Journal of Environmental Management 353 (2024) 120277

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Quantifying potential trade-offs and win-wins between arthropod diversity and yield on cropland under agri-environment schemes–A meta-analysis

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ARTICLE INFO

Handling Editor: Jason Michael Evans

Keywords:
Biodiversity
Ecosystem services
Farmland
Landscape structure
Pollination
Pest control

ABSTRACT

In Europe, agri-environment schemes (AES) are a key instrument to combat the ongoing decline of farmland biodiversity. AES aim is to support biodiversity and maintain ecosystem services, such as pollination or pest control. To what extent AES affect crop yield is still poorly understood. We performed a systematic review, including hierarchical meta-analyses, to investigate potential trade-offs and win-wins between the effectiveness of AES for arthropod diversity and agricultural yield on European croplands. Altogether, we found 26 studies with a total of 125 data points that fulfilled our study inclusion criteria. From each study, we extracted data on biodiversity (arthropod species richness and abundance) and yield for fields with AES management and control fields without AES. The majority of the studies reported significantly higher species richness and abundance of arthropods (especially wild pollinators) in fields with AES (31 % increase), but yields were at the same time significantly lower on fields with AES compared to control fields (21 % decrease). Aside from the opportunity costs, AES that promote out-of-production elements (e.g. wildflower strips), supported biodiversity (29–32 % increase) without significantly compromising yield (2–5 % increase). Farmers can get an even higher yield in these situations than in current conventional agricultural production systems without AES. Thus, our study is useful to identify AES demonstrating benefits for arthropod biodiversity with negligible or relatively low costs regarding yield losses. Further optimization of the design and management of AES is needed to improve their effectiveness in promoting both biodiversity and minimizing crop yield losses.

1. Introduction

Worldwide, biodiversity in agricultural landscapes has been steadily declining. This has primarily been attributed to the rapid intensification, specialisation and scale-enlargement of farming (Egli et al., 2018; Beckmann et al., 2019; Mazor et al., 2018; Grass et al., 2021), through high-input agrochemicals, landscape homogenisation and habitat loss (Benton et al., 2002; Habel et al., 2019). During the last four decades, agri-environment schemes (AES) have been developed in Europe to combat the negative influence of agricultural production on the environment (Stoate et al., 2001; Batáry et al., 2015). However, the effectiveness of AES in promoting biodiversity varies considerably depending on where and when they have been implemented and what specific management measures they prescribe. There are many examples of positive effects of AES on arthropods (Kleijn et al., 2006; Aviron et al., 2009; Gallé et al., 2020; Sidemo-Holm et al., 2021; Jeanneret et al., 2022), even though there is also a large variability in outcomes, and some studies report no apparent positive AES effects on this group (Winqvist et al., 2011; Tuomisto et al., 2012; Mei et al., 2021). Since AES typically either reduce farming intensity (e.g. organic farming) or imply that some land is taken out-of-production (e.g. wildflower strips/areas), the positive effects of AES on biodiversity generally come at a cost of reduced yield or increased expenses for which farmers are being compensated financially (Jones et al., 2023). However, the

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https://doi.org/10.1016/j.jenvman.2024.120277
Received 31 July 2023; Received in revised form 20 December 2023; Accepted 1 February 2024
Available online 6 February 2024

enhancement of biodiversity of beneficial arthropods through AES could also positively affect crop production, i.e. ecological intensification (Bommarco et al., 2013; Campbell et al., 2017; Segre et al., 2020; Seppelt et al., 2020).

Positive effects of AES on arthropod richness and abundance in cropland dominate but with lower relative effectiveness in complex landscapes (Batáry et al., 2011). Intensively managed cropland may benefit from arthropod spillover from the surrounding landscape matrix (Marja et al., 2018). AES effectiveness can depend on how the outcome is measured, e.g. as species richness or abundance, and between functional groups (Marja et al., 2022). Moreover, AES effectiveness can be related to the ecological contrast between AES and control habitats (Scheper et al., 2013; Marja et al., 2019), as well as to whether AESs are implemented on productive or non-productive land (Batáry et al., 2015). However, the majority of previous studies about AES have taken into account only "one side of the coin" and studies that simultaneously examine effects on biodiversity and on crop yield are relatively rare (for instance, Katayama et al., 2019; Albrecht et al., 2020; Gong et al., 2022). Little is known therefore about whether benefits for biodiversity always trade-off against crop yield or whether AES implementation may also result in win-wins. Here we attempt to address this knowledge gap by doing a first synthesis across European cropland systems.

Generally, increasing land-use intensity leads to increases in productivity and losses of biodiversity, but additional factors (for instance production system) influence this trade-off (Beckmann et al., 2019). To date, studies that compared AES management with conventional management and that take into account both biodiversity and yield have focused on a small number of AES types (wildflower strips, hedges, and organic farming). For instance, Albrecht et al. (2020) showed that on average pollination services were not significantly enhanced in the crop next to wildflower fields and crop yield was not positively affected by wildflower strips. Katayama et al. (2019) compared biodiversity and yield in organic and conventional farming only in orchard and vineyard landscapes. Their study indicated that combined abundance and richness over the studied taxa were greater in organic fields (+51 % and +16 %, respectively), but the yield was lower at the same time (−18 %). Recently, a global scale meta-analysis by Gong et al. (2022) highlighted that organic farming supports higher biodiversity than conventional farming, but at the cost of lower crop yields. Organic farming generally had approximately 23 % gain in biodiversity with a similar decline in crop yield. However, none of these studies considered several AES effectiveness concurrently for arthropod diversity and yield.

Here we aim to quantify potential trade-offs between effects on biodiversity and crop yield associated with AES implementation and want to identify conditions that moderate this trade-off, such as arthropod functional groups, AES type or landscape composition. AES effectiveness can depend on arthropod functional groups being more effective for pollinators than natural enemies (Marja et al., 2022). It was also demonstrated earlier that their effectiveness depends on whether they are in-productive or out-of-productive AES (Batáry et al., 2015). We used landscape composition (simple vs. complex) as a moderator because of its influence on arthropods, as AESs are more effective in simple than complex landscapes (Batáry et al., 2011). We also considered studying arthropod taxonomic groups in more detail (spiders, bumblebees, carabids, etc.) or cereals vs. permanent crops, but did not carry out because of sample size limitation.

To facilitate comparisons, we express both biodiversity and yield effects in percentages relative to conventional management. We focus on the quantification of the magnitude of the potential trade-offs between biodiversity and yield because results of earlier case studies (Clough et al., 2005; Holzschuh et al., 2010) indicate that crop yield in AES fields are often (but not always) lower than in conventionally managed fields (hereafter controls) and arthropod diversity is generally higher in AES than in control fields. We selected arthropods since they include functionally important groups, such as pollinators or natural enemies of crop pests, that can play important roles in contributing directly to crop yield. We focused only on studies assessing European AES, which are an essential legal and political tool at the EU level to support biodiversity (Batáry et al., 2015). Organic farming in Europe is, in general, part of AES and therefore studies on organic farming were also included. We conducted a literature-based systematic review of evidence from studies, which concurrently collected data of biodiversity and yield responses in AES and control fields in European agricultural landscapes. We focused on the effectiveness of different in- and out-of-production AES on species richness and abundance (total number of individuals across all species), with the aim of identifying when trade-off and win-win situations occur.

2. Methods

2.1. Data collection and exclusion/inclusion criteria

We conducted a systematic literature search using the ISI Web of Science Core Collection and Elsevier Scopus databases between the years 1945–2021 (last search date: February 26, 2021). We used keyword combinations according to the PICO (Population, Intervention, Comparator and Outcome) search framework (Higgins and Green, 2008), which were linked with logical operators to include the maximum number of relevant studies covering the effect of AES on arthropod diversity. We did not include search terms for yield but checked each selected study for the inclusion of yield amount results. PICO: Population (arthropods); Intervention (European agri-environment schemes); Comparator (conventional management); Outcome (species richness, abundance). We used combinations of the following keywords for the literature search: TOPIC: (arthropod* OR insect* OR pollinat* OR beetle* OR carabid* OR spider* OR hoverfl* OR syrphid* OR "natural enem*" OR predator* OR parasitoid* OR bee OR butterfl* OR pest*) AND TOPIC: (agri-environment* OR organic OR integrated OR hedge* OR "field margin" OR "beetle bank" OR "flower strip") AND TOPIC: (richness OR diversity OR abundance OR density). We filtered out only English language studies. We used only the following Web of Science and Scopus categories for including studies: Agricultural and Biological Sciences, Agriculture Multidisciplinary, Biodiversity Conservation, Ecology, Environmental Sciences and Entomology. Our literature searches confirm the standard guidelines for a comprehensive literature review (Koricheva et al., 2013; Haddaway et al., 2018).

We combined the two searches of Web of Science (n = 1906) and Scopus (n = 2644) databases in Mendeley (2021) and removed duplicates. We found a total of 3434 potential studies. After screening these studies by title, we omitted studies that were clearly unrelated to our study topic. 258 studies remained, and after reading the abstracts, 64 studies remained for full-text filtering. Additionally, we re-checked previous meta-analyses (Beckmann et al., 2019; Katayama et al., 2019; Marja et al., 2019; Albrecht et al., 2020; Gong et al., 2022) with similar topics and contacted researchers to obtain unpublished datasets not reported in the study (Holzschuh et al., 2010; Fischer et al., 2011; Marja et al., 2014; Carrié et al., 2018; Boinot et al., 2020; Mei et al., 2021; Segre et al. unpublished; shared their unpublished datasets) to include all potential data. Performing additional search, including unpublished data, is necessary to reduce potential publication bias (Ahmed et al., 2012). The PRISMA flow diagram representing the detailed selection process (i.e. the number of studies identified, rejected and accepted) is presented in the supplementary material (Fig. S1).

We restricted our search to the 27 countries within the European Union, United Kingdom, Norway and Switzerland. The reason is that EU countries either share agri-environmental policies through the framework of the Common Agricultural Policy (CAP) of the European Union, United Kingdom was a member of the EU until recently, and Norway and Switzerland have developed AES similar to those in the EU (Nitsch and Osterburg., 2005; Kleijn et al., 2006; Batáry et al., 2015). In other European non-EU countries, North America and Australia, agri-environmental policies differ, complicating comparisons. We set up the following criteria for inclusion to filter out only European (EU27 + United Kingdom + Switzerland + Norway) AES arthropod studies, including a yield comparison between AES and control group. Inclusion criteria were: 1.) only European AES studies; 2.) only studies focusing on arthropod diversity (species richness or diversity index, abundance or density); 3.) only arable and horticultural crop systems (excluding grasslands) in which AES were implemented in or adjacent to local focal crop fields (or orchards, respectively) (including fruit, berry and vegetable crops in addition to arable crops); 4.) only studies in which mean, standard deviation (or standard error) and sample size are clearly reported or provided raw data; in case of non-production AES (hedgerow, flower strip), the inclusion of only those studies, which contained data directly next to the non-productive AES (i.e. the field itself). We excluded 1.) all grassland studies because yield is usually not measured or calculated differently. Additionally, we were also interested in insect-moderated yield benefits (pollination and pest control), which is more relevant in crops; 2.) studies with a number of replicates less than three in AES or in the control group; 3.) studies with single field experiments (blocks within fields or field margins), i.e. only taking studies replicated across multiple (≥3) fields at the landscape level, since AES management actions and landscape diversity effect are more relevant at this scale. In total, we found 26 studies with 125 data points for analysis (Table S1). Appendix S2 gives an overview of the included studies.

2.2. Classification of moderators

We used three moderators to test our hypotheses: arthropod functional group, landscape structure, and AES type (in- or out-of-production). We used the following procedures to classify the selected moderators.

As functional groups, we classified bees, bumblebees, butterflies, hoverflies, social bees, solitary bees and wild pollinators as pollinators, listed here as they were determined in the selected articles for the meta-analysis. We classified beetles, predatory ground beetles, rove beetles, carnivorous carabids, omnivorous carabids, spiders and wasps as natural enemies. We found one case of epigeal arthropods, which we treated as natural enemies in the statistical analysis. We classified leafhoppers, mealybugs and granivorous carabids as herbivores.

We used the original GIS dataset from the authors to determine study areas. If GIS data were unavailable, we identified the study areas based on their description in the study text (published coordinates) or from maps of study areas in original studies, similar to previous meta-analyses (Tuck et al., 2014; Marja et al., 2019). Tuck et al. (2014) method is universal to investigate landscape composition when study area sizes vary. The study areas of the synthesized primary studies were 3201 ± 94 km^2 (mean ± SEM). After identifying a study area, we placed five random 1000 m transects per study area to estimate representative landscape complexity (see below). Sets of three randomly generated numbers defined the positions of the five transects. First, we generated the random number between zero (central study area measuring point) and the radius of the study area, which denoted how many metres from the central point the starting point of each transect would be situated. Second, we randomly generated the angle degree defining the direction of the study area's central point for which the central point of the transect should be placed. With these two random numbers, we were able to define the transect location. Third, we randomly selected numbers between 0 and 360° to specify the angle at which the transect should be drawn, 500 m to each side of the central point. Transects were not allowed to intersect or be closer to each other than 2000 m to avoid pseudo-replication in the study regions, and their locations were controlled to represent only agricultural landscapes. I.e., we did not consider using the whole study areas for landscape composition determination because, in general, it also contains build-up areas, forests and water bodies. We collected landscape data in a buffer area of 1 km in each of the five random transects.

For landscape structure, we used the Coordination of Information on the Environment Land Cover databases from the years 2006–2018 (hereafter CORINE database, Büttner et al., 2004). Since case studies were from the last two decades, we used landscape structure information based on the CORINE version closest to the study year. The 17 categories starting with CORINE database codes three or four, indicating semi-natural habitats were used to calculate the proportion within 1000 m buffer area (Batáry et al., 2011). We classified landscape structure as simple or complex. We defined simple landscapes as having a proportional area of semi-natural habitats of less than 20 % and complex landscapes of more than 20 % (Tscharntke et al., 2005). We did not consider the classification of a cleared landscape (<1 %) since we did not find such studies.

Since AES effectiveness for biodiversity and yield can also depend on whether it is applied within or outside crop fields, we classified AES type as in-production and out-of-production (Batáry et al., 2015). AES targeting non-productive areas included hedgerows, wildflower strips or wildflower areas (out-of-production schemes). The only exception was Campbell et al., 2017, which we classified as an in-production scheme because wildflower stripes were established inside apple orchards. In contrast, in-production schemes supported environmentally sensitive approaches to the management of land that are used to grow crops, e.g. low-input and management extensification schemes. We classified organic farming and environmentally friendly management (Marja et al., 2014) as in-production schemes.

2.3. Effect size calculation

We used the log response ratio (lnRR) as a measure of effect size. We calculated effect sizes and their variances for all data points based on the mean, standard deviation and sample size of AES and control for arthropod diversity and yield separately. The effect size was positive if arthropod diversity or yield were higher in the AES than in control fields. To calculate the log response ratio, we obtained (from tables, graphs, text or raw data) the mean values, sample sizes and some variance measures of AES and control (SD, SEM or 95 % CI).

We used the following formulas for calculating the log response ratios of the biodiversity R_b and yield R_y (separate calculations, but based on the same treatment groups) between AES ($\overline{X}_T$) and control ($\overline{X}_C$).

The log response ratio of biodiversity of AES compared to control can be expressed as follows:

$$ln(RR_b) = \ln\left(\frac{\overline{X}_T}{\overline{X}_C}\right)$$

The log response ratio is biased when quantifying the outcome of studies with small sample sizes. This can yield erroneous variance estimates when the scale of study parameters is near zero. Therefore, we used corrections based on Lajeunesse's (2015) correction for effect size:

$$lnR^{\Delta} = ln(RR_b) + 0.5\left[\frac{(SD_T)^2}{N_T\,\overline{X}_T^{\,2}} - \frac{(SD_C)^2}{N_C\,\overline{X}_C^{\,2}}\right]$$

The variance of log response ratio:

$$SD_{pooled} = \sqrt{\frac{(N_T-1)SD_T^2 + (N_C-1)SD_C^2}{N_T + N_C - 2}}$$

$$Variance\ ln(RR_b) = \frac{SD_{pooled}^{\,2}}{N_T\,\overline{X}_T^2} + \frac{SD_{pooled}^{\,2}}{N_C\,\overline{X}_C^2}$$

Corrections for the variance for small sample size (based on Lajeunesse, 2015):

$$Variance\ lnRR^{\Delta} = Variance\ ln(RR_b) + 0.5\left[\frac{(SD_T)^4}{N_T^2\,\overline{X}_T^{\,4}} + \frac{(SD_C)^4}{N_C^2\,\overline{X}_C^{\,4}}\right]$$

For the interpretation of the results, we used percentage change based on Pustejovsky (2018), which can be expressed in terms of the log response ratio parameter as

$$\% \ change = 100 \ \% * [exp(lnRR) - 1]$$

where exp(lnRR) is the exponential function of log response ratio.

2.4. Statistical analysis

For performing the meta-analysis models, we used the "metafor" package (Viechtbauer, 2010) for R (R Core Team, 2023). We used hierarchical models with country and study ID as nesting factors (R syntax in all models: method = "REML", random = list(~1|country/study ID/dyad)), because some studies were carried out in the same countries, and individual studies sometimes included several taxa (for instance, butterflies and spiders). To account for the non-independence of multiple types of AES treatments with the same control (Borenstein et al., 2009), we included the dyad comparisons as a nesting factor (Table S1).

We ran two overall models without distinguishing species richness and abundance to study general effects (% of change) on diversity and yield (lnRR). In all other cases, we analysed species richness and abundance data separately to test the moderators' effect on the effect sizes. We fitted each case in different models with the following moderators: 1) arthropod functional group (pollinators, natural enemies, and herbivores), 2) AES production type (in-production or out-of-production AES), and 3) landscape diversity (simple or complex).

We checked for a potential publication bias using a rank correlation test for funnel plot asymmetry separately for biodiversity and yield effect sizes. The rank correlation test for funnel plot asymmetry indicated no publication bias in the biodiversity dataset (tau = 0.07, p = 0.27). Studies might contain several arthropod groups (for instance, butterflies and spiders), but the yield was always measured only once. Therefore, to avoid pseudo-replication in the yield dataset, we used yield only once for each study to estimate publication bias. The rank correlation test for funnel plot asymmetry indicated no publication bias in the yield subset dataset (tau = 0.13, p = 0.34).

We searched for outlier effect sizes in our dataset. Based on the method of Habeck and Schultz (2015), we evaluated the sensitivity of our analyses by comparing fitted models (biodiversity and yield separately) without effect sizes that we defined as influential outliers. We defined influential outliers as effect sizes with hat values (i.e. diagonal elements of the hat matrix) greater than two times the average hat value (i.e. influential) and standardised residual values exceeding three. We found no outliers in our datasets.

The studies, which fulfilled our search criteria, were carried out in the following countries: Estonia, France, Germany, the Netherlands, Sweden, Switzerland, and United Kingdom indicating a strong geographical bias in the dataset. Approximately half of them were from Germany (53 %). The map of geographical coverage is presented in the supplementary material (Fig. S2).

3. Results

3.1. Arthropod diversity vs. yield effect sizes

The overall model showed that AES significantly increased arthropod diversity (lnRR = 0.27, Q = 384.6, $p < 0.001$, 31 % percentage of change) but significantly reduced yield (lnRR = −0.23, Q = 5129.0, $p < 0.001$, −21 % percentage of change) compared to the control group based on the models without moderators (without distinguishing species richness and abundance, Fig. 1). The trade-off (increased biodiversity and decreased yield) occurred in the majority of the cases for data points of species richness (33.6 %) and for abundance (32.8 %), Figs. 1 and 2 and Fig. S3). Lose-lose situations, where arthropod biodiversity, as well as, yields had lower values in AES than in the control group, were rare (4.8 % cases of species richness and 8.8 % of abundance). There were

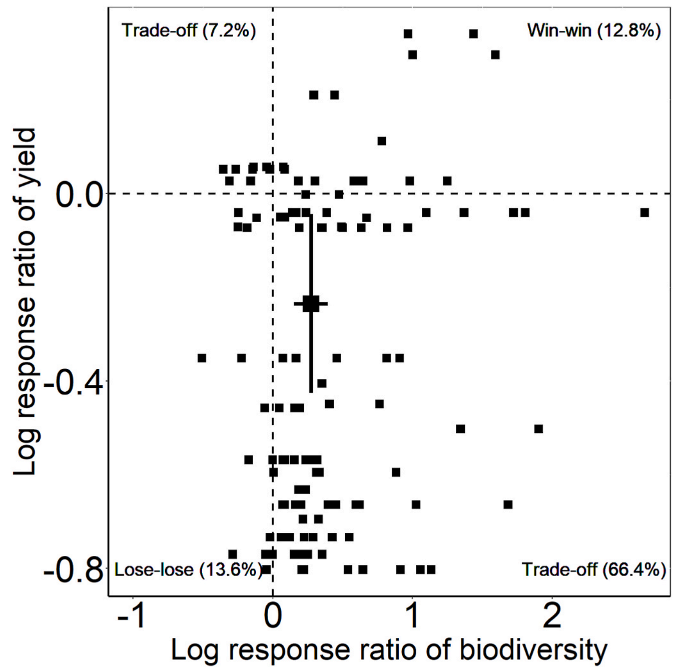

Fig. 1. Scatter plot of log response ratio between biodiversity (pooled species richness and abundance data) and yield in agri-environment scheme vs. control fields on croplands showing mean effect sizes with 95 % CIs. Effects are significant if the CI lines do not cross zero lines. The points represent raw data values. % indicates the percentage of the dataset. The percentages in the plot indicate the proportions of effect size combinations in the four scenarios.

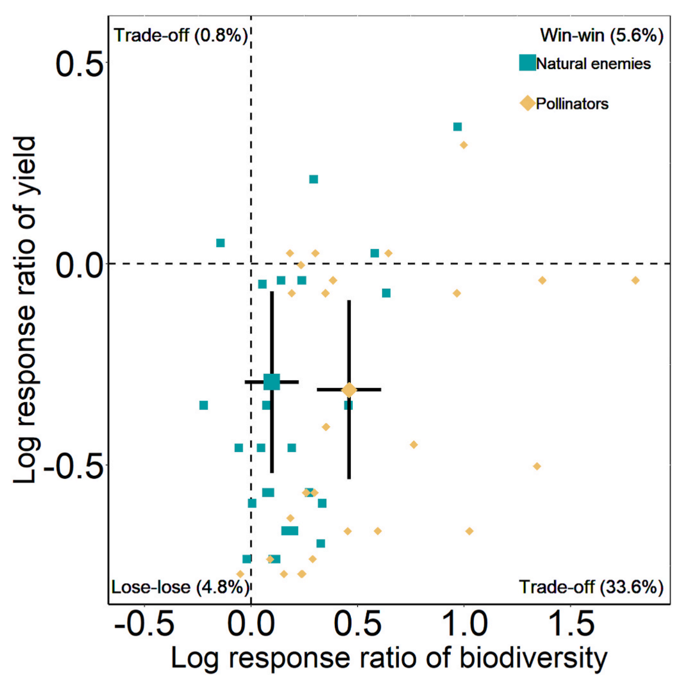

Fig. 2. Scatter plot of log response ratio between biodiversity and yield in agri-environment scheme vs control fields on croplands. Presented are species richness mean effect size by functional groups (natural enemies and pollinators) with 95 % CIs. Effects are significant if the CI lines do not cross zero lines. The points represent raw data values based on the studied functional groups. % indicates the percentage of the dataset (for abundance, see Fig. S3). The percentages in the plot indicate the proportions of effect size combinations in the four scenarios.

also cases when, both arthropods and yields showed higher values in AES than in the control group, resulting in a win-win situation (5.6 % cases of species richness and 7.2 % of abundance). Finally, we also found some cases of the other trade-off, when arthropod biodiversity had lower values in AES than in control but, at the same time, there were higher values of yield in AES than in the control group (0.8 % cases of species richness and 6.4 % of abundance).

3.2. Effects of moderators

3.2.1. Functional group

The functional group was a significant moderator for species richness and abundance. We found significant differences in effect size values of arthropod functional groups for species richness (Table 1, Fig. 2). The species richness of pollinators was significantly higher (58 % increase) in AES than in control fields, whereas the difference in the species richness of natural enemies was non-significant (10 % increase) between management types. However, crop yield was significantly lower in AES than in control fields for both functional groups (pollinators 26 % decrease, and natural enemies 25 % decrease).

The abundance of natural enemies (23 % increase) and pollinators (64 % increase) was significantly higher in AES compared to control fields. In these cases, again, the yield was lower in the AES fields than in the controls (21 % and 22 % decrease, respectively, Table S2, Fig. S3). The abundance of herbivores and yield were not significantly different between AES and control fields (2 % increase, 19 % decrease, Table S2, Fig. S3).

3.2.2. Production type

The production type was an important moderator for species richness (Table 1) and abundance (Table S2). Both arthropod species richness and abundance were significantly higher in in-production (29 % and 32 % increase, respectively) as well as in out-of-production (30 % and 47 % increase, respectively) AES fields than in control fields (Fig. 3 and Fig. S4). However, the yield was significantly lower in in-production (28 % decrease for species richness and 25 % decrease for abundance) AES compared to control fields, but there was no significant difference in crop yield next to the out-of-production (14 % decrease for species richness and 11 % for abundance) AES (the established wildflower strips and hedges) and the crop yield in the control fields (Fig. 3 and Fig. S4).

3.2.3. Landscape type

Landscape structure was a significant moderator for species richness (Table 1) and abundance (Table S2). In simple landscapes arthropod species richness and abundance were significantly higher in AES (29 % and 35 % increase, respectively) than in the control fields, but the yield was significantly lower (36 % and 33 % decrease, Fig. 4 and Fig. S5). The arthropod species richness, abundance (32 % and 39 % increase, respectively), and yield did not significantly differ between AES and control fields in complex landscapes (5 % and 3 % increase, respectively).

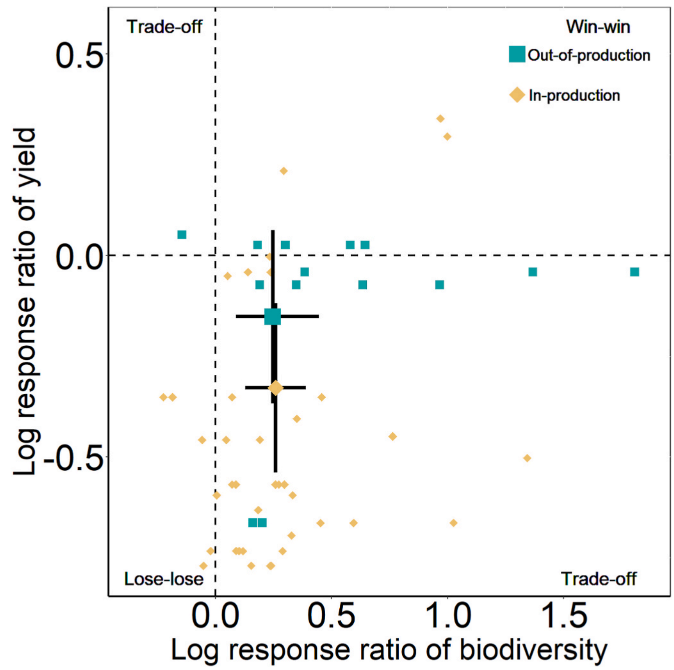

Fig. 3. Scatter plot of log response ratio between biodiversity and yield in agri-environment scheme vs control fields on croplands. Presented are species richness mean effect size by production type (out-of-production and in-production) with 95 % CIs. Effects are significant if the CI lines do not cross zero lines. The points represent raw data values based on the studied production types.

4. Discussion

Our overall model results show that, in general, AES significantly support arthropod diversity (31 % increase) on croplands (Fig. 1). In contrast, at the expense of yield (21 % decrease) in AES compared to control fields indicating the expected trade-off between biodiversity conservation and agricultural production. In the following, we will discuss the effects of AES on functional arthropod groups, the impact of production type and of landscape complexity and, finally, we will try to characterize shortly the win-win situations in which both, biodiversity and yield, benefit from AES.

4.1. Functional group

We found that AES significantly supported pollinator species richness (58 % increase), whereas the AES effect for natural enemies was non-significant (Fig. 2). One possible explanation the difference between the two groups might be related to arthropods' mobility. Pollinators such as bumblebees, other wild bees, and butterflies are generally more mobile taxa than the mostly ground-dwelling natural enemies (such as spiders or beetles) that were investigated. A similar pattern was found recently by Marja et al. (2022), where the authors showed that

Table 1
Summary table of species richness and yield meta-analyses showing tests of moderator, residual heterogeneities and models AICc. Analysis shows moderator (functional group, production or landscape type) between group (level) heterogeneities. Moderator is significant if at least one group (level) confidence intervals do not cross the zero line on the figures.

Model	Moderators	*Arthropods*				*Yield*		
		d.f.	Q	p	AICc	Q	p	AICc
Functional group	Residuals	53	148.4	<0.001	31.2	2398.7	<0.001	436.0
	Moderators	2	36.5	<0.001		7.7	0.02	
Production type	Residuals	54	192.3	<0.001	45.5	1229.6	<0.001	396.6
	Moderators	2	16.2	<0.001		47.9	<0.001	
Landscape type	Residuals	54	191.5	<0.001	45.7	2345.9	<0.001	429.0
	Moderators	2	15.6	<0.001		59.7	<0.001	

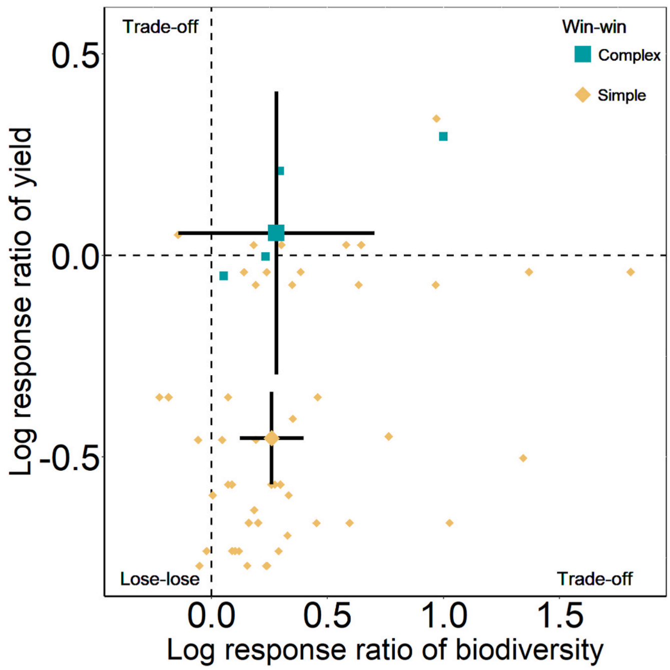

Fig. 4. Scatter plot of log response ratio between biodiversity and yield in agri-environment scheme vs control fields on croplands. Presented are species richness mean effect size by landscape structure types (complex, simple) with 95 % CIS. Effects are significant if the CI lines do not cross zero lines. The points represent raw data values based on the landscape structure types.

AESs were more effective in promoting aerial-than ground-dwelling arthropods. Other flying natural enemies, such as parasitoids, might also benefit similarly but were not tested in the studies we analysed.

Another explanation is that many of the studied AES focused on floral enhancement habitats intended to promote pollinators and other flower-visiting insects, which do not necessarily benefit ground-dwelling natural enemies (Scheper et al., 2021). For example, Mei et al. (2021) showed in a Dutch case study that wildflower strips did not directly affect ground-dwelling natural enemies or crop yield. However, the richness and availability of flowers across the wildflower strips and control margins were positively related to the abundance of the pooled arthropod number of examined natural enemies (carabid beetles and spiders). Hence, the flower richness and cover of the wildflower strips are essential factors for arthropod diversity (e.g., Albrecht et al., 2020) and may influence the crop yield indirectly (see also Tschumi et al., 2016a,b). Balzan and Moonen (2014) showed that arthropod functional diversity is important for controlling different pests.

4.2. Production type

In relation to the production type, our results show that species richness and abundance effect sizes were significantly higher in both in- and out-of-production AES (approx. 30 % increase) than in control fields (Fig. 3). The yield effect size was significantly lower in in-production AES than in control fields. It was not significantly different in out-of-production AES than in control fields, albeit with a negative trend. Also, we have to emphasise that we could not take into account the yield loss due to land opportunity cost i.e., the yield foregone on the productive land used for establishing grassy field margins, wildflower strips/areas, or hedgerows (all of them out-of-production AES in our study) (see Pywell et al., 2015; Batáry and Tscharntke, 2022). The yield effects in our study in out-of-production AES are therefore an underestimation of approximately 5 % of the true yield effect as recently estimated by Batáry and Tscharntke (2022). 5 % also corresponds to the minimum area criterion of greening measures in the Common Agricultural Policy (Zinngrebe et al., 2017). Additionally, out-of-production AES are often implemented on less productive land, minimizing opportunity costs even more (see Pywell et al., 2015; Segre et al., 2019, 2022). However, we would like to emphasise that from an economic perspective, for both production types, yield losses due to AES are compensated via AES payments.

Out-of-production AES, such as grassy field margins, hedgerows, field edges, wildflower strips, may be established to enhance biodiversity status *per se* or to promote ecosystem services. They help increase plant species diversity and create favourable conditions for pollinators and natural enemies. However, farmers are often reluctant to accept these AES due to concerns of negative effects on crop yield, for instance, because of spillover of pests or weeds to crops (Kleijn et al., 2019; Albrecht et al., 2020). Findings by Albrecht et al. (2020) did not confirm such concerns since the authors found a generally positive effect of flower strips on pest control services and no negative impact on yields. We show such conditions are possible, although restricted to only relatively few case studies included to this meta-analysis (win-win quadrat in the figures). Hence, a better understanding of the underlying mechanisms is needed to improve schemes towards such win situations for biodiversity with minimal yield losses or even win-win situations in the future.

4.3. Landscape type

Our results show that landscape structure significantly moderated the effect of AES on arthropod diversity. In simple landscapes, arthropod species richness and abundance were significantly higher (29 % and 35 % increase) in AES than in control fields, but yield was at the same time significantly lower (36 % and 33 % decrease). This shows the trade-off between biodiversity win and yield loss. In contrast, in complex landscapes, yield did not significantly differ between AES and control fields, but neither did arthropod richness nor abundance. However, our sample size was limited in the case of complex landscapes. Batáry et al., 2017 found a similar pattern when comparing simple landscapes of former East and West Germany, but with different landscape configurations, i.e. with fields that were a magnitude of order smaller in the latter. They found that biodiversity was higher in organic (part of AES) than in control fields, but yield was 100 % higher in control than in organic fields in both regions. However, the AES did not lead to a loss in profit owning to the premium prices for organic products. In more complex landscapes, high proportions of semi-natural areas may maintain pollinators, natural enemies and associated ecosystem services, which could help to close the yield gap between AES and control (Tscharntke et al., 2021). Our results support this hypothesis, but our sample size was relatively low. On the contrary, Boetzl et al. (2020) showed that edge effects can significantly reduce yields, especially in small fields. Also, Delphia et al. (2022) found that even in diverse farming systems, including wildflower strips promoting a high diversity of bees, some crops still do not necessarily receive optimal pollination services, regardless if they are at a short distance from the wildflower strips. Thus, more research is needed to better understand the complex interplay of AES and landscape structure affecting both yields and biodiversity.

4.4. The win-win situations

The study results, in general, support our hypothesis that yield in AES fields is often lower than in control fields, and in contrast, arthropod diversity is generally higher in AES than in control fields. However, we also found a few biodiversity and yield win-win situations, where the AES management substantially increased biodiversity and did not reduce yield compared to control fields. Interestingly, two of these studies were done in apple orchards examining the effects of planting wildflower strips (Campbell et al., 2017) or organic farming (Porcel et al., 2018) on beneficial insects and yield. Because permanent cropping systems, such as fruit orchards, vineyards and olive groves have a relatively high proportion of undisturbed surface area that can be used to enhance biodiversity without directly impacting the crop plants, it may be easier to achieve win-wins for biodiversity and yield here than in annual cropping systems.

4.5. Conclusions

Our meta-analysis highlights the overall substantial positive effects of AES on arthropod biodiversity and abundance. Pollinators were generally more enhanced than natural enemies. However, it also indicates that AES and control fields often have a trade-off between biodiversity and yield for both arthropod abundance and species richness on cropland in Europe. Our analyses enable identifying AES showing benefits for arthropod biodiversity with negligible or relatively low costs with respect to yield losses. Although our study also identifies win-win situations and biodiversity win situations with only negligible associated yield loss, their proportion was relatively low, highlighting the need for a better understanding of the factors contributing to effective biodiversity promotion while minimizing trade-offs with yield (despite yield losses being financially compensated through AES payments). Future studies should also consider yield quality, revenue or profit between AES and conventional agriculture, as yield quantity might not be the sole best indicator for producers. Our findings of generally significantly enhanced arthropod biodiversity underpin the important role of AES as an important legal instrument to promote farmland biodiversity in Europe. However, the results are geographically biased because they originate mainly from Western and Central Europe, especially Germany. This does not allow extrapolation of the findings throughout the EU because yield, but also biodiversity, are also dependent on the South-North climate gradient, which is lower in Northern Europe. Still, future optimization of the efficiency of AES should identify factors that maximise biodiversity gains at the minimal land opportunity and yield costs/losses. Harnessing ecosystem services through enhanced biodiversity of functionally essential organisms might contribute to this goal or even result in a win-win in certain producing situations. Additionally, a number of studies (Chen et al., 2021; Tamburini et al., 2020; Beillouin et al., 2021) have indicated that crop diversification seems a promising avenue to avoid the typical trade-off between biodiversity and yield.

CRediT authorship contribution statement

Riho Marja: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Methodology. **Matthias Albrecht:** Writing – original draft, Writing – review & editing. **Felix Herzog:** Writing – original draft, Writing – review & editing. **Erik Öckinger:** Writing – original draft, Writing – review & editing. **Hila Segre:** Writing – original draft, Writing – review & editing. **David Kleijn:** Conceptualization, Writing – original draft, Writing – review & editing. **Péter Batáry:** Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

Data availability

Summary information for each data point included in our meta-analyses will be added to the Zenodo platform after manuscript acceptance and is presented also in Supplementary material Table S1.

Acknowledgements

We want to thank Sébastien Boinot, Romain Carrié, Christina Fischer, Arjen de Groot, Andrea Holzschuh, and Jeroen Scheper, who shared their yield data. This study has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 862480 (the SHOWCASE project), RM work was partially financed by Maria Skłodowska-Curie individual fellowship grant "Happybee" No 101027920 and PB was supported by the Hungarian National Research, Development and Innovation Office (NKFIH KKP 133839). We are thankful for the editor and for two anonymous reviewers for very valuable comments on an earlier version of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.120277.

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