Does sustainable agriculture promote biodiversity and yield? A second-order meta-analysis.

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Abstract

Among the biggest challenges of modern society are biodiversity conservation and food security. Food security requires the increase of agricultural yields, though land use intensification is one of the main drivers of biodiversity loss. Environmentally friendly farming practices, such as organic farming, have positive effects on biodiversity, but are accompanied by yield losses. Other practices, such as diversification, result in a simultaneous increase of biodiversity and yield. In this study, we quantitatively synthesize the results of multiple meta-analyses, to identify the impact of sustainable farming practices on the biodiversity-food nexus. Our results show that sustainable farming practices have a positive effect on biodiversity without compromising productivity. Notably, when we pooled all meta-analytic means, biodiversity and yield gains were significantly correlated. In conclusion, sustainable farming practices have a positive effect on both biodiversity without significant yield losses.

Introduction

Land use intensification is considered one of the main drivers of biodiversity loss[1–3], as it causes habitat loss, grassland degradation, reduction of landscape heterogeneity and environmental pollution. Fertilizer applications can alter soil composition and nutrient cycling, pesticides have detrimental impacts on non-target species, often disrupting food webs and lead to reduction of plant diversity, while intensive tillage disturbs the soil environment. A global meta-analysis on the effects of intensification on biodiversity and yield estimated that, on average, conventional intensification leads to a 20% increase in agricultural or silvicultural yields, but a 9% decrease in species richness[4]. In addition, high management intensity is associated with lower plant diversity[5] and reduced ecosystem functions[6]. Multiple studies have highlighted the need for a more sustainable agriculture that ensures food security and hinders biodiversity loss[3,7–10].

The Target 2 of the Sustainable Development Goals (SDG) is to ensure food security, support smaller farms and achieve sustainable agriculture, while maintaining biodiversity by 2030 (Goal 2: Zero Hunger. *United Nations*, 2015). However, the adoption of sustainable practices is impeded by the agro-chemical industry lobby, armed conflicts, climate change, populism and other socio-political and economic factors[11,12]. One of the main challenges for the adoption of sustainable farming practices is ensuring high productivity[13], since sustainable practices are commonly associated with lower yields. To tackle this issue, ecological intensification has been proposed as the pathway to sustainable food security[14]. Ecological intensification is the process of optimizing ecosystem services to either supplement or replacing human-made inputs (e.g. pesticides, fertilizers), with the goal of sustaining or boosting agricultural productivity[14,15].

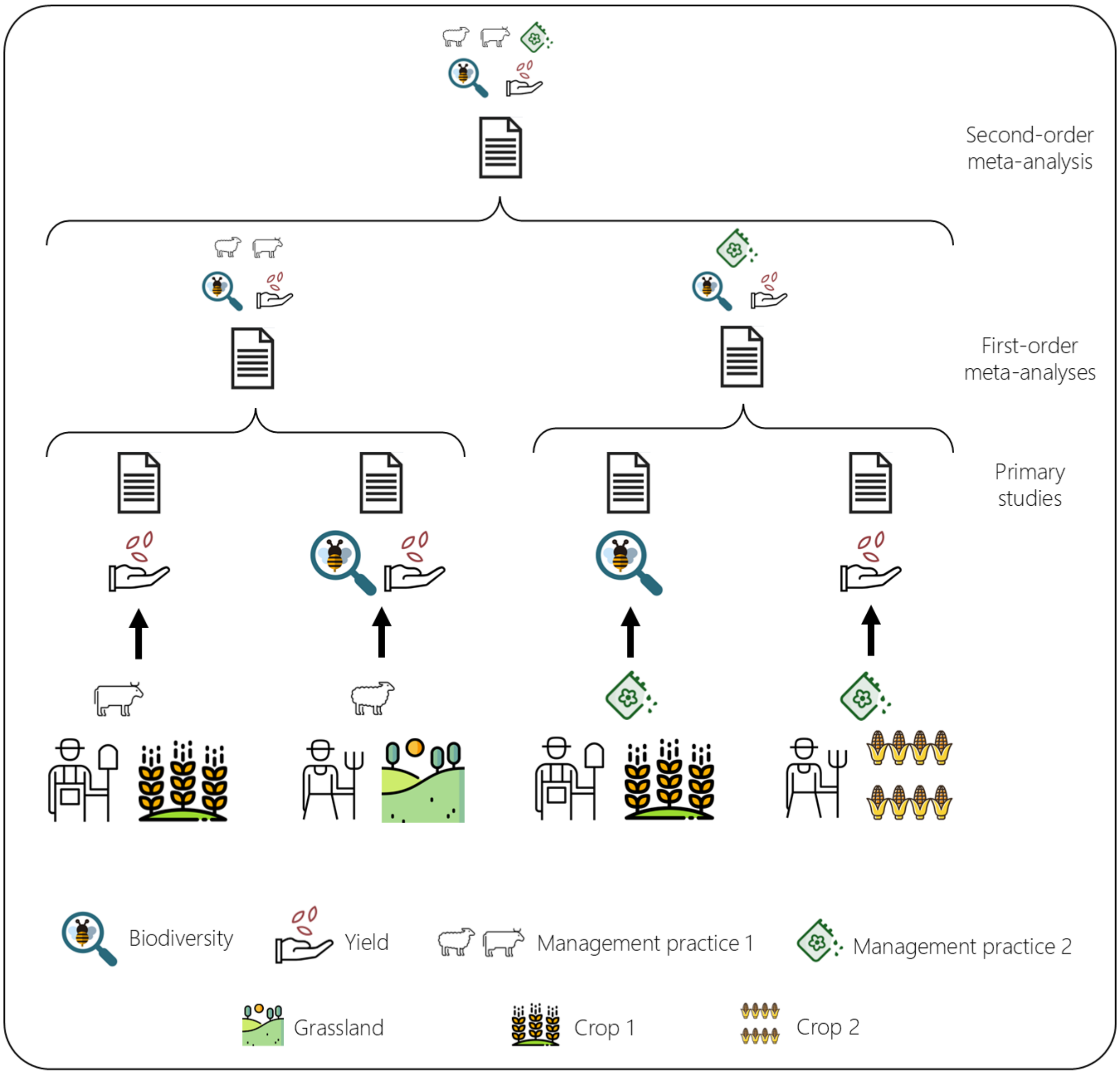
The adoption of sustainable farming practices can lead to three possible cases for biodiversity and yield outcomes: win-win (biodiversity and yield increase), trade-offs (one increases and the other one decreases) or lose-lose (biodiversity and yield decrease). At a global scale, agricultural diversification, for example, is benefitting biodiversity, without compromising yield[16], but in tropical and sub-tropical regions, it is more likely to result in trade-offs[17]. Agri-environment schemes (AES) lead, in general, to an increase of insect diversity but a reduction of yield, whereas the presence of flower strips in orchards has been shown to favour both insect diversity and yield[18]. Lose-lose outcomes (also known as intensification traps) are observed mostly in conventional intensification scenarios, when they are implemented in natural communities[4,19]. In grasslands, spatially optimized management can lead to win-win outcomes for insect diversity and biomass[20], emphasizing the high potential of grasslands in multifunctional landscapes[21]. Grasslands have high economic value[22], as they contribute to global productivity (i.e., feed), and they are fundamental for biodiversity conservation[23]. The outcome, however, is not uniform across systems, biogeographic regions, crop types and taxonomic groups.

In order to reach generalizable conclusions, by surpassing the high heterogeneity between studies, multiple meta-analyses have synthesized the results of observational and experimental field studies on the impact of sustainable farming practices on both crop production and biodiversity[4,17,24]. However, these first order meta-analyses have examined the impact of either single management practices[25,26] or focus on specific crop systems, such as vineyards[27,28].

The goal of this study is to systematically analyse the impact of sustainable management practices on the biodiversity-food nexus and summarize the relevant meta-analytic evidence. The synthesis of meta-analyses is important to inform policy because it integrates a larger body of evidence[29]. Second-order meta-analysis is a method that combines the outcomes of multiple first order meta-analyses using statistical models, while accounting for variation among them[30]. This method has been adopted only recently in the field of Ecology, as a result of the increasing number of first-order meta-analyses published in the last decade and the need for higher level of evidence synthesis. In the present study, second-order meta-analyses allowed for a nuanced understanding of how different management practices influence both biodiversity and productivity across various ecosystems. In this paper, we examine the following research questions:

1) What is the impact of sustainable farming practices on both biodiversity and yield?
2) Which management practices lead to win-win scenarios for biodiversity and yield?
3) Which taxa and crop systems are benefited the most by specific agricultural management practices?

We conducted a systematic review to identify meta-analyses focusing on both biodiversity and agricultural production as response variables, following specific inclusion criteria outlined in Takola et al. (2023)[31]. The study material consists of studies which examined management effects on croplands, grasslands, and agroforestry systems. We conducted a second-order meta-analysis, combining multiple first-order meta-analyses to quantify the effects of various agricultural practices on biodiversity and yield (Fig. 1). We extracted overall meta-analytic means and subgroup estimates, enabling us to perform meta-regressions with moderators and analyze subgroups. We provide a comprehensive overview of the body of literature that examines the interplay of biodiversity and yield in productive ecosystems and quantify the impact of sustainable agricultural practices.

118 

119 ***Figure 1****. The study framework of the present paper; from farm to our second-order meta-analysis.*

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Results

Our systematic review yielded 27 meta-analyses. From these, we used 22 for the second-order meta-analysis (ca. 2,000 primary studies), which provided 41 pairs of overall means for biodiversity and yield. We also extracted subgroup estimates for taxonomic groups and crop systems, from 21 meta-analyses. The subgroup datasets contained 298 estimates for biodiversity and 51 for yield. All data are available online (here).

Trade-off analysis

In order to examine the relationship of biodiversity and yield within the context of sustainable farming, we plotted all the meta-analytic means in a scenario space (Fig. 2).

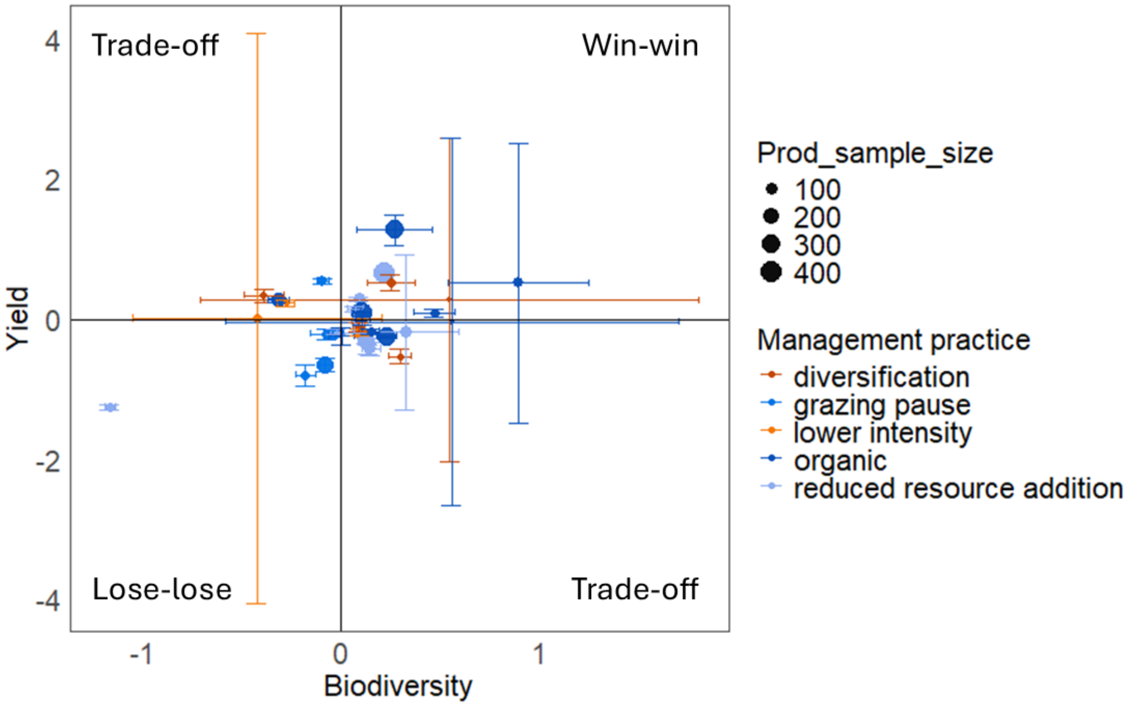

Figure 2*. Cartesian plane showing a scenario space. The top-right quadrant includes the win-win cases, bottom-left quadrant includes the lose-lose cases and the remaining two are showing trade-offs. Points represent the overall meta-analytic means for biodiversity and yields, as reported in each meta-analysis (n = 22). Horizontal and vertical error bars represent the 95% C.I. for biodiversity and yield respectively. Colours represent management practices. Points are scaled based on the number of primary studies that was used for each meta-analytic mean.*

We found that, based on 22 meta-analyses, the effect of sustainable farming on biodiversity is positively correlated to the effect of sustainable farming on yield (slope = 0.55, SE_{slope} = 0.216, p = 0.015). Though, when fitting a linear regression for each management practice separately, some relationships were negative (Fig. 3).

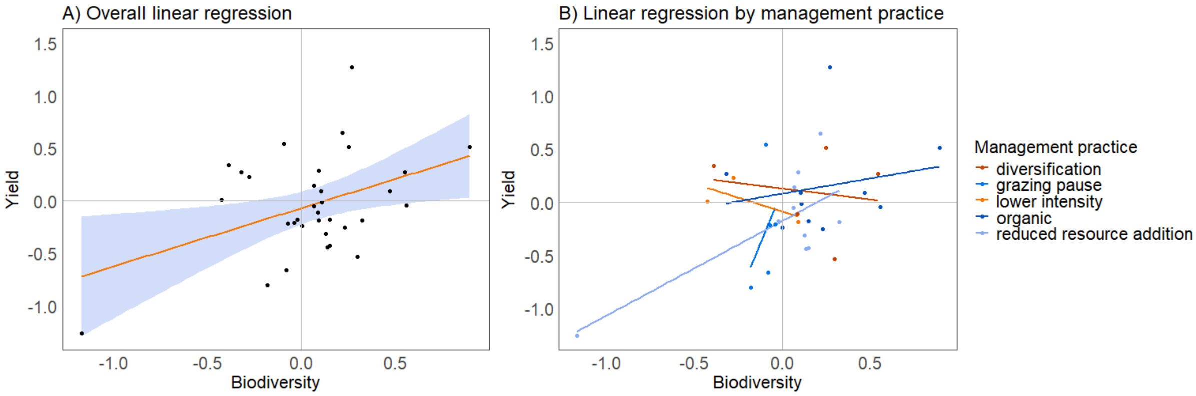

Figure 3*. A) Overall linear regression and B) Linear regression by management practice of the log response ratios (LRR) for yield and biodiversity, as reported in 22 meta-analyses included in our study.*

Win-win scenarios for biodiversity and yield

We examined separately the meta-analyses that reported positive values for both biodiversity and yield (Table 1). In total, these were 11 meta-analyses which contributed 14 effect sizes to our dataset. From these, 13 effect sizes were used in the second-order meta-analysis, because they were reported as log-response ratio (LRR) or some other metric that we could convert to log-response ratio (Table S1). Two meta-analyses were focusing on invertebrates, one was focusing on plants and one was focusing on animals. Ten meta-analyses were focusing on various species groups. Regarding the metrics of biodiversity, one meta-analysis was reporting abundance, one was focusing on biocontrol species, one was not reporting the metric that was used and eight meta-analyses were reporting species richness. Regarding the metrics of productivity, five meta-analyses were reporting crop yields, another five meta-analyses were reporting biomass, and one meta-analysis was reporting productivity. Six meta-analyses were using primary studies with paired control and treatment measurements of biodiversity or yield and five meta-analyses were using unpaired measurements. Five meta-analyses were including non-paired measurements of biodiversity and yield (i.e. measured in the same location), while six meta-analyses were included paired measurements of biodiversity and yield or a mix of paired and non-paired. Two meta-analyses were examining below-ground biodiversity, eight meta-analyses were examining above-ground biodiversity and one meta-analysis both. One meta-analysis was focusing on grapes, one on cocoa plantations, one on herbs, three on various crops and four were referring to grasslands.

Crop type	Reference	Win-win scenario	Sample size
Meadow, forest, grassland	Ma *et al.* (2020)	Reduced resource addition (nitrogen, phosphorus and both) leads to an increase of Shannon's Index of arbuscular mycorrhizal fungi (AMF) and the biomass of above-ground plants in alpine meadows, forests and grasslands.	Biodiversity: 127 Yield: 100
Agroforestry	Neither *et al.* (2020)	When compared to cocoa monoculture, cocoa agroforestry schemes have more animal species richness and higher yields.	Biodiversity: 5 Yield: 8
Agroforestry	Winter *et al.* (2018)	Organic farming increases all species richness (plants, insects and birds) and yields in vineyards.	Biodiversity: 24 Yield: 45
Cropland	Bai *et al.* (2018)	When compared to monocultures, crop rotations result to higher abundance of earthworms and higher yields.	Biodiversity: 2 Yield: 14
Cropland	Iverson *et al.* (2014)	Biocontrol invertebrate species and crop yields are higher in crop rotation schemes, than in monocultures.	Biodiversity: 54 Yield: 39
Cropland	Bai *et al.* (2018)	When adding organic matter to crops, the abundance of earthworms and the crop's yield are higher.	Biodiversity: 6 Yield: 54
Cropland	Shu *et al.* (2022)	Microbial species richness and crop yield are increasing when using organic fertilizer instead of mineral fertilizer in agricultural crops.	Biodiversity: 484 Yield: 379
Grassland	Guldemond *et al.* (2017)	When elephants are removed (through fences) from grasslands, there is an increase of plant and animal species richness diversity and an increase of herb and tree abundance.	Biodiversity: 18 Yield: 132
Grassland	Su *et al.* (2022)	Reduced resource addition increases species richness and biomass of plants in grasslands.	Biodiversity: 12 Yield:35
Grassland	Ploughe *et al.* (2020)	The addition of biosolids increases plant species richness and productivity in grasslands.	Biodiversity: 159 Yield: 269
Grassland	Wang *et al.* (2020)	Reduced resource addition (nitrogen, phosphorus and both) leads to an increase of plant species richness and the above-ground biomass in grasslands.	Biodiversity: 133 Yield: 412

Table 1*. Win-win scenarios in the database identified in the current study.*

Second-order meta-analysis

Overall estimates on the impact of sustainable management on biodiversity and yield

The random effects model of the second order meta-analysis showed that sustainable farming has an overall positive effect on biodiversity but neutral on yield (Table S2, Fig. 4). Meta-analyses examining reduced resource addition, organic farming and grazing pause showed positive relationships between biodiversity and yield, while lower land use intensity and diversification showed a negative relationship (Figure 3).

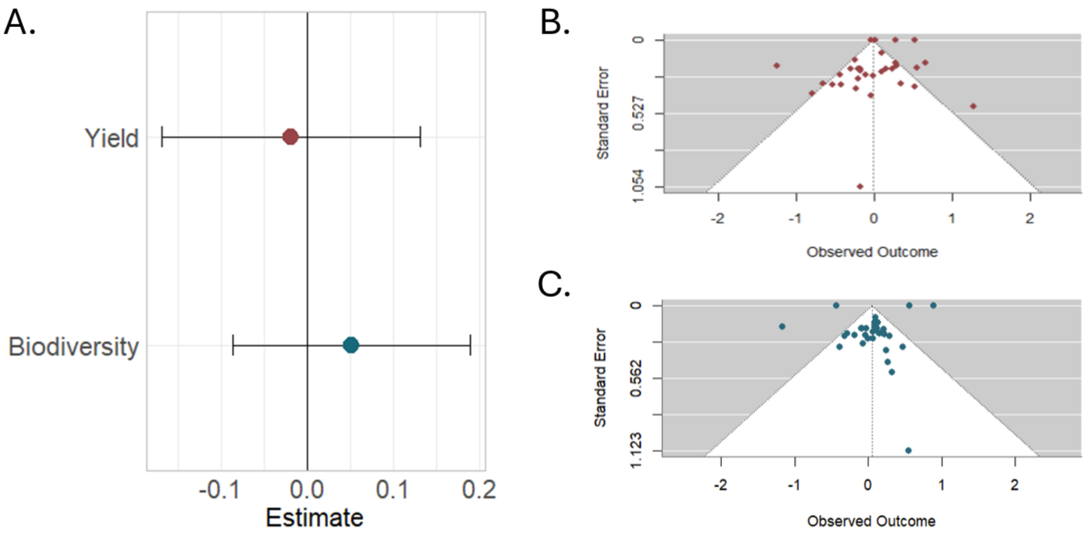

Figure 4. *(A) Overall means of random effects models for biodiversity and yield, (B) Funnel plot for biodiversity means of first-order meta-analyses, (C) Funnel plot for yield means of first-order meta-analyses.*

Meta-regressions to examine the impact of different management practices

To examine the effect of sustainable management on biodiversity and yield, we performed meta-regressions using management practices as a moderator. Overall, diversification and organic farming lead to win-win outcomes for biodiversity and yield, while grazing pause, lower intensity and reduced resource addition have moderately negative effects on the two response variables (Table 2). However, none of the aforementioned estimates was significant.

Response variable	Moderator	Estimate	CI low	CI up
Biodiversity	Diversification	0.13	-0.33	0.59
	Grazing pause	-0.09	-0.50	0.34
	Lower intensity	-0.29	-0.80	-0.22
	Organic	0.23	-0.09	0.55
	Reduced resource addition	-0.06	-0.35	0.22
Yield	Diversification	0.56	-11.23	12.42
	Grazing pause	-21.61	-42.1	-1.12
	Lower intensity	-1.72	-13.6	10.15
	Organic	0.56	-11.23	12.35
	Reduced resource addition	0.23	-17.66	18.13

***Table 2**. Moderator estimates of each management practice on the overall meta-analytic estimates biodiversity and yield.*

We fitted a meta-regression with yield as a response variable and biodiversity as a moderator. The moderator estimate was positive and statistically significant (estimate = 0.42, 95% C.I.: [0.11, 0.72], SE = 0.16, z-value = 2.66, p-value = 0.008).

Overall, diversified farming had positive effects on the diversity of all taxa but this was not the case for crop systems (Table S3, S4). However, the meta-analytic models that we fitted for each taxonomic group showed positive meta-analytic means for all taxa (Table 2). Regarding crop types, the meta-analytic means were positive for productivity of agroforestry schemes, but negative for croplands and grasslands. Reduced resource addition had either a positive or neutral effect on all taxa and crop systems, while lower management intensity, similarly to grazing pause, had a negative or neutral effect on biodiversity and yield (Fig. 5).

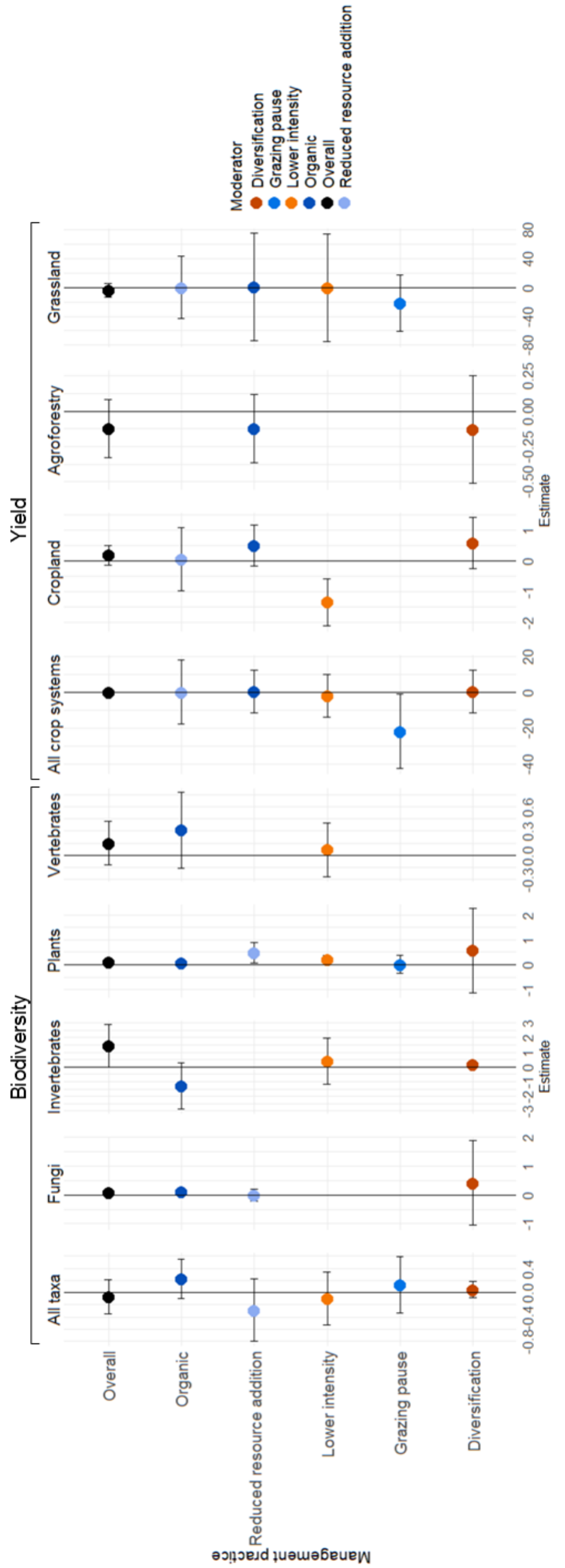

***Figure 5**. Moderator estimates of different management practices for meta-regression models per taxon and crop system subgroup. The category Overall refers to the estimates of the random-only second order meta-analytic models*

Subgroup analysis; taxa and crop systems

The overall meta-analytic means for each subgroup of taxonomic groups and crop systems showed that overall, sustainable farming practices are associated with increased biodiversity and decreased yields in croplands and grasslands, but increased yield in agroforestry schemes (Table 3).

Response variable	Subgroup	Estimate	CI low	CI up	Prediction Interval low	Prediction Interval up
Biodiversity	Invertebrates	0.16	-0.005	0.33	-0.005	0.33
	Plants	0.11	0.02	0.19	0.02	0.19
	Fungi	0.09	0.01	0.16	0.01	0.16
	Vertebrates	0.15	-0.12	0.42	-0.12	0.42
Yield	Cropland	0.19	-0.13	0.51	-1.03	1.41
	Agroforestry	-0.12	-0.33	0.08	-0.33	0.08
	Grassland	-3.87	-13.10	5.36	-46.18	38.44

Table 3*. Meta-analytic means of random-only effect models for all subgroups of taxa and crop systems.*

Interestingly, we observed different patterns when separating the data into above- and below-ground biodiversity and productivity. Some studies did not distinguish between the two groups, so they were excluded. Above-ground effect sizes show significantly higher heterogeneity (based on the Q-test), while below-ground effect sizes have wide confidence intervals (Fig. 6).

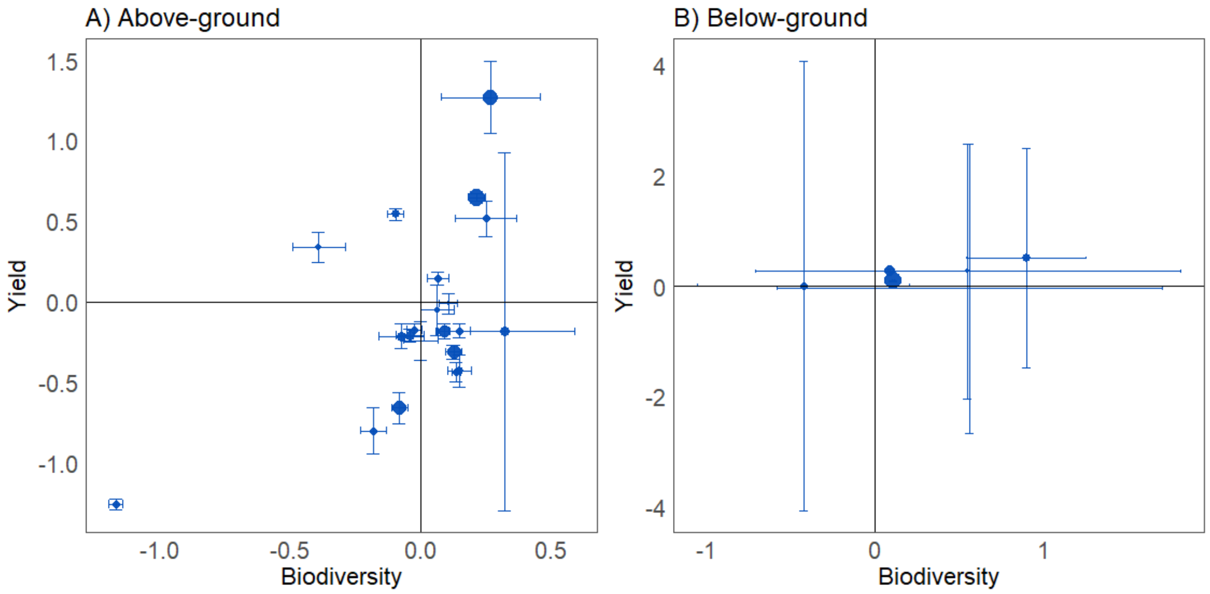

Figure 6. *Visualization of effect sizes referring to (A) Above-ground and (B) Below-ground biodiversity and productivity.*

Discussion

We conducted a systematic review and a second-order meta-analysis of ca. 2,000 primary studies (22 meta-analyses), to summarize the effect of sustainable farming on both biodiversity and yield. Birds, other vertebrates and trees are the most underrepresented taxonomic groups in our meta-analyses database (Fig. 7). This does not mean that there are no relevant studies, but it means that these taxa are rarely studied jointly with yield outcomes.

Biodiversity is mediating yield gains in sustainable farming

Our second-order meta-analysis on sustainable farming practices showed that there was a positive relationship between the change in biodiversity and yield caused by different sustainable farming practices. This relationship has been described in literature[32], but it is highly context-dependent. Indeed, our analysis showed that this effect is not uniform across taxa[33] and in our dataset we even discerned above- and below-ground differences. Organic farming practices, such as the addition of biosolids, organic matter and the replacement of mineral fertilizers with organic fertilizers, as well as diversified farming, were associated with an increase in biodiversity and yield. For example, nutrient enrichment increases invertebrate herbivory and pathogen damage in grasslands[34] and it can lead to eutrophication. Reduced resource addition and lower intensity do not lead to win-win outcomes, possibly due to slower processes of ecosystem restoration after the removal of the disturbances.

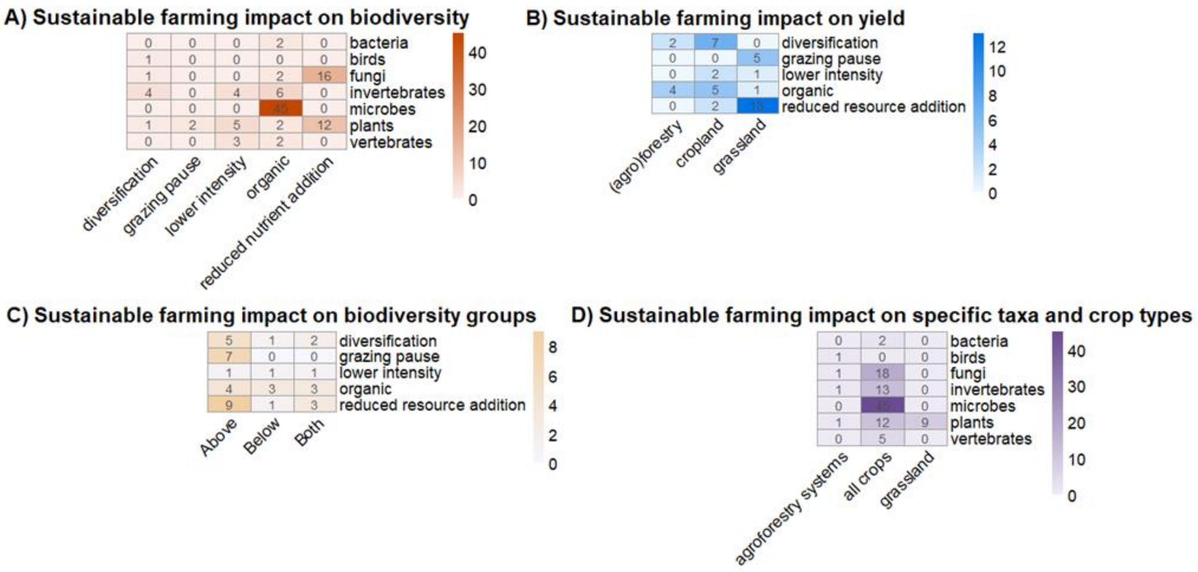

***Figure 7**. Heatmaps of frequencies representing (A) taxonomic groups per management practice, (B) crop types per crop systems, (C) biodiversity groups per management practice, (D) crop types per taxonomic groups, based on the dataset of the present study.*

The relationship between biodiversity and yield within the context of sustainable farming is complex and multi-factorial[35,36], thus we cannot assume causality in every aspect. There are different underlying mechanisms that can be best studied through well-designed long-term experiments rather than through second-order meta-analyses. Although multiple meta-analyses study sustainable farming practices, there is a lack of evidence i) on the effectiveness of the existing yield enhancement measures in relationship to biodiversity and ii) on the specific ways this relationship is mediated by the structure of the surrounding landscape.

The analysis of taxonomic and crop system subgroups resulted in both positive and negative effects. For instance, organic farming having either positive or negative results for different subgroups and a negative effect on productivity for all crop systems, except for agroforestry schemes. Although the test for heterogeneity (Q) was not significant for most subgroups, we performed meta-regressions aiming at examining the effect of management practices. We found that diversification positively affects biodiversity while having a neutral effect on yield. Additionally, within the context of diversification, there is a negative relationship between yield and biodiversity. These findings are in accordance with findings from previous meta-analyses[16,17], that focused on the impact of diversification.

Translating international commitments (i.e. SDGs and COP21 INDCs) into actionable plans requires a focus on environmental contexts due to the highly context-dependent nature of sustainable farming success. Significant knowledge gaps remain regarding farm size and landscape heterogeneity, both crucial for assessing spillover effects. Smaller farms tend to have higher yields and species richness[37], while landscape heterogeneity is known to enhance biodiversity[38]. However, the influence of surrounding landscapes on yields is complex and context-dependent. Additionally, these factors contribute to the adoption of agri-environmental schemes[39] (AES). Developing policies that address contextual challenges and are tailored to fit national, regional or even local scales could be supported by spatially-explicit typologies that capture archetypal patterns of agri-environmental systems[40].

Based on our dataset, win-win scenarios are more likely to be achieved through the following actions: i) reduced addition of nutrients in grasslands is benefitting fungi and plant diversity and biomass production ii) organic farming (such as addition of organic matter, addition of biosolids and substituting mineral with organic fertilizers) is promoting species richness of plants, invertebrates, vertebrates and microbes as well as productivity in vineyards, crops and grasslands iii) crop rotation is increasing the richness of invertebrates (biocontrol species and earthworms) and yields iv) cocoa agroforestry schemes are hosting more animals and higher yields than cocoa monocultures v) removal of large herbivores (i.e. elephants) from grasslands is improving plant and animal richness while increasing herb and tree abundance. More detailed and targeted studies across different crop systems will help to shed light on the synergies between biodiversity and productivity. We don't just “need more data”, though. What we need is coordinated global efforts of carefully designed long-term experiments, which can then be used in evidence syntheses and causal inference[41], with the aim to understand processes, instead of having to conform to “snapshots”[42–44]. When coupled with simulations and models, carefully designed experiments can inform us very well[45]. There has been a long history of efforts to reverse biodiversity loss[46]. Conclusions from the Biodiversity Strategy for 2030 and COP16 re-iterated the need for more political will and legally binding legislation as well as adequate funding[47], because it is linked to motivations for farmers[48].

Methods

Literature search and systematic review

We systematically screened literature (Fig. S1) in order to identify meta-analyses that examine the effect of an agricultural management practice on biodiversity and yield. We leveraged references from three published studies[16,49,50] and Web of Science.

The query we used to search Web of Science was:

(diversity OR species richness OR biodiversity OR (taxonomic AND richness) OR (abundance AND species) OR even*ess OR shannon OR simpson) AND (provisioning OR producti* OR food OR fodder OR feed OR fibre OR logg* OR fuel OR commodit* OR harvest* OR wood OR timber OR coffee OR cacao OR crop* OR yield* OR oil OR abundanc* OR biomass*) AND (diversifi* OR intensif* OR fertili* OR nutrient* OR organic OR manag* OR pest* OR insectic* OR graz*) AND ("meta analys*" OR "meta-analys*" OR "metaanalys*")*

The inclusion criteria were: i) the study had to be a first-order meta-analysis ii) the meta-analysis had to use biodiversity and yield as response variables iii) the meta-analysis had to examine the effect of some management practice on the aforementioned response variables. We did not restrict the studies regarding language, time period or geographical area. We identified 27 meta-analyses and extracted all reported results (overall estimates and subgroup estimates). We used *metaDigitise*[51] to extract data from figures, whenever necessary. All analyses were conducted in R.

Data grouping and pre-processing

We grouped management practices in five categories (Table 4). All categories have been (re)phrased in order to ensure that the sustainable practice (or lower management intensity) is the treatment, while the intensive management is the control (see below for statistical explanation.

Sustainable Management Group (second-order meta-analysis)	First-order groups of practices (first-order meta-analysis)	Crop system
Diversification	Monocultures vs. Polycultures Monoculture vs. Agroforestry Bare Soil vs. Cover Crops Agriculture vs. Agroforestry Monoculture vs. Crop rotation Monoculture vs. Polyculture Bare/Unmanaged Edges vs. Edge Plantings	Cropland, agroforestry
Grazing management	Grazing vs. No grazing Other grazing regimes vs. Communal grazing Continuous grazing vs. Strategic grazing Strategic grazing vs. No grazing	Grassland
Lower intensity	Mowed field vs. Abandoned field Intensification vs. No intensification Tillage vs. No tillage	Cropland, grassland
Organic	Conventional vs. Organic agriculture No Biosolids vs. Biosolids No organic matter vs. Organic matter Conventional vs. Mixed organic Mixed organic vs. Pure organic Mineral-only fertilizer vs. Organic fertilizer Intensive management vs. Organic agriculture	Cropland, agroforestry, grassland
Reduced resource addition	Nitrogen vs. No nitrogen Phosphorus vs. No phosphorus Nitrogen and Phosphorus vs. No Nitrogen and Phosphorus Water addition vs. No water addition	Cropland, grassland

***Table 4**. Grouping of management practices.*

Trade-off analysis

We plotted the reported meta-analytic results in a scenario space, which is depicted as a Cartesian plane with biodiversity in the x axis and yield in the y axis. This scenario space (Fig. 8) allows further quantitative evidence synthesis and the exploration of general patterns, potentially identifying synergies and trade-offs.

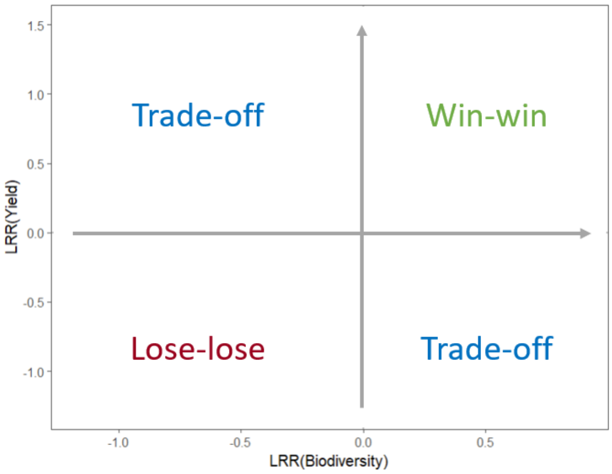

***Figure 8**. Cartesian plot showing the scenario space for the present study.*

We visualized the results of meta-analyses in a Cartesian plot representing a scenario space. Every pair of yield and biodiversity overall meta-analytic means (reported as log-response ratio or some other convertible metric) and confidence intervals was placed in this scenario space. We then fitted a regression line through the points to examine the overall relationship between yield and biodiversity.

We also created a “win-win table”, which is a tabular representation of the effect sizes that were located in the top-right panel of the scenario space. We then fitted a regression line on these values, to assess the effect of biodiversity on yield change in the context of sustainable farming.

Effect size calculations

It is common practice for meta-analyses to convert log response ratios (LRR) to percentages of change, to facilitate interpretation. We converted percentages and response ratios to log response ratios (LRRs).

We standardized all effect sizes based on the reference scenario of each meta-analysis. Some meta-analyses used the intensified management as an intervention, while other meta-analyses used the sustainable management as the intervention. For studies that reported the intensified management as an intervention, we used the inverse of the log response ratio (by inverting the control and treatment in the LRR equation). We did the same for confidence intervals but not with standard errors and standard deviations.

Second-order meta-analysis

We conducted the second-order meta-analysis using first-order meta-analyses that used log response ratio (LRR) as an effect size metric. We excluded studies reporting Hedges' g, Hedges' d, or Cohen's D, because they cannot be converted in LRR. We analyzed log-response ratio data using a multi-level meta-analytic model and meta-regressions without an intercept (with the rma.mv() and rma() functions from the R package metafor) with random and fixed effects. As random effects we used the effect size and study ID. As fixed effects we used management practice (grouping is explained in Table), taxonomic group, crop type and geographic region. We also fitted a meta-regression with biodiversity as a predictor and yield as a response variable.

We analysed separately the taxonomic groups that had enough effect sizes (fungi, insects, vertebrates and plants), as well as the three crop systems (cropland, grassland, agroforestry). In our study, the taxonomic group of plants is not referring to the plants of the crop, but wild plant communities that are related to the crop (e.g. the understory of an agroforestry scheme). An overview of the models used is provided in Tabe S5.

Statistical independence of meta-analyses

First and second order meta-analyses assume independence among studies. Non-independence can be addressed by fitting a correlation matrix (R) in the meta-analytic model. This practice is common in phylogenetic meta-analyses[52]. In our dataset, some meta-analyses used the same primary studies in their sample size, therefore the assumption of independent samples in meta-analytic models was violated. In order to account for non-independence among individual meta-analyses, we fitted a correlation matrix with the percentage of overlap among primary studies from each pair of meta-analyses.

We calculated the percentage of overlap for each pair of meta-analyses using the formula:

$$Percentage\ overlap = \frac{C}{N_i + N_j - C} * 100$$

where

N_i, N_j: are the total number of primary studies included in meta-analysis i and j respectively

C: is the number of primary studies that N_i and N_j have in common

Heterogeneity analysis

Due to the inherent differences between studies in the ecological literature, true effect sizes were presumed to differ between studies.

In order to test for heterogeneity between studies, the weighted sum of squares, *Q,* was calculated as:

$$Q = \sum_{i=1}^{k} W_f g^2 - \frac{\left(\sum_{i=1}^{k} W_f g\right)^2}{\sum_{i=1}^{k} W_f}$$

If the Q statistic is significant, then the meta-analyst should proceed with meta-regressions, to explore the sources of heterogeneity.

We calculated the amount of heterogeneity for each dataset and subgroup using the I-squared (I^2) statistic:

$$I^2 = 100\% * \frac{Q - df}{Q}$$

T^2 is a metric of variability between studies and it was calculated as:

$$T^2 = \frac{Q - df}{C}$$

where

$$df = number\ of\ independent\ datasets - 1$$

$$C = \sum W_f - \frac{W_f^2}{W_f}$$

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Supplement

Figure S1. PRISMA diagram describing the screening process.

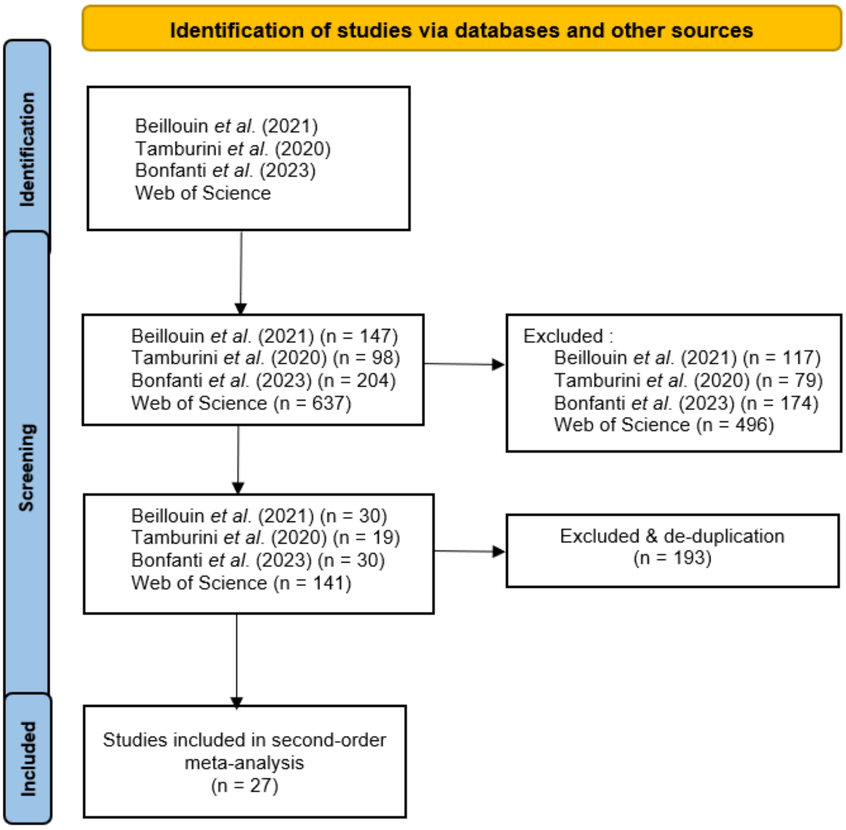

Table S1. Data for the studies that reported win-win outcomes for biodiversity and yield.

No.	Reference	Title	Year	DOI	StudyID	ES_ID	Taxonomic_group	Scenario_raw	Biodiv_ES	Biodiv_ES Metric	Biodiv_measure	Biodiv_sample_size	Management_grouped	Prod_ES	Prod_ESMetric	Prod_measure	Prod_sample_size	Control.TreatPairedYN	LandSharingSparing	BiodivYieldPairedYN.i.e..same.paper.	CropType	SustainableTreatYN	AboveBelowGround	Biodiv_ES_homog	Biodiv_CI_up_homog	Biodiv_CI_low_homog	Prod_ES_homog	Prod_CI_up_homog	Prod_CI_low_homog
1	Ma *et al.* (2020)	Global negative effects of nutrient enrichment on arbuscular mycorrhizal fungi, plant diversity and ecosystem multifunctionality	2020	http://dx.doi.org/10.1111/nph.17077	FEB23_132	ES005	fungi	No nutrient enrichment	-0.09	LRR	Sh	127	reduced resource addition	-0.29	LRR	biomass	100	Y	Sh	Y	all crops	N	Below	0.09	0.06	0.12	0.29	0.22	0.35
2	Niether *et al.* (2020)	Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis	2020	http://dx.doi.org/10.1088/1748-9326/abb053	FEB23_224	ES011	animals	Monoculture vs Agroforestry	4.67	HedgesG	SR	5	diversification	9.06	HedgesG	yield	8	Y	Sh	N	cocoa	Y	Above	4.67	8.13	1.22	9.06	30.49	-12.37
3	Guldemond *et al.* (2017)	A systematic review of elephant impact across Africa	2017	http://dx.doi.org/10.1371/journal.pone.0178935	FEB23_303	ES020	all	Presence vs absence of elephants from plots	-0.18	CohensD	Diversity	18	grazing pause	-0.48	CohensD	abundance	132	Y	Sp	Ysome	herbs/trees	N	Above	0.18	-2.22	2.58	0.48	0.28	0.68
4	Su *et al.* (2022)	Multiple global changes drive grassland productivity and stability: A meta-analysis	2022	http://dx.doi.org/10.1111/1365-2745.13983	FEB23_502	ES030	plants	fertilized vs non-fertilized	-6.57	Percentage change	SR	12	reduced resource addition	-13.48	Percentage change	biomass	35	Y	Sh	Ysome	grassland	N	Above	0.07	0.00	0.14	0.14	0.21	21.35
5	Wang *et al.* (2020)	Effects of nutrient addition on degraded alpine grasslands of the Qinghai-Tibetan Plateau: A meta-analysis	2020	http://dx.doi.org/10.1016/j.agee.2020.106970	FEB23_597	ES036	all	Addition or no addition of nutrients	-0.22	LRR	SR	133	reduced resource addition	-0.65	RR++	biomass	412	Y	Sh	N	all crops	N	Above	0.22	0.15	0.28	0.65	0.60	0.70
6	Ploughe *et al.* (2020)	Revegetation of degraded ecosystems into grasslands using biosolids as an organic amendment: A meta-analysis	2020	http://dx.doi.org/10.1111/avsc.12558	FEB23_95	ES040	all	Biosolids vs no biosolids	0.27	LRR	SR	159	organic	1.27	LRR	productivity	269	N	Sh	Ysome	grassland	Y	Above	0.27	0.65	-0.10	1.27	1.71	0.83
7	Bai *et al.* (2018)	Effects of agricultural management practices on soil quality: A review of long-term experiments for Europe and China	2018	10.1016/j.agee.2018.05.028	JB005	ES043	invertebrates	crop rotation vs monoculture	1.73	RR	Ab	2	diversification	1.31	RR	yield	14	Y	Sh	N	all crops	Y	Below	0.55	8.65	-5.19	0.27	1.50	1.12
8	Bai *et al.* (2018)	Effects of agricultural management practices on soil quality: A review of long-term experiments for Europe and China	2018	10.1016/j.agee.2018.05.028	JB005	ES041	invertebrates	organic matter input vs no input	2.45	RR	Ab	6	organic	1.67	RR	yield	54	Y	Sh	N	all crops	Y	Below	0.90	3.82	1.08	0.51	1.94	1.40
9	Iverson *et al.* (2014)	Do polycultures promote win-wins or trade-offs in agricultural ecosystem services? A meta-analysis	2014	10.1111/1365-2664.12334	JB073	ES045	invertebrates	monoculture vs polyculture	0.25	LRR	Biocontrol	54	diversification	0.52	LRR	yield	39	Y	Sh	Y	all crops	Y	Above	0.25	0.49	0.02	0.52	0.74	0.30
10	Shu *et al.* (2022)	Organic amendments enhance soil microbial diversity, microbial functionality and crop yields: A meta-analysis	2022	10.1016/j.scitotenv.2022.154627	JB158	ES051	all	control: mineral fert, treat.: organic amendment	0.11	LRR	SR	484	organic	0.09	LRR	yield	379	N	Sh	Ysome	all crops	Y	Below	0.11	0.12	0.09	0.09	0.11	0.08
11	Winter *et al.* (2018)	Effects of vegetation management intensity on biodiversity and ecosystem services in vineyards: A meta-analysis	2018	10.1111/1365-2664.13124	JB188	ES053	all	conventional vs organic	60.11	Percentage change	Biodiversity	24	organic	9.46	Percentage change	yield	45	N	Sh	N	grapes	Y	Both	0.47	0.65	0.29	0.09	0.00	-1.04

Methods

We converted the percentage change back into log response ratios using the formula:

$$LRR = ln\left(\frac{Percentage\ change}{100} + 1\right)$$

Reference scenarios

In our second-order meta-analysis we used only results that were reported as log response ratios (LRR). The formula for the log response ratio is

$$LRR = \ln\left(\frac{\bar{X}_T}{\bar{X}_C}\right)$$

Where:

ln is the natural logarithm

$\bar{X}_T$ is the mean of the treatment group

$\bar{X}_C$ is the mean of the control group

The assignment of control and treatment variables depends on the research question. For example, if a meta-analysis is examining the effect of a sustainable agricultural practice, such as replacement of mineral fertilizers with organic amendments, then the control would be the plots with mineral fertilizers, while the treatment would be the organic amendments. However, if a meta-analysis is examining the effect of intensification practices, such as tillage, on a response variable, then the control would be the no-tilled plots and the treatment would be the tilled plots. As expected, the reference scenarios were not homogeneous across our sample.

We standardized reference scenarios by examining closely the phrasing of the research questions of each meta-analysis and keeping a record of the study design. For our analysis, we used all sustainable management practices as treatments. In essence, the control should be an intensified and non-diversified system and the treatment should be a less intensive, diversified system. Since not all meta-analyses were abiding to this design, we inverted some of the effect sizes by multiplying the reported log response ratio by -1, because:

$$LRR_{reversed} = \frac{1}{LRR} = ln\frac{1}{\frac{\bar{X}_T}{\bar{X}_C}} = -\,ln\frac{\bar{X}_T}{\bar{X}_C} = -LRR$$

Table S2. The overall means of the random effects second-order meta-analysis based on first-order meta-analytic means.

Response variable	**Estimate**	**CI low**	**CI up**	**Prediction Interval low**	**Prediction Interval up**	**Sample size (studies)**
Biodiversity	0.05	-0.08	0.19	-0.63	0.73	22
Yield	-0.019	-0.17	0.13	-0.76	0.72	22

Table S3. Moderator estimates per taxonomic group.

Moderator	Estimate	CI.LB	CI.UB	Taxon
Diversification	0.05	-0.09	0.19	All taxa
Grazing pause	0.13	-0.33	0.59	All taxa
Lower intensity	-0.10	-0.53	0.34	All taxa
Reduced resource addition	-0.29	-0.80	0.22	All taxa
Organic	-0.07	-0.35	0.22	All taxa
Overall	0.23	-0.09	0.55	All taxa
Diversification	0.16	0.00	0.33	Invertebrates
Lower intensity	0.41	-1.16	1.99	Invertebrates
Organic	-1.30	-2.85	0.26	Invertebrates
Overall	1.46	0.02	2.90	Invertebrates
Diversification	0.58	-1.13	2.28	Plants
Grazing pause	0.01	-0.35	0.38	Plants
Lower intensity	0.19	0.02	0.37	Plants
Reduced resource addition	0.05	-0.05	0.16	Plants
Organic	0.48	0.08	0.89	Plants
Overall	0.12	0.01	0.23	Plants
Diversification	0.42	-1.05	1.89	Fungi
Reduced resource addition	0.10	0.00	0.20	Fungi
Organic	-0.01	-0.22	0.20	Fungi
Overall	0.09	0.01	0.16	Fungi
Lower intensity	0.07	-0.26	0.40	Vertebrates
Organic	0.31	-0.17	0.79	Vertebrates
Overall	0.15	-0.12	0.42	Vertebrates

Table S4. Moderator estimates per crop type.

Moderator	Estimate	CI.LB	CI.UB	Crop_system
Diversification	-0.44	-15.75	14.87	All crop systems
Grazing pause	-11.92	-38.47	14.62	All crop systems
Lower intensity	-2.76	-18.08	12.56	All crop systems
Organic	-0.44	-15.70	14.82	All crop systems
Reduced resource addition	0.25	-22.93	23.44	All crop systems
Overall	-0.02	-0.17	0.13	All crop systems
Diversification	-2.93	-8.63	2.76	Cropland
Lower intensity	-5.27	-10.95	0.41	Cropland
Organic	-2.99	-8.66	2.67	Cropland
Reduced resource addition	0.02	-9.33	9.37	Cropland
Overall	-2.56	-7.69	2.58	Cropland
Diversification	-0.33	-7.08	6.43	Agroforestry
Organic	4.66	-2.18	11.49	Agroforestry
Overall	2.13	-2.79	7.06	Agroforestry
Grazing pause	-11.94	-61.44	37.57	Grassland
Lower intensity	-0.26	-95.34	94.82	Grassland
Organic	1.27	-93.82	96.36	Grassland
Reduced resource addition	0.35	-54.76	55.47	Grassland
Overall	-4.86	-30.81	21.09	Grassland

Table S5. Structure of models fitted in the study

Model type	**Model name**	**Structure**
		Linear regression
	reg	Yield ~ Biodiversity
		Second-order meta-analysis
Random effects models		
	meta_yield	rma(yi = Prod_ES_homog, vi = Prod_SE3, method = "REML", data = df_lrr)
	meta_bio	rma(yi = Biodiv_ES_homog, vi = Biodiv_SE3, method = "REML", data = biodiv)
	meta_invertebrates	rma.mv(yi = Biodiv_ES_homog, V = Biodiv_SE3, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_invertebrates), data = invertebrates)
	meta_plants	rma.mv(yi = Biodiv_ES_homog, V = Biodiv_SE3, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_plants), data = plants)
	meta_fungi	rma.mv(yi = Biodiv_ES_homog, V = Biodiv_SE3, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_fungi), data = fungi)
	meta_vertebrates	rma.mv(yi = Biodiv_ES_homog, V = Biodiv_SE3, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_vertebrates), data = vertebrates)

	meta_crop	rma.mv(yi = Prod_ES_homog, V = Prod_SE3, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_crop), data = crop)
	meta_agrof	rma.mv(yi = Prod_ES_homog, V = Prod_SE3, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_agrof), data = agrof)
	meta_grass	rma.mv(yi = Prod_ES_homog, V = Prod_SE3, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_grass), data = grass)
Meta-regressions		
	metareg_bioyield	rma.mv(yi = Prod_ES_homog, V = Prod_SE3, mods = ~ 0 + Biodiv_ES_homog, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_df_lrr), data = df_lrr)
	metareg_bio	rma.mv(yi = Biodiv_ES_homog, V = Biodiv_SE3, mods = ~ 0 + Management_grouped, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_biodiv_lrr), data = biodiv)
	metareg_invertebrates	rma.mv(yi = Biodiv_ES_homog, V = Biodiv_SE3, mods = ~ 0 + Management_grouped, random = list(~1|StudyID, ~1|ES_ID), method = "REML",

		R = list(StudyID = A1_invertebrates), data = invertebrates)
	metareg_plants	rma.mv(yi = Biodiv_ES_homog, V = Biodiv_SE3, mods = ~ 0 + Management_grouped, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_plants), data = plants)
	metareg_fungi	rma.mv(yi = Biodiv_ES_homog, V = Biodiv_SE3, mods = ~ 0 + Management_grouped, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_fungi), data = fungi)
	metareg_vertebrates	rma.mv(yi = Biodiv_ES_homog, V = Biodiv_SE3, mods = ~ 0 + Management_grouped, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_vertebrates), data = vertebrates)
	metareg_yield	rma.mv(yi = Prod_ES_homog, V = Prod_SE3, mods = ~ 0 + Management_grouped, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_yield_lrr), data = yield)
	metareg_crop	rma.mv(yi = Prod_ES_homog, V = Prod_SE3, mods = ~ 0 + Management_grouped, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_crop), data = crop)

	metareg_agrof	rma.mv(yi = Prod_ES_homog, V = Prod_SE3, mods = ~ 0 + Management_grouped, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_agrof), data = agrof)
	metareg_grass	rma.mv(yi = Prod_ES_homog, V = Prod_SE3, mods = ~ 0 + Management_grouped, random = list(~1|StudyID, ~1|ES_ID), method = "REML", R = list(StudyID = A1_grass), data = grass)