

Agroecological interventions increase biodiversity and the potential for climate change mitigation in Europe

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ABSTRACT

Agroecology has gained considerable interest as a concept for designing sustainable agrifood systems. To date however, the effects of farming systems and management practices associated with agroecology (i.e., agroecological interventions) on biodiversity and climate change mitigation have not been systematically reviewed. Here, we perform a meta-analysis using observational and experimental studies to assess the effects of agroecological interventions on taxa diversity, as well as on greenhouse gas emissions (GHG) and carbon storage in Europe. Agroecological interventions were classified along a gradient ranging from input substitution to system redesign in order to estimate and compare effects of different agroecological transition types. We found a general positive effect of agroecological interventions across biodiversity and climate change mitigation metrics. Agroecological interventions increased diversity of all functional groups of organisms considered, as well as promoting soil carbon storage, and reducing nitrous oxide emissions. However, agroecological interventions had limited effects on the mitigation of carbon dioxide and methane emissions. Positive effects on biodiversity and climate change mitigation metrics were consistent for transitions from conventional farming interventions to either input substitution or redesign interventions. A win-win situation was found in most studies in which both biodiversity and climate change mitigation data were recorded, driven by changes in micro-decomposer biodiversity and in soil C storage. Our findings demonstrate the multiple environmental benefits that can be obtained from adopting an agroecological approach to farming, and highlight the value of this approach for achieving European Union targets in relation to both GHG emission reduction and biodiversity.

1. Introduction

Adverse effects of the interlinked environmental issues of climate change, biodiversity loss and pollution (the so-called triple planetary crisis) pose increasing threats to food security worldwide (IPCC, 2022, IPBES, 2019). At the same time, agriculture is a major contributor to global greenhouse gas (GHG) emissions, soil pollution, and eutrophication of watercourses in systems which rely on chemical inputs such as pesticides and fertilisers to increase yields (Campbell et al., 2017). To solve these issues, holistic alternative approaches to the design of sustainable agrifood systems, such as agroecology, have gained significant interest in recent years (Bezner Kerr et al., 2023). Agroecology could

contribute to achieving carbon neutrality and biodiversity targets set by the European Union (EU) in their Green Deal and Biodiversity Strategy (European Commission, 2019; European Commission, 2020), but scientific evidence of the benefits of agroecological practices is required to support these European policies and confront the triple planetary crisis.

Agroecology is grounded in a set of core principles, including enhanced biodiversity, improved soil and livestock health, reduced reliance on external inputs, economic resilience and social fairness (Wezel et al., 2020). When applied to agricultural systems, these principles inform specific farming techniques. Incremental changes at the field level such as adopting better soil practices or improving animal welfare can initiate a shift toward agroecology, but more comprehensive

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agroecological transitions require redesigning farms around key principles including biodiversity, nutrient cycling, as well as accounting for social values (HLPE, 2019). The overall aim of agroecological interventions is to optimise ecological processes and promote multiple ecosystem services within agroecosystems in addition to food production (Palomo-Campesino et al., 2018; Wezel et al., 2020). Unlike conventional farming that often strives for a simplification of the system, agroecological practices aim to promote interactions between organisms and their integration into ecosystems, with a particular focus on agrobiodiversity (Wezel et al., 2014a; Dumont et al., 2020). Consequently, agroecological interventions are expected to provide greater benefits for biodiversity and biodiversity-associated processes than conventional farming practices. Agroecological interventions are also intricately linked to biogeochemical cycling, with implications for GHG emissions, soil carbon sequestration, and potential synergies between biodiversity and biogeochemical cycling. Whilst a number of recent studies have addressed links between agricultural practices and either biodiversity (Tuck et al., 2014; Tamburini et al., 2020; Sanchez et al., 2022; Rasmussen et al., 2024) or climate change mitigation (Tamburini et al., 2020; Beillouin et al., 2021; Lessmann et al., 2022), a comprehensive analysis of the benefits of agroecology on multiple ecosystem services is lacking.

Effects of agroecological interventions on biodiversity and climate change mitigation may differ depending on the context in which they are implemented. The application of specific agroecological interventions depends on local contexts, constraints, and opportunities, which may lead to variation in the responses of taxa diversity, GHG emissions, or carbon storage (Beillouin et al., 2021; Rasmussen et al., 2024). For example, soil organisms in annual cropping systems with regular tillage may be particularly sensitive to agroecological interventions which reduce soil disturbance, but effects on aboveground taxa are likely to be more limited (Lal, 2004; de Graaff et al., 2019; Li et al., 2020a; Betancur-Corredor et al., 2022). Complex interactions among ecosystem properties or ecological processes may further promote variation in the provisioning of different ecosystem services (Richter et al., 2024). In the case of biodiversity-friendly, rotational grazing practices, designed to enhance the flowering intensity and sward heterogeneity of pastures, the actual benefits on biodiversity were shown to vary according to livestock species and stocking density, with benefits on some functional groups while others remained unaffected (Farruggia et al., 2012; Ravetto Enri et al., 2017). In the case of reduced tillage intensity, stubble retention is often associated with this practice, which can lead to positive effects on bacteria diversity via resource inputs (Li et al., 2020b) or negative effects due to an increased abundance of dominant organic matter degraders (Tyler, 2019). The effect of reduced tillage on carbon dioxide emissions may also vary due to additional processes such as soil macro-aggregate formation (Six et al., 2002), soil aeration, and incorporation of organic matter (Abdalla et al., 2016). These varying effects on both biodiversity and climate change mitigation variables can lead to trade-offs between both dimensions. However, co-benefits to biodiversity and climate change mitigation have been reported for agricultural management aimed at reducing biodiversity loss or mitigating climate change (Shin et al., 2022; Smith et al., 2022). One example is the positive effect that intercropping can have on carbon (C) storage while also increasing bacteria diversity (Cuartero et al., 2022). There is a clear need to better understand how multiple ecosystem services are impacted by agroecological interventions for multiple land-use types and multiple ecosystem service metrics, to determine the overall impact of agroecology on ecosystem multifunctionality.

Agroecological principles encompass different organisational and spatial levels, providing general guidelines for managing farms along a transitional gradient towards maximum sustainability and resilience (Gliessman, 2015). At the agroecosystem level, interventions can be classed into one of three levels representing different degrees of change within an agroecological transition gradient: level 1 requires an increase

in efficiency of use of resources to reduce external inputs (e.g., efficiency of fertilizer applications), level 2 substitutes conventional practices with alternative, more environmentally-friendly practices (e.g., substituting synthetic N fertilizer with symbiotic N fixation), and level 3 involves a redesign of the agroecosystem to mimic natural ecosystems and make use of ecological processes (e.g., introduction of flower strips, diversified crop rotations, multi-species livestock systems) (Gliessman, 2015). Assuming that agroecological interventions are indeed associated with benefits for biodiversity and climate change mitigation, we might expect these benefits to increase along a gradient of agroecological transition, from conventional farming to a management system based on redesign and a high level of ecological integration at the field-scale. To date, the influence of different agroecological transition levels on the magnitude of change in ecosystem properties has faced little attention.

Here, we investigate the influence of agroecological interventions on biodiversity and climate change mitigation across multiple agricultural land-use types in Europe. We explore impacts of different degrees of agroecological farming system change on key metrics of biodiversity, on soil carbon storage, and on GHG emissions. We place a special emphasis on studies with a holistic approach rather than focusing on individual field practices to better understand the implications of agroecological interventions at the agroecosystem level (Wezel et al., 2014b). Our primary hypothesis is that agroecological interventions have a positive effect on biodiversity and climate change mitigation metrics. In addition, we hypothesise that:

- i) The magnitude of positive effects of agroecological interventions on biodiversity may vary depending on the type of organism considered;
- ii) The magnitude of agroecological benefits on biodiversity, soil C storage, and on the mitigation of GHG emissions may vary with agricultural land-use type; and
- iii) Positive effects of agroecological interventions are greater where the degree of agroecological transition is larger (i.e., when comparing conventional interventions to redesign interventions rather than input substitution interventions).

2. Materials and methods

2.1. Systematic literature searches

We focused on studies carried out in Europe as defined by the United Nations (United Nations, 1999), to only consider farming systems embedded within the socioeconomic, cultural and environmental framework of Europe. Given the large number of terms in the search string, two separate systematic literature searches were conducted: one addressing the effects of agroecology on biodiversity, the other addressing the effects of agroecology on climate change mitigation. Here, we consider climate change mitigation as any reduction of GHG emissions, or increase in soil C stocks. A detailed protocol for the systematic searches and data extraction is available in the [Supplementary Information](#) (Appendix A). The searches were conducted on both the Scopus and Web of Science databases. Each search query was composed of two groups of search terms, one associated with agroecological practices or systems, and the other associated with response variables: either biodiversity metrics or climate change mitigation metrics (Appendix B: [Table S1](#) and [Table S2](#)). We limited our search to primary research studies published between 2013 and the date of the final literature search due to the large number of articles obtained in preliminary searches and the strong increase in the body of scientific literature about agroecology during the last decade. The biodiversity search was completed on 08/01/2024 and 13,262 articles were found, while 13,660 articles were obtained from the final search on climate change mitigation which was conducted on 10/01/2024.

2.2. Inclusion criteria

We use the term agroecological intervention in this study to describe system-level practices which follow at least one of the 13 principles of agroecology (HLPE, 2019). Because the study focused on metrics of biodiversity and climate change mitigation measured in the field, the studies extracted from the literature dealt with agroecological interventions associated with principles linked to the agroecosystem scale (HLPE, 2019). Food system scale principles, such as, social equity and responsibility, which were less likely to be associated with direct effects on biodiversity or climate change mitigation were therefore not considered. The interventions identified in the studies were classified along a gradient of agroecological transition based on the efficiency-substitution-redesign (ESR) framework (Hill and MacRae, 1996). This framework has been adapted to describe the different levels of change that occur at the field and farm scale when transitioning from a conventional farming system to a more sustainable farming system (Gliessman, 2015). Detailed description of the levels can be found in Gliessman (2015). We further adapted this classification to classify interventions in three categories: conventional (C), substitution (S), and redesign (R). Interventions at the redesign level (R) were always considered as being agroecological, and their data was therefore retained. We classified interventions that involved either a diversification of a farming system or the addition of an ecological infrastructure in the agroecosystem, i.e., biophysical structures which can provide ecosystem services (Perschke et al., 2023), in class R (Gliessman, 2015; Wezel et al., 2014a). Input substitution (S) interventions were only considered as being agroecological if the study took a systems approach at a farm scale (i.e., comparison of well-described farming systems and management strategies containing multiple agricultural practices, see Table 1 for examples). This is in line with the agroecological approach of considering the whole farming system rather than focussing on individual practices (Wezel et al., 2020; Dumont et al., 2025). It also led to the exclusion of studies from the analyses which compared organic agriculture with conventional agriculture without providing information on farm management. Included in class S were interventions that went beyond merely reducing farm management intensity, by replacing synthetic inputs or certain intensive management practices with organic based inputs or environmentally-friendly practices without redesigning the production system by integrating new elements in the system. In the case of livestock systems, we considered a reduction of stocking rate or mowing frequency in livestock production systems as a level S intervention (thus only kept if applied at farm scale) since it is a common agricultural extensification measure in a system with few possibilities of

Table 1

Examples of agroecological interventions classed as S and respectively R interventions in this study, in line with the food system change framework (Gliessman, 2015).

S. Substitution of synthetic inputs or intensive practices with alternative practices	R. Management based on ecological redesign (integration of non-productive ecological infrastructures and system diversification)	
	Non-productive ecological infrastructures	Diversified production system
No tillage	Hedgerows	Diversified crop rotations
No mineral fertilizer application	Tree lines	Intercropping
No synthetic pesticide	Flower strips	Mixed grazing
Extensive grazing	Unmowed refuge	Integrated crop-forestry
Extensive mowing		Integrated crop-livestock
Cover cropping		Integrated livestock-forestry
Delayed mowing		
Animal manure		
Green manure		

substituting inputs compared to cropping systems. Interventions which did not meet the criteria for the S or R classes were classified as C. Interventions which included the use of synthetic pesticides were not retained to remove all risks of potential confounding effects in the biodiversity analysis. We kept this exclusion criteria for the climate change mitigation analysis to have the exact same framework for the two analyses. Only experimental data from studies with true replicates were considered; studies modelling GHG emissions and soil C storage were therefore also excluded from the dataset. Additional inclusion criteria used for selection are listed in Table S3.

2.3. Article screening

The open-source systematic review software with machine learning, ASReview LAB (v. 1.3.4; ASReview LAB developers, 2023), was used to screen the results for relevancy at the title and abstract level. This software orders the articles according to relevancy using machine learning based on a pre-selection by the research team of a subset of relevant and irrelevant articles (Van De Schoot et al., 2021). Articles were excluded if one or more of the inclusion criteria were not met. All articles selected during the title and abstract screening phase (1261 studies for biodiversity and 847 studies for climate change mitigation) were then screened at the full-text level according to the list of study selection criteria (Appendix B: Table S3). Articles which met all the criteria were retained for data extraction. The selection process for both biodiversity and climate change mitigation study search is portrayed using PRISMA flow charts (Page et al., 2021) in figures S1 and S2 in Appendix B.

2.4. Data extraction

Means and standard deviations of the effects of agroecological interventions and their comparators on biodiversity and climate change mitigation were extracted from each study. Data on biodiversity was collected as taxa abundance (individuals per area or volume), taxa richness, taxa evenness, and diversity indices (Shannon diversity index and Simpson's index of diversity). Data on carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emissions, as well as soil C storage were collected to estimate climate change mitigation. We emphasize that this data allows us to estimate the effect of agroecological interventions on parameters that play an important role in climate change, but it does not allow us to estimate a complete GHG balance. GHG emission values were subtracted from zero to generate intuitive mitigation metrics where greater values represent a greater contribution to climate change mitigation. GHG emissions were expressed per unit area since this was the most common unit found in studies and it is also more comparable with biodiversity data (expressed per unit area or soil volume). Insufficient data was available to estimate C sequestration and we therefore only considered soil C stocks. Soil C concentrations were converted to soil C stocks (Mg per ha) using the following formula:

$$SOC_{stock} = SOC \times BD \times D \quad (1)$$

SOC = soil organic carbon concentration (%), BD = bulk density, D = soil depth.

If bulk density data was missing from a study, it was calculated using the following pedotransfer function (Howard et al., 1995):

$$BD = 1.3 - (0.275 \times \ln(SOC)) \quad (2)$$

SOC = soil organic carbon concentration (%).

Where studies contained multiple estimates (e.g., for multiple levels of agroecological interventions, multiple metrics, multiple locations, and multiple years), we extracted all estimates. Indeed, multiple effect sizes in studies can be accommodated by using nested models which is preferable to losing information by omitting data (Mengersen et al., 2013; Assink and Wibbelink, 2016). However, we pooled means and

standard deviations for studies with multiple sampling rounds within a year, and we focussed on data gathered at the A horizon for soil samples if multiple soil depths were included in a study as this was the most common soil horizon sampled. A data extraction tool, WebPlotDigitizer v.4.6 (Rohatgi, 2022), was used to obtain data in numerical format from articles which displayed comparisons in graphical format only.

Information concerning the location of the studies, the taxa, and the interventions studied were collected from each paper. These data were used to describe the effect sizes, and to construct moderators (explanatory variables) for the meta-analysis. Pairwise comparisons between agroecological interventions and comparators were grouped based on their position along our CSR gradient. These groups are hereafter referred to as agroecological transition types. For instance, the comparison between an input substitution (S) intervention and a conventional (C) intervention has been defined as a C-S agroecological transition type (see Appendix B, Fig. S3).

Agricultural land-use type was divided into four groups: arable, grassland, horticulture, perennial (Appendix B: Table S4). In the case of mixed land-use type systems, the effect sizes were classified according to the land-use type in which the measurements were made. Taxa were classified into five functional groups; macro-decomposers, micro-decomposers, arthropod predators, plants, and pollinators (Appendix B: Table S5). This was done in order to associate agroecological interventions with organisms contributing to different ecological functions in agroecosystems. In the case of plants, abundance data was not retained as a diversity metric since this can be used to describe a disservice in agriculture in terms of weed infestation.

2.5. Statistical analysis

Standardised mean differences (SMD) were calculated for all pairwise comparisons between agroecological interventions and their comparators using Hedges' g unbiased estimator (Formula 3; Hedges, 1981). This effect size measure was chosen because it can handle negative means, and negative estimates of GHG gas fluxes were included in the database. The estimator is based on Cohen's d which tends to overestimate effects in studies with small sample size (Borenstein et al., 2009). This bias is corrected by Hedges' g.

$$g = d \times \frac{\Gamma\left(\frac{m}{2}\right)}{\sqrt{\left(\frac{m}{2}\right)\Gamma\left(\frac{m-1}{2}\right)}} \quad (3)$$

d = Cohen's d (Formula 4), $m = n_1 + n_2 - 2$, n_1 and n_2 = sample sizes for the agroecological intervention and its comparator, with Γ denoting the Gamma function.

$$d = \frac{y_1 - y_2}{\sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}} \quad (4)$$

n_1 and n_2 = sample sizes, y_1 and y_2 = sample means, s_1^2 and s_2^2 = sample variances for the agroecological intervention and its comparator.

Mixed-effect models were first fitted to estimate an overall effect of agroecological interventions on biodiversity using all the biodiversity metrics, and the overall effect for climate change mitigation was estimated using effect sizes for C stocks and GHG emissions, while taking into account within-study and between-study variance (Assink and Wibbelink, 2016). We also calculated the within-experiment variance to take into account studies conducted on the same experimental setup. Moderators were added to the models as fixed effects to test potential influences of agricultural land-use type and agroecological transition types on the calculated average effect sizes, and to test the influence of functional groups for the biodiversity meta-analysis and between C stocks and different GHG emissions for the climate change mitigation analysis. We also aimed to detect effects of the different types of agroecological intervention. However, we did not obtain enough data for

each intervention type to perform a meaningful analysis. Effect size averages for each intervention type are nonetheless reported in Appendix B (Table S6 to S13). We took a space for time approach to analysing agroecological transition effects by comparing the difference between plots or systems representing two different agroecological levels. Two models were retained to analyse the effects of agroecological interventions on functional groups; one considering all biodiversity measurement types, and another without considering abundance. The latter model was used to estimate the effects on plant diversity since there are no plant abundance data in the dataset. Effects of the moderators were considered to be statistically significant when the confidence interval around the estimated marginal means did not overlap with zero. Differences between factor levels were tested using pairwise comparisons with Tukey adjusted p values on the marginal means. An analysis was also conducted on a subset of the data which represented the studies which contained both biodiversity and climate change mitigation data. The average effect size for each study for both biodiversity and climate change mitigation effects was calculated to observe if synergies or trade-offs existed between the two variable types in these studies. The mean effect for both metric types across all studies was also calculated to estimate a general trade-off or synergy in the dataset.

Data extraction errors were checked by drawing a funnel plot of the standard errors and the inverse standard errors against the effect sizes to detect outliers, and then corrected (Nakagawa et al., 2022). We tested for small-study effects (increase in effect size when uncertainty increases) and time-lag bias (positive results are published faster than other results) by using a multilevel meta-regression approach (Nakagawa et al., 2022; Yang et al., 2023). This consisted in running meta-regressions with the square root of the inverse of effective sample size and the year of publication as moderators. No time-lag bias was detected, but a small-study effect was found for the biodiversity meta-regressions. Consequently, the square root of the inverse of effective sample size was added to the biodiversity mixed effect models in order to calculate adjusted overall effect sizes.

All analyses were performed on R (v. 4.0.4, R Core Team, 2021) using the following packages: metafor (v. 4.4, Viechtbauer, 2010), emmeans (v. 1.10, Lenth, 2024), and orchard packages (v. 2.0, Nakagawa et al., 2023). The data used for the analyses is available in the supplementary information (Appendix C) as is the list of studies included in the meta-analyses (Appendix D).

3. Results

3.1. General overview of the data

A total of 123 studies were retained for analysis of the effects on biodiversity, while 72 studies were retained for climate change mitigation (Appendix D). Among these studies, 25 contained data on both biodiversity and climate change mitigation. The full dataset contained studies spread across 21 countries in Europe (Fig. 1). We found more studies with data on biodiversity in western Europe and the Mediterranean region, with the highest number of studies found in Germany. Most climate change mitigation studies also originated from western Europe, with the highest number of studies being found in Spain. In general, studies conducted in arable systems came from France, Germany, Italy, Netherlands, Sweden, or Switzerland (Appendix B: Table S14 and S15). Grassland studies were mostly conducted in France, Germany, Switzerland, and the United Kingdom, whereas horticulture studies were mainly conducted in Italy and Spain, and perennial studies in Spain, Germany, and Italy.

3.2. Effects on biodiversity and climate change mitigation variables

Agroecological interventions had positive overall effects on biodiversity and climate change mitigation (Fig. 2). Positive biodiversity effects were also obtained for all five functional groups of organisms

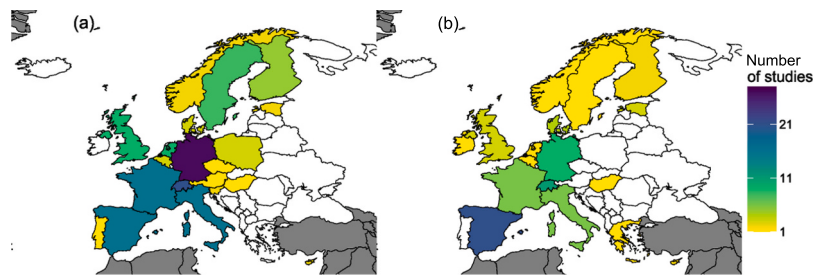


Fig. 1. Distribution of studies by country for (a) biodiversity and (b) climate change mitigation. Countries in white are European countries in which no data were found.

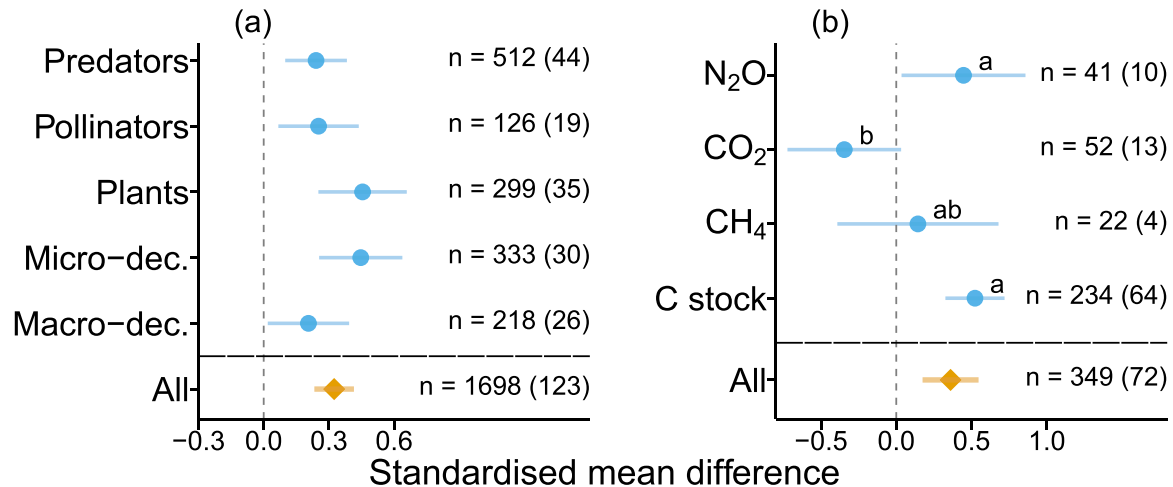


Fig. 2. Average effect sizes for (a) biodiversity and (b) climate change mitigation. The number of effect sizes used to calculate the average is given with the number of studies in parentheses. Error bars represent 95 % confidence intervals. Effects are considered as statistically significant if error bars do not overlap with zero. Positive effect sizes represent positive effects of agroecological interventions. Emissions of CH₄, CO₂, and N₂O are inverted so that positive values represent reduced emissions. Different letters beside average effect sizes indicate statistically significant differences between categories. Micro-dec. = micro-decomposers; Macro-dec. = macro-decomposers.

considered, and the magnitude of the effect sizes did not statistically differ between groups. There were differences in effect sizes, however, between the type of metrics used to estimate biodiversity with the greatest effects observed for taxa richness and no significant effect found for taxa evenness (Appendix B: Fig. S4). In the case of climate change mitigation, positive effects of agroecological interventions were observed for C stocks (est. = 0.55, 95 % CI = 0.35, 0.75) and N₂O

emission reduction (est. = 0.48, 95 % CI = 0.06, 0.90) (Fig. 2b). No effect was detected for CO₂ and CH₄ emission reduction, although we observed a negative trend for CO₂ emissions. Both C storage ($t = 4.4$, $p < 0.001$) and N₂O ($t = 3.42$, $p < 0.01$) emission reduction have a significantly greater effect size than CO₂ emission reduction.

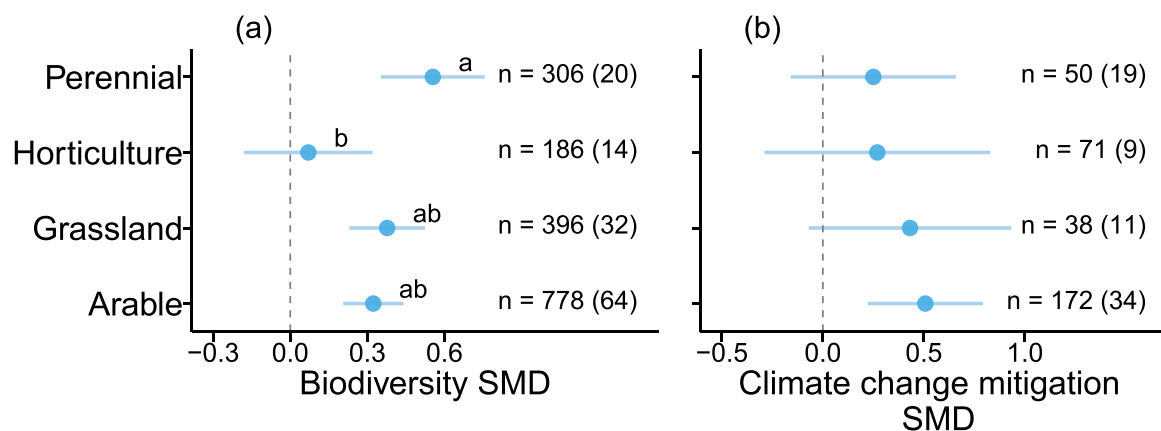


Fig. 3. Average effect sizes for (a) biodiversity and (b) climate change mitigation for each land-use type. The number of effect sizes used to calculate the average is given with the number of studies in parentheses. Error bars represent 95 % confidence intervals. Effects are considered as statistically significant if error bars do not overlap with zero. Positive effect sizes represent positive effects of agroecology. Different letters beside average effect sizes indicate statistically significant differences between categories. SMD = standardised mean difference.

3.3. Agricultural land-use type

Agroecological interventions had a positive effect on biodiversity in all agricultural land-use types except horticulture (Fig. 3a). Significant differences in effect size were also observed between land-use types with agroecological interventions having a more positive effect on biodiversity in perennial cropping systems than in horticulture ($t = 3.25$, $p < 0.01$). A positive effect of agroecological interventions was only observed in arable systems (est. = 0.55, 95 % CI = 0.26, 0.85) for the climate mitigation variables (Fig. 3b). Effects on different functional groups or climate change mitigation variables in each land-use type were either positive or not significant (Appendix B: Fig. S5 to S9).

3.4. Agroecological transition types

A positive effect of agroecological interventions on biodiversity was observed for all agroecological transition types (Fig. 4a). With the exception of S-S', the effect of agroecological interventions on climate change mitigation variables was positive for all agroecological transition types (Fig. 4b). No statistical differences were detected between agroecological transition types for both biodiversity and climate change mitigation effects. Effects on different functional groups or climate change mitigation variables for each transition type were either positive or not significant (Appendix B: Fig. S10 to S14).

3.5. Relationship between biodiversity and climate change mitigation effects

For studies in which both biodiversity and climate change mitigation data were recorded, agroecological interventions had generally positive effects on both biodiversity (est. = 0.24, 95 % CI = 0.01, 0.47) and climate change mitigation variables (est. = 0.46, 95 % CI = 0.18, 0.73) (Fig. 5), i.e., a win-win situation was found in a majority of the studies. Effects on biodiversity were driven by changes in micro-decomposer biodiversity (Appendix B: Fig. S15), while effects of agroecological interventions on climate change mitigation were driven by changes in soil C storage (Appendix B: Fig. S16).

4. Discussion

Agroecology is a paradigm recommended for sustainable food production and the provision of multiple ecosystem services. Despite many of its principles being aligned with biodiversity conservation and climate change mitigation goals, no review to date has assessed how

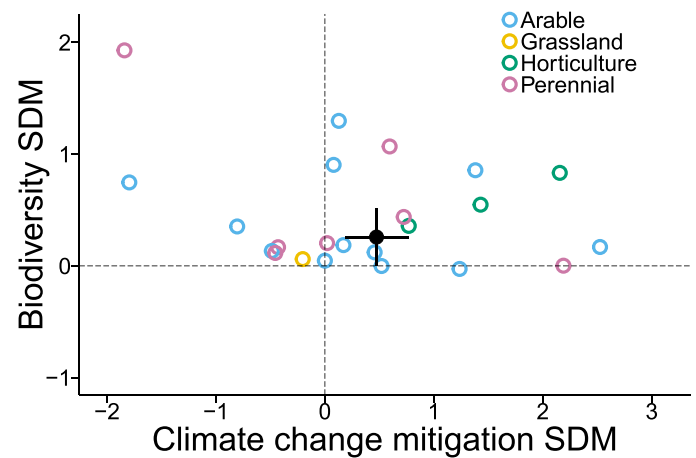


Fig. 5. Relationship between the effects of agroecological interventions on biodiversity and climate change mitigation. Dots without error bars represent the average effect size of each study containing data on the effects on both biodiversity and climate change mitigation. The black dot represents the overall average effect sizes. Error bars represent 95 % confidence intervals. Effects are considered as statistically significant if error bars do not overlap with 0. Positive values represent positive effects of agroecology.

agroecological interventions contribute to achieving these goals. In this meta-analysis, we demonstrate the potential benefits of agroecology for increasing biodiversity on agricultural land and mitigating climate change in the European context.

4.1. Agroecology benefits biodiversity on agricultural land except in horticultural systems

In line with expectations, we found that agroecological interventions had an overall positive effect on biodiversity on European agricultural land. Our results are in agreement with previous work in arable and grassland-based systems which highlights positive effects of added ecological infrastructures (Van Vooren et al., 2017; Kühne et al., 2022; Couthouis et al., 2023; Donkersley et al., 2023) and increased diversification of farming systems (Beillouin et al., 2021; Sánchez et al., 2022; Staggenborg and Anthes, 2022) on biodiversity. Surprisingly, the magnitude of positive effects of agroecological interventions on biodiversity was consistent across all functional groups considered. A recent meta-analysis of the effects of diversification in farming systems on

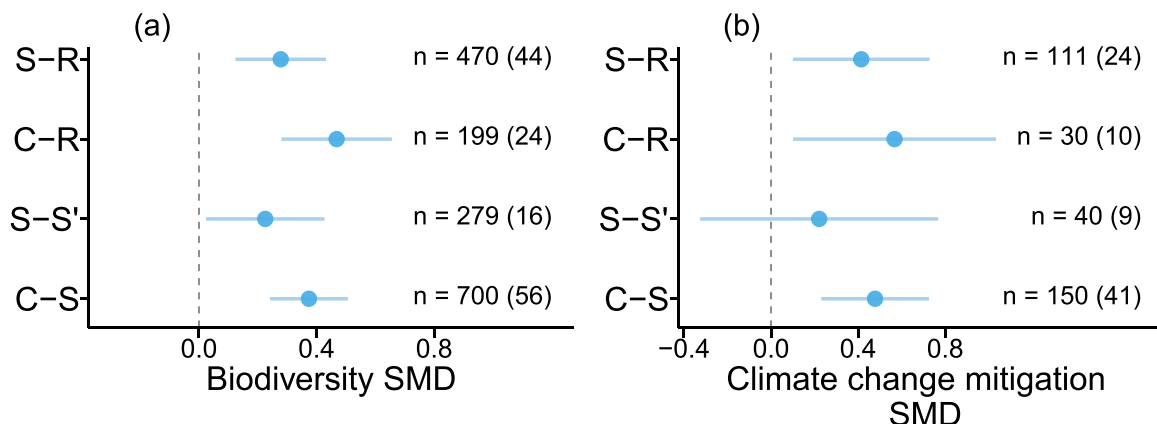


Fig. 4. Average effect sizes for (a) biodiversity and (b) climate change mitigation for each agroecological transition. The number of effect sizes used to calculate the average is given with the number of studies in parentheses. Error bars represent 95 % confidence intervals. Effects are considered as statistically significant if error bars do not overlap with 0. Positive effect sizes represent positive effects of agroecology. C = conventional, S = input substitution, R = redesign. A prime symbol is used to identify the intervention that is considered to be the most agroecological when the two interventions compared are in the same class. SMD = standardised mean difference.

biodiversity also found positive effects on pollinators and decomposers, although no significant effect was found for natural enemies or plants (Sánchez et al., 2022). Results observed in our study may at least partly reflect the broad range of agroecological interventions considered, as well as variation in the organisms recorded across studies. These variations in taxa type between studies may also be associated with covariation between types of organisms and the agroecological interventions studied. For example, studies on management and soil disturbance are more likely to measure biodiversity of belowground organisms while studies on flower strips tend to focus on pollinating arthropods. All the studies included in our meta-analysis which analysed the effects of flower strips or unmowed refuges measured aboveground taxa biodiversity, while all but one of the studies focussing on tillage only considered plants, belowground taxa, and epigeal arthropods. Where aboveground dwelling taxa react differently to management intensity compared with belowground taxa (Gossner et al., 2016; Le Provost et al., 2021), choice of study taxa may influence interpretation of management effects. Nevertheless, the positive results obtained for the different functional groups in our study have implications for supporting and regulating multiple ecosystem services, with cascading effects on ecosystem provisioning (Woodcock et al., 2019).

In the present study, woody perennial systems, grasslands, and arable cropping systems all showed similar levels of positive response to agroecological interventions. In contrast, biodiversity in horticultural systems showed a limited overall response to agroecological interventions, showing a significantly different response pattern to that of perennial systems. Conventional horticultural systems are known for their high use of pesticides (Gensch et al., 2024), and might reasonably be expected to show positive biodiversity effects under agroecological practices. It is not clear why horticultural and perennial systems showed the strongest divergence in biodiversity responses to agroecological interventions. In horticulture systems, the most common type of agroecological intervention was the inclusion of additional crop or non-crop herbaceous strips, whereas in perennial systems, agroecological interventions typically modified interrow vegetation. One possible explanation for the difference in biodiversity response between these two systems could therefore be that the addition of herbaceous plants in perennial systems creates a new type of habitat within the field for organisms, and increases the vertical structure diversity. This can be beneficial for arthropod diversity even in the case of intensive orchard management (Ploeg et al., 2025). Our results suggest that a given agroecological intervention may have varying efficiency in different land-use systems, and highlight the need for further studies evaluating agroecological interventions in multiple agricultural systems.

4.2. Agroecological interventions have mixed results on climate change mitigation metrics

In light of previous studies demonstrating the positive impact of environmentally-friendly agricultural systems on climate change mitigation (Bosco et al., 2019; Quemada et al., 2020; Mondière et al., 2024), we hypothesized that agroecological interventions would have a positive effect on our metrics of soil C storage and GHG mitigation. This idea is supported by the overall positive effect of agroecological interventions on climate change mitigation metrics observed in the present study (pooled across all mitigation variables, i.e., the effect “All” in Fig. 2). Of course, the overall mitigation response does not necessarily imply a positive effect on the net GHG balance, as our meta-analytical approach involved different metrics recorded in different studies. The overall response of the climate mitigation variables was driven by strong positive effects of agroecological interventions, such as organic farming, in arable systems, although the overall response of mitigation metrics to agroecological interventions showed a positive trend in all types of agricultural land-use. Absence of significant results for land-use types other than arable cropping systems could be due to the limited data that we found for these land-use types. Our results using a system-level,

multi-intervention approach complement previous studies on the implementation of single practices at the plot scale (Beillouin et al., 2023). In grasslands for example, studies have shown that certain increases in grazing intensity lead to an increase in soil C storage (Zhou et al., 2017; Xu et al., 2023; Niu et al., 2025), as well as in GHG emissions (Sándor et al., 2018; Ma et al., 2021; Wan et al., 2025).

Overall positive effects of agroecological interventions on climate change mitigation were mirrored by positive effects on soil C storage and the reduction of N₂O emissions. However, agroecological interventions did not have a positive effect on the mitigation of CO₂ or CH₄ emissions. Moreover, average effects on CO₂ emissions were significantly different from those on N₂O emissions and C storage. Results for CO₂ emissions are perhaps not surprising because in our meta-analysis, all of the retained studies with data on CO₂ fluxes focussed on soil respiration, and thus on biogenic CO₂. Increased biogenic CO₂ emissions agree with the results on increased decomposer populations, suggesting active communities and potentially healthier agro-ecosystems. Increased biogenic CO₂ emissions can also be explained by increases in plant root biomass associated with increases in plant biodiversity and plant productivity (Mommer et al., 2015). In the case of CH₄, our findings fit with previous meta-analyses showing contradictory results regarding the effects of sustainable agricultural practices on CH₄ emissions in cropping systems. For example, no tillage was found to have positive, negative, or no effects on CH₄ emissions depending on crop type and on other management practices used (Shakoor et al., 2022; Yue et al., 2023). Together, our results suggest that both soil respiration and CH₄ emissions show a more ambiguous signal in response to diverse agroecological interventions, likely due to complex biological interactions and strong context-dependency. In contrast, C storage and N₂O emissions may be particularly useful as indicators of ecosystem responses to agroecological interventions in the context of climate change mitigation.

Data on system-level C sequestration was lacking and we were therefore unable to investigate this aspect in our meta-analysis. Previous meta-analyses on cropland and agroforestry systems have suggested that net C sequestration increased for soils under sustainable management practices such as agroforestry and no tillage (Lessmann et al., 2022; Shang et al., 2021; Mayer et al., 2022). Our strict inclusion criteria regarding study location, year of publication, pesticide use, and study scale (i.e. a system-level approach), meant that the studies included in these meta-analyses were not included in our analyses. Two studies in our dataset did provide, however, information on C sequestration. Autret et al. (2016) showed a significant increase in C sequestration in an organic cropping system compared to its conventional control, while Sánchez-Navarro et al. (2020) found that organic intercropping had no effect on C sequestration in a horticultural system. Instead of estimating effects on C sequestration, we therefore focused on soil C stocks. Whilst our results provide further evidence of the benefits that agroecological interventions can have on soil C stocks in agroecosystems, we emphasize the need for field studies explicitly addressing the linkages between agroecological interventions and C sequestration in multiple land-use systems.

4.3. Consistent benefits of transitioning away from conventional agriculture

Agroecological transitions represent a key concept of the agroecology paradigm, where both the number and nature of agricultural practices implemented can move farming systems along a gradient towards increased sustainability (Bezner Kerr et al., 2021). To our knowledge, no studies have analysed the effects of agroecology on biodiversity or climate change mitigation along an agroecological transition gradient. We found that transitioning away from the “conventional” level or “input substitution” level yielded positive results for both biodiversity and climate change mitigation. Contrary to expectations, we found that the magnitude of the positive effect on biodiversity did not differ between transition types. A similar result was reported by Beckmann et al.

(2019), who found that species richness was greater in low intensity systems compared to medium intensity systems, and also greater in medium intensity systems compared to high intensity systems. Whilst C-R transitions might be predicted to show greater benefits for biodiversity and climate change mitigation compared with C-S transitions, it is probable that the magnitude of these benefits depends not only on transition type but also on the agroecological intervention type. Beilouin et al. (2021) found significantly different effects between diversification practices on biodiversity which corroborates this rationale. Unfortunately, our lack of data for most agroecological intervention types meant that we were not able to statistically test differences in effects between intervention types. We reiterate the recommendation by Bezner Kerr et al. (2021) for more studies with rigorous research designs to better understand the drivers of agroecology outcomes

4.4. Mostly win-win situations between biodiversity and climate change mitigation

In our dataset, 23 studies contained data for both biodiversity and climate change mitigation analyses. In addition to the general positive effects of agroecological interventions on biodiversity and climate change variables, we detected a synergy between both dimensions based on this subset of studies. This result is likely driven by increases in C storage which provide resources which support greater micro-decomposer diversity (Bastida et al., 2021). Whilst the majority of studies with both biodiversity and climate change mitigation data showed a synergy between the two types of metrics in response to agroecological interventions, we did however, also find a few studies which pointed to trade-offs between biodiversity and climate change mitigation variables. These were partly driven by increases in CO₂ emissions associated with more diverse and abundant bacterial and fungi communities under agroecological interventions (Santoni et al., 2023). Another type of trade-off has been reported in the literature for livestock systems which employ forage-related methane mitigation strategies such as feeding ruminants with more highly digestible grass (young herbage compared to highly lignified herbage) or replacing different forage types with cereals or concentrate feed (van Gastelen et al., 2019). Indeed, a trade-off between feeding management practices benefiting biodiversity in which animals graze or feed on roughages, and those decreasing methane emissions per kg of product can be observed in those systems.

Given the holistic ambition of agroecology, future studies could aim to explore additional trade-offs or synergies resulting from the implementation of agroecological interventions. Win-win or trade-off situations could for example arise with agricultural production, as some agroecological interventions can be implemented without any negative impact on agricultural productivity (e.g. Ravetto Enri et al., 2017), while others reduce provisioning services (e.g. Rapidel et al., 2015). Enhancing biodiversity in farming systems is often considered to lead to reduced short-term crop yields, especially when high-diversity systems replace high-input, high-yield crops, although this trade-off may be offset over time by increased resilience, improved ecosystem services, and reduced input dependence (Liebert et al., 2022). Most of the studies available for the current meta-analysis did not report on the effects on agricultural production or profitability and thus, further studies would be necessary to clarify the effects of agroecological interventions on potential trade-offs between biodiversity conservation, climate change mitigation and agricultural production, profitability, or social justice.

4.5. Conclusions

In this meta-analysis, we have demonstrated the benefits that agroecological interventions can provide for biodiversity and climate change mitigation across multiple agricultural land-use types in Europe. By categorising agroecological transitions using existing frameworks, we found a consistent increase in biodiversity and climate change

mitigation variables between levels along an agroecological transition gradient, and evidence for some synergies between biodiversity and climate change mitigation in response to agroecological interventions. We also found divergence in the responses of GHG variables to agroecological interventions, highlighting the potential value of soil C storage and N₂O emissions rather than biogenic CO₂ emissions as operational indicators of climate change mitigation effects of agroecological interventions. In general, more empirical research needs to be conducted on the effects of agroecological interventions on GHG emissions to allow for a more accurate assessment of the topic. Indeed, we found that empirical studies conducting analysis on a full GHG balance data are lacking. Furthermore, additional research studies need to be conducted to improve our understanding of the causal biological mechanisms responsible for the patterns observed in our study. This may help to better design agroecological transitions which benefit both biodiversity and climate change mitigation. Lastly, despite agroecology being associated with a holistic approach, we could not address principles or practices linked to its socio-economic dimensions in this study. Indirect effects of agroecological interventions occurring at the food system scale could however be imagined, such as shorter food supply chains leading to lower GHG emissions. Expanding the assessment of synergies and trade-offs to evaluate the full potential of agroecology and guide effective decision-making is thus a priority area of future research.

CRedit authorship contribution statement

Olivier Huguenin-Elie: Writing – review & editing, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization. **Frédéric Joly:** Writing – review & editing, Data curation. **Bloor Juliette:** Writing – review & editing, Methodology, Data curation. **Bertrand Dumont:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Géraldine Fleurance:** Writing – review & editing, Data curation. **Cecilia Zagaria:** Writing – review & editing, Data curation. **Cian Blaix:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agee.2025.109938](https://doi.org/10.1016/j.agee.2025.109938).

Data availability

The data used are available in Appendix C. [Appendix C](#) (Zenodo)

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