GfÖ
GfÖ Ecological Society of Germany, Austria and Switzerland
Basic and Applied Ecology 67 (2023) 14−31
Basic and Applied Ecology
www.elsevier.com/locate/baae
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RESEARCH PAPER

Achieving win-win outcomes for biodiversity and yield through diversified farming

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Received 18 February 2022; accepted 18 December 2022
Available online 21 December 2022

Abstract

To leverage agriculture's potential to better benefit both people and nature, policymakers need clear messages about which farming practices positively impact biodiversity and yields, and when trade-offs arise. Existing reviews analyse effects of different agricultural practices on either biodiversity or yield, without considering interactions. Here, we applied multinomial and quantile regression models to synthesize global evidence of synergies and trade-offs between biodiversity and yield, using 764 paired observations (from 43 studies across 18 countries) comparing diversified and simplified farming systems. Results show that farmland diversification led to win-win outcomes for biodiversity and yield in 23% of cases, while a win for biodiversity coupled with a loss in yield was the most likely outcome (28% of cases). Yield and biodiversity responses were negatively correlated, meaning that diversifying farming systems solely in pursuit of production goals is unlikely to lead to markedly better outcomes for biodiversity, or vice-versa. Yet certain situations made win-win significantly more likely, including when crop and animal production, or multiple diversification practices (e.g., intercropping and cover crops), were combined, when no agrochemicals were applied, when diversification occurred in temperate climates, and when diversification enhanced below-ground taxa. Win-win was also more likely than lose-lose when biodiversity was measured as richness or richness-evenness, but not abundance, suggesting that in certain contexts diversified farming can effectively enhance species diversity while increasing agricultural yields. Overall, crop commodity group and bioclimatic location were amongst the most important contextual factors influencing the likelihood of a synergy or trade-off between biodiversity and yield, and diversification that accounts for these is less likely to lead to unexpected outcomes. Our novel method and up-to-date review show that farmland diversification frequently leads to better outcomes for biodiversity and/or agricultural production when compared to monocultures and farmland stripped of natural vegetation, opening a pathway to more sustainable agricultural production.

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Keywords: Systematic review; Multinomial modelling; Trade-offs; Synergies; On-farm diversification

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https://doi.org/10.1016/j.baae.2022.12.005
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Introduction

Globally, agricultural production is a major driver of biodiversity loss now and for the foreseeable future (IPBES, 2019; Tilman et al., 2017; Williams et al., 2021; WWF, 2020). At the same time, our current food system fails to provide sufficient quantities of nutritious food for everyone (Willett et al., 2019). The challenge of safeguarding the world's biodiversity and closing nutritional gaps are interlinked (Aizen et al., 2019), yet are often pursued in isolation (Schmidt-Traub et al., 2019). For years, the agriculture sector has sought to increase yields ignoring the consequences for biodiversity. Conversely, conservationists have focused on safeguarding wilderness areas and largely side-lined interventions on agricultural land. The land-sharing-sparing debate (Kremen, 2015; Phalan et al., 2012) and the rise of agroecology along with other examples of multi-objective farming approaches (Coutinho et al., 2018; Garibaldi et al., 2017; Holt et al., 2016; Loos et al., 2014; Pretty & Bharucha, 2014; Wezel et al., 2020) have stimulated much dialogue and research on how to achieve both agricultural production and biodiversity conservation goals (Bezner Kerr et al., 2021; Fastré et al., 2021; Leclère et al., 2020; Mehrabi et al., 2018). Now, many have moved past the idea that agricultural land exists solely as a space to maximise yields. It is increasingly recognised that agricultural land can and must contribute to multiple sustainability objectives beyond food production, for the environmental effects of food systems to stay within a safe operating space for humanity (Springmann et al., 2018).

Diversifying farming systems, through practices such as intercropping, agroforestry, integrated crop-livestock management and other approaches that increase primarily domesticated biodiversity (Kremen et al., 2012), can benefit non-domesticated biodiversity and multiple ecosystem services, including agricultural production (Beillouin et al., 2021; Tamburini et al., 2020). Yet, the magnitude and direction of (non-domesticated) biodiversity responses varies across taxonomic groups (Aguirre-Gutiérrez et al., 2016; Lichtenberg et al., 2017; Öckinger et al., 2010; Shackelford et al., 2013), bioclimatic factors (Millard et al., 2021), diversification practices (Beillouin et al., 2021; Tamburini et al., 2020), crop habitat characteristics (Pumariño et al., 2015; Shackelford et al., 2013), agrochemical applications (Beckmann et al., 2019; Gonthier et al., 2014; Ridding et al., 2020; Tuck et al., 2014; Woodcock et al., 2016) soil tillage practices (de Graaff et al., 2019) and surrounding landscape complexity (Sánchez et al., 2022). The magnitude and direction of yield responses to farming system diversification also vary with several contextual factors, including diversification practices (Beillouin et al., 2021; Rosa-Schleich et al., 2019; Tamburini et al., 2020), crop traits (Reiss & Drinkwater, 2018), agrochemical applications (Beckmann et al., 2019; Ponisio et al., 2015; Tscharntke et al., 2021), pedoclimatic factors (Reiss & Drinkwater, 2018) and farm size (Delvaux et al., 2020; Ricciardi et al., 2021).

While some contextual variables are known to influence effects of agricultural practices on both biodiversity and yield (e.g., agrochemical applications), these variables do not necessarily have a synergistic positive or negative influence. Situations that favour or maximize biodiversity can sometimes have negative effects on agricultural productivity (Gong et al., 2022), and vice-versa (Abdi et al., 2021; Beckmann et al., 2019). Knowing how biodiversity and yields covary can help identify ways to diversify farmland with synergistic positive impacts for biodiversity and yields, and when trade-offs are likely. Several previous reviews have analysed effects of agricultural practices where biodiversity and yields were not necessarily collected at the same control and treatment sites (Beillouin et al., 2021; Niether et al., 2020; Tamburini et al., 2020). This is problematic because obtaining positive mean effects from two independent meta-analyses does not necessarily imply that there is a positive interaction between biodiversity and yield, since positive responses may be linked to differences in soil type, crop arrangements, or management, or based on experiments specifically dedicated to increasing one of the two variables. Surprisingly few global reviews quantitatively assess effects of agricultural practices on biodiversity and yield from studies that measured effects for both variables using the same control-treatment pairs. A notable exception is Beckmann et al. (2019), who synthesized 115 studies analysing yield and biodiversity simultaneously. They found that transitioning from low intensity farming practices (e.g., no synthetic inputs used, crop rotation) to high intensity practices (e.g., monoculture, chemical inputs used) was associated with an overall gain in yield and loss in biodiversity in terms of species richness. Yet the Beckman et al. (2019) review was dominated by experiments in timber production systems, and by intensification that involved an increase in energy, labour, or agrochemical inputs, and not necessarily any change in biological diversity. This means their dataset cannot be used to understand biodiversity and yield outcomes of different farmland diversification pathways.

A review of experiments reporting the effects of farmland diversification on both biodiversity and yield across various systems and regions is needed to better understand potential synergies and trade-offs between these outcomes. This analysis could help uncover opportunities and pitfalls for designing interventions that contribute to both agricultural production and biodiversity conservation goals (Ortiz et al., 2021). In this paper, we analysed local non-domesticated biodiversity and agricultural yield responses to farmland diversification, using a published database of field experiments that measured biodiversity and yield responses simultaneously in diversified treatments and simplified controls (Jones et al., 2021). We seek to address one core question: When is increasing farming system diversity most likely to have a positive effect on biodiversity and yields, and when are trade-offs likely? To answer this question, we explore how the direction (positive, neutral, or negative), significance, and magnitude of biodiversity and yield responses covary across sites differentiated by diversification practice, crop type (woodiness, life cycle) and commodity, agrochemical use, bioclimatic and geographic region, biodiversity organisms assessed, and biodiversity and yield metrics used.

Materials and methods

Database on the effects of farming system diversification

The data used here represent a subset of a published dataset of the effect of diversified farming on terrestrial biodiversity and/or agricultural yields (Jones et al., 2021). In this subset, diversified farming systems are those that aim to increase diversity on-farm at multiple temporal and/or spatial scales, such as through the association of different plant species, or different varieties/cultivars of crop, or the integration of livestock or fish production with crop production (Table 1). The studies included in the subset were identified through a systematic literature search in Scopus and Web of Science last updated on 5 January 2021 (Appendix A: Table A.1), following a pre-established protocol (Sánchez et al., 2021). All primary articles directly retrieved through the search were screened, together with primary articles listed in all meta-analyses retrieved through the search, and 20 articles identified through other sources (Jones et al., 2021). To be included in the present paper, articles had to meet the inclusion criteria described in Appendix A (Table A.2), notably to report quantitative responses for both (non-domesticated) biodiversity and yield, including means, sample sizes and variance measures. Articles needed to report responses collected using comparable approaches in a diversified farming system and a simplified control, with the latter representing either a monoculture or a farming system with an absence of embedded natural vegetation. In the case of intercropped treatments, the article must have provided sufficient data to enable calculation of the land equivalent ratio as a measure of yield (see Appendix A: Supplementary Methods).

The resultant dataset used in this paper includes information from 43 articles reporting biodiversity and yield responses collected through field experiments in the same diversified and simplified farming systems and paired for analysis (see Appendix A: Fig. A.1 for an overview of the literature search and screening steps, and Table A.3 for a list of included articles). For each comparison of diversified farming systems relative to a simplified control, information on biodiversity and yield were extracted pertaining to the population, intervention, comparator, outcome, and context (PICOC) (Appendix A: Table A.4). We classified information in the database to group cases (i.e., pairs of biodiversity and yield responses collected in the same control and treatment sites) by farming practice (control: simplified farming; treatment: agroforestry, associated plant species, crop rotation, cultivar mixtures, embedded natural features, intercropping, and combined practices − see Table 1), crop type (woodiness and life cycle), crop commodity (according to FAO commodity groups), agrochemical inputs (pesticide and fertiliser use), biodiversity organism assessed (taxonomic, functional, and ground-relation group, where the latter distinguished whether the organism was surveyed above or below ground), continent, latitude, and bioclimatic location (Appendix A: Table A.5). We classified metrics used to assess biodiversity into three categories: abundance, richness, and richness-evenness. Abundance represented the number of individuals, the colonization percent (for fungi), or the area under disease progress curve (for fungi). Richness represented the number of different species measured directly or using the Chao1 Index. Richness-Evenness represented indices that combined measures of richness and evenness and included the Shannon Diversity Index, Simpson's Reciprocal Index, Simpson's Dominance Index, and the Pielou Index. For yield, metrics included the land equivalent ratio (see Supplementary Methods), mass per area (e.g., kg per hectare), mass or count per plant or plant part (e.g., kg grape per vine, apples per branch) or, for a few vegetable crops, above-ground biomass (e.g., whole dry plant weight) (Appendix A: Table A.5).

Assessing the likelihood of synergies and trade-offs − accounting for direction

For each control-treatment pair, we used log response ratios (log-RR) (Borenstein et al., 2009) to quantify the mean effect of farmland diversification on biodiversity and yield, separately. Zero mean values were adjusted by adding 0.01 to allow computation of log-RR. Then, each pair of biodiversity (B) and yield (Y) effect sizes was classified into one of five outcome categories, based only on the direction of the effect sizes (positive, neutral, or negative): Win B-Win Y, Win B-Lose Y, Lose B-Win Y, Lose B-Lose Y, or Other. Win B-Win Y was assigned when effects were positive for both biodiversity (B) and yield (Y); Win B-Lose Y, when effects were positive for biodiversity, and negative for yield; Lose B-Win Y, when effects were negative for biodiversity, and positive for yield; Lose B-Lose Y, when effects were negative for both outcomes; and Other when effects were neutral (equivalent in the control and treatment sites) for biodiversity and/or yield.

Intercept-only multinomial models were applied to assess the likelihood of a Win B-Win Y, Win B-Lose Y, Lose B-Win Y, or Other outcome, relative to a Lose B-Lose Y outcome. Multinomial models compute the probability of a specific outcome, relative to the probability of a reference outcome, based on the number of cases in each outcome category. Model estimates represent log odds (η), meaning the relative likelihood on a logarithmic scale (Hilbe, 2009). The models are similar to logistic regression models with a

Table 1. Farming system definitions and representation in this paper.

Farming system	Farming practice	Definition	Specific farming systems represented in the database
Control: simplified farming system	Simplified farming	This includes i) monocultures, defined as a single crop species or variety grown in the same plot, at the same time or continually across different seasons, and ii) fields with an absence of embedded natural vegetation when compared to fields with embedded natural vegetation (adapted from Sánchez et al. 2021).	Monocultures, absence of embedded natural vegetation (e.g. absence of hedgerows, or flower strips, or grass borders, or fallow periods >6 months).
Treatment: diversified farming systems	Agroforestry	Agroforestry satisfies three conditions: (i) at least two plant species interact biologically, (ii) at least one of the plant species is a woody perennial, and (iii) at least one of the plant species is managed for forage, annual or perennial crop production (Beillouin et al., 2019).	Shade coffee, alley cropping, tree borders.
	Associated plant species	Following (Beillouin et al., 2019), associated plant species are plants sown in addition to the main crop for agronomic or environmental purposes. There is normally one main plant that is harvested for consumption, while the other plant is not harvested for consumption and instead provides a specific function, such as to deter pests, improve soil health, or reduce erosion.	Trap crops, cover crops, green manure.
	Crop rotation	Crop species or varieties grown in succession on a plot of land, on a seasonal or annual basis (Beillouin et al., 2019).	Crop-pasture annual rotations, crop annual rotations (e.g., rice-soybean-wheat), crop seasonal rotations (e.g., spring wheat, winter wheat).
	Cultivar mixtures	Multiple cultivars of the same species grown together simultaneously in the same field. All cultivars are harvested (Beillouin et al., 2019).	Two or more crop varieties grown in adjacent strips, rows, or mixed within a strip.
	Embedded natural vegetation	On-farm land used for non-productive purposes and where natural or semi-natural vegetation is sown or allowed to naturally regenerate next to productive land or as part of a crop rotation cycle, usually for environmental purposes (Sánchez et al., 2021).	Hedgerows, flower strips, grass borders, fallow periods (>6 months).
	Intercropping	Simultaneous cultivation in the same field of two or more crop species, varieties, or cultivars, for all or part of their growth cycle. All crops are harvested (Beillouin et al. 2019).	Two or more crop species grown in adjacent strips, rows, or mixed within a strip.
	Combined practices	Combinations of single diversified farming practices, such as crop rotation and cover crops practiced together, or integrated crop-animal production systems (Sánchez et al., 2021).	Intercropping and crop rotation together, embedding natural vegetation (flower strips) and intercropping together, integrated crop-fish production, integrated crop-livestock production.

multinomial instead of binomial probability distribution (Hilbe, 2009). The Lose B-Lose Y outcome was used as the reference in the intercept-only models. We report log odds transformed into relative risk ratios (*RRR)* to ease interpretation (i.e., *RRR* = exp(η)) (Hilbe, 2009). *RRR* is an estimate of the change in odds of one outcome relative to another, given a one unit increase in the predictor. For example, if *RRR* = 1.11 for a Win B-Lose Y outcome calculated from an intercept-only model using lose-lose as the reference, this means that a Win B-Lose Y outcome is 1.11 times (or 11%) more likely than lose-lose in a diversified relative to a simplified farming system. The intercept-only model was fitted to all cases and to cases subset by biodiversity metric (abundance, richness, richness-evenness).

We fitted univariate multilevel multinomial models to test whether the following ecological and agronomic variables influenced the log odds of each paired biodiversity-yield outcome: agrochemical use, biome, latitude, continent, crop commodity, crop type, diversification practice, yield measure, and biodiversity organism taxonomic group, pest group, ground relation, and measure. The maximum likelihood estimator was used, which can lead to very large or non-finite estimates and large confidence intervals when there are empty cells or very small sample sizes (Devika et al., 2016; Kosmidis & Firth, 2021). To reduce this problem, we grouped classes with <5 samples into broader categories during data classification (e.g., nuts and stimulants, within the crop commodity variable), and models were fitted after ensuring no empty cells in the reference category across variable levels. Univariate models were fitted using Lose B-Lose Y as the reference, except for variables with no Lose-B-Lose Y outcomes in one or more variable class (i.e., diversification practice, taxonomic group, and crop commodity). For these variables, when another outcome category had complete data (no empty classes), this was used as the reference category (e.g., for taxonomic group, Win B-Lose Y was used as the reference). Otherwise, the model was fitted using Lose B-Lose Y as the reference. For diversification practice, the data supported fitting a second model including only the removed cases and setting the reference category to Win B-Lose Y. Fitting a second model for removed cases was not possible for crop commodity due to incomplete data across all reference categories. The data did not support multivariate analysis since, with many categorical predictors, combining two or more variables introduced many empty cells and small class sizes.

Two complementary methods were applied to explore the importance of each variable in determining synergies and trade-offs between biodiversity and yield outcomes. First, likelihood ratio tests were used to assess whether adding the variable to the multinomial model led to a significant reduction in unexplained variance compared to the intercept-only model. Significance was assessed using a cut-off of p= 0.05, correcting p-values to account for multiple testing using the Bonferroni method (*p-value* x *number of variables tested*). Second, we used randomForest (Breiman, 2001) to account for non-linear interactions amongst variables. RandomForest bootstraps the data iteratively and randomly selects variables on which to split each node, used here to grow 10,000 predictive and testing trees. Variable importance was measured as the average mean decrease in outcome classification accuracy for data classified after versus before splitting on a variable. We compared results to the likelihood ratio tests to identify which variables were consistently identified as important predictors of synergies and trade-offs across both methods.

Multiple biodiversity-yield effect size pairs in our database were non-independent because they were sourced from the same studies, and/or from experiments where treatments shared a control plot, and/or from multiple experiments in the same control and treatment plots (e.g., representing different taxonomic or functional groups, collected using different biodiversity metrics, or collected in repeat surveys within or across years). In addition, yield effect sizes were often paired with multiple biodiversity effect sizes, representing different organisms, metrics, or sampling points within the same cropping season and study. Effect sizes can be pooled within studies to reduce dependencies but this results in a large loss of information (López-López et al., 2018). Alternatively, random effects can be added into a hierarchical model structure to explicitly account for possible variance due to repeat measures and other sources of dependencies between effect sizes (Cheung, 2019; Konstantopoulos, 2011; Van den Noortgate et al., 2014). We included numeric identifiers for each study (published article) and for each case (unique biodiversity-yield effect size pair) as nested random effects in all of the multilevel multinomial models to account for dependencies between and within studies (Assink & Wibbelink, 2016; Van den Noortgate et al., 2013).

Assessing the likelihood of a synergy and trade-off − accounting for direction and significance

To assess whether the predicted likelihood of a synergy or trade-off changed when accounting for both direction and significance of biodiversity and yield effect sizes, we selected Win B-Win Y, Win B-Lose Y, Lose B-Win Y and Lose B-Lose Y outcomes for which both effects were significant (at the 5% level) and classified all other outcomes as non-significant. We refitted the intercept-only multinomial models using this alternative outcome classification and compared the likelihood estimates against those obtained when classifying outcomes solely based on direction.

Assessing the co-variance of biodiversity and yield effect sizes

Classifying outcomes according to direction and significance of effect sizes is akin to vote counting, which is widely used but also widely criticized. Vote counting can lead to incorrect conclusions by giving equal weight to all effect sizes (ignoring sample size and effect size magnitude) and lacking statistical power (Bushman, 2009; Harrison, 2011). Multinomial models overcome one key shortcoming of vote-counting, by providing an estimate and confidence intervals for the odds of each outcome rather than just identifying which outcome occurs most frequently (Arslan et al., 2022; Bushman, 2009). They do not, however, account for sample size or magnitude of effect sizes.

We complement the multinomial analysis with an analysis of how paired biodiversity-yield effect sizes covary, using a mixed effects quantile regression model. Quantile regression characterizes the distribution of a response variable at multiple predictor values and not only the mean as in conventional regression. It is therefore relatively robust to outliers and to non-parametric error distribution (Morales & Lachos, 2015). The regression model included biodiversity effect sizes as the response, yield effect sizes as fixed effects, and study and case identifiers as nested random effects. The model was fitted while setting the maximum iterations to 200 and number of Monte Carlo simulations to 10. The regression model was applied to all cases and to cases separated by biodiversity metric (abundance, richness, richness-evenness).

Sensitivity analysis

A lack of internal validity within experiments can reduce the quality of synthesis studies. Internal validity refers to whether it is reasonable to attribute effects observed in an experiment to the independent variable being tested (in this case, farming system diversification) and that the effects are not influenced by unrepresentative sampling, inappropriate controls, or another type of experimental bias (Boutron et al., 2019). Following Sánchez et al. (2021), we classified experiments as potentially biased if at least two of the following conditions were either met or could not be determined (insufficient information provided): i) the control or treatment sample size was very small (<5), ii) the control and treatment sites were further than 1 km apart, and iii) the control or treatment had been in its experimental state for <1 year (Appendix A: Table A.6).

We tested the robustness of modelled estimates of the probability that farmland diversification results in a Win B-Win Y, Win B-Lose Y or Lose B-Win Y outcome, relative to Lose B-Lose Y, by running the intercept-only multinomial models after removing potentially biased effect sizes. If the direction and significance of the model results were unchanged, the results were considered robust. We similarly tested the robustness of the quantile regression model results by removing potentially biased effect sizes. If the slope representing the expected effect on biodiversity given the median value of yield was unchanged, the results were considered robust.

Code and data availability

Statistical analyses were performed in R (R Core Team, 2021) using the metafor (Viechtbauer, 2010), QRLMM (Morales & Lachos, 2015), nnet (Venables & Ripley, 2002) and randomForest (Breiman, 2001) packages. The dataset was sourced from Jones et al. (2021). The R code is available at: https://github.com/skatejones/SustainableFoods.

Results

The dataset used for this analysis included 764 cases (experiments simultaneously measuring biodiversity and yield in diversified and simplified farming systems) from 43 studies, distributed across 18 countries (Fig. 1). North America was the best represented region (53.3% of cases), followed by sub-Saharan Africa (15.7%), Asia (15.3%), Europe (11.4%), and Latin America and the Caribbean

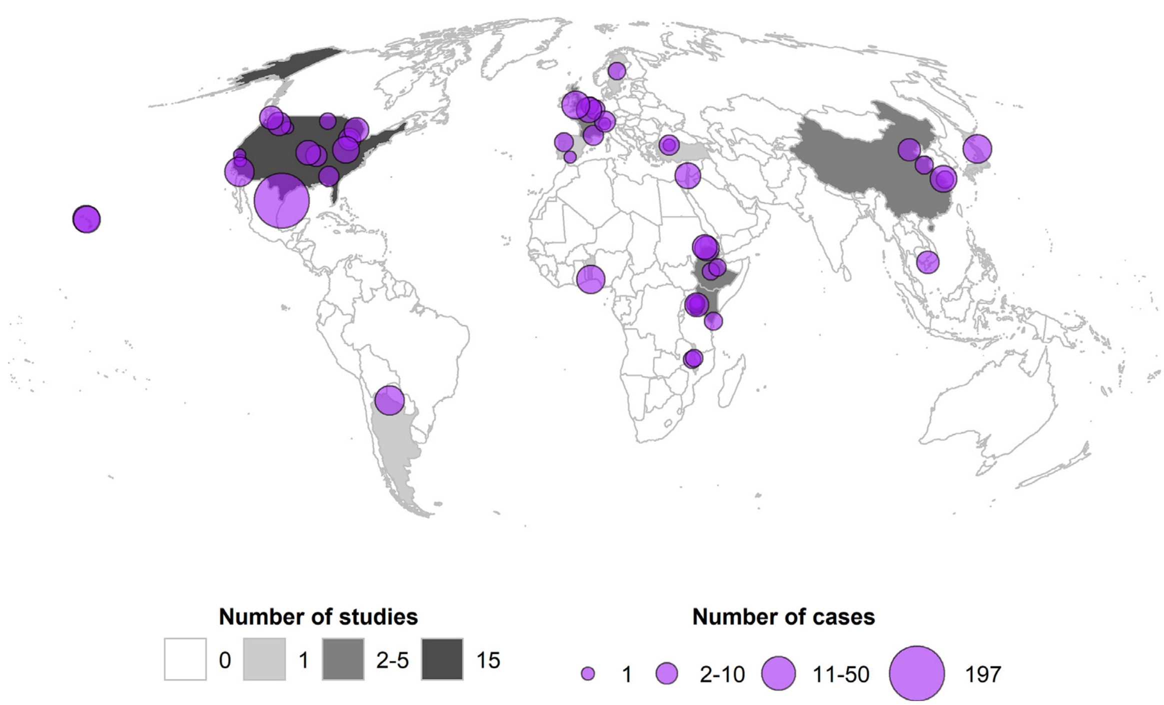

Fig. 1. Geographic distribution of 764 paired biodiversity and yield effect sizes from 43 studies comparing responses in diversified relative to simplified farming systems.

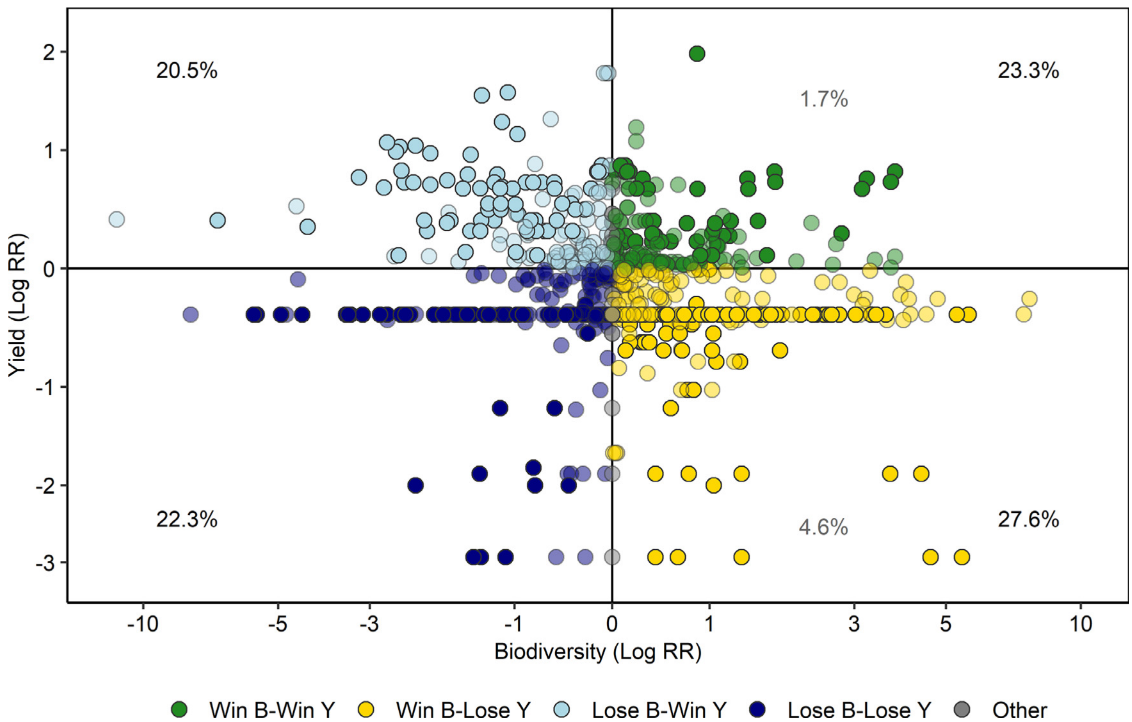

Fig. 2. Distribution and proportion of synergies and trade-offs between biodiversity (B) and yield (Y) effect sizes when comparing diversified to simplified farming systems. Labels in black show the proportion of cases with a Win B-Win Y, Win B-Lose Y, Lose B-Win Y, and Lose B-Lose Y, while labels in grey show the proportion of Other outcomes (i.e., neutral effects on biodiversity with either positive or negative effects on yield). Non-significant effect sizes are semi-transparent.

(4.3%). Across biomes, tropical and subtropical grasslands (biome names modified slightly for analysis, see Appendix A: Table A.5) had the largest share of cases (41.8%), and together boreal, montane and desert biomes the least (3.9%).

Trade-offs are slightly more common than synergies

Based on the direction of effect sizes, we found that win-win outcomes for biodiversity (B) and yield (Y) occurred in 23% of cases (Fig. 2) and were not statistically more likely than lose-lose (*RRR* = 1.02, *p*= 0.668) (Fig. 3, Appendix A: Table A.7). Diversification most frequently resulted in Win B-Lose Y (28% of cases) and this outcome was 11% more likely than lose-lose (*RRR* = 1.11, *p*= 0.036). The inverse, where yields benefit but biodiversity does not, occurred in 21% of cases and was not significantly more likely than lose-lose (*RRR* = 0.96, *p*= 0.472). In a minority of cases (6%), diversification resulted in an 'Other' outcome involving no effect on biodiversity coupled with a variable effect on yield, and this outcome was almost half as likely as lose-lose (*RRR* = 0.53, $p < 0.001$). Win B-Lose Y remained significantly more likely than lose-lose after removing potentially biased cases (Appendix A: Fig. 2) and when classifying outcomes based on both the direction and significance of effect size pairs (Appendix A: Fig. 3). The likelihood of a Lose B-Win Y outcome shifted to significantly less likely than lose-lose when potentially biased effect sizes were removed suggesting that, in general, farming system diversification is unlikely to benefit only yield (Appendix A: Fig. 2).

Increases in richness and evenness of biodiversity are likely to coincide with increases in yield

Sub-setting the dataset by biodiversity metric altered the likelihood of finding a synergy or trade-off for biodiversity and yield. Results show that diversification was significantly more likely to lead to synergistic gains for biodiversity and yield, compared to loses for both, when biodiversity was measured as species richness (*RRR* = 1.61, *p*= 0.010) or richness-evenness (*RRR* = 2.14, *p*= 0.002) (Fig. 3, Appendix A: Fig. A.4 and Table A.7). In contrast, synergistic outcomes and trade-offs were equally likely when biodiversity was measured in terms of abundance.

Likelihood of a synergy or trade-off depends on agronomic and ecological context

We found that several contextual factors strongly influence the likelihood that diversification benefits biodiversity and/or yield. Crop commodity and biome were consistently identified as important determinants of whether synergies or

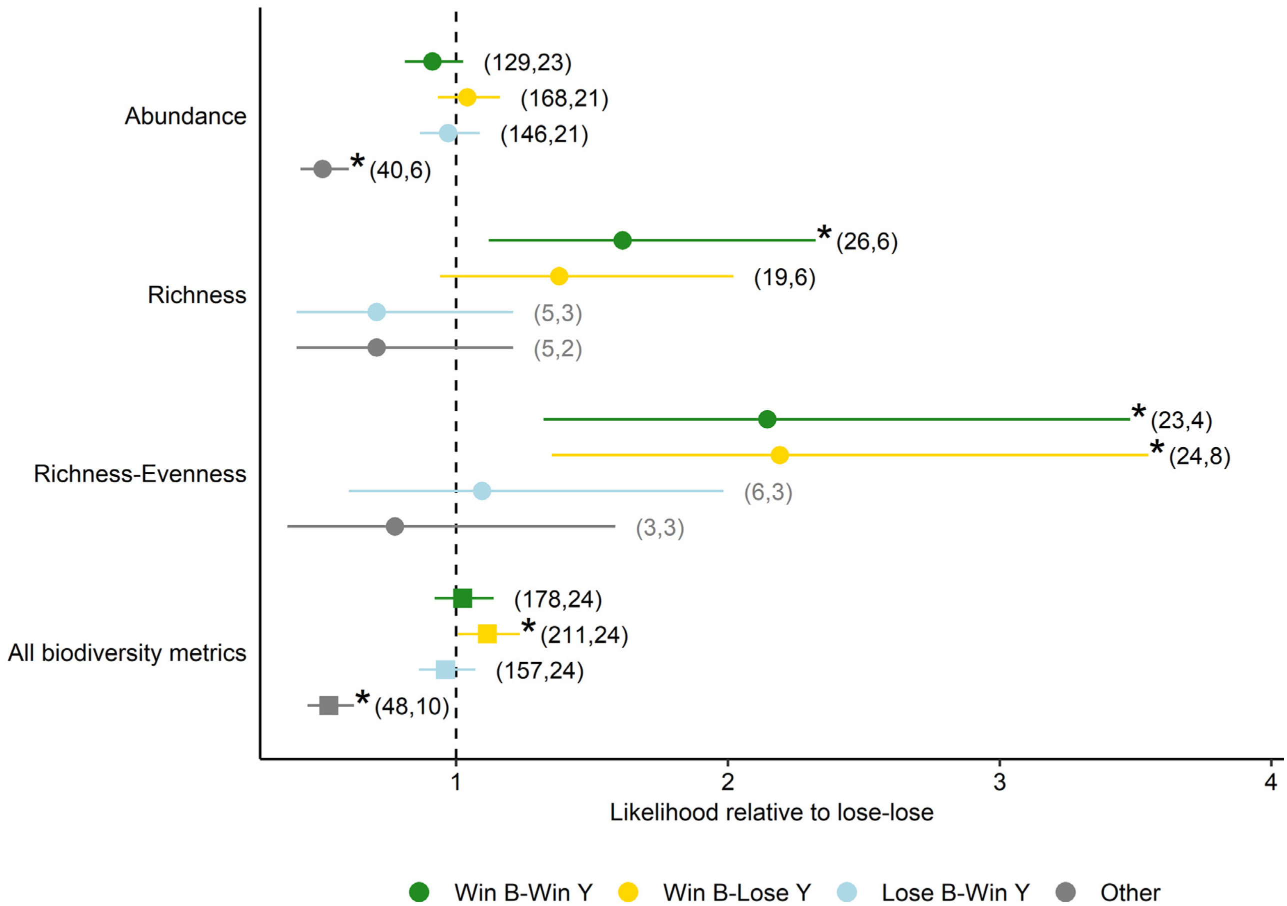

Fig. 3. Likelihood of farming system diversification resulting in a Win B-Win Y, Win B-Lose Y, Lose B-Win Y or Other outcome, relative to Lose B-Lose Y, for biodiversity (B) and yield (Y), for the full dataset and subsets representing cases where biodiversity was measured as abundance, richness or richness-evenness. Labels on the plot indicate where estimates are significant (*, $p<0.05$) with the number of paired effect sizes followed by the number of articles shown in parentheses (in grey when the number of cases ≤10 or number of studies ≤3, indicating a small sample size). Likelihoods represent log odds transformed to relative risk ratios, plotted with 95% confidence intervals.

trade-offs occurred, across both methods used to assess variable importance (Appendix A: Fig. A.5 and Table A.8). Crop type, diversification practice, agrochemical use, latitude, continent, and pest group, were identified as important by a single method, while taxonomic group, ground relation, biodiversity metric, and yield metric consistently had a smaller influence. The relatively small influence of biodiversity metric on overall likelihoods, despite evidence of variation in likelihoods across abundance, richness, and richness-evenness (Fig. 3), indicates that other variables explain a larger proportion of the variability in outcomes. For this reason and given the small sample sizes in the richness and richness-evenness datasets (i.e., <10 cases in the Lose B-Win Y and Other outcome categories), subsequent analyses were conducted on the dataset containing all cases.

In temperate forest and Mediterranean biomes, win-win was the most likely outcome of farming system diversification and was, respectively, 3.55 ($p < 0.001$) and 4.61 ($p < 0.001$) times more likely than lose-lose (Fig. 4, Appendix A: Table A.9). While win-win was the most likely outcome in temperate forests, diversification was also 2.47 ($p < 0.001$) times more likely to lead to gains in biodiversity and losses in yield, compared to losses in both. In tropical and sub-tropical forests, diversification was most likely to benefit only yield, and this outcome was 4.28 ($p < 0.001$) times more likely than lose-lose. The tendency for positive biodiversity and yield responses in temperate environments and losses to biodiversity in tropical was broadly consistent with the modelled effect of latitude on relative likelihoods. The likelihood of a win-win outcome increased (*RRR* = 1.05, $p < 0.001$), while the likelihood of a Lose B-Win Y decreased (*RRR* = 0.99, p= 0.022), with latitude (Fig. 5). This may reflect that the potential for diversification to improve ecosystem functioning depends on inherent ecosystem characteristics (such as soil fertility, surrounding landscape complexity), climate, and land use histories (e.g., conversion to agriculture).

Regional differences in ecosystem characteristics and climate may in part explain the variation in estimated likelihoods across continents. In Asia, win-win outcomes were more likely than any other outcome (*RRR* = 18.96, $p <$ 0.001), while trade-offs were also more likely than lose-lose (for Win B-Lose Y: *RRR* = 4.09, p= 0.02, and for Lose

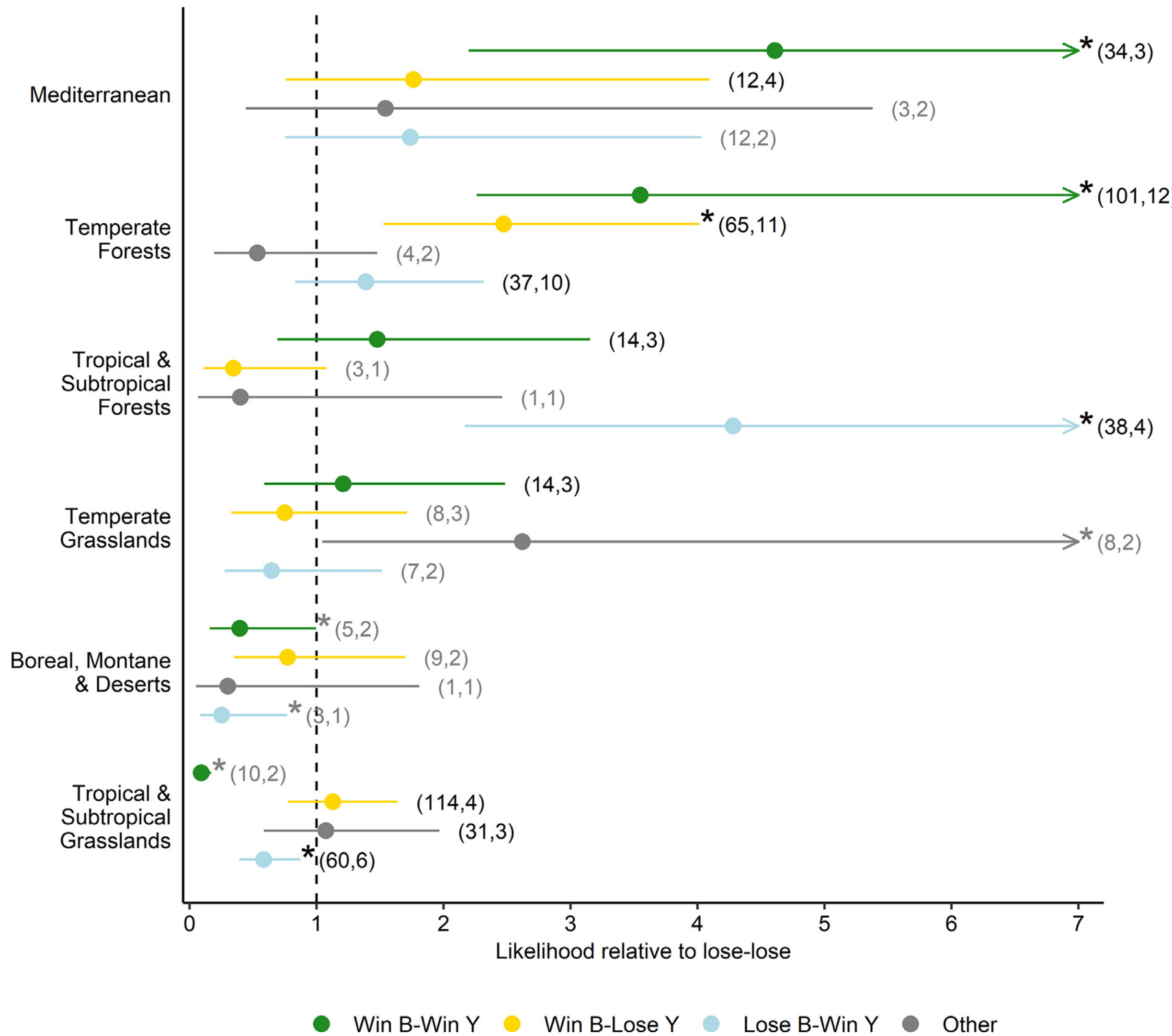

Fig. 4. Variation across biomes in the likelihood of farming system diversification resulting in a Win B-Win Y, Win B-Lose Y, Lose B-Win Y or Other outcome, relative to Lose B-Lose Y, for biodiversity (B) and yield (Y). Labels on the plot indicate where estimates are significant (*, p<0.05) with the number of paired effect sizes followed by the number of articles shown in parentheses (in grey when the number of cases ≤10 or number of studies ≤3, indicating a small sample size). Likelihoods represent log odds transformed to relative risk ratios, plotted with 95% confidence intervals. Confidence interval limits with a value >7 are removed for display purposes (see Appendix A: Table A.8).

B-Win Y: *RRR* = 9.76, $p < 0.001$) (Appendix A: Fig. A.6A and Table A.9). In contrast, win-win was as equally likely as lose-lose in Europe, and less likely than lose-lose in Africa (*RRR* = 0.41, p= 0.004) and the Americas (*RRR* = 0.27, $p < 0.001$). In Africa, Lose B-Win Y was the most likely outcome (*RRR* = 2.15, p= 0.005), which may in part be linked to the large yield gaps prevalent on the continent. amongst diversification practices, win-win outcomes were the most common outcome in systems diversified through combined practices, such as integrated crop-fish systems, or intercropping and cover crops in the same plot (75% of 24 cases, *RRR* = 2.65, p= 0.018, relative to Lose B-Win Y) (Fig. 6, Appendix A: Table A.9). Trade-offs with benefits only for yield were over 6 times more likely than a lose-lose outcome in intercropped systems (*RRR* = 6.18, $p < 0.001$) (Fig. 6, Appendix A: Table A.9). In contrast, trade-offs where only biodiversity benefits, was the most likely outcome in systems embedding natural vegetation and were nearly twice as likely as a lose-lose outcome (*RRR* = 1.79, p= 0.019).

The log odds of a win-win outcome were comparable across crop commodities, and across crops with different woodiness and life cycles (i.e., win-win remained as equally likely as lose-lose), whereas the likelihood of a trade-off varied across cropping systems. Trade-offs where only yield benefits were the most likely outcome of diversification in vegetable crops and 66 times more likely than lose-lose (*RRR* = 65.89, $p < 0.001$) (Appendix A: Fig. A.6B and Table A.9). The opposite, where only biodiversity benefits from diversification, was the most likely outcome in fruit cropping systems (*RRR* = 2.38, p= 0.002), where fruits represented solely woody plants (grape, blueberry, apple and cherry). Diversification of annual herbaceous was most

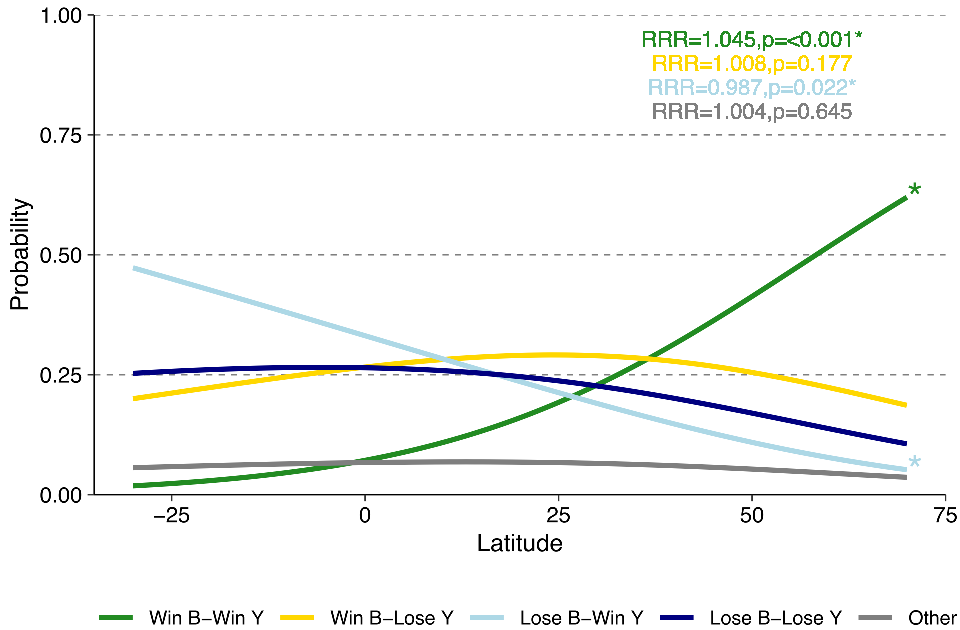

Fig. 5. Effect of latitude on the probability of farming system diversification resulting in a Win B-Win Y, Win B-Lose Y, Lose B-Win Y, Lose B-Lose Y, or Other, outcome, for biodiversity (B) and yield (Y). Text on the plot shows the relative risk ratios (RRR) of each outcome relative to lose-lose. Labels indicate where estimates are significant (*, $p<0.05$).

likely to lead to a Lose B-Win Y outcome, relative to lose-lose (respectively, *RRR* = 81.16, *p*= 0.007) (Appendix A: Fig. A.6C and Table A.9), whereas diversification in tree systems was most likely to lead to a Win B-Lose Y, occurring in 50% of cases (*RRR* = 3.34, $p < 0.001$).

Removing agrochemicals increased the likelihood of synergistic positive biodiversity and yield responses. Win-win was the most likely outcome (39% of 104 cases) when diversification happened in systems with no agrochemical use (*RRR* = 2.40, $p < 0.001$), whereas diversification where agrochemicals were applied was most likely to lead to a gain in yield and a loss in biodiversity (*RRR* = 1.45, *p*= 0.040) (Appendix A: Fig. A.6D and Table A.9). Gains in yield were less likely when yield was measured in terms of mass per area, such as tons per hectare, and more likely when yield was measured in terms of land equivalent ratio (used for intercropping only) or biomass (vegetable crops only) (Appendix A: Fig. A.6E and Table A.9). This may reflect that some diversification practices, such as embedding natural vegetation, agroforestry, and use of associated plant species, can reduce productive area and introduce pests (in addition to pollinators and biological controls) with variable effects on yield. It may also reflect that the dominant metric for measuring yields (mass per area) captures only part of the production value and complementary measures are needed to capture the missing elements, e.g., whole production value (which includes LER), yield stability, food quality, and nutritional value.

Our results suggest that synergistic positive outcomes for agricultural production and biodiversity are easier to find below ground, likely related to increases in soil biodiversity benefiting soil health and fertility. Across biodiversity taxonomic groups, diversification was most likely to result in win-wins when soil micro-organisms were the target organism, such as bacteria (71% of cases, *RRR* = 4.84, $p < 0.001$, relative to Win B-Lose Y) and fungi (80% cases, *RRR* = 10.88, $p < 0.001$, relative to Win B-Lose Y) (Appendix A: Fig. A.6F, Table A.9). Related to this, gains for biodiversity, yield, or both, were all more likely than lose-lose, when biodiversity represented below-ground taxon, and all less likely than lose-lose when biodiversity represented above-ground taxon (Appendix A: Fig. A.6 G and Table A.9). A Lose B-Win Y outcome was more likely than lose-lose when the target organism was a crop pest (*RRR* = 2.35, $p < 0.001$), and less likely when it was not a crop pest (*RRR* = 0.44, $p < 0.001$) (Appendix A: Fig. A.6H and Table A.9). This result reflects that reduced abundance and diversity of pests are associated with gains in yield and suggests that diversification could effectively reduce crop pests.

Biodiversity and yield covary under farmland diversification

Mixed-effects quantile regression showed a weak negative relationship between biodiversity and yield responses to diversifying farming systems at the median (−0.002 - (0.18 * yield), *p*= 0.001, where *p* relates to the certainty around the slope estimate), meaning that for every 1% increase in yield, biodiversity decreases by 0.18% (Appendix A: Fig. A.7 and Fig. A.8). This result was robust to the removal of potentially biased effect sizes (0.06 − (0.18 * yield), *p*= 0.001) (Appendix A: Fig. A.9). The negative relationship was stronger at

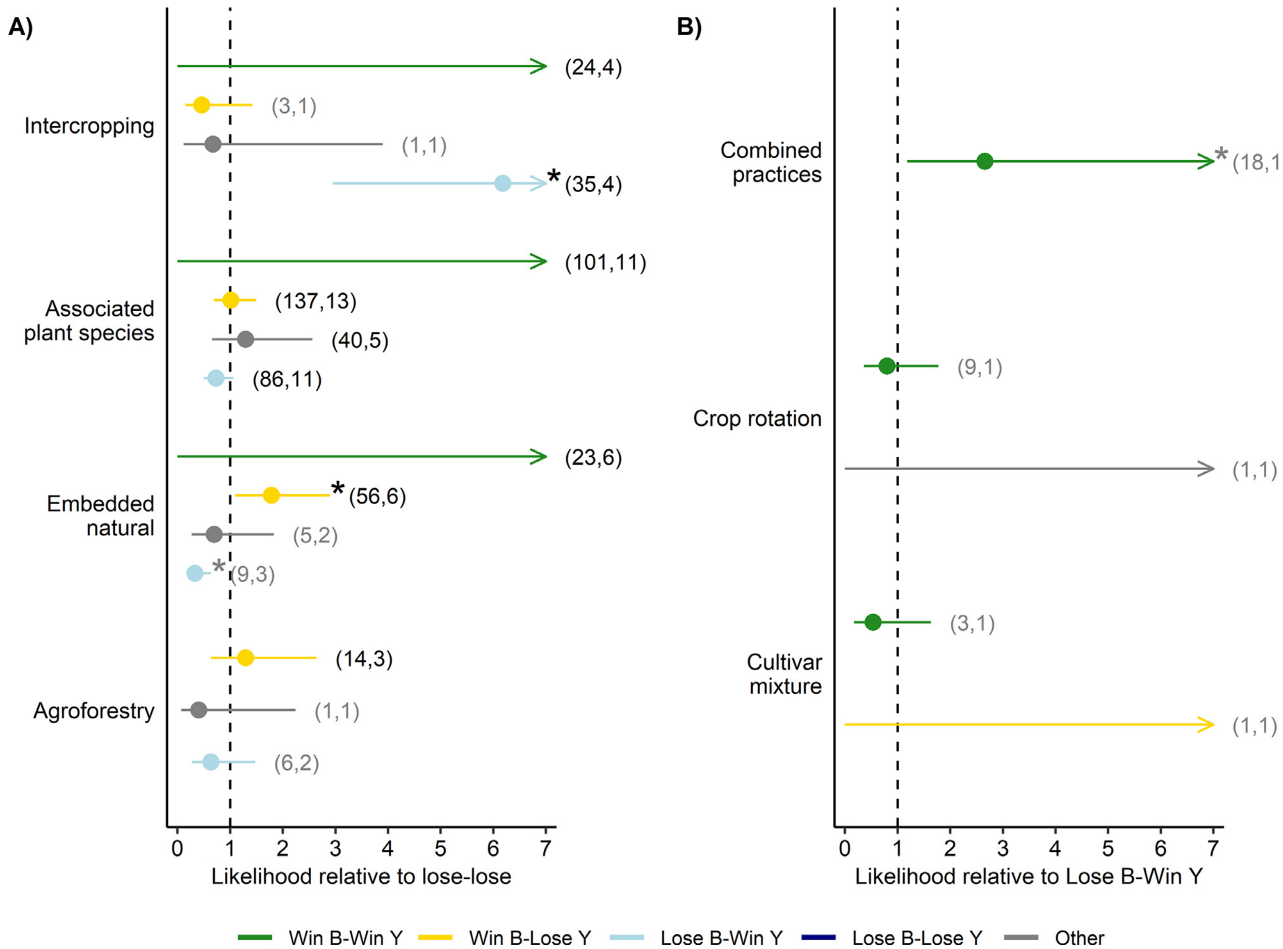

Fig. 6. Variation across diversification practices in the likelihood of farming system diversification resulting in a Win B-Win Y, Win B-Lose Y, Lose B-Win Y, Lose B-Win Y, or Other outcome, for biodiversity (B) and yield (Y), using Lose B-Lose Y (panel A) and Lose B-Win Y (panel B) as the reference category. Labels on the plot indicate where estimates are significant (*, $p<0.05$) with the number of paired effect sizes followed by the number of articles shown in parentheses (in grey when the number of cases ≤10 or number of studies ≤3, indicating a low sample size). Likelihoods represent log odds transformed to relative risk ratios. Likelihoods and confidence intervals limits with a value >7 are removed for display purposes (see Appendix A: Table A.8).

higher quantiles, meaning larger yield increases were associated with stronger declines in biodiversity. While the weak negative relationship was present and significant at nearly all quantiles when biodiversity was measured as abundance, there was a slightly positive but non-significant (i.e., high uncertainty around the slope estimates) relationship at most quantiles when biodiversity was measured as richness, and a slightly negative but non-significant relationship when biodiversity was measured as richness-evenness. This suggests that when yields increase, species abundance decreases while effects on richness and evenness are unpredictable when no attention is paid to contextual factors.

Discussion

This study represents the largest global analysis to date of biodiversity and yield responses to farming system diversity based on data collected from the same control-treatment pairs. It is the first to consider interactions between biodiversity and yield and the probability of synergies and trade-offs in different agronomic and ecological contexts.

Targeting interventions to maximize synergies

We found that diversified farming systems lead to gains in biodiversity and/or yield in 80% of cases, adding to the body of evidence showing that diversification can provide benefits for nature and people (Beillouin et al., 2021; Rosa-Schleich et al., 2019; Tamburini et al., 2020). While some reviews suggest there is a strong potential for synergies between agronomic and ecological outcomes (Rosa-Schleich et al., 2019; Tamburini et al., 2020), in our study, synergistic positive outcomes for biodiversity and yield happened in less than a quarter of cases. One reason for this divergence may be that we focused solely on biodiversity and yield, and synergies may be easier to find when other or broader sets of ecological or agronomic outcomes are considered. For example, most of the synergistic outcomes in Tamburini et al. (2020) were between soil nutrient-related ecosystem services and yield.

While synergies between biodiversity and yield outcomes are not always possible, our results show they are the most likely outcome when combined diversification practices are used (e.g., integrated crop-livestock or crop-fish systems, or cover crops and intercropping employed together), no agrochemicals are applied, and in certain regions such as in Asia, or milder climates. Combining practices, for example intercropping and adding flower strips, or integrated crop-fish systems, are amongst the most promising of diversification strategies, leading to gains in both biodiversity and yield in 75% of cases in our study. This finding is consistent with previous studies (Beillouin et al., 2019; Rosa-Schleich et al., 2019) and may reflect that more complex vertical and horizontal arrangements better mimic natural habitat, thus enhancing ecological functioning and associated benefits (Boincean & Dent, 2019; Wilson & Lovell, 2016). Cases involving combined practices in our study were from experiments in the temperate forest biome (Appendix A: Fig. A.10) and further research is needed to confirm the effect for other regions. Regarding agrochemicals, our results show that zero use of pesticides and chemical fertilizers increases the likelihood that diversification has synergistic positive effects on biodiversity and yields, while applying agrochemicals is more likely to lead to yield gains and biodiversity losses. Many previous studies show that agrochemicals, and pesticides in particular, are associated with steep declines in species numbers (Sánchez-Bayo & Wyckhuys, 2019), including bees (Woodcock et al., 2016), birds and wild plants (Geiger et al., 2010). Removing agrochemicals will help halt these declines, and our results suggest coupling this with in-field diversification can safeguard and even increase yields. Where yield losses occur, evidence shows that diversification can help close yield gaps between organic and conventional farms (Ponisio et al., 2015) enabling farmers to maintain high yields while removing harmful chemicals from agricultural systems.

Across biomes and, across tropical to temperate latitudes, we found that positive synergies are the most likely outcome of on-farm diversification in Mediterranean and temperate biomes, while trade-offs are more likely in tropical and subtropical biomes mainly at the expense of yield. This result could be driven by a mix of environmental, climatic, and methodological factors. For example, not all diversification strategies are effective at boosting yields in regions where low soil fertility is a major limiting factor, as is common in tropical arable fields (Jeffery et al., 2017). This may explain the lack of yield gains under farmland diversification for experiments in the tropical grassland biome in our study. Here, boosting yields may require actions to improve soil fertility, such as intercropping with legumes, using nitrogen-rich cover crops, adding biochar and manure. The frequent positive biodiversity response to farmland diversification in temperate and Mediterranean biomes in our analysis may reflect bioclimatic differences in community composition and habitat dependencies of non-domesticated biodiversity. For example, in certain parts of the tropics, species may be at the limits of thermal tolerance (Sunday et al., 2014) and changes to vegetation cover on agricultural land, particularly if this does not add new shade cover, may not provide sufficient reprieve for these species (Williams et al., 2020). Land use history and current landscape complexities may also play a role and could also partly explain the variation in outcomes across continents. Evolutionary processes may not yet have had time to affect species assemblages in the relatively recently converted, more complex agricultural landscapes, in tropical regions (Hurtt et al., 2011), whereas species may be better adapted to the more simplified agricultural landscapes and to land use changes in regions where conversion to agriculture happened many centuries ago (Newbold et al., 2020). Different responses across biomes, continents, and latitudes, for both biodiversity and yield, may also reflect that the experiments in our database do not capture all diversification practices in every region and the included practices may not be the most effective at driving positive responses for the crops and taxon represented. For example, there were no experiments in our database on the effects of embedding natural vegetation on-farm in the tropical forest biome, and an absence of farms cultivating tree or perennial shrubs crops in the tropical forest and grassland biomes (Appendix A: Figure 9).

Trade-offs are often minimal making diversification a low-risk strategy

In our study, trade-offs (Win B-Lose Y or Lose B-Win Y) occur in 44% of cases yet less than half of these (20.2% of all cases) were associated with significant changes in both biodiversity and yield. This means that improvements in biodiversity often have either negligible or uncertain effects on yield, and vice-versa. Given the risk of significant losses is low, and there are numerous potential co-benefits of diversification for people and nature (Beillouin et al., 2021; Frison & Clément, 2020; Kremen et al., 2012), this result strongly suggests that diversification of farming systems is a better strategy than monocropping and other simplified farming approaches, for shifting towards sustainable production systems.

Trade-offs in our study involving yield losses were very likely when embedding natural vegetation on-farm (e.g., hedgerows, flower strips, introducing fallow periods), which positively affected biodiversity in 65% of cases but with yield losses in almost three-quarter (73%) of cases, including significant losses in nearly a quarter (24%). Embedded natural habitat at the farm and landscape level is recognized as globally important for maintaining healthy ecosystem functioning (Garibaldi et al., 2020). Our results support the notion that maintaining natural vegetation on farmland is an effective biodiversity conservation strategy, and show that this is not often associated with significant yield losses, yet careful planning will be needed to minimize and manage agricultural production losses in some contexts. Additionally, trade-offs where only biodiversity benefits were also very likely, happening half of the time, when diversifying tree cropping systems through agroforestry, use of associated plant species, or by embedding natural vegetation. However, only main crop yields were accounted for in the experiments in agroforestry systems and, while the number of cases was small (10 out of 70 cases), collecting whole system yields may reveal more win-win outcomes.

Enhancing farm and landscape outcomes through multi-objective planning

Conservation of biodiversity requires integrated solutions that improve conditions on-farm while safeguarding and restoring natural and semi-natural vegetation off-farm (Locke et al., 2019; Mokany et al., 2020). Our results show that diversified farming is highly likely to benefit biodiversity in certain situations, yet in others the benefits are not guaranteed. For example, diversification through intercropping increased yields in 86% of cases, while biodiversity benefited in only 39% of cases. This may reflect that while combining two or more crops can increase land productivity due to more efficient and complementary use of space and resources (Ponisio et al., 2015; Snyder et al., 2020), this does not necessarily improve ecological functioning or associated biodiversity if the crops have similar ecological traits (e.g., flowering stage and duration, canopy structure) (Wood et al., 2015). It also suggests that shifting to diversified farming systems to pursue production goals in isolation will not necessarily benefit biodiversity. Therefore, halting the erosion of existing diversified, often smallholder, farms and incentivizing a transition to more sustainable agricultural systems elsewhere will require repurposing policies, subsidies and investments to encourage and enable farmers to pursue both goals in tandem, while removing perverse incentives that promote simplified, unsustainable agriculture (Ding et al., 2021; FAO et al., 2021; OECD, 2021). Such repurposing efforts should recognize that farmer decisions to diversify are constrained by many factors including market opportunities, labour availability, and government policies (Schroth & Ruf, 2014) that need addressing to enable widespread adoption while helping farmers and rural communities to thrive.

For biodiversity, the benefits of diversified farming can be substantial and should not be overlooked at a time when taking action to halt biodiversity loss has become critical (Ceballos et al., 2017, 2020; Leclère et al., 2020; WWF, 2020). Our study suggests diversifying farming systems can have conservation value at the same time as benefiting agricultural production within a landscape. Diversification more frequently benefited both biodiversity and yield when biodiversity was measured in terms of species richness or richness-evenness, rather than abundance. Species richness and evenness are often more effective indicators of places of conservation value, because measures of abundance can remain stable while species richness and evenness vary greatly, for example between locations with similar numbers of common species (Bock et al., 2007). However, abundance can be positively correlated with species richness for some taxa, such as plants, grasshoppers, butterflies, birds and rodents in pasture and semi-natural grasslands (Bock et al., 2007). Abundance was the dominant biodiversity measure in our database and, while positive effects on abundance were much more common than a neutral or negative effect, trade-offs with yield were more likely than positive synergies. This is in part related to the fact that agronomic pests (representing 32% cases) were predominantly measured in terms of abundance, and where diversification increased pests (positive biodiversity response), this was often associated with yield losses, and vice-versa (Appendix A: Fig. A.10). While some pests may be invasive or over-abundant species and reducing numbers may be compatible with biodiversity conservation goals, often this is not the case. Some agronomic pests, such as birds, rely heavily on farmland habitat for their survival making it challenging to align agricultural production and biodiversity conservation goals (Garcia et al., 2020).

Our results suggest that biodiversity responses depend on organism functional traits, consistent with previous studies (Flynn et al., 2009; Gonthier et al., 2014; Shackelford et al., 2013). The positive response of below-ground biodiversity to diversification, and more variable above-ground biodiversity response, suggests it may be harder to positively impact above-ground biodiversity through on-farm diversification. Many above-ground species are mobile and landscape context may be a key driver affecting responses for these taxa (Gonthier et al., 2014; Lichtenberg et al., 2017; Monck-Whipp et al., 2018). Research shows that crop heterogeneity can positively affect biodiversity at the landscape level (Estrada-Carmona et al., 2022; Sirami et al., 2019) pointing to the scale-dependency of biodiversity responses. Achieving positive outcomes for biodiversity and yield therefore requires integrated planning strategies to increase diversity at both farm and landscape levels (Jeanneret et al., 2021).

Limitations and future research needs

New field experiments and expansion of the Jones et al. (2021b) dataset as new publications emerge would help close evidence gaps. While the dataset used in this analysis includes hundreds of comparisons, increasing the number of cases and studies for under-represented taxa, production systems, and regions, would enable more in-depth analyses and strengthen the findings. For example, temperate and tropical regions, certain taxa, including mammals, reptiles, amphibians, and soil organisms (fungi, annelids), were poorly (or not at all) represented. As these are the regions where agriculture covers the most land and expansion is happening fastest (Winkler et al., 2021), evidence gaps urgently need closing to help halt biodiversity loss. In terms of crops, our dataset included many experiments in cereal, fibre (cotton), fruit and vegetable cropping systems, which are important cash crops, while roots, tubers and pulses were under-represented despite their nutritional importance and reliance by many smallholder farmers. Cereal crop species in the dataset were dominated by maize, rice, sorghum, and wheat, while millet, barley, rye, and oats were missing.

Our analysis was constrained by the availability of studies reporting outcomes for both biodiversity and yield, in simplified and diversified farming systems. Inter-disciplinary experiments that collect data on agronomic, ecological, economic and human wellbeing outcomes are in short supply and experimental approaches are highly variable and often incomparable (Hufnagel et al., 2020). In intercropped and agroforestry treatments in our study, the lack of yield data needed to calculate land equivalent ratios may reflect the resource and technical challenges involved in conducting experiments that collect data on multiple outcomes and applying best practices to every measurement category (Brooker et al., 2015). Closing this gap through future field studies will be vital to enable evidence-based shifts towards agricultural practices that contribute to multiple objectives.

Conclusion

Intensive agricultural systems have contributed to exceeding planetary boundaries. Identifying alternative systems that meet agricultural production needs and simultaneously support biodiversity is a crucial issue for current and future generations. This study highlights the importance of carefully selecting agriculture diversification strategies to minimize trade-offs between ecological and agronomic objectives, and the potential risks of extrapolating biodiversity-yield outcomes across studies without considering contextual factors, particularly crop commodity, diversification practice, bioclimatic location, and outcome metric. In general, there is a decline in species abundance when yields increase under diversification, while effects on species richness and evenness appear more context dependant. We show that the overall likelihood of farming system diversification leading to a win-win is higher when combinations of diversification practices are implemented, no agrochemicals are applied, perennial woody crops are diversified, and in milder climates. Biodiversity is highly likely to increase when tree crops or woody fruit crops are diversified, or when natural vegetation is embedded into farming systems, and these situations rarely lead to significant changes in yield. Strategies that reward farmers who are already implementing diversified systems while enabling wider adoption of the most promising interventions should be integrated into agricultural production and biodiversity conservation policies to accelerate the shift to sustainable food and agricultural systems.

Author contributions

S.K.J. conceived of the study, and designed the study in consultation with all authors. A.C.S., S.D.J., S.K.J and N.E.C. conducted the article search, screening and data entry. A.C.S., D.B., S.K.J. and N.E.C. completed the data validation and quality control. S.K.J. conducted the analysis and wrote the first draft of the manuscript. All authors reviewed and edited the manuscript.

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.

Acknowledgments

We are grateful to David Makowski and Fabrice DeClerck for excellent suggestions that improved the data analysis. We thank two anonymous reviewers for their constructive inputs. This work was supported by the CGIAR Research Program on Water, Land and Ecosystems as part of the *Sustainable Foods through diversity-based practices* project, and the OneCGIAR Nexus Gains initiative as part of the *Agrobiodiversity Index* project.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.baae.2022.12.005.

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