 to CIFOR-ICRAF) (http://www.worldagroforestry.org/), the Association for Temperate Agroforestry (AFTA) formed in 1991 (http://www.aftaweb.org), or the European Agroforestry Federation (EURAF) founded in 2011 (www.eurafagroforestry.eu).

Agroforestry has the reputation for providing multiple environmental, economic and social benefits and thus contributing to several Sustainable Development Goals (SDGs) (Nair, 2014; Agroforestry Network, 2018; Andersson, 2018; FAO, 2018; Miller et al., 2020; van Noordwijk, 2020). The benefits of agroforestry appear to be widely accepted. Agroforestry is said to have positive effects on environmental resilience, biodiversity conservation, soil enrichment, air and water quality, carbon sequestration, agricultural productivity, food security, stable incomes, farmer livelihoods and other benefits to human welfare. The EU Green Deal calls agroforestry "a sustainable practice" (EU Commission, 2019), and the World Bank titles agroforestry "a climate-smart practice", while describing agriculture as "a major part of the climate problem" (The World Bank, 2021). Furthermore, half of the developing countries intend to use agroforestry as a climate change adaptation and mitigation strategy (Rosenstock et al., 2018). It is thus not surprising that agroforestry seems to be promoted as a universal remedy. However, it seems questionable to evaluate a land use system as generally good or bad, be it agroforestry, treeless agriculture or forestry.

As large as the number of the alleged benefits of agroforestry systems is, so is the diversity of reported agroforestry systems and practices, including their local circumstances and site conditions. Agroforestry outcomes are highly dependent on the considered temporal and spatial scales (Huxley, 1999). General statements about the effects of agroforestry must therefore be considered in a differentiated manner according to the specific agroforestry practice, outcome and site conditions. Although many studies address specific aspects of agroforestry, the overall message about agroforestry outcomes remains unclear due to the wide variety of agroforestry definitions and contexts. Thus, it remains uncertain whether there is a scientific evidence base for making judgments about (all of) the alleged benefits of agroforestry.

Research on the environmental, economic and social impacts of agroforestry increased in the last decade (Miller et al., 2020; Shin and Park, 2020), with several case studies providing evidence for the positive effects of individual agroforestry practices on individual outcomes in case study locations. Furthermore, several review studies on agroforestry outcomes exist, but they are equally limited in scope. These studies usually synthesize the evidence from selected contexts, which are related either to certain geographical regions, individual agroforestry practices or to specific outcomes. For instance Muchane et al. (2020) published a meta-study on the impact of agroforestry on soil-mediated ecosystem services in the humid and sub-humid tropics compared to crop monocultures. Such review studies help to condense and interpret the evidence for individual contexts. But the overall picture of agroforestry outcomes addressed by policy makers remains still scattered and a synthesized overview does not exist to date. Beillouin et al. (2019) conduced a meta-review of crop diversification strategies, which includes agroforestry, on environmental, productivity and economic outcomes. They, however, did not distinguish between individual agroforestry practices, did not include social outcomes and did not allow for before and after comparisons, which are usually applied for analyzing impacts on climate

change. It is difficult for decision makers to get an overview over existent and missing evidence in this field of research. As such it remains challenging to draw conclusions on the effectiveness of 'agroforestry' when faced with a large number of studies that only provide evidence to single pieces of a puzzle. This raises the question of whether the political support for agroforestry in general is scientifically justified and well-founded, or whether, on the one hand, a differentiation and specification of funding objectives and objects is more appropriate, and, on the other hand, research activities in specific areas should be strengthened in a targeted manner.

To provide a more comprehensive overview of the existing evidence on agroforestry outcomes, this study provides an evidence review map of environmental, economic and social outcomes of different agroforestry systems and practices compared to other land use systems. In doing so, the study provides a systematic synthesis of available systematic reviews and meta-analyses on the topic. Systematic reviews and meta-analyses were chosen as subject, as their aim is to analyze a large number of context-specific case studies, to determine whether and to what extent (for which parameters) transferable results can be identified. An evidence review map, comparable to an evidence and gap map for individual case studies, aims to provide an accurate description of the evidence base relating to a particular question or topic (O'Leary et al., 2017; Pullin et al., 2018). Evidence review maps follow the same principles as systematic reviews and apply a comprehensive literature search, a screening against explicit inclusion and exclusion criteria, as well as a systematic coding, analysis and reporting, but do not aim to synthesize results of included studies (O'Leary et al., 2017; White et al., 2020). The present study aims to systematically map the state of the evidence base on the various outcomes of different agroforestry practices in their geographic contexts. The study further discusses the strength of scientific evidence from existing review studies by providing a systematic quality appraisal of the applied study selection. Resulting from this, the study highlights areas where knowledge gaps remain in agroforestry outcome research.

The specific research questions of the study are:

A. What is the evidence base for agroforestry outcomes?
   - o For which agroforestry systems and practices have systematic reviews been published that assess their impact on environmental, economic and social outcomes?
   - o Which geographical locations were covered by the published literature?
B. Are existing review studies transparent and comprehensible in their selection of literature?
C. For which thematic areas (combinations of agroforestry practices, outcomes and locations) there exist no systematic synthesis in the literature up to date?

This study does not provide a full systematic review or meta-analysis of the results (performance of agroforestry compared to other land uses) identified through the literature selection, but is a first step in conducting this follow-up work. A discussion of the evidence map methodology, its interpretation, and the steps necessary for further analysis of the results are included in this study.

2 Methods

2.1 Literature search and screening strategy

A systematic review of literature was conducted following the "RepOrting standards for Systematic Evidence Syntheses" (ROSES) approach (Haddaway et al., 2017; Haddaway et al., 2018). ROSES provide reporting guidelines for systematic reviews and maps from the field of environmental research that have been further developed from PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses), which was originally developed for healthcare research (Haddaway et al., 2018). A systematic review protocol was developed for the search and screening strategy, which is provided in the reposited supplementary materials (see Köthke et al., 2021, Table S1). The literature selection includes systematic reviews and meta-analyses dealing with the effects of agroforestry systems and practices on environmental, economic or social outcomes. Agroforestry systems and practices were defined for this study following the definition of Nair (1985) as "an approach of integrated land-use that involves deliberate retention or admixture of trees and other woody perennials in crop/animal production fields to benefit from the resultant ecological and economic interactions".

An extensive literature review was conducted in the SCOPUS and Web of Science databases in October 2020. Systematic reviews and meta-analyses dealing with the effects of agroforestry systems and practices on environmental, economic or social outcomes were searched. The search string comprised of search terms related to the study type in combination with search terms for agroforestry systems and practices. For the latter, definitions and wordings were taken from Nair (1985) (the complete search string is provided in Köthke et al. (2021, Section B)).

Altogether, peer reviewed studies as well as edited books and book chapters in English or German language were included that were published before October 2020. No restriction was given for the starting date of the search. 23 studies, which had been known to the authors prior to the systematic search were used as control group for the comprehensiveness of the search strategy (see Köthke et al., 2021, Table S2) for the list of the 23 studies). After removing duplicates, titles, abstracts and keywords of the studies were screened according to the following inclusion criteria related to study type and content: 1) Articles are published in peer-reviewed scientific journals or edited books;

unpublished and grey literature was excluded. 2) Study type is a systematic review or meta-analysis. Scoping reviews, evidence and gap maps, systematic review protocols and literature reviews without systematic search strategy were excluded. 3) The review study analyses the environmental, economic or social outcomes of agroforestry practices or systems in comparison to a segregated land use system (e.g. agriculture, pasture or forestry). Agroforestry systems and outcomes were comprehensively defined as inclusion criteria for selecting eligible studies to allow a wide range of studies for analysis. As outcome, any outcome indicator defined by the review studies' authors was acceptable as long as it was used to measure an environmental, economic or social situation. For example, studies that only measured the success of implementing agroforestry projects were not included. Studies without applying a comparator were excluded. No restriction was given to the considered study design and for instance experiments, observational studies, permanent plots, chrono sequences, before-and-after designs, or surveys were allowed as long as a specific outcome indicator was addressed. Review studies at any location and any temporal and spatial scale were included such as plot, farm, landscape or regional level.

Screening for inclusion criteria of study type and content was performed by all three authors. To test and improve screening protocols, 72 randomly selected articles were screened in triplicate or duplicate before the remaining articles were divided among authors. If an author was unable to judge whether an article should be included for the next step of full-text screening, double screening was conducted by another author (89 articles). Disagreements in screening were discussed and resolved between all authors. If disagreements remained about whether an article should be included or excluded, the article was included and moved to the full-text screening step. Ineligible articles were removed before the start of full-text screening. The results of the screening and the reasons for exclusion were recorded.

The remaining articles were screened in full-text for data extraction and quality appraisal according to predefined templates (available in Köthke et al., 2021, Table S4 and S5). In case review articles were found to not meet the inclusion criteria during full-text screening as described above, articles were excluded at this stage. Screening results and reasons for exclusion were recorded. Full-text screening was performed by all three authors. Articles for which an author was unclear whether to include or exclude were subjected to double screening by another author. Unclear items were discussed among all authors. Bibliographies of included studies were screened for further relevant publications.

A critical appraisal of the search and screening strategy of all review articles was performed after full-text screening based on the extracted data. Eleven pre-defined quality criteria were drawn from the "Checklist for making judgements about how much confidence to place in a systematic review of effects" by the International Initiative for Impact Evaluation. (International Initiative for Impact Evaluation. (2020) (see Figure 10 for criteria). The original checklist was designed for systematic review studies of effects in the field of medical research, focusing on participants/populations, interventions and outcomes. Adjustments were made to the original checklist to fit the study context. Criteria fulfilment for all articles was recorded (see Köthke et al., 2021, Supplementary Material 2). Articles were not excluded because of not meeting one or more of these criteria per se. Instead, the fulfillment of the criteria is reported, which allows the reader to assess the rigor of the methods used in the review studies.

Articles whose search and screening processes were not comprehensible for the authors were not included in the synthesis of the evidence review map. The criterion for exclusion of an article on the grounds of incomprehensibility is that it does not report any of the following search criteria: 1) study types included, 2) databases searched, 3) languages included, 4) type of agroforestry system and 5) type of outcome considered. Further, studies were excluded if less than 2 of the following screening criteria were fulfilled: 1) inclusion criteria reported, 2) number of found studies reported, 3) number of included studies reported or a reference list provided, and 4) summary of study exclusion reported.

2.2 Data extraction, coding and classification

Data was extracted from all included review articles in a pre-defined data extraction table (available in Köthke et al., 2021, Table S5) during full-text screening. In this step, information is systematically extracted on the topics: reference information, study design, agroforestry practices, outcomes and indicators, geographical locations, search strategy, screening strategy, and included studies. A pre-classification of agroforestry systems distinguishes agrisilvicultural systems, silvopastoral systems, agrosilvopastoral systems and others (based on the definition provided by Nair (1985)). Expecting a manageable number of review articles and a given pre-definition and pre-classification of the studied components by the review studies' authors, a suitable classification for agroforestry practices was defined after the data extraction. The data extraction sheet therefore records the original definitions of agroforestry practices and outcomes as defined by the review study authors, enabling a subsequent content analysis, if further categorization deemed necessary.

For recording and coding outcomes, the applied definition by the review study authors was extracted as well as the indicators applied. Outcomes were classified according to the categories "environmental", "economic" and "social". Environmental outcomes include all impacts on regulation and support of ecosystem services (see Millennium Ecosystem Assessment,

2005, Figure A), which comprise, e.g., effects on climate, flood, and disease regulation, or water purification. Environmental outcomes include effects on biodiversity and animal welfare. Indicators might be greenhouse gas balances, water retention, soil formation, nutrient cycling, waste production, and use of chemicals or energy. Economic outcomes cover the provisioning of products such as food, fodder, fuel or material. Those might be measured by agricultural productivity compared to other land use systems using indicators such as factor productivity, yield, or costs and returns. Economic indicators with a direct link to household economy, such as household income, property rights, food security and nutrition, standard of living, economic stability and liquidity, are classified under social outcomes. Further social outcomes include impacts on human well-being, health, safety, access to goods and clean water and air, employment and labor markets, job quality, social inclusion, and gender equality. Cultural ecosystem services are included under social outcomes as well. Cultural services include, e.g. recreational, aesthetic, educational, and spiritual benefits (see Millennium Ecosystem Assessment, 2005, Figure A). A finer categorization was performed after data extraction, building on the definitions of outcomes as described for h review article.

Descriptive statistics were used to present the results of the literature selection. Frequency distributions of selected articles and included studies are displayed or reported in terms of publication years, geographic locations, outcome categories and indicators, agroforestry systems and practices, comparators, as well as critical appraisal criteria met. All data collection and processing were done in MS Excel.

3 Results of the literature search and screening

The database search resulted in 2,799 hits. An additional 9 potential articles were found during the literature management process and added to the first screening step (see Figure 1). After the removal of duplicates, 2,157 articles remained and were screened by title, keywords and abstracts. Most articles did not meet the inclusion criteria and were excluded. 119 articles remained for full text screening, to which another 7 articles were added after searching the bibliographies. After the completion of the full text screening, one article was excluded because the manuscript was not accessible. 39 articles were found not to meet the inclusion criteria: systematic review conducted, comparator applied, effect of agroforestry on a social, economic or environmental outcome analyzed. Three articles were excluded to avoid double reporting of results in this article. Of this, one article was a meta-review, compiling systematic review studies instead of original case studies. Two articles performed a meta-analysis based on systematic reviews published in other articles already included. Another twelve articles were excluded because the definition of the considered agroforestry practice was unclear. This was mainly the case for studies which included agroforestry in a broader land use category; the results related to agroforestry were thus not separable from the other land use categories.

A total of 71 articles remained after full text screening. Out of these, further seven articles were excluded after quality screening because their search results and screening strategy were not comprehensible (see criteria in Methods section). The remaining 64 articles were included in the further analysis. The list of all 64 references is available in Köthke et al. (2021, Table S6).

4 Spatial distribution and temporal pattern of research

The 64 identified review articles were published between 2007 and 2020 (where the search ended) (see Figure 2). Prior to the publication year 2013, only a few systematic review studies focusing on agroforestry outcomes met our inclusion criteria, while the number of publications thereafter increased substantially. The absence of eligible publications from earlier years, as well as the increasing trend in recent years is not surprising. The application of systematic review or meta-analysis methods is only useful if a sufficient number of case studies has been published previously. Standardized methodologies for systematic reviews were developed in the end of the 20th century only, which was in line with the improvement of online libraries and search engines (Chalmers et al., 2002). While originating from the field of clinical research, methods and standards were advanced in past decades and gradually transferred to social and environmental research topics. However, the application of standardized review methods has not yet penetrated environmental research fully (O'Leary et al., 2017). Numerous narrative literature reviews of agroforestry outcomes have been published in environmental research journals, but they did not meet the requirements for systematic reviews as defined by our inclusion criteria.

The outcome categories considered (environmental, economic, and social) in the review articles can also be seen in Figure 2. The majority of review articles (88%) addresses environmental outcomes (exclusively or in combination with other outcomes). 34% of review articles consider economic outcomes and only six review articles (9%) consider social outcomes as one aspect among others. Systematic review articles about social outcomes have not been published at all before 2015.

A total of 31 review articles did not apply a spatial restriction in their search strategy, and included literature that addressed agroforestry outcomes on a global scale. About half of the review articles limited their literature search to spatial areas of different extents and used different classification schemes, such as geographic and ecozonal classifications, which may overlap

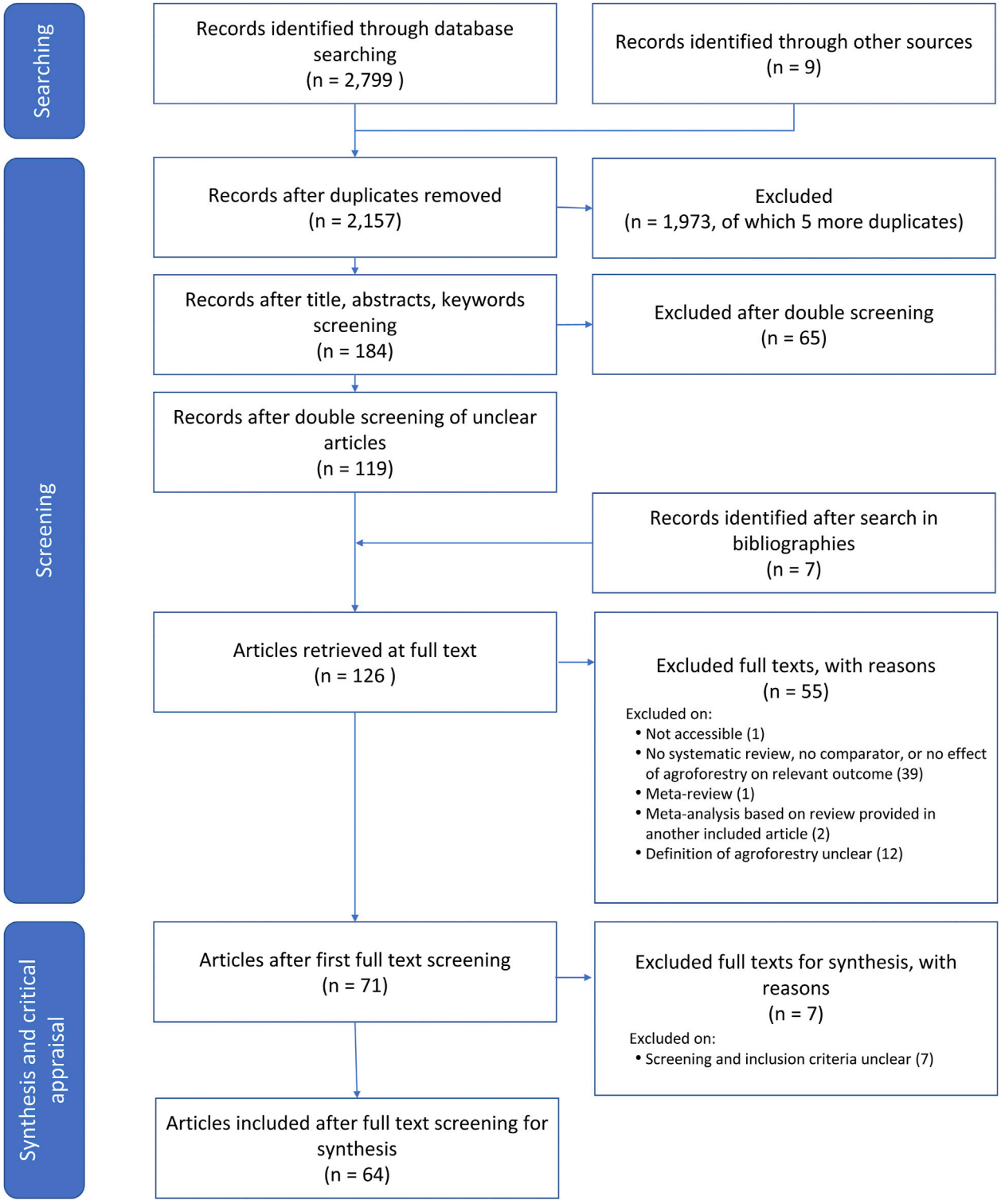


FIGURE 1
Flow diagram of study selection (template ROSES Flow Diagram for Systematic Reviews. Version 1.0). From 2,799 articles identified in an initial database search, 64 studies were selected by screening based on inclusion and exclusion criteria.

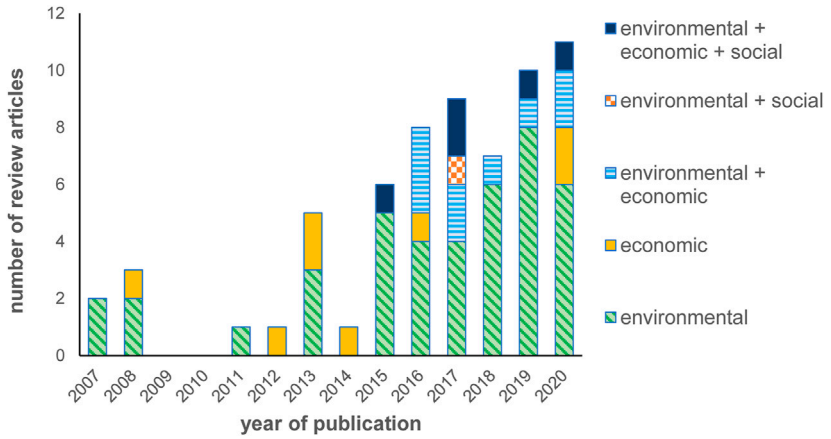


FIGURE 2
Number of systematic review articles about agroforestry outcomes published per year (n = 64) with type of outcome addressed (the year 2020 only contains articles until October 2020). The number of articles is increasing over time. Most articles address environmental outcomes, followed by economic outcomes. Only few articles consider social outcomes.

(see Figure 3). Eight review articles focused on the tropics, subtropics or Neotropics, six on the temperate region, and two on the Mediterranean climate. A total of nine review articles focused on African regions, like Sub-Saharan Africa or the Sudan-Sahelian zone, or considered a subset of African countries. The other articles (n = 8) applied spatial limitations which are each represented only once (see Figure 3), with Africa, Latin-America and Asia representing an example of large spatial coverage and the California rangelands representing a very limited one.

5 Thematic coverage

5.1 Agroforestry systems and practices

Of the 64 review articles, 36% focused in their literature search on specific agroforestry practices (e.g. shaded coffee under forest canopy), 39% searched for agroforestry in general (without further definition or restriction), and 25% included agroforestry or a specific agroforestry practice in a search for broader land use categories (e.g. conservation agriculture including agroforestry).

The definitions of agroforestry systems and practices as provided by the review studies were categorized as described in Table 1. The presented categories were formed in such a way that the varying levels of agroforestry definition for the identified review studies were considered and a given classification according to functions or arrangement of agroforestry components was clearly assignable. Subsequently, agroforestry types were assigned to the level of aggregation that the review studies applied in presenting their results. For example, if a review study included different agroforestry practices in its search but presented results for all types as an aggregate, the study was assigned to the category "agroforestry in general".

Some studies referred to the strategies of biomass transfer and mulching, where the biomass of trees and shrubs is used for mulching of agricultural fields. However, in most cases the agroforestry component was not distinguishable from other types of biomass transfer, as different mulches were combined in the results or no clear definitions were provided. Thus, we did not include the agroforestry practice of biomass transfer and mulching in our analysis.

The most commonly studied agroforestry type is agrisilviculture which was considered in 66% of the identified review articles. The systems of silvopasture and agrosilvopasture are less represented by review articles (15 and 7% respectively) (see Figure 4). A total of 12 review articles (11%) focused on agroforestry in general without differentiating between individual systems. The most studied agrisilvicultural practices are fallow systems including shifting cultivation, alley and intercropping systems as well as multi-strata systems with shaded perennial crops, such as shaded coffee or cocoa (covered by 13–14 review studies each) (see Figure 4). Studies focusing especially on agrisilvicultural practices of, e.g., homegardens or cropping under forest canopy are less represented. A total of 14 review articles presents results for agrisilviculture in general, i.e. no differentiation between individual practices is made. Review articles including silvopastoral systems mostly apply an aggregated definition of silvopasture (n = 10). 3 articles consider trees/shrubs on pasture. Each of the other individual practices like forest grazing or shelterbelts are considered by one review article. Most review studies which are included in the category of agrosilvopasture focus on the outcomes of scattered trees and parklands (n = 4) or apply a general definition of agrosilvopasture (n = 3).

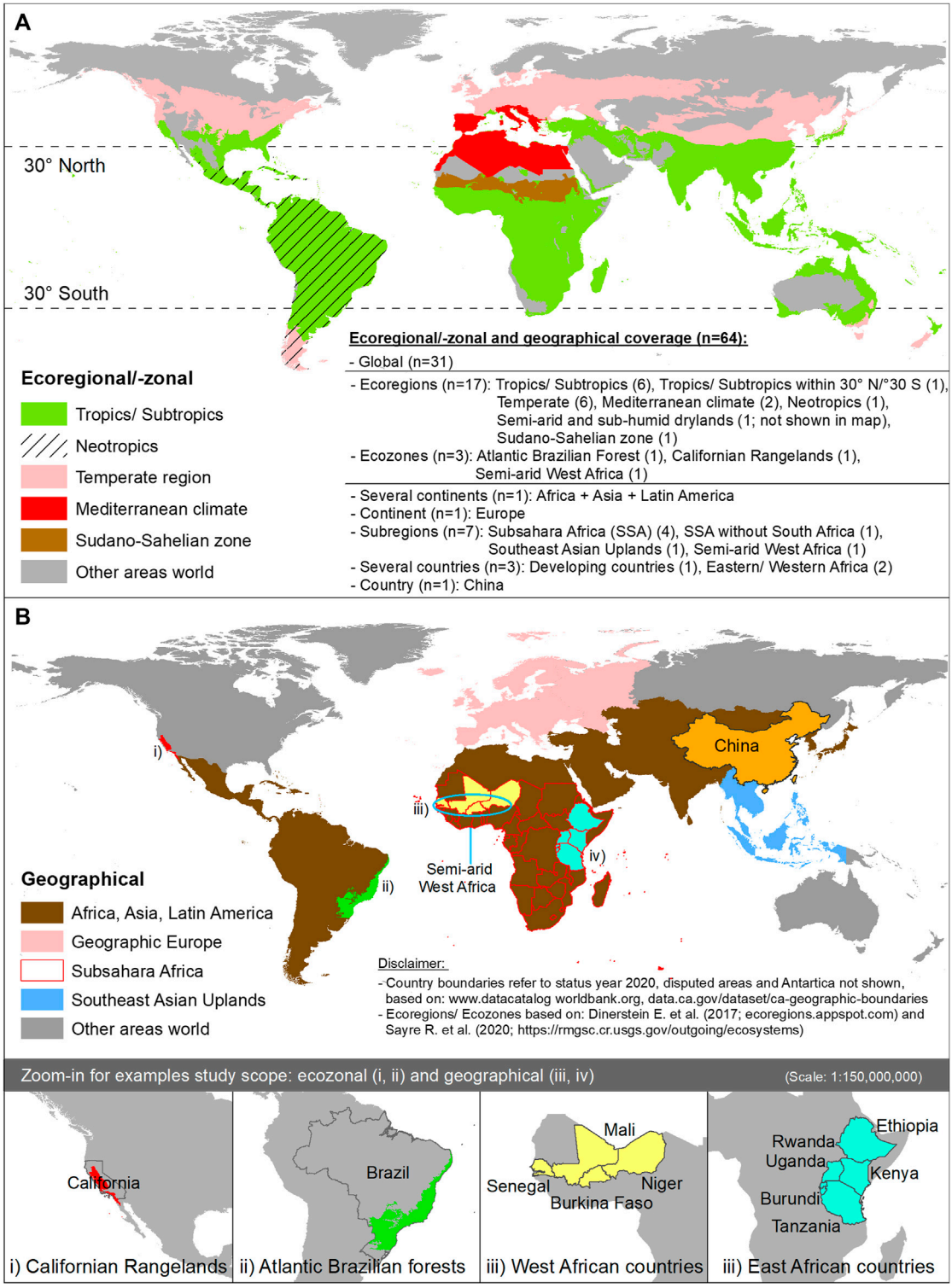


FIGURE 3
Spatial coverage applied by systematic reviews of agroforestry outcomes (n = 64 articles). The classification is displayed as defined by the studies' authors. Map **(A)** shows the ecoregional and ecozonal classification applied by 20 review articles and map **(B)** the geographical classification applied by 13 review articles (classification based on Dinerstein et al., 2017; Sayre et al., 2020). 31 articles are referred to global as they did not apply any spatial restriction.

TABLE 1 Categorization of agroforestry systems and practices. Specific practices are assorted to the aggregated categories of agroforestry, agrisilvicultural, silvopastoral, and agrosilvopastoral systems.

Agroforestry system/practice category	Description
agroforestry (AF) in general	aggregated consideration of diverse AF systems and practices, applied if different AF systems were combined in the results, or no further definition of AF was given
agrisilviculture (AS) in general	combination of trees/shrubs and crops, applied if diverse AS practices were combined in the results, or no further definition of AS was given
shaded perennial-crop systems, multi-strata agroforestry	perennial crops shaded with trees, e.g. shaded coffee/cocoa, multilayer plant association
alley cropping, intercropping	trees/shrubs planted in alleys or other spatial arrangement, intercropped with agricultural crops, e.g. intercropped apple orchards, shade trees for cash crops
fallow systems, shifting cultivation	trees/shrubs planted and left to grow during the fallow phase between crop rotations to replenish soil fertility, includes shifting cultivation, improved and rotational fallow
multipurpose trees, parklands	trees scattered on farmland with crops
windbreaks, buffers strips, hedgerows	trees/shrubs around crop land to protect the farmland, e.g. as windbreaks, includes riparian buffers between crop land and water bodies/rivers
homegardens, tree gardens	combinations of trees and crops around homesteads
under forest canopy	crops or perennials are grown under the forest canopy, forest farming
silvopasture (SP) in general	combination of trees/shrubs and animals, applied if diverse SP practices were combined in the results, no further definition of SP was given
forest grazing	animals grazing in the forest
trees/shrubs on pasture	trees/shrubs on pasture or rangelands
shelterbelts, living fences for fodder	trees/shrubs used as fences for pastures, for fodder or as shelterbelts for animals
protein banks, fodder trees	trees/shrubs coppiced for fodder
agrosilvopasture (ASP) in general	combination of trees/shrubs, crops and animals, applied if diverse ASP practices were combined in the results, or no further definition of ASP was given
multipurpose hedgerows (mulching, fodder)	woody hedges coppiced for multi-purposes, such as fodder/browse, mulch, green manure
scattered trees, parklands (without further definition)	trees scattered in the landscape which are combined with pasture/grazing animals and/or crops or are used for mulch and/or fodder

The agroforestry practices of entomoforestry and apiculture were not considered by any of the identified review articles, nor were conclusions drawn on these practices in any review article that considered agroforestry in general. A negligence of other individual agroforestry practices has not been detected when following the classification of Nair (1985).

5.2 Outcomes

The outcomes considered by the review articles were categorized into environmental, economic and social outcomes and their associated thematic subcategories (see Figure 5). Most articles address multiple outcomes. Within the largest category of environmental outcomes, the impacts of agroforestry on mitigating climate change were most frequently considered (n = 27 review articles). Impacts of agroforestry on water and biodiversity (n = 24) and soil properties (n = 21) were also frequently studied. The economic indicator 'yield' was frequently addressed (21 articles), while six articles only addressed social outcomes which mostly refer to household income. Three studies included cultural ecosystem services in their search strategy, but yielded none or too few results and thus discarded this outcome category for further synthesis (thus, they were not counted in Figure 5). Altogether, this information shows that the evidence base for cultural ecosystem services remains insufficient.

5.2.1 Environmental outcomes

5.2.1.1 Climate change mitigation

The outcomes on climate change mitigation are captured in the review articles through various indicators that consider the stock or emissions of greenhouse gases. A total of 6 studies compiled information on biomass carbon, of which 2 distinguished above- and below-ground carbon and 2 focused on above-ground carbon only. Soil carbon was

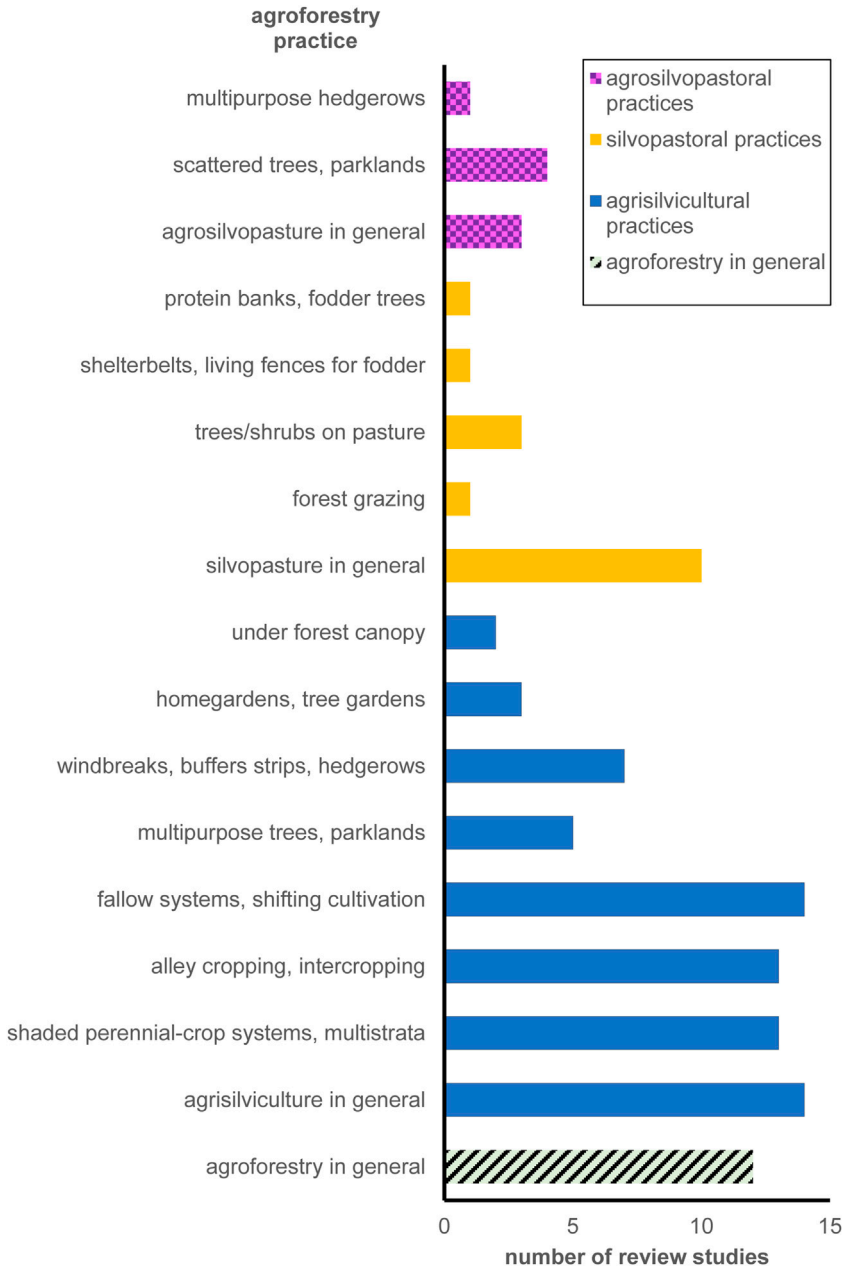


FIGURE 4
Agroforestry practices considered in the review studies (n = 64 review articles, of which some cover more than one practice). Most review studies consider an agrisilvicultural practice or an aggregated agroforestry system.

considered on an aggregated level by 9 studies and soil organic carbon (SOC) was addressed separately by 16 studies. SOC has both impacts on climate change as well as other physical, chemical and biological traits of soils. However, it is only assigned to the category of climate change outcomes to avoid double counting. Another 3 studies considered carbon storage without differentiation by individual components. Only one study addressed other greenhouse gases than carbon, and analyzed methane (CH_4) and nitrous oxide (N_2O) emissions.

5.2.1.2 Water

A total of 16 studies on water outcomes focus on water regulation services and water retention by applying the indicators field capacity, infiltration rate, soil moisture, surface runoff, soil

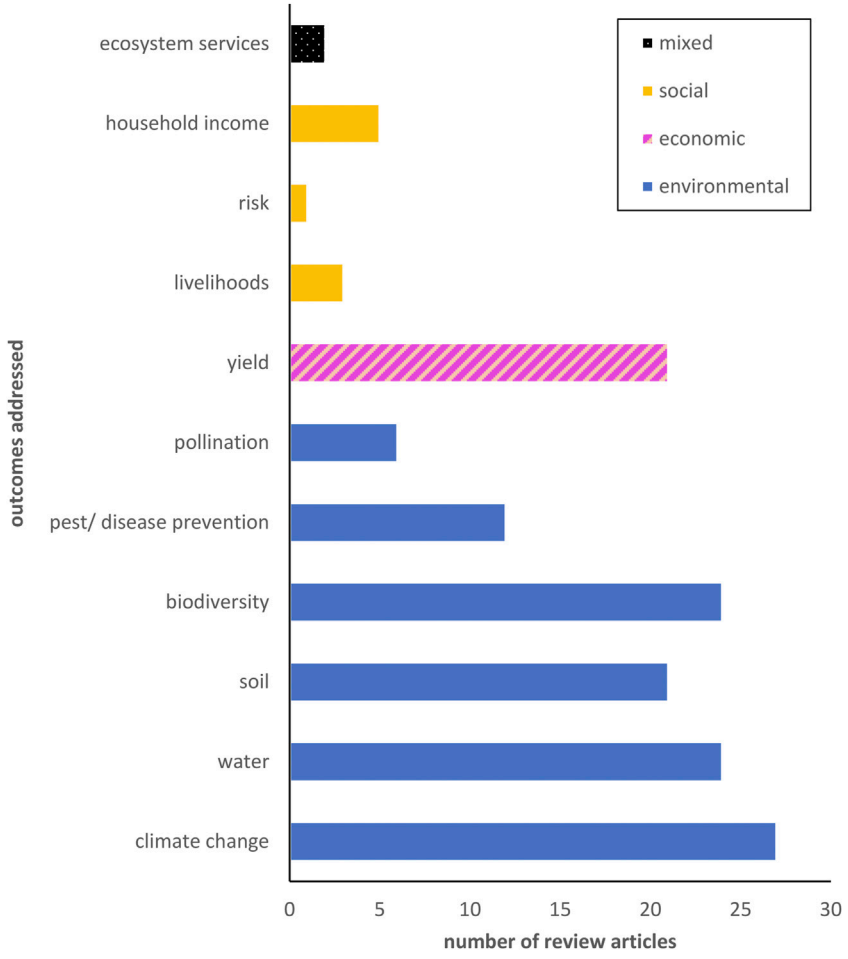


FIGURE 5
Frequency distribution of outcomes examined by the 64 review articles (some studies cover more than one outcome). Environmental outcomes related to climate change, water and biodiversity were most frequently examined. Productivity aspects of agroforestry (economic outcome) were considered comparatively frequent. Social outcomes were considered less frequent. Hh = household, ES = diverse ecosystem services.

water content or porosity. These soil hydrological properties were assigned to the water outcome category instead of the soil outcome category. Only one study assesses water quality, which is determined by the runoff of sediment, nutrients and/or faecal bacteria and one assesses water purification.

5.2.1.3 Soil

Most studies consider soil chemical properties (n = 18), with the focus on soil nutrients. The most often applied indicators are soil nitrogen (n = 10), soil phosphorus (n = 8), nutrient cycling (n = 7), and soil pH (n = 5). Soil fertility or cation exchange capacity was addressed 7 times. Other chemical properties like individual cations are less often studied.

Soil physical properties are considered in 11 studies, which most often focus on erosion (n = 8). 4 studies consider soil structural indicators such as bulk density, aggregate stability or macroaggregates.

Only 4 studies consider soil biological properties like the macro-, meso, or microfauna.

5.2.1.4 Biodiversity

Biodiversity was most often measured in terms of species richness (n = 15) and abundance (n = 9). 4 studies applied other diversity indices, such as composition, functional or taxonomic diversity. The delimitation between those indicators is sometimes unclear or overlapping. 7 articles referred to biodiversity as an aggregate measure of several indicators or did not provide a clear definition. The indicators activity, habitat heterogeneity, community evenness and community similarity were applied each once.

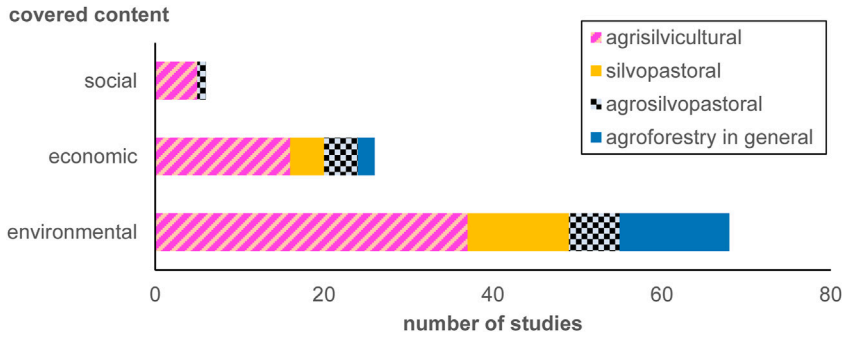


FIGURE 6
Distribution of agroforestry systems considered by outcome type (n = 64 review articles, some articles discuss more than one outcome and/or agroforestry system).

Most articles provided results aggregated groups of animals or plants (n = 11), 6 studies considered plants, 4 arthropods, 3 bats, 4 birds, and 2 mammals. One study each considered: dung beetles, insects, wildlife animals, bryophytes, vertebrates, invasive species, reptiles, nematodes, fungi, liches and amphibians.

5.2.1.5 Pest and disease control

Studies on pest and disease control most often applied the abundance, density or diversity of natural enemies/predators as an indicator (n = 7). A total of 6 studies analyzed the abundance or density of pest species or disease occurrence. Only one study considered plant damage as an indicator. 5 studies did not specify the indicators applied for measuring pest and disease control or provided qualitative analysis without focus on individual indicators. 3 review articles focused on cocoa pests and diseases, one on apple pests and one on millet pests. The other articles did not restrict or describe the type of pests/diseases included.

5.2.1.6 Pollination

Only 6 studies analyze agroforestry outcomes on pollination services. 2 studies apply pollinator richness and abundance as indictors. The other studies provide qualitative summaries of included studies, with reference to, e.g. habitats, landscape connectivity and mitigation of pesticide exposure.

5.2.2 Economic outcomes

5.2.2.1 Yield

Studies focusing on the yield of agroforestry compared to other land uses dominantly apply crop yields as an indicator (n = 15). Of those 8 studies combine yields of diverse crops, 3 studies analyze coffee and/or cocoa, 4 maize, 3 sorghum, 3 millet, and 2 peanuts. Other crops are considered once each: tree fruits, cotton, chili, taro, cowpea, tomato, and eggplant.

Pasture yields and timber production were considered in 3 studies each and one study analyzed milk yields. Only 3 studies analyzed system yields by considering a combined yield of either crops, fruits and animals or trees, forage and animals.

5.2.3 Social outcomes

Only six review articles included at least one social outcome indicator in their literature search. Thus, most review articles have refrained from even investigating social outcomes.

5.2.3.1 Livelihoods

Three studies addressed the outcomes on livelihoods. One study defined livelihood outcomes as an aggregated multiple system-wide effect of diverse provisioning and regulating ecosystem services. The other article distinguished the livelihood indicators: access to land, decline in staple yield, socio-cultural wellbeing, livelihood options, deprioritization of upland rice, labor input, and customary practices. The third study applied the livelihood indicators nutritional diversity, medicinal uses, material assets, sustain livestock, and energy.

5.2.3.2 Risk

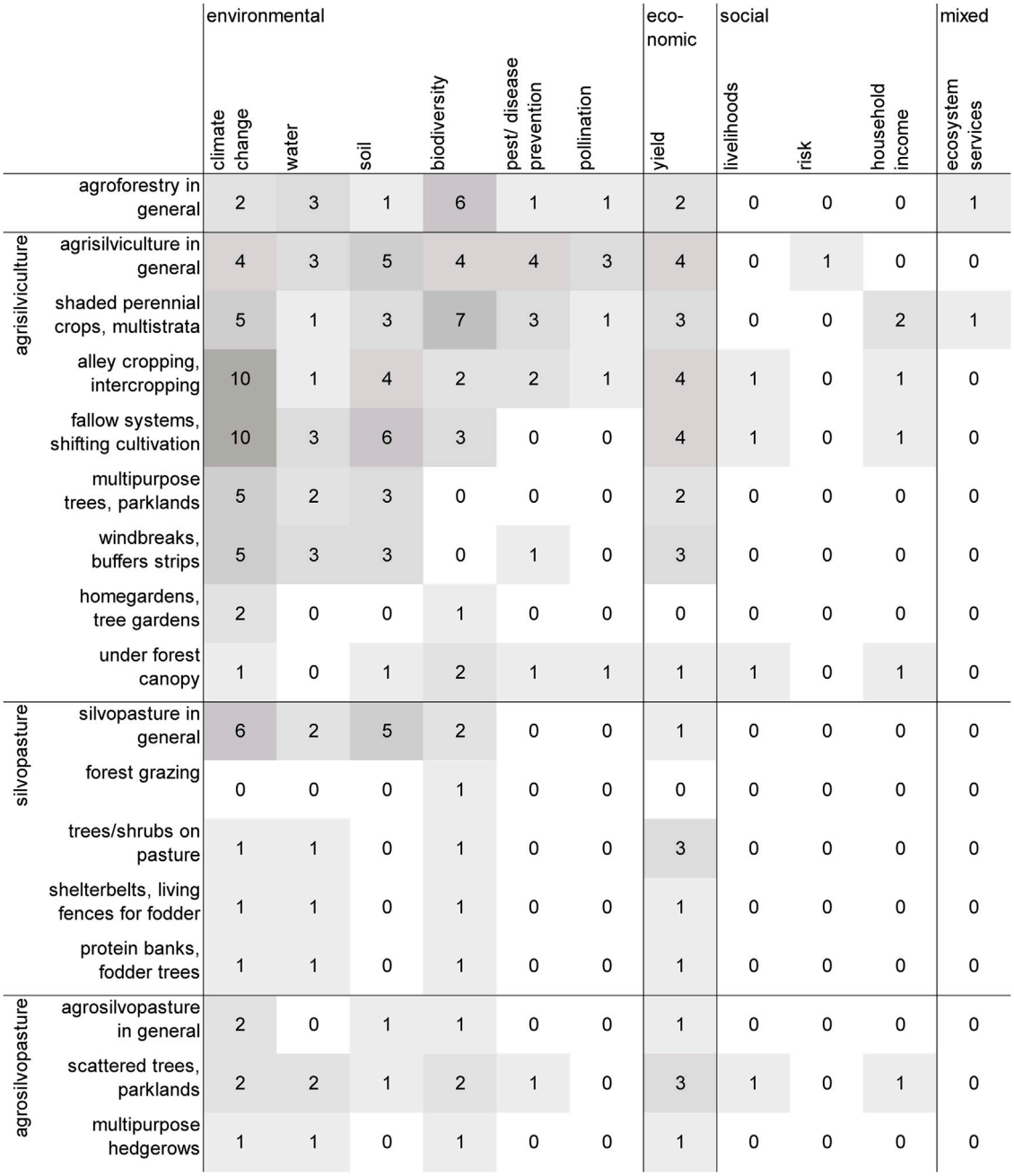
Only one article analyses risk, which is defined as the potential of fluctuating profitability over time caused by damage, injury, liability, loss, or other negative events.

5.2.3.3 Household income

Economic indicators that directly refer to or conclude on household income are assorted to the social outcome category "household income" (n = 5). 3 studies apply income as an indicator without further definition, all of them apply other livelihood indicators as well. 2 studies conclude on household income by analyzing costs, prices, revenues and cost-benefit ratios.

5.2.3.4 Diverse ecosystem services

Diverse ecosystem services (provisioning, regulating and supporting) were comprised by 2 studies on aggregated levels. Both studies do not allow to draw conclusions on individual indicators and were thus assorted to this aggregated category.



		environmental						eco-nomic	social			mixed
		climate change	water	soil	biodiversity	pest/ disease prevention	pollination	yield	livelihoods	risk	household income	ecosystem services
	agroforestry in general	2	3	1	6	1	1	2	0	0	0	1
agrisilviculture	agrisilviculture in general	4	3	5	4	4	3	4	0	1	0	0
agrisilviculture	shaded perennial crops, multistrata	5	1	3	7	3	1	3	0	0	2	1
agrisilviculture	alley cropping, intercropping	10	1	4	2	2	1	4	1	0	1	0
agrisilviculture	fallow systems, shifting cultivation	10	3	6	3	0	0	4	1	0	1	0
agrisilviculture	multipurpose trees, parklands	5	2	3	0	0	0	2	0	0	0	0
agrisilviculture	windbreaks, buffers strips	5	3	3	0	1	0	3	0	0	0	0
agrisilviculture	homegardens, tree gardens	2	0	0	1	0	0	0	0	0	0	0
agrisilviculture	under forest canopy	1	0	1	2	1	1	1	1	0	1	0
silvopasture	silvopasture in general	6	2	5	2	0	0	1	0	0	0	0
silvopasture	forest grazing	0	0	0	1	0	0	0	0	0	0	0
silvopasture	trees/shrubs on pasture	1	1	0	1	0	0	3	0	0	0	0
silvopasture	shelterbelts, living fences for fodder	1	1	0	1	0	0	1	0	0	0	0
silvopasture	protein banks, fodder trees	1	1	0	1	0	0	1	0	0	0	0
agrosilvopasture	agrosilvopasture in general	2	0	1	1	0	0	1	0	0	0	0
agrosilvopasture	scattered trees, parklands	2	2	1	2	1	0	3	1	0	1	0
agrosilvopasture	multipurpose hedgerows	1	1	0	1	0	0	1	0	0	0	0

FIGURE 7
Number of review studies addressing the combination of individual agroforestry practices and outcomes (n = 64 review articles, some articles include several studies). The highest density of review studies is visible for climate change, water, soil, biodiversity and yield outcomes of agrisilvicultural practices and aggregated agroforestry systems. Gaps exist in studies of social outcomes.

5.3 Combination of practices and outcomes

The combination of agroforestry systems and environmental, economic and social outcomes, as synthesized by the review articles, is displayed in Figure 6. Environmental and economic outcomes are analyzed for all three agroforestry systems as well as for agroforestry in general. Social outcomes are, however, only considered for agrisilvicultural and agrosilvopastoral systems.

Figure 7 shows the combination of agroforestry practices and outcome subcategories addressed in the review articles. The figure shows which components are represented by many, a

		environmental						eco-nomic	social			mixed
		climate change	water	soil	biodiversity	pest/ disease prevention	pollination	yield	livelihoods	risk	household income	ecosystem services
	agroforestry in general	2	1	0	4	0	0	1	0	0	0	0
agrisilviculture	agrisilviculture in general	3	3	3	3	3	2	2	0	1	0	0
agrisilviculture	shaded perennial crops, multistrata	4	1	3	4	3	1	2	0	0	1	0
agrisilviculture	alley cropping, intercropping	3	0	0	0	1	0	0	0	0	0	0
agrisilviculture	fallow systems, shifting cultivation	3	0	1	1	0	0	1	0	0	0	0
agrisilviculture	multipurpose trees, parklands	1	0	0	0	0	0	0	0	0	0	0
agrisilviculture	windbreaks, buffers strips	3	1	1	0	0	0	0	0	0	0	0
agrisilviculture	homegardens, tree gardens	2	0	0	0	0	0	0	0	0	0	0
agrisilviculture	under forest canopy	0	0	0	0	0	0	0	0	0	0	0
silvopasture	silvopasture in general	5	1	2	0	0	0	0	0	0	0	0
silvopasture	forest grazing	0	0	0	0	0	0	0	0	0	0	0
silvopasture	trees/shrubs on pasture	1	1	0	1	0	0	2	0	0	0	0
silvopasture	shelterbelts, living fences for fodder	1	1	0	1	0	0	1	0	0	0	0
silvopasture	protein banks, fodder trees	1	1	0	1	0	0	1	0	0	0	0
agrosilvopasture	agrosilvopasture in general	2	0	0	0	0	0	0	0	0	0	0
agrosilvopasture	scattered trees, parklands	1	1	0	2	0	0	1	0	0	0	0
agrosilvopasture	multipurpose hedgerows	1	1	0	1	0	0	1	0	0	0	0

FIGURE 8
Number of review studies with no geographical restriction in their search strategy (n = 31 review articles, some articles include several studies) (see also Figure 3 for further details), sorted by agroforestry practice and outcome.

few, or no studies. The highest density of review articles can be found for agrisilvicultural systems and practices, silvopasture in general and agroforestry in general. Especially reviews on climate change mitigation, water, soil, biodiversity, and yield outcomes show a broad coverage. The coverage of different outcomes, is greatest for agroforestry and agrisilviculture in general, multistrata systems, alley cropping, cropping under forest canopy and scattered trees in parklands. The fewest outcomes were analyzed for homegardens and forest grazing. About one-third of review studies summarize results for aggregated agroforestry systems or agroforestry in general.

The thin evidence base for social outcomes becomes even more obvious when the coverage of studies by subcategories is mapped, as shown in Figure 7. Risk is only considered for one

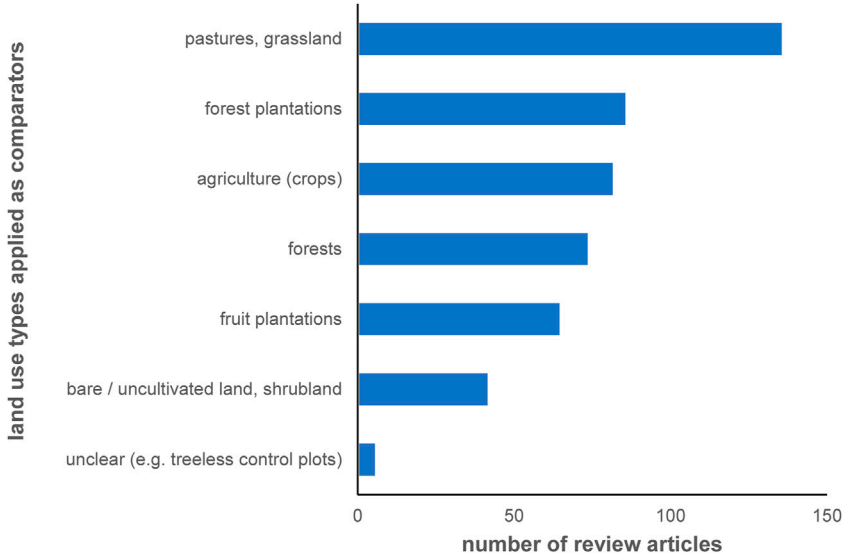


FIGURE 9
Land use types applied as comparators in review articles (n = 64 review articles, some articles consider more than one comparator). Forests and agriculture (crop monoculture) were most often applied as a comparator.

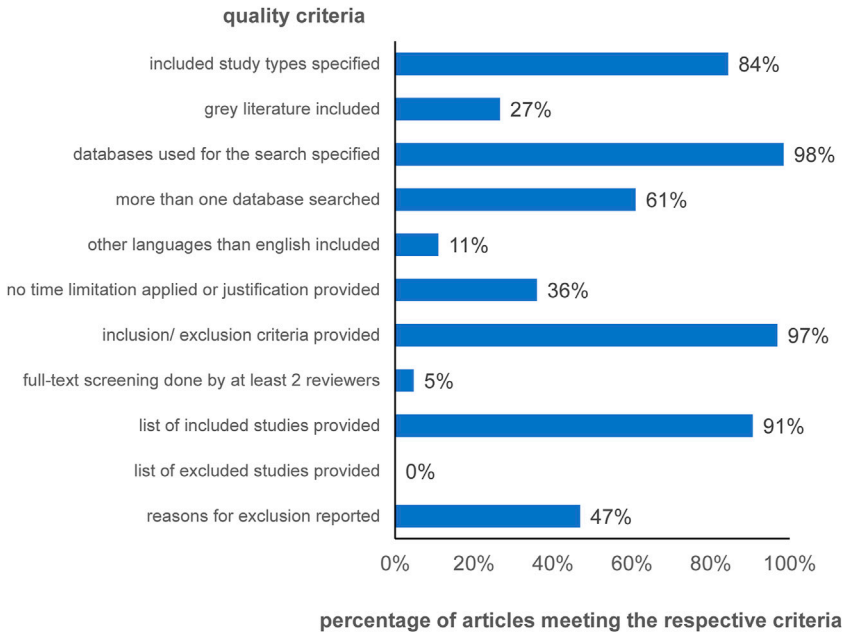


FIGURE 10
Fulfillment of individual quality criteria for assessing search and screening strategy (n = 64 review articles) (Criteria applied from 3ie (2020)). More than half of the criteria were met by less than 50% of the articles. Only three criteria were fulfilled by more than 90% of the articles.

system, while the indicators livelihoods and household income are only considered for few individual practices. For most practices, social outcomes are not addressed in any review study.

Overviews of pest and disease control and pollination services are lacking for silvopastoral and agrosilvopastoral systems and practices (except pest/disease prevention in

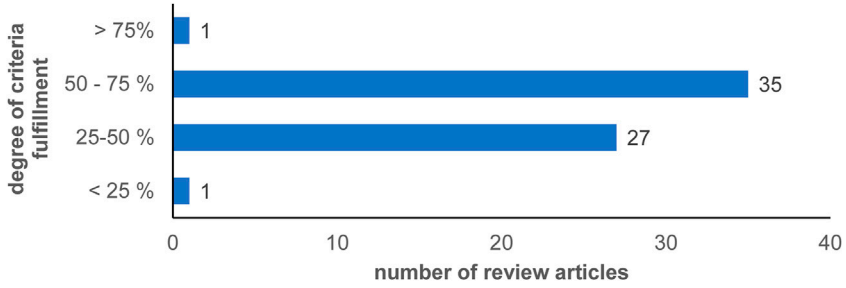


FIGURE 11
Percentage of quality criteria met by review articles (n = 64). Most articles fulfilled between 25 and 75% of the eleven quality criteria for assessing search and screening strategy. Only one article fulfilled more than 75% of the criteria.

scattered trees). For silvopasture, however, this can be explained by the absence of a crop component, for which these outcomes would be most relevant.

Figure 8 shows the same assignment of studied components as displayed in Figure 7, but counts only review articles which cover the global scale. Articles not counted here focused on a restricted geographical or ecoregional/- zonal scale as shown in Figure 3. The highest density of studies on a global scale is given for agrisilviculture in general and multistrata systems. The best coverage of practices is depicted for studies addressing climate change mitigation, where only two of the listed agroforestry practices are not explicitly considered by a review. For the topic of social outcomes, only two studies remain with a global coverage, no studies on livelihoods are left. The number of economic studies reduces from 34 to 12, if only global scale studies were considered.

5.4 Comparators applied

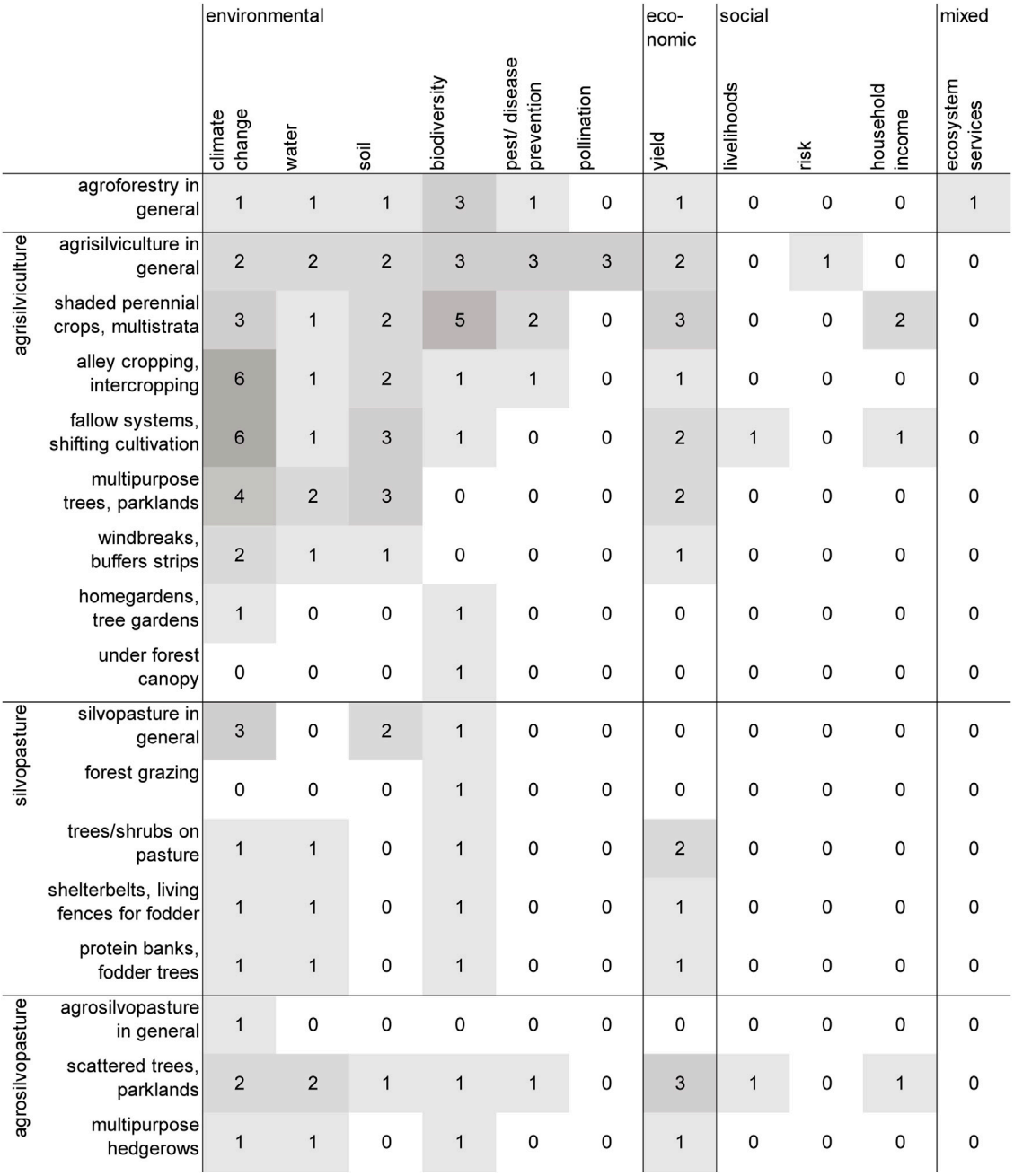
An inclusion criterion for the selection of studies in case of this article was the consideration of another land use as comparator for agroforestry. In most of the identified review articles, adjacent plots were applied as comparators (i.e. as paired design). In five review articles, land use change analysis between agroforestry and another land use type was performed. Out of these, four articles applied before-and-after comparisons, and one article allowed for various experimental designs such as paired sites, pseudo-replication, chrono sequence, as well as repeated measures. The most commonly used comparators are forests and agriculture, mostly in the form of crop monocultures (see Figure 9). The category of forests includes various definitions like mature forests, primary and secondary forests, as well as comparators designated as forests by the review study's authors without further definitions provided. Forest plantations were distinguished from forests, as done by several authors. The agriculture (crops) category usually refers to monocultural cultivation of the same type of crops considered in the compared agroforestry practice. Fruit plantations are distinguished as a separate category, comprising for instance cocoa and coffee plantations, vineyards and apple or olive orchards. This comparator is usually applied for shaded perennial-crop systems. Similarly, pasture and grassland were usually applied as comparator for silvopastoral systems and practices. Uncultivated plots and treeless control plots were used as comparison plots six times without further definition.

6 Critical appraisal

The quality of analyzed systematic reviews in terms of transparent and comprehensible search and screening strategy was assessed by applying the predefined quality criteria as listed in Figure 10. No articles fulfilled all criteria. Most review articles reported the study types they included in their literature search, reported the databases used for search, provided inclusion and exclusion criteria and a list of included studies. No article, however, provided a list of excluded studies and less than half of the articles reported the reasons for study exclusion. Full-text screening by at least two reviewers was performed in only 5% of the review articles, and languages other than English were included in only 11% of the articles.

Figure 11 displays that only one article fulfilled more than 75% of the listed quality criteria (no weighting of criteria was applied). Most articles fulfilled between 25 and 75% of the listed criteria and only one article fulfilled less than 25% of the listed criteria.

Figure 12 displays the number of review studies which fulfill at least 50% of the quality criteria (as depicted in Figure 11) by agroforestry system/practice and outcomes considered. While the



		environmental						eco-nomic	social			mixed
		climate change	water	soil	biodiversity	pest/ disease prevention	pollination	yield	livelihoods	risk	household income	ecosystem services
	agroforestry in general	1	1	1	3	1	0	1	0	0	0	1
agrisilviculture	agrisilviculture in general	2	2	2	3	3	3	2	0	1	0	0
	shaded perennial crops, multistrata	3	1	2	5	2	0	3	0	0	2	0
	alley cropping, intercropping	6	1	2	1	1	0	1	0	0	0	0
	fallow systems, shifting cultivation	6	1	3	1	0	0	2	1	0	1	0
	multipurpose trees, parklands	4	2	3	0	0	0	2	0	0	0	0
	windbreaks, buffers strips	2	1	1	0	0	0	1	0	0	0	0
	homegardens, tree gardens	1	0	0	1	0	0	0	0	0	0	0
	under forest canopy	0	0	0	1	0	0	0	0	0	0	0
silvopasture	silvopasture in general	3	0	2	1	0	0	0	0	0	0	0
	forest grazing	0	0	0	1	0	0	0	0	0	0	0
	trees/shrubs on pasture	1	1	0	1	0	0	2	0	0	0	0
	shelterbelts, living fences for fodder	1	1	0	1	0	0	1	0	0	0	0
	protein banks, fodder trees	1	1	0	1	0	0	1	0	0	0	0
agrosilvopasture	agrosilvopasture in general	1	0	0	0	0	0	0	0	0	0	0
	scattered trees, parklands	2	2	1	1	1	0	3	1	0	1	0
	multipurpose hedgerows	1	1	0	1	0	0	1	0	0	0	0

FIGURE 12
Number of review studies meeting at least 50% of the quality criteria, sorted by agroforestry practice and outcome (n = 36 review articles).

total number of available reviews has decreased considerably (from 64 to 36), the overall distribution of studies across topics has not changed substantially when compared to Figure 7. Large gaps emerged for studies of cropping under forest canopy, where only a study on biodiversity outcomes is left. Furthermore, studies on pollination outcomes only remain for agrisilviculture in general, if the 50% quality criteria threshold was applied.

7 Discussion of the applied methodology, possible interpretations, and further necessary steps for the analysis of the results

This study applies the methodology of an evidence review map aiming at mapping the research landscape around the

chosen topic. It does not analyze and synthesize the results contained in the identified literature and thus does not allow conclusions about the performance of agroforestry compared to another land use. It provides the basis for conducting such a synthesis in follow-up work, but for which further in-depth analysis and critical appraisal of the methods used to synthesize the results in the selected review articles is required. The evidence review map does not collect individual case studies itself, but identifies systematic review studies and meta-analysis published about the topic. The level of synthesis studies was chosen because of the broad scope of the research, covering an entire land use system.

A systematic literature search and screening was performed, and the conduct of each step was disclosed, ensuring a high degree of accuracy and comprehensibility of study selection. However, as any systematic review, our study is at risk of being influenced by publication bias. Publication bias occurs when studies with less "interesting results" (e.g., non-significant results) are not published and thus would not appear in our literature search. For our study, this can be explained by the example of studies analyzing social and cultural outcomes, for each of which only a few results were identified. Three review studies describe in their articles that they systematically searched for case studies to analyze cultural outcomes, but found too few results to provide a conclusive synthesis on this topic. Therefore, we can conclude that there is too little research on this topic to synthesize. However, most potential indicators of social outcomes (e.g., human well-being, health, safety, property rights) were not mentioned as search and inclusion criteria in any review article. Thus, we cannot conclude from our map about the (non-)existence of case studies on this topic. One explanation for the underrepresentation of social review studies might be that authors excluded social indicators from the outset because they expected too few results, but also because social indicators are much more difficult to measure than, for instance, soil physical properties. The synthesis of study results for social outcomes is expected to be much more challenging as the synthesis for indicators for which a narrow range of measurement methods and study designs is given.

The literature selection presented revealed a large number of systematic reviews and meta-analyses published on agroforestry outcomes. In addition, it was found that several narrative reviews were published on the topic that were excluded during the screening process because the underlying literature selection was not comprehensible. Therefore, these articles will not be suitable for further comparison of the included results. However, these studies show on the one hand the great research interest in the topic and on the other hand the necessity to design studies also in the land use, environmental and socio-economic context in a precise, systematic and comprehensible way, so that a basis is given at all to gain superordinate knowledge instead of case study evidence.

Our evidence review map shows for which agroforestry practices and outcome indicators in which locations systematic synthesis can be found in literature. In doing so, it also identifies research areas for which such a synthesis has not yet been created. Conversely, however, it does not claim that the research areas covered by the systematic synthesis allow generalizable conclusions about agroforestry per se. Further unfolding of the identified review studies is strongly recommended to draw conclusions about the performance of agroforestry compared to other land uses in a follow-up review or meta-analysis. For synthesizing the review studies results, it would be necessary to consider in more depth the context to which the underlying case studies were subjected and to critically assess whether contextual factors were controlled for in the review studies. We did not restrict our study selection to plot-level studies, however, most identified review studies did so. Many case study results are therefore supposed to be location-specific, i.e., the results depend on the context of time, space and study design. van Noordwijk (2019) calls this kind of research theory of place research, which is valid in a specific context but not transferable out of context, such as theory of induced change research would allow (compare also van Noordwijk et al. (2014); van Noordwijk and Coe (2019)). To determine whether and for which contexts the review studies identified transferable results, further in-depth analysis is needed.

8 Conclusion

The evidence review map shows that agroforestry is a much-studied land use system. The study identified 64 systematic reviews and meta-analysis on the topic, which is only possible due to a much larger number of individual case studies, which they synthesized. However, the evidence review map shows that generalized statements about the outcomes of agroforestry, whether positive or negative, cannot be based on evidence in every subject area. Comparable to treeless agriculture and forestry, also the land use system of agroforestry is diverse and multidimensional and not the one universal statement about agroforestry can be valid. The mapping of outcomes considered in the review articles clearly shows an imbalance between environmental, economic and social outcomes. While environmental and economic outcomes have been searched and synthesized intensively, social outcomes were hardly considered. The present state of synthesis does not allow general conclusions to be drawn about the social outcomes of agroforestry, neither in terms of human-wellbeing, health, safety, nor in terms of household related economic indicators like household income or property rights, nor in terms of cultural ecosystem services. Only six review articles consider social outcomes at all, but relate them to specific agroforestry practices, and most of them have a restricted geographical focus. Most social outcome indicators were neglected in principle, meaning that no efforts have been made by

any review article to search for these social indicators. Whether intense social outcome research exists on a case study level cannot be concluded by this study. The evidence review map, however, shows that more emphasize is required on the systematic research on the impact of agroforestry on social indicators. In comparison cultural outcomes were searched by three of the identified review articles but without any results identified. This hints on a lack of case study research on cultural outcomes.

A systematic compilation of study results would be promising against the background of the large number of studies summarizing evidence for various environmental indicators as well as productivity aspects, particularly for agrisilvicultural systems.

Altogether, agroforestry systems and individual practices are fairly well covered by environmental outcome studies on climate change mitigation, water, soil and biodiversity. Especially on the aggregated level of agroforestry systems, several review studies are existent, with the broadest evidence base for shaded perennial-crop systems, alley cropping practices and fallow systems. The consideration of individual indicators, however, shows weaknesses in the evidence base of environmental outcomes. For instance, greenhouse gases other than carbon dioxide were almost completely neglected in climate change studies, which have a dominance of studies on soil carbon aspects. Soil studies focused mainly on chemical and physical soil properties, but almost neglect biological soil properties. Half of the biodiversity studies analyze only one species, which cannot be considered representative for statements on biodiversity in a wider sense.

Economic outcomes in terms of yield have intensively been studied and synthesizes were conducted for all agroforestry practices individually, except for homegardens and forest grazing. Nevertheless, less than one-third of studies with an economic outcome have a global coverage. Furthermore, the consideration of individual indicators applied revealed that productivity aspects have predominantly been addressed for crop yields, while pasture, animal and tree yields are hardly considered. Especially productivity aspects of animals have been considered by one study only, in this case referring to milk yield. Moreover, there is only a low number of studies that shift the focus from just agricultural yield to total system yield. Thus, also the evidence base for economic outcomes of agroforestry cannot be considered sufficient either.

The overall weaker evidence base for agrosilvopastoral systems as well as for social outcomes might be attributed to the less clear definition of this system and its attributed practices, which is equally attributable to the unclear definitions of social outcome indicators and their measurement methods. While studies about agrisilviculture might have been included at a more aggregated level of agroforestry in general, there hardly exist systematic reviews on social outcomes.

The critical appraisal of the review studies detected qualitative deficiencies of most articles related to the comprehensibility of the literature search and study selection. Instead of excluding most existing review articles due to very strict quality criteria, we decided to relax requirements for inclusion a bit, combined with a presentation of the extent to which the articles met quality criteria. However, it is clear that the rigorous application of systematic methods for evidence synthesis for ecological, social and economic studies could be expanded and would contribute to quality assurance.

Overall, the large number of comprehensible systematic studies summarizing the impacts of agroforestry compared to segregated land uses is promising and provides a basis for gaining overarching insights in further systematic comparisons. However, these relate primarily to environmental indicators and agroforestry yield. In other topic areas, policymakers and researchers should be aware of further research needs, particularly with respect to cross-cutting research on social and cultural impacts. Caution should be exercised in making generalized statements about agroforestry, as not every purported benefit of agroforestry has been studied beyond the case study level.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: OpenAgrar repository https://www.doi.org/10.3220/DATA20211109081609. A list of excluded studies is available from the corresponding author on reasonable request.

Author contributions

Conceptualization: MK. Draft of systematic map protocols and templates: MK. Discussion and review of templates: MK, VA, and ML. Data screening: MK, VA, and ML. Data analysis: MK. Writing—original draft: MK. Writing - review and approval of final manuscript: MK, VA, and ML. All authors agree to be accountable for the content of the work.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Agroforestry Network (2018). Scaling up agroforestry: Potential, challenges and barriers. A review of environmental, social and economic aspects on the farmer, community and landscape level. (ISBN: 978-91-985041-0-1), 85.

Andersson, L. (Editor) (2018). *Achieving the global Goals through agroforestry* (Stockholm: Agroforestry Network). Vi-skogen.

ASEAN Secretariat (2018). *ASEAN guidelines for agroforestry development*. Jakarta: Association of Southeast Asian Nations. (ASEAN) Secretariat).

Beillouin, D., Ben-Ari, T., and Makowski, D. (2019). Evidence map of crop diversification strategies at the global scale. *Environ. Res. Lett.* 14 (12), 123001. doi:10.1088/1748-9326/ab4449

Dinerstein, E., Olson, D., Joshi, A., Vynne, C., Burgess, N. D., Wikramanayake, E., et al. (2017). An ecoregion-based approach to protecting half the terrestrial realm. *BioScience* 67 (6), 534–545. doi:10.1093/biosci/bix014

EU Commission (2019). "Communication from the commission to the European parliament," in *The European council, the council, the European economic and social committee and the committee of the regions* (Brussels: The European Green Deal).

EU (2013a). *Regulation (EU) No 1305/2013 of the European parliamnet and of the council of 17 december 2013 on support for rural development by the European agricultural fund for rural development (EAFRD) and repealing council regulation*. Luxembourg): Official Journal of the European Union. (EC) No 1698/2005.

EU (2013b). *Regulation (EU) No 1307/2013 of the European Parliamnet and of the Council of 17 december 2013 establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and repealing Council Regulation*. Luxembourg): Official Journal of the European Union. (EC) No 637/2008 and Council Regulation (EC) No 73/2009.

FAO (2015). Agroforestry. Definition. [Online]. Food and agriculture organization of the united Nations (FAO). Available: http://www.fao.org/forestry/agroforestry/80338/en (Accessed 08 10, 2020).

FAO (2018). *The State of the World's Forests 2018 - forest pathways to sustainable development*. Rome, Italy: FAO, 139. Licence: CC BY-NC-SA 3.0 IGO.

Haddaway, N. R., Macura, B., Whaley, P., and Pullin, A. S. (2017). ROSES for systematic map protocols. (Version 1.0). doi:10.6084/m9.figshare.5897284

Haddaway, N. R., Macura, B., Whaley, P., and Pullin, A. S. (2018). ROSES RepOrting standards for systematic evidence Syntheses: Pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. *Environ. Evid.* 7 (1), 7. doi:10.1186/s13750-018-0121-7

Huxley, P. (1999). *Tropical agroforestry*. Oxford: Wiley-Blackwell.

International Initiative for Impact Evaluation (2020). *Checklist for making judgements about how much confidence to place in a systematic review of effects (adapted version of SURE checklist)* [Online]. (3ie). Available: http://3ieimpact.org/sites/default/files/2019-01/quality_appraisal_checklist_srdatabase.pdf (Accessed 05 25, 2020).

Köthke, M., Ahimbisibwe, V., and Lippe, M. (2021). *Dataset for an evidence review map on agroforestry outcomes*. Greifswald: Open Agrar Repository. 2021(09.11.2021). doi:10.3220/DATA20211109081609

Millennium Ecosystem Assessment (2005). *Ecosystems and human well-being*. Geneva, Switzerland: Health SynthesisWorld Health Organization.

Miller, D., Ordoñez, P., Brown, S., Forrest, S., Nava, N., Hughes, K., et al. (2020). The impacts of agroforestry on agricultural productivity, ecosystem services, and human well-being in low-and middle-income countries: An evidence and gap map. *Campbell Syst. Rev.* 16, e1066. doi:10.1002/cl2.1066

Muchane, M., Sileshi, G., Gripenberg, S., Jonsson, M., Pumariño, L., Barrios, E., et al. (2020). Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis. *Agric. Ecosyst. Environ.* 295, 106899. doi:10.1016/j.agee.2020.106899

Nair, P. K. R. (1985). Classification of agroforestry systems. *Agroforest. Syst.* 3 (2), 97–128. doi:10.1007/BF00122638

Nair, R. (2014). Grand challenges in agroecology and land use systems. *Front. Environ. Sci.* 2. doi:10.3389/fenvs.2014.00001

O'Leary, B. C., Woodcock, P., Kaiser, M. J., and Pullin, A. S. (2017). Evidence maps and evidence gaps: Evidence review mapping as a method for collating and appraising evidence reviews to inform research and policy. *Environ. Evid.* 6 (1), 19. doi:10.1186/s13750-017-0096-9

Pullin, A. S., Frampton, G. K., Livoreil, B., and Petrokofsky, G. (2018). Guidelines and standards for evidence synthesis in environmental management VERSION 5.0. Available: https://environmentalevidence.org/information-for-authors/(Accessed 10 22, 2021).

Rosenstock, T., Wilkes, A., Jallo, C., Namoi, N., Bulusu, M., Suber, M., et al. (2018). Making trees count: Measurement, reporting and verification of agroforestry under the UNFCCC. *Agric. Ecosyst. Environ.* 284, 106569. *Paper no. 240*. doi:10.1016/j.agee.2019.106569

Santiago-Freijanes, J. J., Mosquera-Losada, M. R., Rois-Díaz, M., Ferreiro-Domínguez, N., Pantera, A., Aldrey, J. A., et al. (2018a). Global and European policies to foster agricultural sustainability: Agroforestry. Agroforest. Syst. doi:10.1007/s10457-018-0215-9

Santiago-Freijanes, J. J., Pisanelli, A., Rois-Díaz, M., Aldrey-Vázquez, J. A., Rigueiro-Rodríguez, A., Pantera, A., et al. (2018b). Agroforestry development in Europe: Policy issues. *Land Use Policy* 76, 144–156. doi:10.1016/j.landusepol.2018.03.014

Sayre, R., Karagulle, D., Frye, C., Boucher, T., Wolff, N. H., Breyer, S., et al. (2020). An assessment of the representation of ecosystems in global protected areas using new maps of World Climate Regions and World Ecosystems. *Glob. Ecol. Conservation* 21, e00860. doi:10.1016/j.gecco.2019.e00860

Shin, S., Park, M. S., Lee, H., Kim, T. H., and Lee, S. (2020). A systematic map of agroforestry research focusing on ecosystem services in the asia-pacific region. *Forests* 11 (368), 368. doi:10.3390/f11040368

The World Bank (2021). *Climate-smart agriculture*. The World Bank. Available: https://www.worldbank.org/en/topic/climate-smart-agriculture (Accessed 09 21, 2021).

USDA (2019). Agroforestry strategic framework. Fiscal years 2019–2024. *Miscellaneous Publication 1615*.

van Noordwijk, M. (2020). Agroforestry as nexus of sustainable development goals. *IOP Conf. Ser. Earth Environ. Sci.* 449, 012001. doi:10.1088/1755-1315/449/1/012001

van Noordwijk, M., Bizard, V., Wangpakapattanawong, P., Tata, H. L., Villamor, G. B., Leimona, B., et al. (2014). Tree cover transitions and food security in Southeast Asia. *Glob. Food Secur.* 3 (3), 200–208. doi:10.1016/j.gfs.2014.10.005

van Noordwijk, M., and Coe, R. (2019). "Methods in agroforestry research across its three paradigms," in *Sustainable development through trees on farms: Agroforestry in its fifth decade*. Editor M. van Noordwijk (Bogor, Indonesia: World Agroforestry (ICRAF) Southeast Asia Regional Program), 381–402.

van Noordwijk, M., Coe, R., and Sinclair, F. L. (2019). "Agroforestry paradigms," in *Sustainable development through trees on farms: Agroforestry in its fifth decade*. Editor M. van Noordwijk (Bogor, Indonesia: World Agroforestry (ICRAF) Southeast Asia Regional Program), 1–14.

van Noordwijk, M. (2019). Integrated natural resource management as pathway to poverty reduction: Innovating practices, institutions and policies. *Agric. Syst.* 172, 60–71. doi:10.1016/j.agsy.2017.10.008

White, H., Albers, B., Gaarder, M., Kornør, H., Littell, J., Marshall, Z., et al. (2020). Guidance for producing a Campbell evidence and gap map. *Campbell Syst. Rev.* 16 (4), e1125. doi:10.1002/cl2.1125

Zomer, R. J., Trabucco, A., Coe, R., Place, F., van Noordwijk, M., and Xu, J. (2014). *Trees on farms: An update and reanalysis of agroforestry's global extent and socio-ecological characteristics*. Bogor, Indonesia: World Agroforestry (ICRAF) Southeast Asia Regional Program. *Working Paper 179*. doi:10.5716/WP14064.PDF