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REVIEW ARTICLE

Multiple agroecological practices use and climate change mitigation. A review

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Abstract

Agriculture is increasingly affected by climate change but is also a significant contributor of greenhouse gas (GHG) emissions. This global study aims to find evidence on the impact of agroecological practices on climate change mitigation, namely GHG emissions (CO_2, N_2O, and CH_4) and carbon sequestration. We used a rapid review methodology, screening more than 16,000 publications to retrieve evidence on the implementation of multiple agroecological practices on climate mitigation, for which a knowledge gap exists. We addressed the positive, negative, and inconclusive effects of agroecological multi-practices on climate change mitigation as compared to conventional counterparts. The results of the review indicate that (1) multiple agroecological practices are often associated with statistically significant positive climate change mitigation outcomes across the broad range of evaluated metrics (46% positive, 13% negative, <1% inconclusive outcomes). For all four metric types, there were always more positive than negative outcomes. (2) Within GHG emissions, the highest share of positive outcomes was for CO_2 with 0.69 followed by N_2O (0.67). For carbon stock, positive significant results dominated with 70%, whereas significant negative outcomes were reported for only 7%. (3) For 28% of all metrics, no statistical tests were used or not applied for the combination of practices, resulting in 57% positive, 31% negative, and 11% inconclusive outcomes. (4) A general trend with more positive outcomes with increasing number of agroecological practices was found for carbon sequestration but not for GHG emissions metrics. (5) The majority of studies focused on arable systems, where many metrics showed positive outcomes in particular for carbon sequestration; however, a considerable number of negative outcomes were found for CO_2 and CH_4 emissions, particularly in rice. Although the results of this review show more positive outcomes with multiple agroecological practices, there are trade-offs, e.g., between carbon sequestration (positive effect) and GHG emissions (negative effect).

Keywords Agroecology · Carbon sequestration · Greenhouse gas emission · Methane (CH4) · Carbon dioxide (CO_2) · Nitrogen dioxide (NO_2)

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1 Introduction

Climate change is defined by the United Nations Framework Convention on Climate Change (UNFCCC) as a change in climate due to direct or indirect human activity that results in an alteration of the composition of the global atmosphere, in addition to the observed climate variability over comparable time periods (IPCC 2014). Rockström et al. (2009) identified climate change as one of the planetary boundaries, defined as crucial Earth system processes that regulate ecosystem stability on the planet. Climate change, along with other planetary boundaries such as altered nitrogen and phosphorus cycles, loss of biodiversity and changes in land use, is the result of anthropogenic action: all together, these drivers are contributing to the destabilization of the Earth system.

Global food systems have been singled out as the sector that contributes most to exceeding the threshold of these planetary boundaries, causing the destruction of ecosystems, the consumption of hydric reserves, and massive greenhouse gas (GHG) emissions (Rockström et al. 2020). Agriculture, forestry, and other land uses have generated 13–21% of global anthropogenic GHGs in the period 2010–2019 (Aoki et al. 2022), and agriculture, in particular, accounts for 20–30% of global GHG emissions (Liu et al. 2021).

Scientific evidence has also demonstrated the negative impacts of increased overland average temperature in terms of changes in precipitation patterns, along with an increase in frequency and severity of droughts and floods and in outbreaks of pests and diseases, which altogether result in poorer yields, reduction of water availability, crop failure, and higher livestock mortality (Agus et al. 2019; Harvey et al. 2014; Yuan et al. 2024).

An urgent transformation of global food systems towards sustainable practices is therefore imperative to meet the Paris Agreement GHG limits and the United Nations Sustainable Development Goals (Rockström et al. 2020). Four main avenues for making agriculture less climate impacting, to be followed simultaneously, include (i) carbon sequestration, (ii) reduction of GHG emissions through adaptation or new agricultural practices, (iii) reduction of fossil energy use in agricultural production, and (iv) reduction of inputs, whose production requires high use of energy and materials and releases massive GHG amounts. Research has proven that well-managed agroecosystems and natural ecosystems have the capacity to absorb one-third of CO_2 emissions produced by human activities (Aoki et al. 2022). For example, increased soil organic carbon stock was found with agroforestry across all regions except for temperate ones (Chatterjee et al. 2018) or with reduced tillage and ley-arable rotations (Jordon et al. 2022). Similarly, no till can reduce GHG emissions in dry climates as well as reduce global warming potential in rice fields (Huang et al. 2018), and perennial alley cropping reduced CO_2 and N_2O emissions in Mediterranean almond orchards (Sánchez-Navarro et al. 2022).

The question is, which practices, farming management, or farming systems can contribute to climate change mitigation? In this respect, agroecology and its holistic approach appear in debates as promising; however, scientific evidence is largely lacking. Agricultural practices and systems that achieve significant food production by respecting ecological processes and through the provision of ecosystem services are defined as agroecological practices (Wezel et al. 2014). The agroecological approach constitutes also a preferential avenue to ensure food security (Bezner Kerr et al. 2021) as well as to improve the sustainability of agroecosystems and food systems (HLPE 2019; Wezel et al. 2020) towards a stable Earth system respectful of the planetary boundaries.

Previous meta-analyses and literature reviews have analyzed the impacts of individual agroecological practices on climate change mitigation and/or adaptation (e.g., Abalos et al. 2022; Bregaglio et al. 2022; Chatterjee et al. 2018; Collins et al. 2022; Grados et al. 2022; Huang et al. 2018; Jordon et al. 2022; Poeplau and Don 2015; Rietra et al. 2022;

Shakoor et al. 2021; Shakoor et al. 2022; Young et al. 2021). However, an in-depth investigation of the impact of multiple practices use (Figure 1) and systemic farming management associated with agroecological farming on climate change mitigation and adaptation is currently missing.

This global study aims to fill this knowledge gap and to find evidence on the impact of the implementation and use of agroecological management on GHG emissions and other relevant indicators related to climate change mitigation. The specific focus of this study is on the simultaneous implementation of more than one agroecological practice and of more complex agroecological farming systems, such as agroforestry or organic farming. In particular, we have addressed the positive, negative, or neutral effect of agroecological multi-practices and systems on climate change mitigation as compared to conventional counterparts.

2 Material and methods

2.1 Frameworks of agroecological practices and climate mitigation indicators

Transitioning to agroecological farming systems involves different levels of complexity: improving resource use efficiency, substituting contentious inputs, redesigning farming systems, and integrating social values, such as co-creating knowledge and promoting social justice (Bezner Kerr et al. 2021; Gliessman 2014; HLPE 2019; Wezel et al. 2014). In this study, we have limited our search to those agroecological practices (AEPs) applicable at the field or farm scale; i.e., we have addressed the "incremental" stage of the agroecological transition (Gliessman 2014).

Our focus was on agroecological multi-practices, i.e., cases combining two or more agroecological practices and on more complex agroecological systems (e.g., agroforestry or organic farming), as opposed to the performance of single agroecological practices, for which large scientific evidence already exists. In addition, this study aims to provide evidence regarding the benefits of multiple agroecological practices or agroecological systems compared to conventional agriculture practices or systems. By "conventional" agriculture we refer to "ordinary or commonplace agriculture" and/or "agriculture that falls outside a clearly circumscribed category" (Sumberg and Giller 2022; Wezel et al. 2022).

The practices or systems compared in the articles were characterized using an agroecological framework that structured the portfolio of considered practices. We utilized the same framework developed as in a previous literature review study on the socio-economic impact of agroecological practices (Mouratiadou et al. 2024) (Table 1).

The farming systems or practices compared in the selected studies varied significantly based on various aspects such as the research design and in particular the environmental context in which they were conducted. In cases where studies referred to multiple sites, comparisons among several management systems, or various climate change-related indicators, each combination was meticulously recorded and represented a different comparative case study. It is not uncommon for conventional management systems to incorporate certain agroecological practices. To ensure a fair comparison between management systems and avoid excluding too many articles due to the absence of a perfect conventional counterpart, each comparative case study was separately analyzed according to the abovementioned agroecological framework and categorized according to the number of practice groups that differed from the conventional counterpart: combinations of two agroecological practices (2 AEPs), three agroecological practices (3 AEPs), and agroecological systems (AE systems), here intended as those studies in which more than three AEPs were involved.

Although agroecological systems are normally expected to be free of synthetic agrochemicals or organic contentious inputs, transitioning systems might still require a reduced use of agrochemicals, especially in case of farmers' perception of emergencies such as unexpected pest outbreaks (Migliorini et al. 2020). In this regard, we also ensured to include articles that included farming systems along the

Figure 1 Multiple agroecological practices use. Intercropping of wheat and clover combined with cultivar mixture (left; Photo A. Wezel), no till/direct seeding of soybean and rye cover crop use (right; Photo J. Peigné)

Table 1 Conceptual framework of agroecological practices. The agroecological practices refer to 1: Wezel et al. (2014), 2: WOCAT database, 3: found and added during the literature review.

Management category	Agroecological practices
Crop fertilization management	Split fertilisation1
	Mixed organic fertilisation3, Balanced fertilisation2
	Biofertiliser1, Mycorrhizae inoculation2, beneficial microbials and microorganisms2
	Organic fertilisation1,2: manure1,2, compost1,2, zai3/planting2 pit, biochar2, biodigestate2, biodynamic preparation2, biofermentation2
Water management	Drip irrigation1, Micro-irrigation/drip irrigation/variable rate irrigation2
	Water harvesting1,2
	Raised bed/ridge cultivation2
	Contour bunds3, contour farming2, soil drainage2
Weed management	Ecological weed management2, allelopathic plants1
Pest and disease management	Natural pesticides/botanical pesticides1, pesticide reduction2, antibiotic reduction2
	Beneficial arthropods/natural enemies, beneficial microbials and microorganisms2
	Push-pull strategies3, allelopathic plants1
Crop choice, crop spatial distribution, and crop temporal successions	Crop residue application2, coppice management2
	Multi-story cropping/syntropic agriculture2
	Stress tolerant, disease resistant crop/cultivar1,2
	Cover crop and mulching: green manure1,2, cover crops1,2, mulching1,2, catch crop2
	Cropping system diversification1: variety/cultivar mixture2, crop diversification3, diversified crop rotation1,2, improved fallow3, crop-livestock integration1,2 (i.e., pasture3, grassland2, grass-feeding2, permanent grassland2, rotational/controlled grazing2, forest grazing2, rice-fish system/rice-duck system2, aquaculture/fish farming2)
	Intercropping1,2, alley cropping2, relay cropping2, living mulch2, mixed cropping2
	Agroforestry1,2: silvoarable1,2, silvopastoral1,2, agro-silvo-pastoral1,3, homegarden2
Tillage management	No tillage1, reduced tillage1, direct seeding1, conservation tillage2, controlled traffic2
Management of landscape elements	Integration of semi-natural landscape elements at field or farm scale1: Hedgerows, windbreaks and living fences1,2, flower strip2, field-margins and semi-natural patches1, buffer/vegetative strip2
	Planting or managing landscape elements1: stone wall/terracing2, paludiculture/wetland management2, semi-natural areas1,2, conservation headland2
	Dune stabilisation2, erosion control2, soil/land rehabilitation/restoration2, afforestation2
Other—package of practices	Sustainable rice intensification2, organic farming1, climate change adaptation practices (e.g., adjusting planting dates)3, agroecological farming3, biodynamic farming3

agroecological transition. As such, agroecological management systems showing an occasional use of fertilizers/pesticides/herbicides were retained, as long as these substances were applied also in the corresponding conventional (CONV) system, and thus, they did not represent an additional variable in the comparative analysis.

Table 2 presents the framework that was constructed for the identification and selection of relevant articles presenting evidence on mitigation. From this, each metric encountered in the studies is listed in the column under each metric type and effect (e.g., mitigation) type. In this way, it has been possible to appraise the metrics' diversity and establish subcategories to aggregate results.

2.2 Literature review methodology

We applied a rapid review methodology (Bezner Kerr et al. 2021; Tricco et al. 2015), based on a four-phase PRISMA-RR protocol (Stevens et al. 2018). This method has been recognized as a useful tool for evidence-based decision-making at the policy level (Yost et al. 2014). The four phases are as follows: the identification phase for identifying articles and duplicates, the abstract screening phase (partly done using a Machine Learning (ML) approach), the eligibility phase for full-text assessment and quality evaluation, and the final evidence retrieval phase (Figure 2).

2.2.1 Identification phase

To identify the relevant articles in our rapid review, we utilized a dedicated search string (Table 2), addressing both greenhouse gas (GHG) emissions and carbon sequestration for climate mitigation, and terms related to climate adaptation, such as "resilience," "extreme event," and "drought." These adaptation terms covered concepts like

Table 2 Framework showing the mitigation indicators (metrics) expected to be encountered and analyzed in the literature review. Following the objective of this study, the framework has been broken down into two main domains (mitigation types): reduction of greenhouse gas emissions (atmospheric metrics) and absorption of these gases in different forms in the soil (sequestration). These are then divided into metric types, each including the different measured metrics. Representative examples of data sources for these metrics are shown

Mitigation type	Metric type	Metrics (directly measured)	Data source (examples)
GHG emissions	CO_2	CO_2 soil fluxes Cumulative CO_2 emissions from soil (between periods) Soil CO_2 emissions Global warming potential (CO_2eq)	Organic biomass/organic matter Soil respiration Soil fluxes
	N_2O	N_2O soil fluxes Cumulative N_2O emissions from soil (between periods) Soil N_2O emissions	Manure Fertilization Nitrification/denitrification
	CH_4	CH_4 soil fluxes Cumulative CH_4 emissions from soil (between periods) Soil CH_4 emissions	Livestock
Sequestration	Carbon stocks	Soil organic carbon sequestration CO_2 soil concentration Net carbon storage Difference in soil organic carbon	Organic biomass Crop residues

climate vulnerability and adaptive capacity. We used wildcards (asterisks, *) at the end of root words to maximize relevant article retrieval. Different search strings with four lists for keywords for the agroecological practices/systems part and three lists for climate change keywords were tested in October 2022. Out of the 12 combinations, the search string in Table 3 was selected and further tested with a subsample of articles.

The search string was executed in January 2023 on the Clarivate Web of Science™ core collection, spanning from January 1, 2000, to January 15, 2023, and resulted in $n = 16{,}006$ articles. The full database was downloaded to an Excel file, ranked based on relevance by Clarivate Web of Science™. Subsequently, it was checked for duplicates, which were eliminated ($n = 72$).

2.2.2 Abstract hand-screening phase

The abstracts of the identified articles were screened and either excluded from further analysis or kept for the evaluation phase. For this process, a list of inclusion and exclusion criteria was defined with respect to consideration of agroecological practices, relevant climate change-related outcomes, article quality, accessibility, and language. Figure 2 shows the overall list of the reasons for exclusion at the abstract and full-text screening phases. At this level, abstracts were retained when their primary focus was on empirically assessing climate change impacts and/or reporting outcomes related to climate change indicators within the broader context of sustainable management systems, such as organic agriculture, conservation agriculture, and the system of rice intensification, and/or specifically referring to the application of agroecological practices at field and farm levels.

Some critical decisions regarding the inclusion or exclusion at the abstract level were taken and justified as follows:

- At the abstract level, we also included systematic reviews and meta-analyses when having a relevant abstract from which we could possibly extract useful outcomes to be compared to ours. These were labelled differently and were neither full-text assessed nor analyzed but used as references for the discussion part. Instead, we excluded review articles that only discussed a specific topic with political purposes and narrative review articles.
- Although our focus was on combinations of agroecological practices, we included relevant abstracts assessing single AEPs by labelling them differently. This decision was made for two reasons: firstly, to train the machine learning (ML) model in recognizing both specific agroecological practices and broader agroecological systems (Section 3.2 provides more details on the use of ML), and secondly, because it was not always possible to discern the number of agroecological practices applied within a study solely from the abstract.
- Studies that explicitly relied only on hypothetical scenarios, scenario modelling, laboratory-based experiments, pot experiments, or in vitro experiments were excluded, since the objective was to create a dataset based on actual on-field or on-farm evidence.
- Articles that only focused on the production or management of specific agroecological inputs (e.g., manure or biopesticide production) without considering their on-field/on-farm application were excluded.
- Articles assessing practices unrelated to the food production level (e.g., renewable energy in food process-

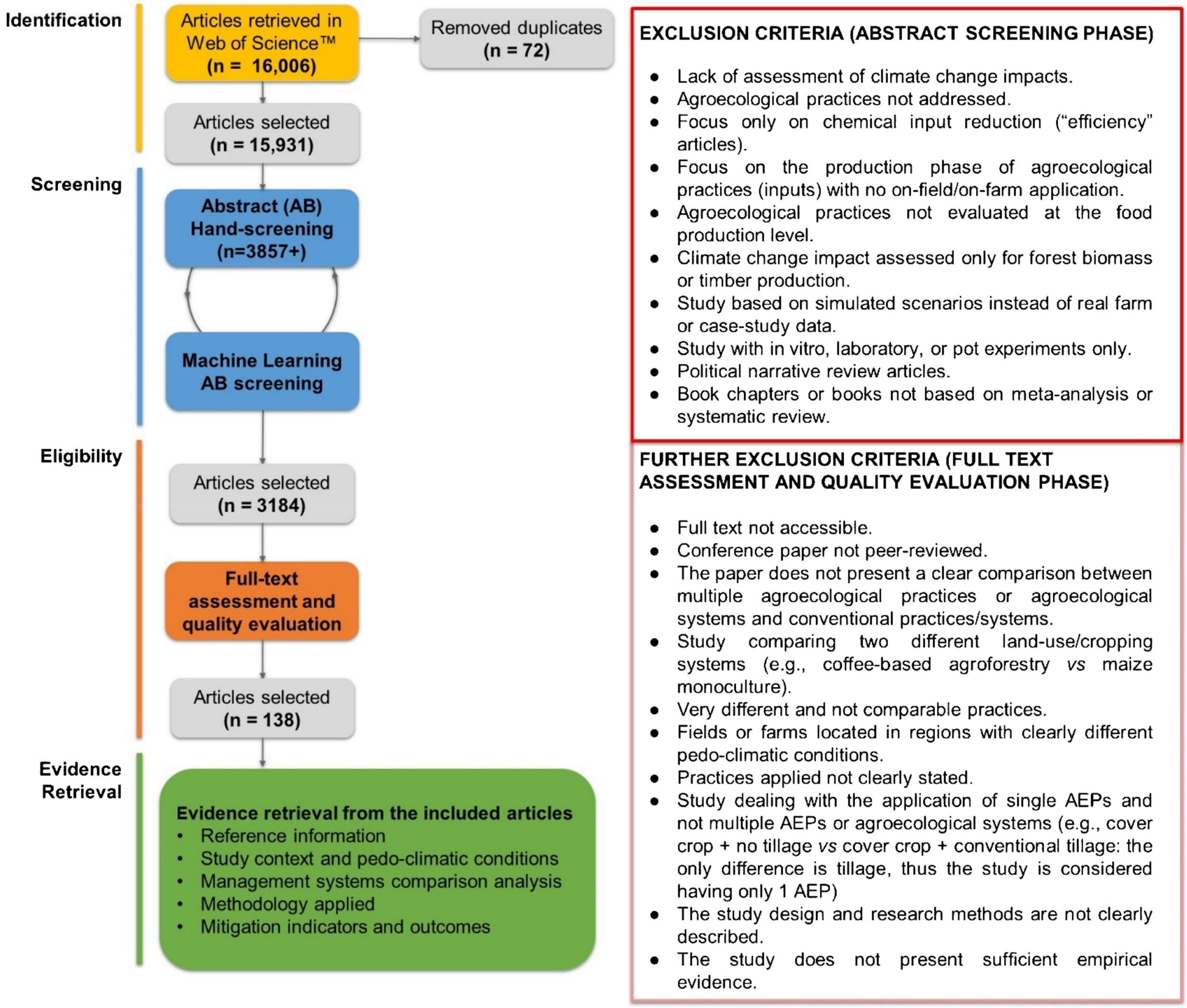

Figure 2 PRISMA-RR flow diagram, representing the stepwise process of record identification, de-duplication, and abstract screening (with the use of machine learning), full-text assessment, and additional quality evaluation phase for the systematic review. The total number of articles refers to those retrieved in the WoS database from 1 January 2000 to 15 January 2023. A total of 138 articles with evidence were finally retrieved

ing, wastewater treatment, consumers’ behavior, and dietary shifts) were excluded. Although demand-side mitigation measures that seek to achieve mitigation by changing people’s consumption behavior fall within the broader scope of agroecology, they were considered outside the scope of this study.

- Articles assessing the climate change impacts of forest biomass or timber production in forests were also outside the scope of our study and thus excluded.

In general, when other exclusion criteria were not directly detectable from the abstract, the article was included to be further inspected as full text. The reason for exclusion was always annotated in the database to keep track of the criteria in a transparent way.

Following this screening procedure and including machine learning (see next section), 3182 abstracts were selected for full-text assessment.

Application of machine learning for the remainder of articles The abstract screening process was done with the aid of machine learning (ML). Supervised ML is the primary technique for the automation of systematic reviews and is mostly applied in the “selection of primary studies” step, which is also the most time-consuming one (Goldfarb-Tarrant et al. 2020; van Dinter et al. 2021). A first round of articles was annotated by a team of three annotators using their title and abstract, regarding whether or not they were relevant to the systematic literature review. Each article was annotated by at least two annotators. In case of disagreement, a third

Table 3 Search string (combination of search terms through Boolean operators) used for screening the scientific literature database Clarivate Web of Science™ Core Collection. Records retrieved with the inclusion criteria were 16,006.

Search string	Literature databases and online repositories searched	Records retrieved (No.)
((agroecolog* OR agro-ecolog* OR"diversified farming system"OR"diversified cropping system"OR"ecological agriculture"OR"ecological farming"OR"organic agriculture"OR"organic farming"OR agrobiodivers* OR agro-biodivers* OR"regenerative agriculture"OR"regenerative farming"OR"mixed farming"OR"conservation agriculture"OR "climate smart agriculture" OR"climate-smart agriculture"OR"low input agriculture"OR"crop livestock"OR"crop-livestock"OR"agropastoral"OR"agro-pastoral"OR"organic fertili*"OR"cover crop*"OR"crop diversification"OR"cultivar mixture"OR"diversified crop rotation"OR"intercropping"OR"agroforestry"OR"agro-forestry"OR"rice intensification")) **AND** (("climat* change" OR "global warming" OR " climate change mitigation" OR "climate change adaptation" OR"greenhouse gas*"OR "GHG*" OR "emission*" OR "climate resilien*" OR"Carbon sequestration"OR"Carbon storage"OR"Carbon farming"OR "Carbon dioxide" OR "CO2" OR "nitrous oxide" OR "N2O" OR "methane" OR "CH4" OR "drought*" OR "extreme event*" OR "flood*"))	Clarivate Web of Science™ Core Collection	16,006

annotator would arbitrate, which happened in 12.5% of the cases.

To facilitate the subsequent stages of our research, we divided the dataset into training and test sets, following an 80/20% split. We employed a logistic regression model with a Bag-of-N-Grams (Harris 1954) to train the model. In order to enhance the training set with the more complex examples, we introduced an active learning approach. This involved the selection of 1000 new samples, particularly those where the model had difficulty deciding the class (i.e., a probability of inclusion/exclusion close to 50%). These examples were then integrated into the training dataset. On this final dataset, we compared the model previously used to different types of transformers such as a BERT (Devlin et al. 2018), a RoBERTa (Liu et al. 2019), a sciBERT (Beltagy et al. 2019), and a DeBERTa-v3 (He et al. 2021). For optimization, we employed the Adam algorithm (Kingma and Ba 2014) with a fine-tuning learning rate set to $2 \times 10^{\wedge}(-6)$ and a batch size of 32. The maximum sequence length used was 512. Our experiments were conducted using TensorFlow 2.4.1 (Abadi et al. 2016), transformers 4.28.1 (Wolf et al. 2019), on an Nvidia RTX-8000 GPU with CUDA 12.0.

The best results were obtained with the DeBERTa-v3 model, reaching an accuracy and a macro-F1 of 0.81 and 0.804. To put this in context, these results are on par with what is reported by Ricciardi et al. (2020) for comparison. In order to automatically discard articles, we used the ROC curve to select an optimum probability threshold corresponding to the level of agreement achieved by the annotators. We found out that using a probability of 0.9 allowed us to reach a Precision of 0.836 for the "INCLUDE" class with a recall of 0.892 for the "EXCLUDE" class. This allowed us to automatically discard articles from the 13,000 remaining.

2.2.3 Eligibility phase

The full texts of the selected articles ($n = 3182$, 19.8%) were examined, and the list of articles was further constrained using criteria on (i) the number of AEPs involved (all studies with just 1 AEP were excluded) (ii) the specification of agroecological practices and the farming context, (iii) the assessment of the methodological approach, and (iv) the article quality evaluation. In addition, review articles were excluded. Figure 2 shows the overall list of the actual reasons for exclusion at the abstract and full-text screening phase.

(i) Number of AEPs involved A preliminary screening, which involved reviewing both the abstract and, if necessary, the full text of articles, was conducted to identify articles that evaluated the use of single agroecological practices and were labelled as "1 AEP." As a result, a total of n = 440 articles were excluded from our analysis. This included articles that assessed combinations of multiple practices but had only one practice that varied in the comparison.

(ii) Specification of agroecological practices and farming context Soil emissions are intimately linked to pedo-climatic conditions, such as rainfall, soil moisture, and soil temperature, as well as various management factors, such as crop residue types, tillage, or crop rotation type and timings (Krauss et al. 2017; Luo et al. 2013; Trozzo et al. 2020). For this reason, only articles that presented a clear comparison between agroecological practices and a conventional counterpart and where such comparison is done under similar pedo-climatic conditions and land-use systems (e.g., the same crops or rotation) were retained.

We recognize that this approach can introduce a bias into the final dataset. Transitioning from a conventional system to an agroecological one might entail significant changes, including adopting different crops or redesigning crop sequences. However, landscapes with greater complexity and heterogeneity, encompassing various farm components (e.g., multiple crops), management practices (e.g., fertilization), and seasonal variations, tend to exhibit more pronounced spatial and temporal variations in greenhouse gas (GHG) emissions (Ortiz-Gonzalo et al. 2018; Rosenstock et al. 2016) and are then difficult to compare to less complex conventional systems. As a consequence, we decided to include only studies which allowed a representative comparison between systems.

Agroecological management systems showing an occasional use of fertilizers/pesticides/herbicides were retained as long as these substances were applied also in the conventional (CONV) system, and thus, they did not represent an additional variable in the comparative analysis. However, for instance, studies involving 2 AEPs (no-tillage and cover crops) were still excluded if they used herbicides to eliminate the cover crops. Another example of exclusion is a study using herbicides for weed control in an alternative system, while in the conventional system, no herbicides are used (e.g., because tillage was performed). To guarantee a transparent documentation of the comparison, we kept record of all practices applied in each comparative study (Annex 1, Supplementary data).

(iii) Assessment of the methodological approach Methods of data testing in the articles were included both when conducted in on-farm experiments run by researchers and when involving on-farm actual implementation and on-farm intervention studies. Instead, laboratory-based experiments, pot experiments, or in vitro experiments were excluded due to their nature of highly controlled environments, which may not adequately represent real-world conditions. Additionally, studies that relied solely on hypothetical scenarios or scenario modelling, even if they might be relevant for future analysis and exploration, were excluded as they lacked the basis of real, existing situations. Similarly, studies that based their results and analysis on data extracted from the literature or relied on large-scale, existing databases of farm data were also excluded to avoid introducing biases due to selection criteria used by the researchers conducting the study. Although several methods exist for GHG calculations such as life cycle assessment and emergy analysis, for this review, we focused only on articles that directly measured GHG fluxes from soil.

Overall, our intention was to ensure data consistency and facilitate direct comparability, ultimately enhancing the validity and reliability of study findings based on real, on-field or on-farm evidence.

(iv) Evaluation of article quality During the evaluation of article quality, non-peer-reviewed articles or those that did not contain quantitatively specified information about climate change mitigation outcomes were excluded. Additionally, we excluded articles lacking clear descriptions of the study design and research methods and those that did not provide sufficient empirical evidence. The latter included articles not having enough detailed dataset, e.g., those lacking range of variation of inputs and outputs for systems under comparison. Furthermore, articles not actually using AEPs but relying on modelling scenarios derived from data available in the existing literature were not taken into account. The whole eligibility phase led to the selection of 138 relevant articles that were submitted to the evidence retrieval phase.

2.2.4 Evidence retrieval phase

From the 138 articles, relevant evidence of the application of agroecological farm management practices compared to conventional counterparts on GHG emissions and other relevant indicators related to climate change mitigation was retrieved.

All the selected articles were included in a synoptic table of a dedicated Excel database with the following information: reference details, study country, cropping system and crop types, the existence of comparison between management systems, methodology type, and detailed metrics reported in the study, with the corresponding final outcome. The methodological approach specified the implementation of agroecological practices (on-station, on-farm actual implementation, or on-farm intervention study), as well as the measurement methods. We classified studies done in the experimental field as "on-station," studies where information was taken directly from farms as "on-farm," and studies where the authors mentioned some intervention in the set-up and implementation of the practices as "on-farm intervention."

Furthermore, we proceeded with the entry of climate change outcomes from the articles into the database. We carefully documented the specific mitigation metrics addressed in each article. When dealing with articles that employed mixed-method approaches, we exclusively extracted information that conformed to the criteria detailed in Section 2.2.3 under the assessment of the methodological approach. For instance, in studies where both survey-based actual data collection and analysis as well as future simulation modelling were employed, we exclusively captured results from the former analytical method.

For each metric, if a statistical method was used, then we assigned a specific outcome. These outcomes have been categorized as "significant" ("positive," "negative," "inconclusive") or "not statistically significant." "Positive" outcomes were assigned to those metrics where agroecological management systems have given more favorable results compared to conventional ones (e.g., lower CO_2 emissions, or higher C stocks). Conversely, "negative" outcomes were assigned when the metric for the agroecological management system demonstrated a less favorable climate impact compared to conventional methods (e.g., higher N_2O emissions, higher global warming potential, or lower C stocks). An "inconclusive" outcome is one where several contrasting results (positive and negative) are reported for the comparison between the agroecological multi-practices or system and the conventional counterpart, for example year-to-year or seasonal variations in the effect. If an outcome had no statistical significance, we assigned it as "not statistically significant." For studies where statistical tests were not applied, the outcomes were categorized as positive, negative, or inconclusive based on the actual values of the agroecological vs the conventional treatment. Although they were retained, these records are obviously less important in terms of scientific evidence.

3 Results

3.1 Overview of the analyzed studies

A total of 138 peer-reviewed scientific publications have been included in the final review analysis, resulting in 285 recorded cases of agroecological practices compared to a conventional counterpart. This is because, when an article evaluated multiple combinations of practices, crops, or conducted studies across different countries, each combination study was counted separately. A third of the selected articles ($n = 49$, 36%) investigated the effects, factors, or impact of climate change by comparing one alternative system, while the remaining articles assessed two or more alternative systems. Twenty percent of the articles was published between 2005 and 2015 and the remaining 80% between 2015 and December 2022. Over half of the articles were published between 2019 and 2022, highlighting growing interest in the research topic during the latest period.

The geographical distribution of research conducted in these articles spans across 41 different countries, but with a significant concentration in a few key regions. More than half of these articles (98, 61%) are conducted in just six countries: China (29, 21%), the USA (18, 13%), India (16, 12%), Spain (10, 7%), and Brazil and Italy (8 each, 6%). The share of studies conducted in Europe was 25% (34 articles). It is important to note that two articles (Ambaw et al. 2020; van Rikxoort et al. 2014) presented case studies conducted in more than one country, while in all the other articles, studies were conducted in just one country.

Among the 285 comparative studies of agroecological vs conventional systems, most were on-station experiments (248 studies, 87%), while a small proportion dealt with on-farm intervention studies (24 studies, 8%) or with actual farm data from farmers already implementing practices (13 studies, 5%). Regarding the type of farm management in the different systems, around half of the studies dealt with conservation agriculture (143, 52%) followed by organic agriculture (59, 21%) and diversified farm systems (35, 12%). The remaining studies (48, 17%) had more specific management systems such as integrated crop-livestock, low-input, or system of rice intensification.

A significant proportion of studies (177, 62%) focused on cereals (wheat, maize, oats, rice (rice systems with crop diversification (rotation or intercropping) and millet) as the main crop. Fruit orchards ranked second in terms of frequency (26 studies, 9%), followed by vegetables (23, 8%), specialized rice (Rice systems without crop diversification) (22, 8%), agroforestry (18, 6%), and crop-livestock (9, 3%) systems. For other (non-food) crops and livestock, 10 other studies (4%) were assessed.

Based on our analytical framework, the farming practice components of each agroecological farming system were compared with the corresponding conventional systems. Among the 285 comparative studies, a majority included the combination of 2 AEPs (174 studies, 61%), followed by 3 AEPs (85, 30%) and AE systems and studies with 4 or more AEPs (26, 9%).

3.2 Climate change mitigation outcomes

A total of 499 mitigation metrics (and their outcomes) were evaluated, which measured GHG emissions and carbon sequestration. These outcomes were categorized under GHG emissions or sequestration mitigation types and their respective metric types (see Table 2), and if they were analyzed with or without statistical tests. The total number of metrics for GHG emissions from soils under different agricultural systems was 309, which were largely contributed by carbon dioxide (140, 62%), as shown in Figure 3. This was followed by nitrous oxide (118, 24%) and methane (51, 10%). The carbon sequestration category included 185 metrics (37%).

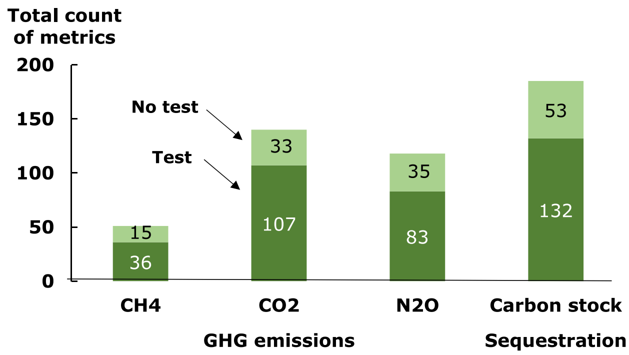

Figure 3 Total count of metrics, with or without statistical test, in the GHG emissions and sequestration categories

Among the total metrics, the proportion of those that were evaluated with statistical tests was 72% (358 metrics).

3.2.1 Statistically tested outcomes

Within metrics analyzed with statistical tests ($n = 358$), a large number of outcomes (163, 46%) was significantly positive, while 47 outcomes (13%) and 21 outcomes (6%) had negative and inconclusive results, respectively (Figure 4). A bit more than one third of the metrics (127, 35%) showed no significant difference between conventional and agroecological systems but also indicated positive (80, 22%) and negative (47, 13%) outcomes.

Within the GHG emissions mitigation type, the majority of the metrics analyzed were CO_2 related emissions, followed by N_2O and methane emissions. A high proportion of metrics, specifically 66% (61 metrics), showed significant tested positive outcomes. For the significant negative outcomes, it was 38 metrics (34%). The highest share of positive outcomes was for CO_2 with 0.69, followed by N_2O (0.67). Overall, for GHG emissions, many outcomes were not statistically significant or inconclusive.

Sequestration metrics contribute to 37% (132) of the total metrics with statistical tests ($n = 358$). Within the outcomes for carbon stock, positive significant results dominated with 86 outcomes (70%), whereas significant negative outcomes were reported for only 7%, the others being inconclusive or non-significant outcomes.

3.2.2 Non statistically tested outcomes

It was found that 141 out of 499 total metrics (28%) had no statistical tests. This share also includes metrics for which the statistical tests applied were not clearly described. The share of GHG emissions and sequestration were 62% (88 metrics) and 38% (53 metrics), respectively.

Regarding GHG emissions mitigation type, more positive outcomes (21, 64%) were reported for N_2O emissions compared to negative (12, 37%) or inconclusive outcomes (2, 6%) (Figure 5). Overall, 57% of outcomes were positive, 31% negative, and 11% inconclusive.

For CO_2 metrics, the highest outcomes were negative (16, 59%), followed by positive (11, 41%) and inconclusive (6, 22%). Similarly, for methane-related metrics, higher negative outcomes (11, 73%) were reported compared to positive (3, 20%) or inconclusive (1, 7%). There were also 5 other positive outcomes for metrics which combined different GHG emissions cases in aggregated indices.

For carbon sequestration, positive outcomes (41, 77%) largely outweighed negative (5, 9%) and inconclusive (7, 13%) outcomes.

3.2.3 Agroecological practices and climate change mitigation outcomes

Regarding the number of AEPs and mitigation metrics, Figure 6 shows the positive and negative outcomes, both

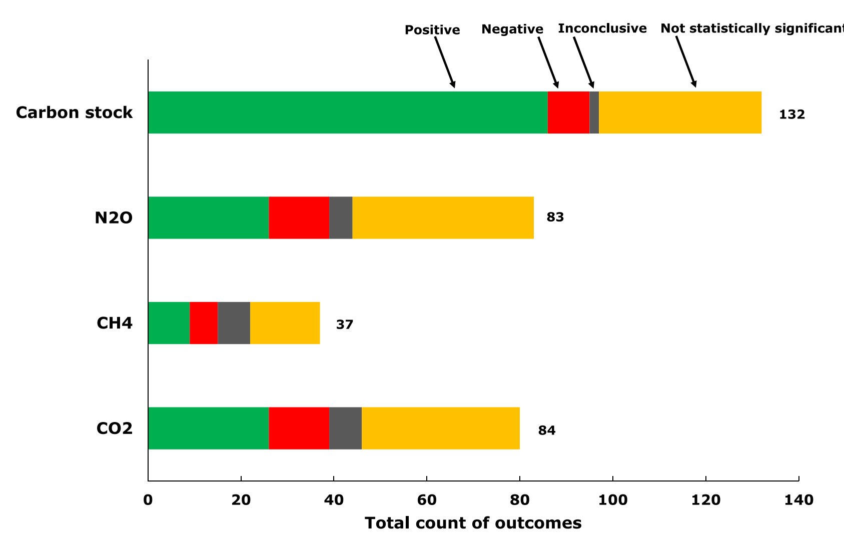

Figure 4 Total count of outcomes (positive, negative, inconclusive and not statistically significant) by mitigation type, sequestration, and GHG emissions and metric types

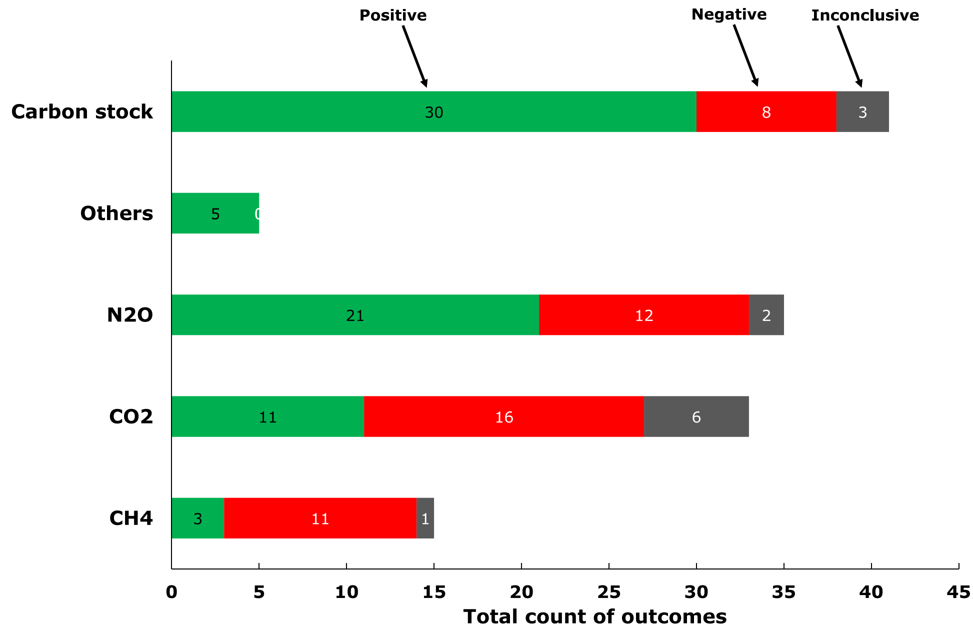

Figure 5 Total count of outcomes (positive, negative, and inconclusive) without statistical test categorized based on mitigation type, sequestration, and GHG emissions and metric type

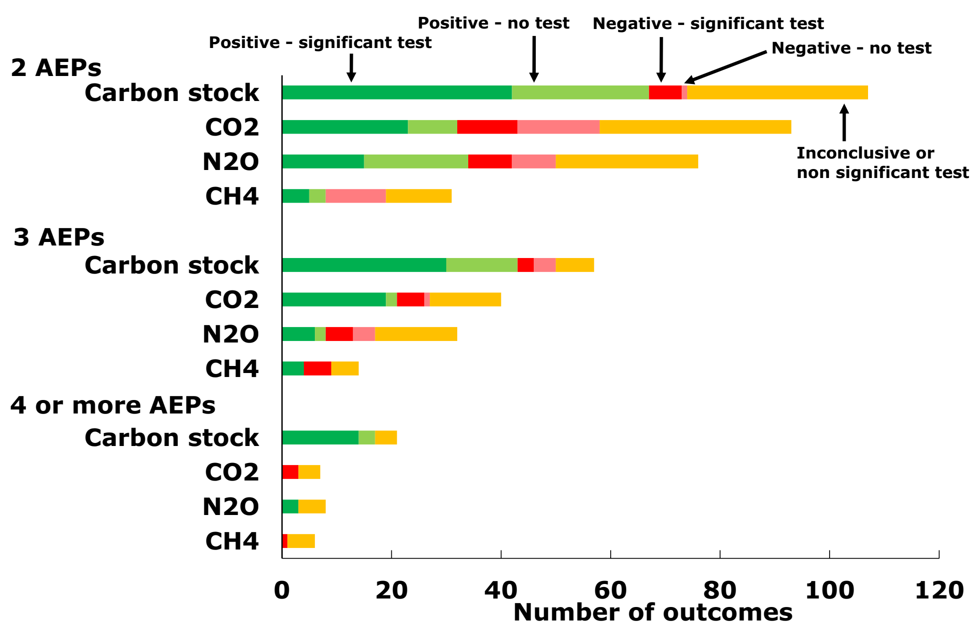

Figure 6 Climate change mitigation outcomes of agroecological practices combinations on mitigation-type sequestration and GHG emissions. Count of metrics includes outcomes with and without statistical tests. AEPs, agroecological practices

with (with significant test or no test) and inconclusive or non-significant test outcomes for different mitigation metric types and regarding the use of 2 or more AEPs combined in systems.

For carbon stock, a large share of positive outcomes was found across the three aggregation levels of AEPs, most of which were supported by the use of statistical tests. For 2 or 3 AEPs, few negative outcomes were found, whereas this was not the case for 4 AEPs or more. Data on GHG-related metrics show that implementing 2 or 3 AEPs has more positive outcomes for CO_2 and with 2 or 4 AEPs for N_2O emissions. Only N_2O with 3 AEPs was found with more negative outcomes as well as for CO_2 for 4 AEPs. Outcomes for CH_4 emissions were always more negative than positive for 2, 3, or 4 AEPs. Overall, many inconclusive or non-significant outcomes can be observed. A general trend with more positive outcomes with more complex farming systems (increasing number of AEPs) can be stated for carbon stock but not for GHG emissions metrics.

3.2.4 Climate change mitigation and cropping/farming systems

Most research with evidence analyzing GHG emissions or carbon sequestration focused on cereals (in the arable crops category), followed by rice systems (Figure 7). In the arable crop systems, many cases and their related metrics showed positive outcomes, in particular for carbon stocks. However, for GHG emissions, quite a large share showed also negative outcomes. This was also found in vegetable and mixed crop-livestock systems. Overall, results on carbon stock were exclusively positive for some systems without negative outcomes (rice, vegetables) or very highly positive (orchards, agroforestry, crop-livestock) with only very few negative outcomes.

Arable crops in general, and in particular rice, stand out as the predominant cropping systems that are responsible for a substantial number of negative outcomes. For arable farming without rice, 27% negative, 42% positive, and 31% inconclusive or non-significant tested outcomes were found, majorly contributing to CO_2 and CH_4 emissions. For rice, it resulted in 44% negative outcomes, 44% positive, and 11% inconclusive or non-significant tested outcomes.

The results also showed that the majority of studies focused on practices pertaining to what has been termed as "conservation agriculture" in the analyzed papers, such as reduced tillage/no till, cover crops/crop residue retention, and crop rotations, with more than half (51%) of all comparison cases. Higher levels of complexity in management practices, such as in systems with crop-livestock integration, diversified farming systems, or agroforestry, were much less studied (17%). Many of the remaining comparisons (22%) focused on cropping systems under organic vs conventional management.

4 Discussion

4.1 Agroecological practice combinations

A higher number of the selected cases included only 2 AEPs (61%) rather than 3 (30%) or more AEPs, due to the high share of comparative studies with classical, factorial combinations of AEPs, e.g., reduced tillage with residue retention or nitrogen fertilization. These practices are largely implemented in conservation agriculture, explaining why many studies focused on arable farming, where conservation agriculture originated (Figure 7). A general trend with a higher share of positive over negative outcomes with more complex farming systems was observed for carbon stock, but not for GHG emission metrics (Figure 6). Dumont et al. (2021) emphasized that evaluating agroecological systems within a broader context needs to refrain from reducing agroecology to a few practices. Although our results are still largely represented by studies with a combination of 2 AEPs, we believe that this work is filling this knowledge gap, considering that the vast majority of comparative studies include only one agroecological practice. This evidence shows that more system-based research is needed to fully address the issue of climate change-related effects of agroecology.

Our results showed that emphasis on climate change impact analysis was largely focused on farming practice components related to reduced tillage/no till, cover crops, residue retention, and crop fertilization and crop rotation (Annex 1 Supplementary data). Higher levels of management practices, such as crop-livestock integration or inclusion of landscape elements, have so far been scarcely studied. The difficulty in applying a highly complex

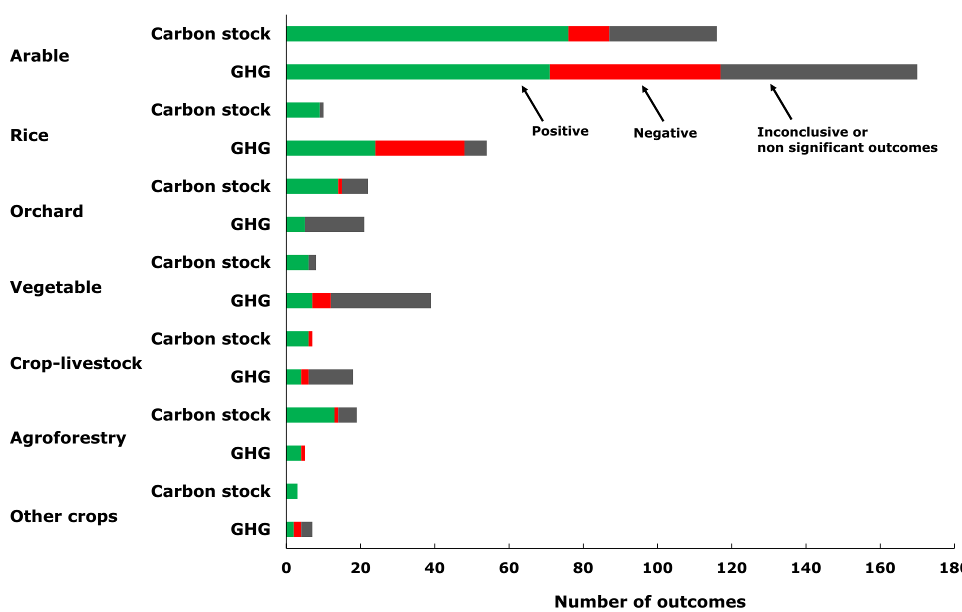

Figure 7 Climate change mitigation outcomes in different crops and farming systems for carbon stocks and GHG emissions metrics. Positive or negative outcomes include results with statistically significant tests and without tests

agroecological approach at farm level has been pointed out in several publications (e.g., Mier y Terán Giménez Cacho et al. 2018; Rosset and Altieri 2017; Vanloqueren and Baret 2017). Constraints or barriers such as access to affordable land, institutional difficulties (administrative license and certification), lack of financial support, risk, lack of knowledge, and access to resources are mostly considered to be the factors determining a low complexity of agroecological practices combination in real farms (Pimbert and Moeller 2018; Silva et al. 2023).

Teixeira et al. (2018) stressed the fact that sometimes there are blurred boundaries between agroecological and conventional farms, in that some conventional farms adopt agroecological practices that can generate benefit. Furthermore, it is important to evaluate the process of the agroecological transition by including also the transformative (food system) level, to support farms to implement agroecological principles as a whole and not just agroecological practices, for example, by assessing changes that go beyond farm management and address the entire food production, distribution, and consumption system. Nevertheless, Teixeira et al. (2018) explained that farms adopting more agroecological practices are considered moving along further in the journey towards transformation, as these are assumed to potentially provide more ecosystem services.

4.2 Agroecological practice use and climate change impact, and trade-offs

This review has provided important insights into the effects of implementing multiple agroecological practices on a range of climate change indicators. According to the climate change framework presented in this review, studies on agroecological practices and their impact on carbon sequestration had a very high number of positive outcomes (70% for cases with statistical tests and 77% for cases without tests). Although positive impacts regarding GHG emissions reduction were also found (66% with statistical tests, 49% without test), there were also many examples with negative outcomes (33 and 51%, respectively).

Globally, the results of this review confirm that climate change impact from agroecological practices is highly context- and metric-dependent, but, overall, they show a higher share of positive outcomes than their conventional counterparts. However, there are common trade-offs to be considered. For example, in vegetable production with an agroecological approach, there is often more organic fertilization or compost used, which can often generate more N_2O or CH_4 emissions. However, these practices clearly improve soil health and can increase carbon sequestration. Therefore, an overall quantification of all climate mitigation effects is needed to assess if GHG emissions are outweighing carbon sequestration effects, knowing that the latter manifest themselves in a longer time period whereas GHG emissions can occur on a very short time scale. Additionally, a too narrow focus on climate mitigation disregards the long-term positive effects of manures and composts on soil health, which is expected to lead to higher levels of production and resilience, which are key determinants of climate change adaptation. It has also to be stressed that trade-offs related to the use of certain practices are not only restricted to agroecological practices but apply also to conventional practices. For example, chemical N fertilization can lead to higher N_2O emissions (compared to no or lower fertilization rates), but on the other side, it also increases overall crop production, including root biomass development and its consequent positive effect on carbon sequestration. Therefore, the discussion about trade-offs between agricultural production and climate change mitigation is not unique to agroecological farming and needs to take into account the complexity of any agroecosystem management type and the respective local conditions, including the interplay between the geophysical and socio-economic domains.

Practices that focus on soil management can mitigate emissions largely. For example, Fuentes-Ponce et al. (2022) conducted a study on emissions originating from three primary sources: inputs, soil, and tillage. The findings of their study on conservation vs conventional agriculture revealed that emissions from the soil significantly overshadowed the contributions from the other two sources. Absence of mineral fertilizers and inclusion of grass-based or aromatic plants as soil cover considerably reduced N_2O emissions, but increased with leguminous species (Hüppi et al. 2022). Intercropping practices such as maize-legume were shown to reduce N_2O fluxes from soil efficiently by Sommer et al. (2016).

Arable farming in general, and in particular rice, stands out as the predominant cropping systems that are responsible for a substantial number of negative outcomes (Figure 4), majorly contributing to CO_2 and CH_4 emissions. However, 63% of these negative outcomes for arable were results without tests or with tests but with non-significant differences; for rice, it was 81%. For rice, the decomposition of organic matter in crop residues is the main cause of them, as microbial activity accounts for a higher proportion of CO_2 emissions from soils (Jayaraman et al. 2022). A review by Linquist et al. (2012) on GHG emissions and fertilizer management practices in rice systems showed that low inorganic N fertilization rates increased CH_4 emissions, while high N rates decreased CH_4 emissions, indicating the trade-off between N rate and gas emissions. Furthermore, they reported that organic amendments such as farmyard manure and green manure increased CH_4 emissions significantly. Our study confirms this evidence, likely due to the low C/N ratio of organic manures, resulting in faster biomass mineralization and consequent higher CH_4 emissions (Malav et al. 2020; Toma et al. 2021).

Practices such as organic amendments and crop residue retaining generally increase the content of organic carbon in the topsoil. Jayaraman et al. (2022) showed that soil organic carbon was higher with residue retention in no-till plots or plots with reduced tillage compared to conventional tillage without residue retention for both soybean–wheat and maize-chickpea rotations, although differences were significant only in the topsoil. Similarly, the combined effect of reduced CO_2 emissions and increased soil C can be achieved with no tillage and residue retention (Nath et al. 2017; White et al. 2021). Another practice that demonstrated significant positive outcomes for carbon stock is cover cropping, in combination with no-till (Constantin et al. 2010; Guzzetti et al. 2020).

4.3 Challenges to evaluate climate change outcomes of agroecological practice combination

This literature review also provided important information on the challenges of comparing combinations of agroecological practices in terms of climate change impact. First, climate change indicators varied across a large array of metrics. Second, we observed significant trade-offs between metrics, especially where some GHG emissions were negative while carbon sequestration was positive for the same practice combination. This can also occur within GHG emission metrics, with a decrease in CO_2 emissions (positive outcome) paralleled with an increase in N_2O or CH_4 emissions (negative outcome). Quantification of all GHG together, i.e., studies where all three gases were measured, was very rarely the case, and many of them just evaluated one of the three target GHGs.

Third, GHG measurements and the heterogeneity of farming systems pose additional challenges. Most studies used experimental chamber setups to measure GHG emissions, but there was a large diversity in how this was measured. Further, important differences emerged across studies relate to the duration of measurements, what was compared, and the metrics used (e.g., direct CO_2 measurement or estimation of CO_2 equivalents). For example, measurement time varied between a few weeks and several months, and sometimes, measurements were aggregated for a few years to account for different crops in crop rotations, but without having full coverage of measurements across years. Indeed, the heterogeneity of farming systems makes the design of GHG sampling approaches complicated (Rosenstock et al. 2016).

Fourth, site-specific conditions exert a strong influence on outcomes. GHG emissions from soils are strongly related to local pedo-climatic conditions (e.g., rainfall, soil temperature) and management factors (e.g., crop, crop residue amount and management, tillage), which thus represent the main drivers of variation in emissions (Krauss et al. 2017). For the abovementioned dual effect of organic amendments on soil health vs GHG emissions, their on-field distribution may potentially hinder the comparison between agroecological and conventional systems and hamper the identification of other possible drivers of climate mitigation effects, e.g., crop rotation (Leifeld and Fuhrer 2010). An important factor to be taken into account is the rate or amount of application of organic amendments as compared to synthetic fertilizers. Many articles in this review used different rates or amounts for organic vs inorganic fertilizers in their comparisons. This is often related not only to site-specific conditions and local farming systems, but also to application of standard inorganic fertilizer rate recommendations from extension or state authorities.

The diversity in agroecological management also revealed the sometimes blurred line between agroecological and conventional practices, which makes it challenging to cover and compare the implementation and development of agroecological practices combination across all possible situations. For example, a comparison between no till and seeding into cover crop mulch vs conventional plowing with no cover crops is challenged when the agroecological no till system uses herbicides to terminate cover crop before seeding, whereas the conventional tillage system does not. Examples like this have been excluded from this systematic review as no complete separation between agroecological and conventional management was possible. Furthermore, while it is clear that farmers need to consider GHG emissions associated with their practices, this may conflict with the complexity of agroecological management that they would like to adopt. This could possibly lead to the use of new practices or maintenance of practices that do not perform well on mitigating GHG emissions but allow farmers to position themselves at an intermediate level of transition without introducing too much management complexity (Martin and Willaume 2016). In other words, management challenges stemming from increased agroecosystem complexity—whether real or perceived—may partially hinder the potential of multiple agroecological practices to meet climate mitigation goals and may slow down the agroecological transition.

5 Conclusions

Agroecological approaches are seen as one of the preferential avenues to increase the sustainability of agricultural and food systems, including positive contributions to climate change mitigation and adaptation. Despite the large number of studies on individual agroecological practices and their impact on climate change, studies addressing the effect of the implementation of more than one agroecological practice or more complex agroecological farming systems on climate change mitigation indicators are relatively scarce. This review aimed to shed light on this issue by analyzing recent evidence on the outcomes of multiple agroecological practices or agroecological systems on climate change mitigation vis-à-vis conventional systems. The major finding of this review is that agroecological approaches combining more than one practice have more often positive climate change impact outcomes than negative or inconclusive outcomes across the broad range of mitigation type metrics evaluated. In particular, for carbon sequestration metrics, the outcomes were largely positive. For GHG emissions, the picture is more nuanced. In arable systems, the most frequent ones, many metrics showed positive outcomes. However, quite a large share showed also negative outcomes for CO_2 and CH_4 emissions, in particular in rice systems. Most of the studies addressed farming systems with a combination of only two agroecological practices. A general trend of more positive outcomes with an increasing number of agroecological practices applied was found for carbon stock but not for GHG emissions metrics. Reduced tillage/no till, cover crops, residue retention, crop fertilization, and crop rotation were the main practices analyzed.

These results are showing just a glimpse of the climate change impact of agroecological system management, and more in-depth analysis of the studies may need to be included in future work, such as a better understanding of the agroecological analysis, and inclusion of qualitative and ex ante data or information, such as preceding crops or crop rotations before measurement of carbon sequestration of GHG emissions, to have a more comprehensive understanding of trends in climate change impact. Moreover, future research could feature an in-depth assessment of the magnitude to which these results were positive or negative. An issue deserving further investigation is the more frequent negative outcomes highlighted with the use of organic fertilizers/amendments as an AEP, regarding GHG emissions and in particular CH_4, which partly shadows their well-known positive effects on soil fertility and soil health.

Overall, the results of this review show that agroecological practices have lower climate change impact and more positive outcomes than their conventional counterparts. However, there are trade-offs to be considered, like the common case of positive effects on carbon sequestration and concomitant negative effects on N_2O or CH_4 emissions. Therefore, a comprehensive appraisal of the multifaceted effects of agroecological vs conventional management systems on climate change mitigation should be approached, taking into account issues like site-specific geophysical and socio-economic conditions, different spatial and temporal dynamics of the effects, and the actual magnitude and consequences of positive vs negative outcomes on agroecosystem performance across different scales.

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Data Availability The datasets generated during and/or analyzed during the current study are available from the author(s) having conducted the relevant research on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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