Benefits of crop diversification for biodiversity and ecosystem services

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Abstract

Increasing the diversity of cultivated crops, species or cultivars is expected to help preserve biodiversity and enhance ecosystem services in agricultural landscapes. But individual local experiments evaluating crop diversification practices and even meta-analytical synthesis of experimental studies are scattered in their scope, quality and geographical focus. In an effort to make sense of this trove of information, we integrate the results of 5,662 experiments representing more than 48,600 paired observations over 80 experimental years, through the compilation of 83 meta-analyses covering more than 120 crops and 85 countries. The diversification strategies analyzed in the literature are diverse and are here regrouped into five broad categories (i.e., agroforestry, associated plants, intercropping, crop rotation and cultivar mixture). Our exhaustive literature synthesis shows that overall, crop diversification significantly enhances crop yields (median effect +13%), associated biodiversity (+24%), and several ecosystem services including water quality (+84%), pest and disease control (+63%), and soil quality (+11%). While these aggregated global results support the many benefits of adopting more diversified cropping systems, we also identified high variability between meta-analyses for most of the diversification practices examined. This strong global heterogeneity highlights the importance of contextual information about agricultural diversification for local decision-making. Our global database provides important insights into the contextual performance of crop diversification practices that can provide this needed guidance to agricultural and environmental decision-making.

Keywords: meta-synthesis, agroforestry, crop rotation, agrobiodiversity, ecosystem services, research synthesis

Main

Throughout the 20th century, driven by productivity-oriented incentives, agricultural practices have converged in many parts of the world towards a strong simplification of agro-ecosystems, landscapes and agronomic practices[1]. While intensive agricultural practices are a major contributor to the crossing of several planetary boundaries[2], a large array of solutions to more sustainable farming systems has been proposed to ensure adequate food availability while minimizing the environmental impacts of food production[3]. Crop diversification, emerging as a cornerstone in this debate[4], is proposed to have far-reaching positive impacts on agro-biodiversity, landscapes but also supply chains and food trade[5]. The growing popularity of this concept is reflected in an exponential increase in the number of experiments and meta-analyses on a large variety of crop diversification strategies (Fig 1a). But while more diverse cropping systems are often proposed as a promising solution to more sustainable agriculture in theory[6], the actual rate of adoption of more diversified agriculture in practice is still rather low[7,8]. This is caused not only by a persistent focus of agricultural policies on the single dimension of production, but also by a lack of robust scientific evidence on the potential ecological and economic benefits of crop diversification. Several qualitative syntheses[9–12] have developed narratives on the expected performances of such systems. But, these are based on non-systematic literature searches; most often do not quantify the available evidence nor look to meet the standards of evidence-based science[13,14]. One important limitation is that the fast-growing body of evidence available on the impact of crop diversification practices in the scientific literature tends to be fragmented and of heterogeneous quality[14]. The concept of crop diversification also remains itself poorly defined which further limit the quality and transparency of the scientific debate[6].

To make progress, we collated the findings of 83 meta-analyses published since 1994, synthetizing the experimental results since 1936, on the impact of five, well-delineated crop diversification strategies (i.e., agroforestry, associated of non-productive plants -hereafter called associated plants, cultivar mixture, crop rotation and intercropping- Extended Data T1). Our dataset includes the results of 5,662 experiments equivalent to 48,600 paired observations, spanning more than 120 crops and 85 countries in Africa, America, Asia, Europe, and Oceania. It cover a broad range of ecosystem services: agricultural production (37 meta-analyses and more than 21,000 experiments- Extended Data T2), soil quality (31; 12,000 experiments), pest and disease control (12; 3,100 experiments), associated biodiversity (12; 4,800 experiments – associated biodiversity refers to biodiversity of non-crop species), water quality (10; 1,500 experiments), and greenhouse gas (GHG) emissions (7; 1,300 experiments), input use efficiency (4, 950), product quality (3, 1807), profitability (2, 120), Yield stability (1, 366). We selected only the experiments containing both a side-by-

side comparisons between a diversified and a less-diversified counterpart and quantitative data. The quality of selected meta-analyses (Extended Data F1-2, T3 and their redundancy (i.e., how many common primary studies are shared between distinct meta-analyses - Extended Data F3). were assessed, and their effect sizes were subjected to a weighted second-order meta-analysis (see method).

If we consider all diversification strategies together, diversified cropping systems provide significant benefits for the majority of the ecosystem services analyzed (Fig 2.a, Extended Data Excel): improved water quality (median effect estimate equal to + 84%; 95% confidence interval CI: 35, 151%), more efficient pest and disease control (+63%; CI: 31, 103%), higher associated biodiversity (+24%; CI: 13, 37%), better soil quality (+11%; CI: 7, 16%) and higher production levels (+13%; CI: 7, 19%). Our results reflect the positive effects expected at higher biodiversity levels from experiments in natural ecosystems[15] and are in contrast to the proposition that an increase of biodiversity in agricultural systems leads to a yield penalty[16,17]. Ecosystem services typically show complementary or synergistic effects on crop yield[18,19]. However, our results are less conclusive for water-use (+20%; CI: -2, 46%). While for GHG emissions, input use efficiency, product quality and profitability only limited evidence was available (Extended Data F4-5) with both somewhat positive (i.e., improved input-use efficiency, quality) and somewhat negative results (higher GHG emissions, reduced profitability). Our results are robust to the type of statistical model used and to publication bias (see Extended Data F6-9).

When examining different diversification strategies individually, we see, however, that these do not all have the same level of performance. Production benefits depend, for example, on the crop diversification strategy. For example, the two strategies relying on the simultaneous cultivation of different species within one field (i.e., agroforestry and intercropping) strike out as significantly improving crop production (+35%; CI: 11, 65%; +22%, CI: 12, 34%, respectively; see Fig 2.b). Crop rotation, i.e., alternating single crop-species over time, leads to a median increase of 15%, (CI: 11, 20%) in production levels. Association of non-productive plants (+6%; CI: 1, 11%) and cultivar mixture (+2%; CI:1, 3%) promote modest yield improvements compared to more simplified systems. These results possibly reflect the degree which each diversification strategy increases the diversity of functional traits within a system[20,21]. Greater trait diversity increases both the magnitude and stability of ecosystem functioning [22,23].

The increases in biodiversity are particularly strong for agroforestry (+60%, CI: 27, 102%), crop rotation (+37%; CI:17,60%) and associated plants (+19%, CI: 12, 25%), strategies

favoring highly heterogeneous and non-crop habitat diversity. This is true in more than 80% of the estimated effect-sizes for species richness, evenness and taxa diversity (Fig 3, Extended Data F10). Intercropping and variety mixture are, on the other hand, associated with smaller or non-significant effects on associated biodiversity (+7%; CI: 3,12% and CI: 2; -12,18%, respectively). By detailing precise impacts of various agricultural practices on biodiversity, our results complement those of Newbold and co-authors[24] obtained for very broad types of land management.

A significant increase in pest and disease control is estimated for intercropping (+66%; CI: 42, 96%), associated plants (+125%; CI:83,177%), and agroforestry (+59%; CI: 40, 81%) (Fig 2.b). These impacts could be driven by an increased canopy complexity providing refuges to natural enemies[25,26] (Fig 4), or reducing the spread of diseases[27]. The relative contribution of each of the above-mentioned mechanisms are difficult to untangle because of sparse evidence[28]. Pest and disease control may certainly contribute to the significant yield gains observed in our analysis and this benefit of more diversified cropping systems is of particular importance in the face of climate change, as crop losses due to pests and diseases, estimated at 5 to 30% for major grain crops, are expected to further increase with climate change[29,30].

Soil quality and water quality are significantly improved for all the documented strategies (Fig 2b, Extended Data F11-12). These effects are particularly strong for agroforestry and intercropping (+19%; CI: 16, 23% and +12%; CI: 6, 18% respectively for soil quality; +100%; CI: 51, 164% and +89%; CI: 19, 198% respectively for water quality).For example, agroforestry leads to a higher soil nitrogen content (+23%; CI:15, 34%), higher levels of other nutrients (+17%; CI: 8, 27%) and better water infiltration, drainage and runoff (+75%; CI: 63, 93%). These effects may be induced by higher soil biological activity and an improved soil structure (Fig 4). Our synthesis thus confirmed the well-documented role of agroforestry in enhancing and maintaining long-term soil productivity and quality[31]. Note that other diversification strategies are also associated with significant positive effects: crop rotation, in particular, increases soil nitrogen content (+54%; CI: 21, 97%), other soil nutrients (+55%; CI 39, 72%) and also water drainage and infiltration (+17%, CI: 7, 31%).

In contrary to other ecosystem services, diversification strategies show variable climate mitigation potentials. As diversified systems tend to produce more biomass than simplified systems (Fig. 2), a positive effect on carbon storage potential is expected. Increased above and below plant litter favor the formation and accumulation of soil organic carbon (SOC) . Simultaneously, agronomic practices such as crop residue management (e.g., incorporated into the soil or exported) or soil tillage modify soil carbon storage dynamics[34]. We find that

agroforestry (+21%; CI: 13, 31%), intercropping (+21%; CI: 11, 32%) and associated plants (+14%; CI: 10, 18%) contribute significantly to carbon sequestration in agricultural soils (see Fig 4, Extended Data F13). On the contrary, crop rotations show a negative but highly uncertain average effect on carbon sequestration (-30%; CI: -12, +78%), and crop cultivar mixture has a small and non-significant impact on carbon sequestration (+8%; CI: -3, +21%). Nitrogen cycling is also affected by crop diversification. For example, intercropping improves nitrogen use-efficiency (+20%; CI: 0, 42%), alleviating the need for synthetic inputs and associated nitrous oxide emissions. These results, as those for others strategies, are hampered by a relative scarcity of meta-analyses on the impact of diversification on nitrogen use-efficiency (Extended Data F4-5). But, increased soil cultivation frequency, for example as expected from cover-cropping (here grouped in the associated plants category) may on the other hand increase GHG emissions[35]. We find that associated plants have a small negative effect on GHG emissions reduction (-29%; CI: -49, -2%) and that this impact is non-significant for crop rotation (2%; CI: -12, +18%).

While confidence intervals reflect the uncertainty in the estimated mean effect-sizes, prediction intervals (PIs) describe the variability of the results obtained in individual experiments. Large discrepancies between individual experiments and the overall mean translate into large prediction intervals. Here, because we perform a synthesis of meta-analyses, PI express a between-meta-analyses spread. In our study, we find that PIs are wide (e.g. Fig 2) and heterogeneity statistics (I2) higher than 75% (Extended Data T2) indicating important discrepancies between meta-analyses. This result theoretically downplays the generality of the results of any given diversification meta-analysis. In other words, the large heterogeneity measured here and the wide PIs imply that the benefits of crop diversification are not consistent over all bioclimatic conditions and diversification practices.

This heterogeneity is partly due to the broadness of each diversification category. For example, agroforestry is a terminology encompassing a large variety of systems (i.e., silvo-pastoralism, shaded perennial-crops, hedgerows, parkland, alley cropping or sub-tropical fallow)[31,36]. The effects of agroforestry on crop yields are here both significantly positive, on average, and highly variable across meta-analyses (+35%; CI: 11, +64%; PI: -41%, +208%). This variability reflects both the variable results observed for different sub-systems (i.e., -24% for perennial shaded systems; +11% for hedgerows; +47% both for alley cropping and parklands, see Fig 3) and the variability between environmental conditions of a given sub-system. Note that we only considered the production of the main crop in agroforestry systems, i.e. we do not include fibers, fruits or leaves of woody-crops. It is important to note

the highly contrasted conditions covered (i.e., a variety of climates, soil characteristics – Fig 1b, crop species or taxa, landscapes, practices and initial diversification levels of the control plot.). These intricate levels of variability and their sources are also observed for the other four diversification strategies studied here.

A finer analysis of different types of impacts within each broad category (for example, a separate analysis of biodiversity for different groups of organisms) allows for a better and more nuanced understanding of the potential benefits of crop diversification (Fig 4). For example, the overall effect of crop diversification on biodiversity relies on consistent significant positive effects on the fungi (+41%, CI: 29-53%), animalia (38%, CI: 11-72%) and bacteria kingdoms (14%, CI: 9-18%)**.** Similarly**,** the overall positive effect of crop diversification on pest and disease control is based on a strong significant positive effect on natural enemy abundance (54%, CI: 23-93%), disease control (41%, CI 15-73%), a decrease in plant damage (63%, CI: 37-92%), and on a non-significant impact on pest control (33%, CI: -14%-106%).

Our work allows identifying agricultural practices that effectively reduce air, soil and water pollution, reduce greenhouse gas emissions and increase biodiversity and crop production. It is based on robust scientific evidence emerging from thousands experiments and observations carried out around the world. This exhaustive and quantitative review of the literature, by precisely depicting the evidence on crop diversification practices at the planetary scale, provide robust information for policymakers responsible for evaluating and validating agricultural and environmental public policies all over the world. These results can thus contribute to the new "Green Deal" that sets clear goals for the European food system to become a global standard for sustainability, i.e. safe, nutritious and meeting high environmental production standards[37]. At the planetary scale, they can also contribute to help the Food agricultural Organization (FAO) monitoring and orientating policies towards Sustainable Development Goals and help to contribute the ongoing land sharing-land sparing debate in the international policy arenas[38]. Indeed, with caution, our results support the hypothesis of win-win effects of crop diversification on yields and biodiversity. We anticipate our method and results to be a starting point for developing golden standard evidence-based assessments for other agricultural practices or in other fields of research.

Methods

Data collection and extraction

We conducted a systematic search of the peer-reviewed and gray literature for meta-analyses publications investigating the effects of crop diversification on May 2019, and updated the search in September 2020 using Web of Science, CAB abstract, Greenfile, Environment Complete Database, Agricola and Google Scholar. The search equation was defined as follows: *(meta-analysis OR meta analysis) AND (cropping system OR crop* OR agriculture) AND ((rotation OR Diversification OR intercrop* OR cover crop OR mixture) OR (organic AND (system OR agriculture)) OR (conservation AND (system OR agriculture)) OR no till* OR agroforestry OR agroecology).* The search was performed on the article title, abstract and keywords, with no restriction on the date of publication. We also screened the references cited in each selected meta-analysis.

This search produced a total of 717 publications (duplicated removed – see Extended Data F14), which were screened on the basis of the following criteria: (i) study dealing with at least one crop diversification strategy (defined in table S1) (ii) meta-analysis reporting the results of a quantitative analysis based on several primary experiments, (iii) study including control plots (less diversified systems) adjoined to treatment plots (with the implementation of at least one diversification strategy). (iv) the meta-analysis express the results as ratios (or similar metrics) and present indicators of variability of the results. Studies dealing with pure forestry or wood production were excluded. Based on these criteria, 83 meta-analyses were selected.

All the effect sizes reported in the selected meta-analyses, i.e all quantitative measures of the effects of crop diversification strategies compared to a reference (less diversified) cropping system, were extracted with their confidence intervals or other indicators of dispersion, and the sample sizes. All effect sizes were expressed as ratio of performances of diversified *vs.* less diversified systems, in order to ensure the comparability of the results. Relative differences and Hedge's metric were converted into ratio, following Borensetein[39]. The definitions of all outcomes (e.g. Land equivalent ratio, yield, soil water content, soil water budget) were precisely documented. Outcomes were then grouped in 10 general categories, e.g., production, soil water (see Fig 2). Data was extracted from text, table or figure using Plot Digitizer (http://plotdigitizer.sourceforge.net/).

Different meta-analyses could be partly based on the same pool of individual experiments. To avoid over-representation of redundant experiments, we retrieved all the references of primary studies to calculate the level of redundancy between each pair of meta-analyses, and then include it in our meta-analytical model (see *DataAnalysis section*).

The meta-analyses differ in the quality of the methodology used to retrieve the primary study and analyze the data. To lower the importance of low-quality studies in our analysis, we calculated a quality score, based on 20 criteria as a proxy of their internal quality (see Extended Data F1-2), and integrate it in our meta-analytical model (see *Data Analysis section*).

Data analysis

The objective of our statistical analysis is to conduct a second-order meta-analysis[40] to estimate the global impacts of the various crop diversification strategies on each of the outcomes reported in the literature. The analysis is performed with a weighted mixed model including a random effect associated with the different studies (defined by the ID of the published first-order meta-analyses), and a random effect associated with the ID of the diversification scenarios (i.e., diversification strategy*environmental condition) considered in each study. The random effect allows for the heterogeneity between the different studies and between the scenarios within studies included in our database. We weighted each study according to the variance of the effect-size, but also performed an adjustment of the model variance based on our quality appraisal [41]. This translates into giving less weight to studies of lower quality, or to effect-sizes with large uncertainties. According to [41] this approach is robust to subjectivity in quality assessment. Finally, we also considered the possible redundancy of primary studies across meta-analyses (see Extended Data F3), through a variance-covariance matrix, adapted from [42]. In brief, the covariance was estimated based on the level of redundancy (i.e. a proxy of the correlation) of primary studies between each pair of meta-analyses. This latter was estimated as $\frac{2\times m}{n1+n2}$, where m is the number of common primary studies between each pair of meta-analyses, and n_1 and n_2 are the total number of primary studies in the two meta-analyses, respectively. The parameters of the model were estimated by restricted maximum likelihood using the R lme4 package. We used log-transformed ratio for performing the statistical analyses, but for ease of interpretation, all results were back-transformed and reported as percentage change to the less diversified systems.

Uncertainty was analyzed by computing 95 % confidence intervals and 95% prediction intervals. The prediction interval predicts in what range a future study will fall, while the confidence interval shows the likely range of values associated with the mean effect size. To estimate the robustness of our results against publication bias, we calculated the Rosenthal fail-safe number[43] using the metafor package[44] and plotted funnel plots (see Extended Data T1, F8). We also analyzed the robustness of our results to the type of model used (with or without random effect), the type of random effects included in the model (ID meta-analysis and scenario vs. only ID meta-analyses), and the potential impact of quality of the results (model considering quality of the meta-analyses or not). All statistical analyses were conducted with R[45] (version 3.0.2).

Contribution:

DM, TBA and DB participated in the design and the coordination of the study. DB performs the data collection, with the help of DM and TBA. DB performed the statistical analyses with the help of DM, and designed the figures. DB wrote the draft, all authors provided critical feedback and contributed significantly to the writing.

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Competing interests

The authors declare no competing interests.

Data availability statement

The data that support the findings of this study are openly available in the supplementary materials.

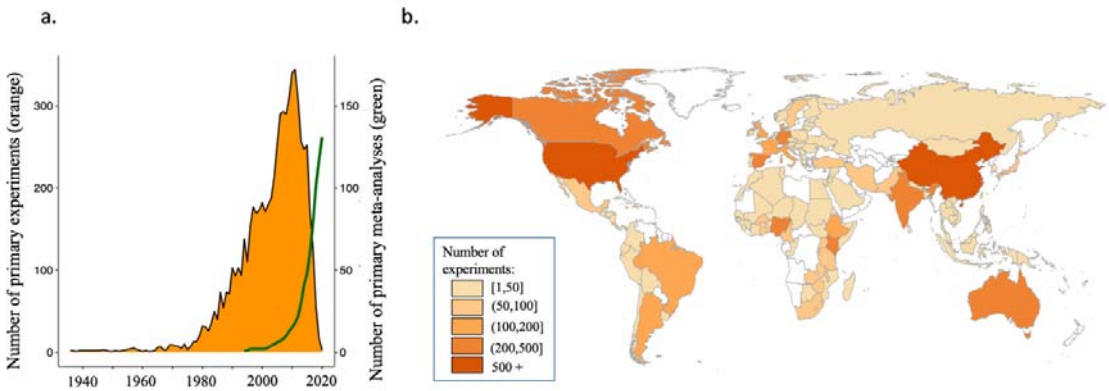

Figure 1. **Temporal and spatial count of the 5,662 primary studies summarized in our dataset**. Each primary study estimates the effect of one or several diversification strategies on biodiversity, ecosystem services or profitability. (a) Time series of the publication dates of each primary study is shown in orange (left axis) and the publication year of the meta-analyses that collected them as a green line (right axis). (b) World map of the location of each primary study, circle sizes indicates the number of primary studies in each country.

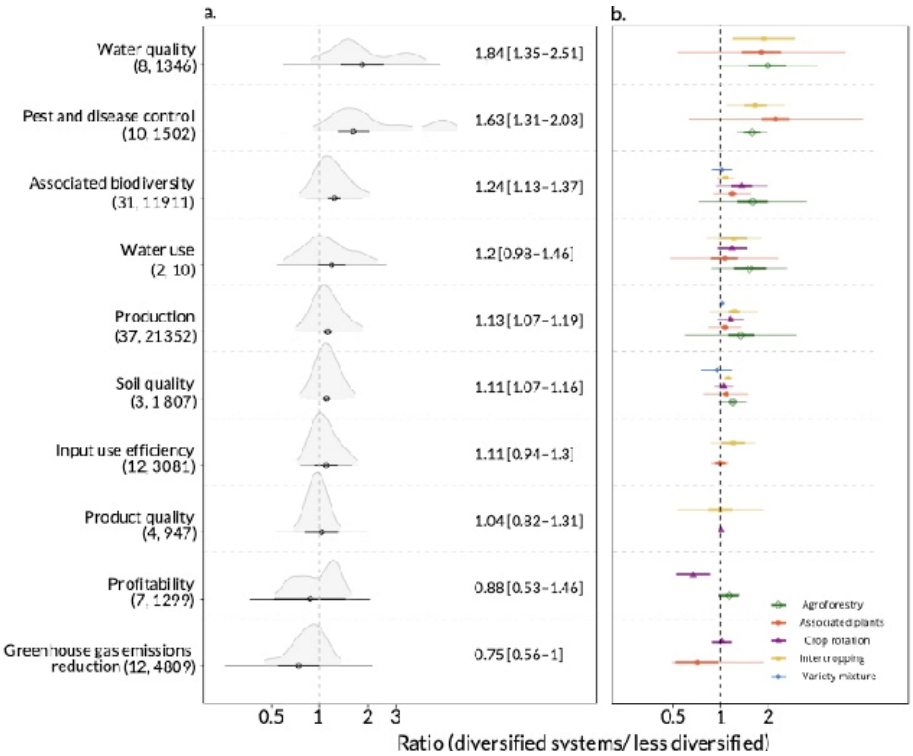

Figure 2. **Summary effects of the performances of crop diversification**.

The y-axis corresponds to our ten biodiversity, ecosystem services and profitability criteria. The number of meta-analyses and of paired observations is displayed in parentheses below each criterion. (a) Probability distribution of the compiled effect-sizes of the primary meta-analysis in our dataset for all diversification strategies together (grey shaded area). Points, thin lines and thick lines represent the estimated median summary effect, 95% confidence intervals, and 95% prediction intervals, computed from a weighted mixed effect model. Number on the right hand side indicate the median and 95% confidence intervals. (b) Median summary effect, 95% confidence intervals, and 95% prediction intervals, computed from a weighted mixed effect model, detailed for each crop diversification strategies when applicable.

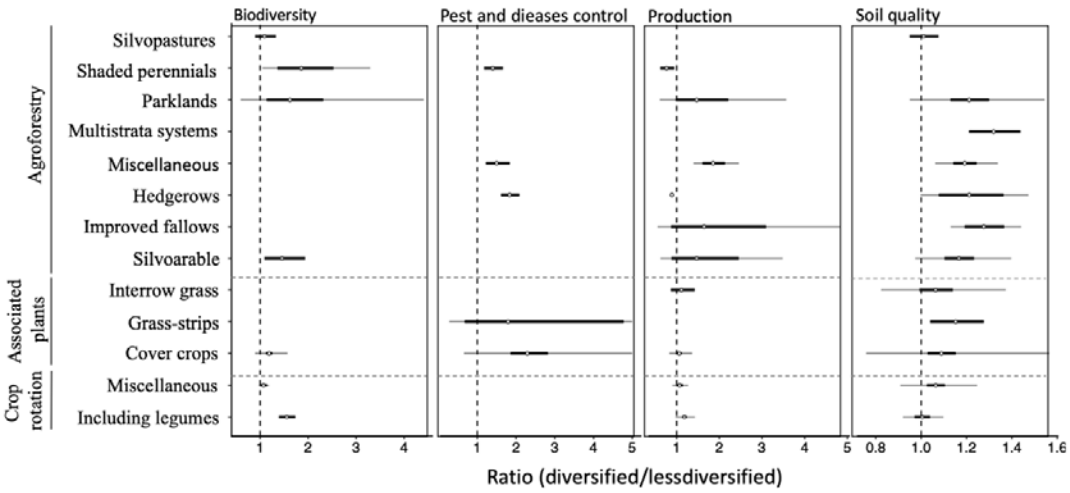

Figure 3. **Detailed impacts of agroforestry, associated plants and crop rotation detailed impacts on biodiversity and ecosystem services.** The y-axis presents specific management practices for these three crop diversification categories and their estimated impacts on biodiversity, pest and disease control, production and soil quality. Points, thin lines and thick lines represent the estimated median summary effect, 95% confidence intervals, and 95% prediction intervals, computed from a weighted mixed effect model. All quantifications are available in Extended Data Excel

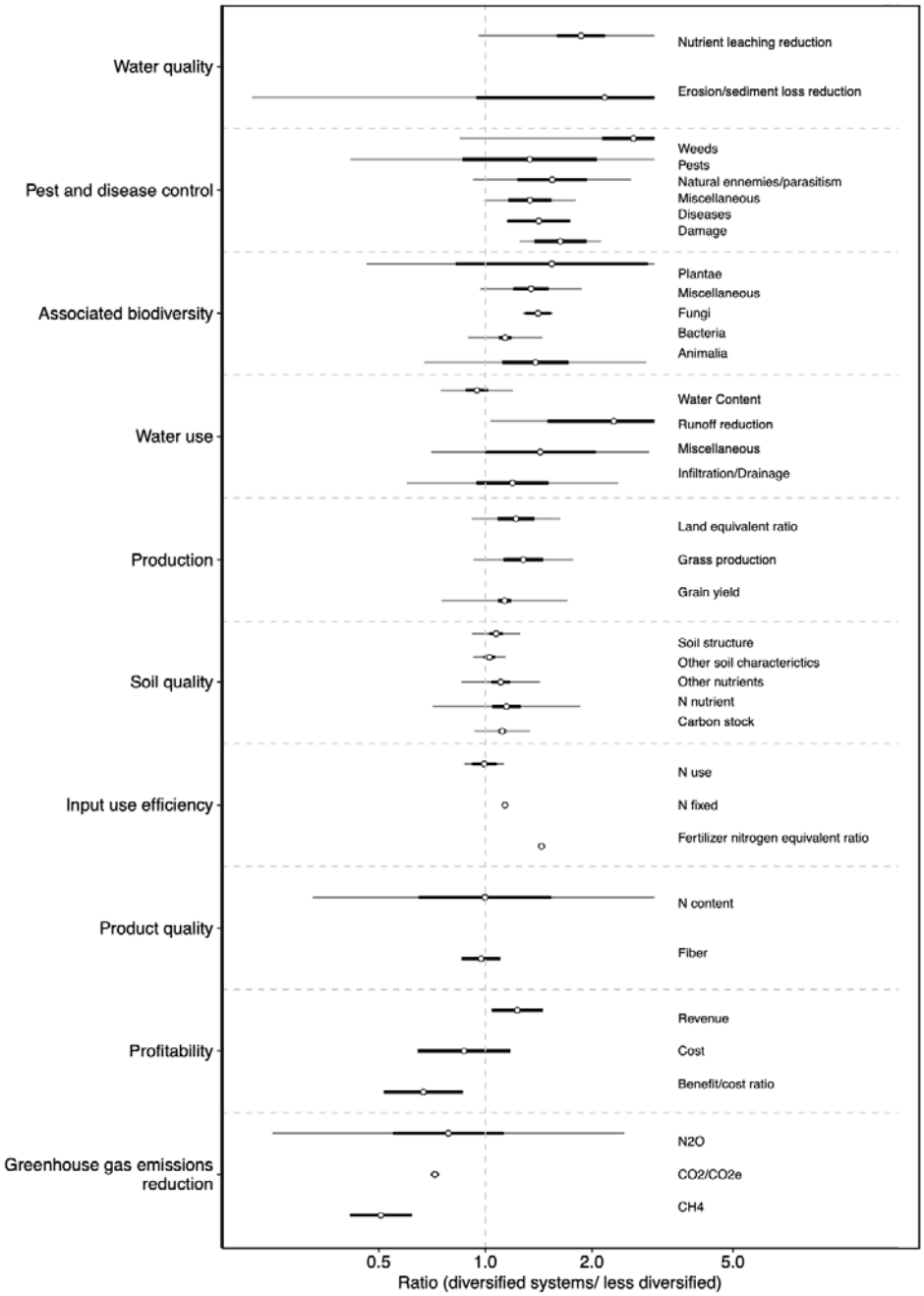

Figure 4. **Detailed summary effects of the impacts of crop diversification on biodiversity, ecosystem services and profitability**. The y-axis corresponds to the ten biodiversity, ecosystem services and profitability criteria considered in our study. These criteria are developed, according to the effect-sizes informed in the 83 primary meta-analyses, to two to six specific indicators (e.g., water quality is measured via nutrient leaching and sediment loss). Median summary effect, 95% confidence intervals, and 95% prediction intervals, computed from weighted mixed-effect model, detailed for each indicator when applicable.

Values higher than are not displayed on the figure. All quantifications are available in Extended Data Excel

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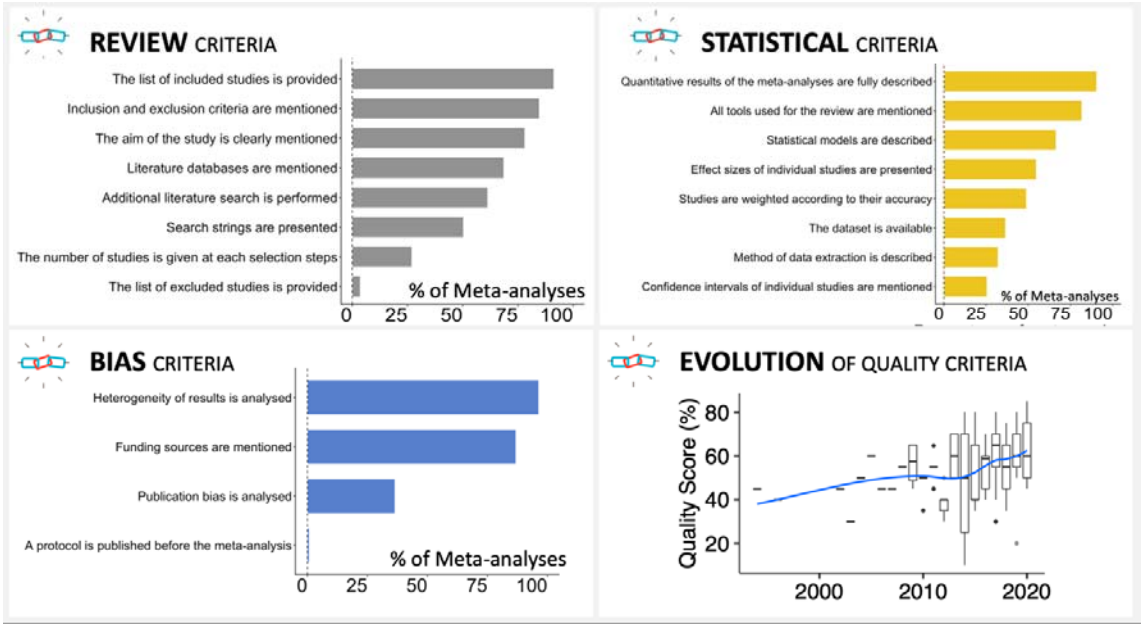
Supplementary materials

Figure S1. **Detailed quality score for each of the 20 individual quality criteria and evolution of the quality across time.** Quality criteria are organized in three main groups: review criteria (grey bars), statistical analyses (yellow bars) and bias (blue bars). The quality score represents the proportion of criteria met. Precise description of quality items are



available in Table S3.

Figure S2. **Boxplot of the quality score for each diversification strategies.** The quality score represents the proportion of individual quality criterions met. Precise description of quality items are available in Table S3.

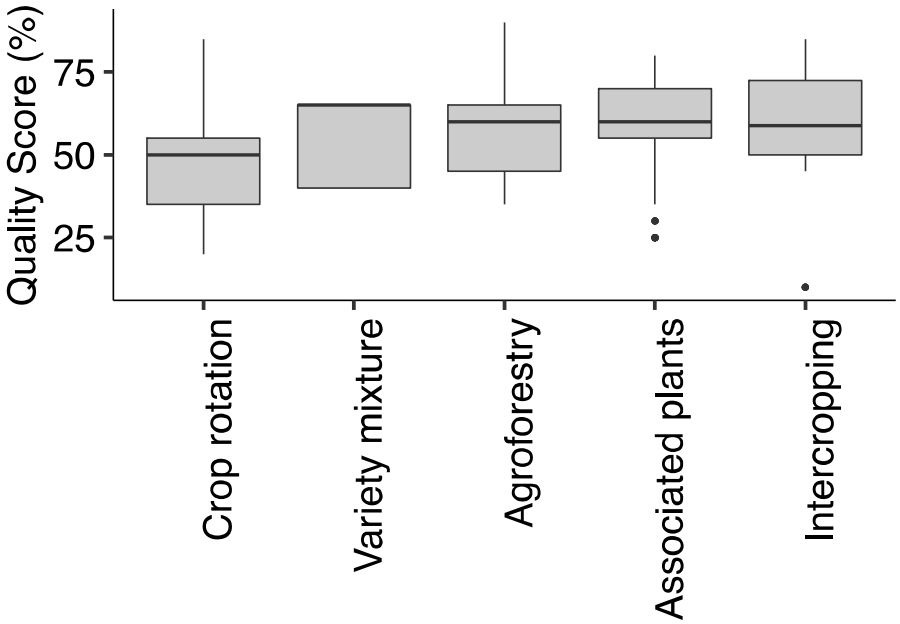


Figure S3. **Apparent redundancy of primary studies among meta-analyses.** Results on the x-axis are expressed as fractions of common primary studies in two meta-analyses. Note that two meta-analyses with large set of common primary studies can analyses different ecosystem services, and thus do not provide redundant information.

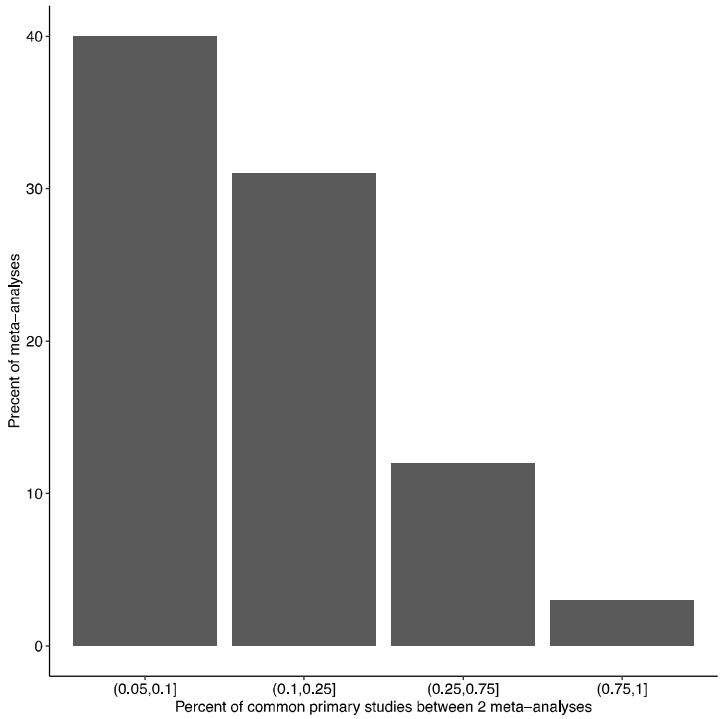


Figure S4. **Available evidence of impacts of the various crop diversification strategies on the biodiversity, d**

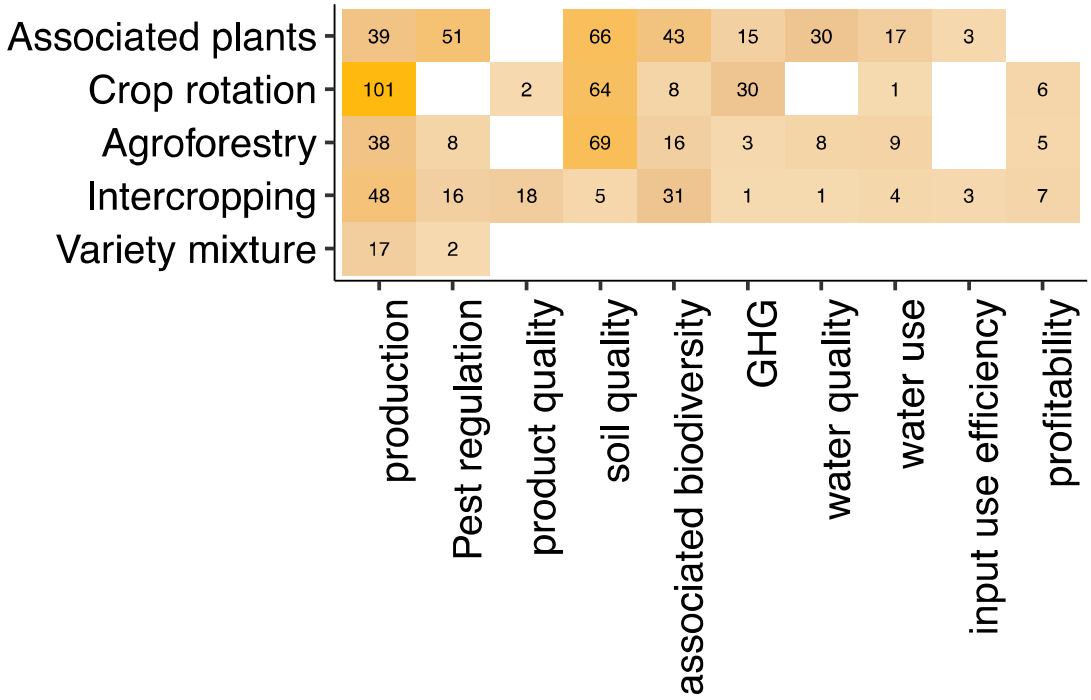
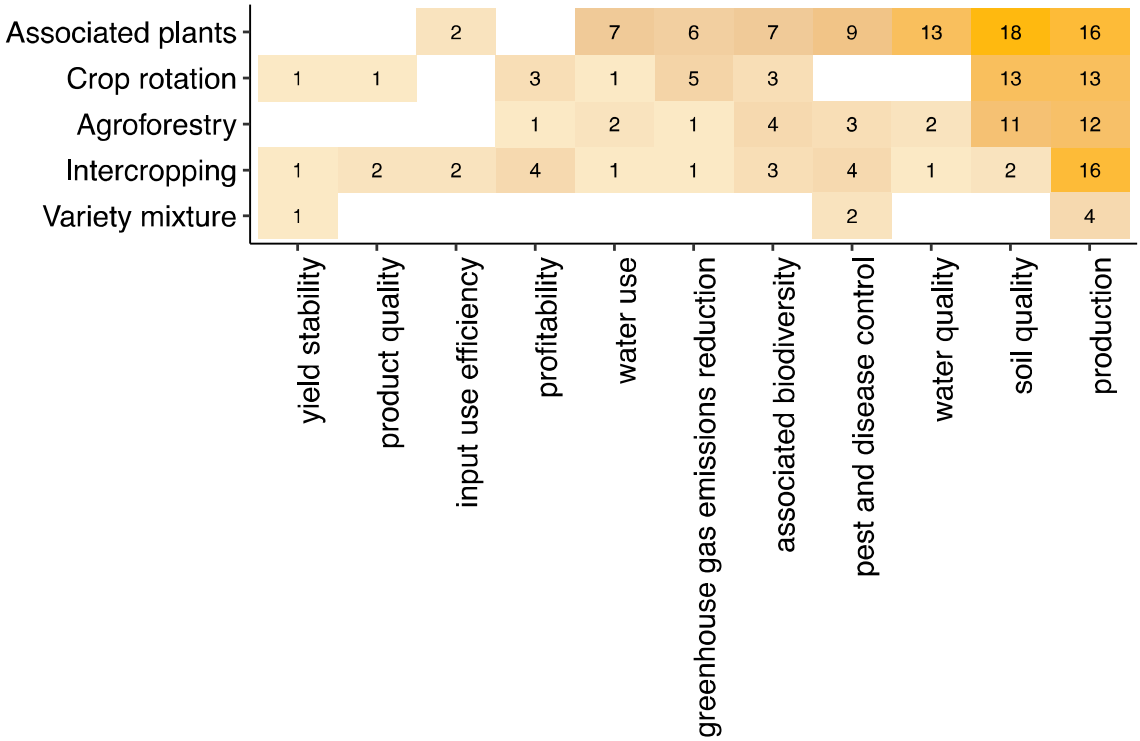


Figure S5.

Available evidence of impacts of the various crop



diversification strategies on the biodiversity, ecosystem services and profitability. Numbers indicate the number of meta-analyses.

Figure S6. **Analysis of the impact of potential publication bias.** The mean effect-sizes calculated with a random effect model (ID and scenario as random effects) are plotted against the same effect-sizes calculated with the trim and fill method (see *Duval et al., 2000* for further details). Blue points indicate significant egger tests (p-value <0.005). Results are presented for the five strategies of crop diversification on the main ecosystem services. For details on the few categories presenting significant egger test, see Fig figure S8, S9.

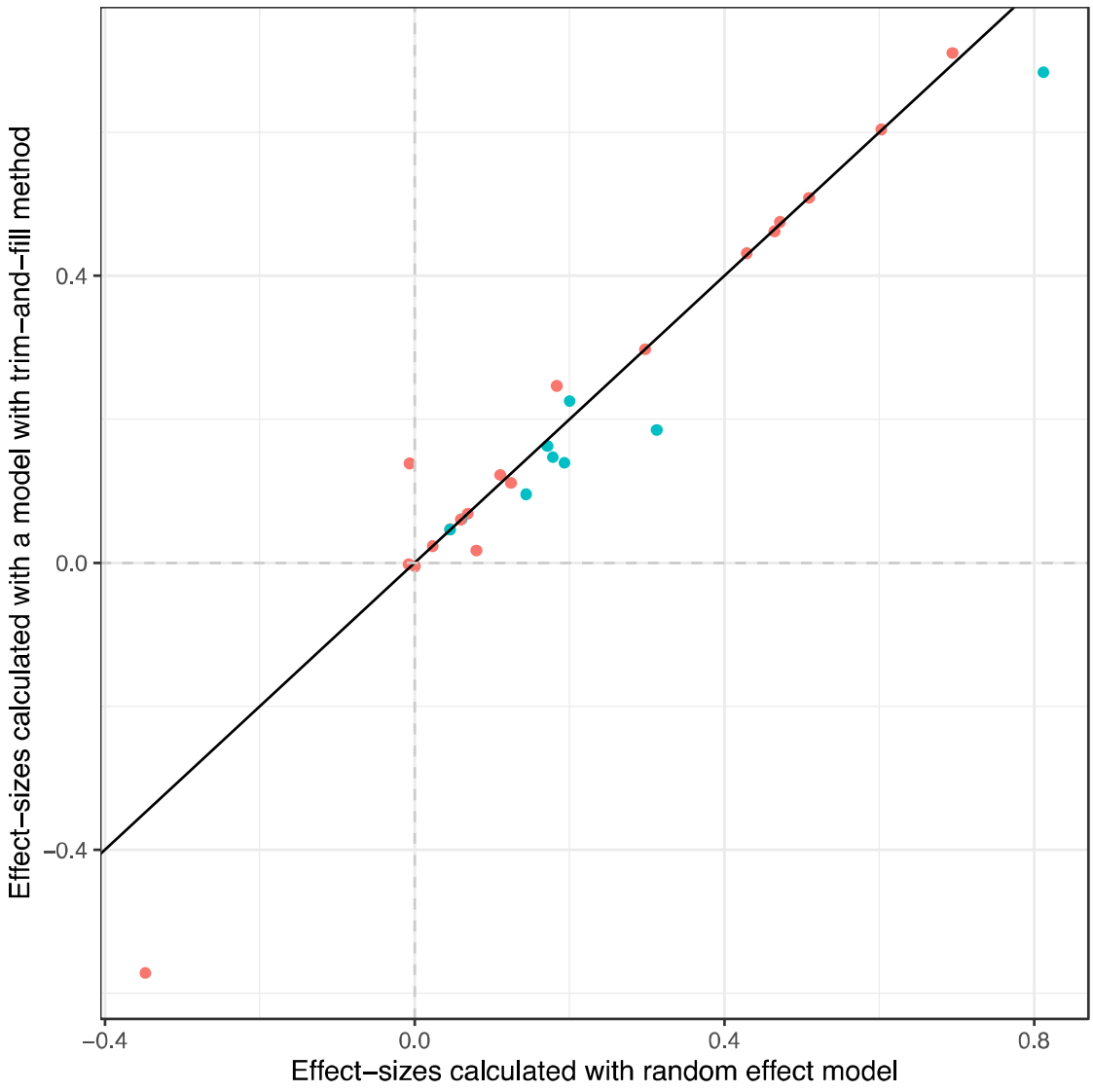


Figure S7. **Analysis of the potential impact of the quality of the meta-analyses.** The mean effect-sizes calculated with a random effect model (ID and scenario as random effects) are plotted against the same effect-sizes calculated considering the quality of each meta-analyses in the random effect model (see *Doi et al., 2005* for further details). Blue points indicate significant egger tests (p-value <0.005). Results are presented for the five strategies of crop diversification on the main ecosystem services.

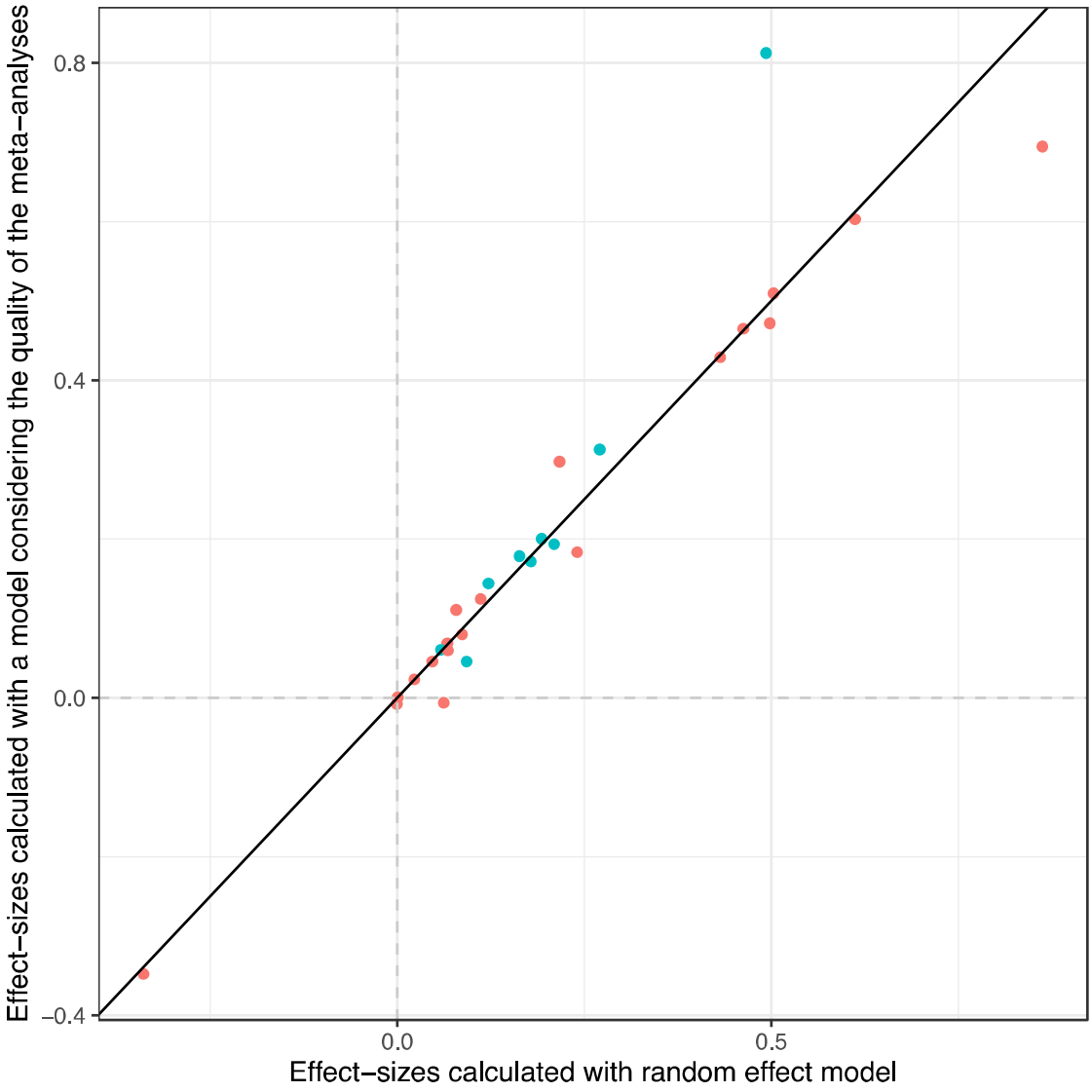


Figure S8. **Funnel plot of the impacts of agroforestry on soil quality.** The funnel plot represents a scatter plot of the intervention effect estimates from the primary meta-analyses against their precision (white points). The outer solid lines indicate the triangular region within which 95% of studies are expected to lie in the absence of both biases and heterogeneity. The solid vertical line corresponds to the estimated effect of the intervention. The dashed-red line represents the Egger's regression line. Significance contours (for the 5% and 1% level) and 95% confidence contours (fixed effect model) are shown in shaded gray. Plot are created with metaviz package (*Baumer et al., 2009*)

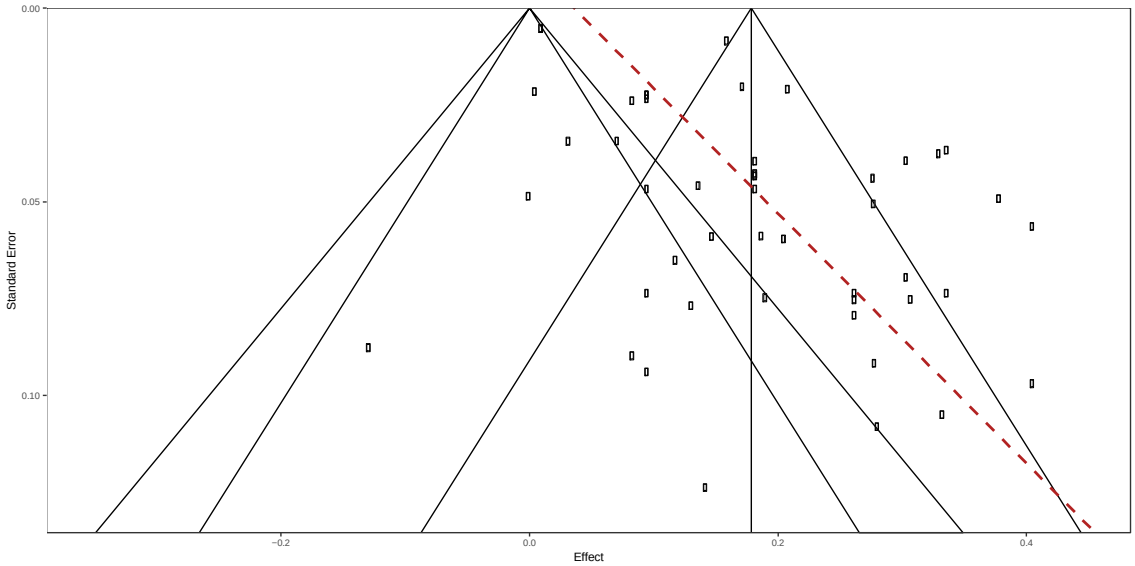


Figure S9. **Forest plot of the impacts of agroforestry on soil quality.** Points, and thin lines represent the estimated mean value of the effect, its 95% confidence intervals of individual effect-sizes collated from the primary meta-analyses. Light and dark shaded area represent the 95% confidence and prediction intervals of the second-order meta-analysis, respectively, calculated with a random effect-model.

The number on the left of the plot represent the number of paired-data used to calculate each effect-size in the primary meta-analyses. The colors of the points indicated the quality score of the primary meta-analyses. Effect-sizes are expressed as log(ratio)

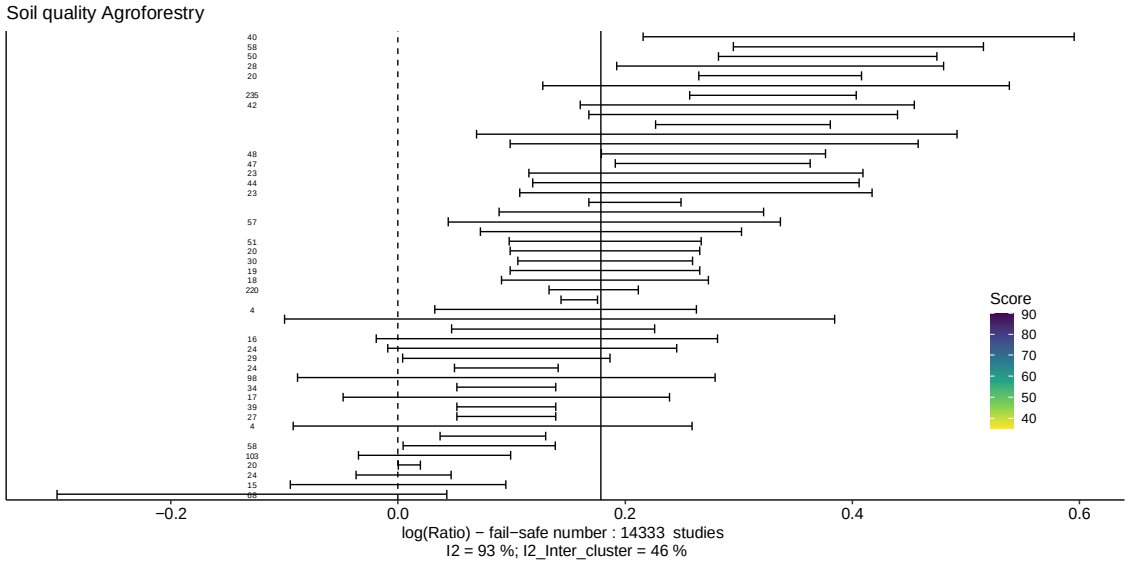


Figure S10. **Forest plot of the impacts the various crop diversification strategies on the associated biodiversity.** Points, and thin lines represent the estimated mean value of the effect, its 95% confidence intervals of individual effect-sizes collated from the primary meta-analyses. Light and dark shaded area represent the 95% confidence and prediction intervals of the second-order meta-analysis, respectively, calculated with a random effect-model. The number on the left of the plot represent the number of paired-data used to calculate each effect-size in the primary meta-analyses. The colors of the points indicated the quality score of the primary meta-analyses. Effect-sizes are expressed as log(ratio)

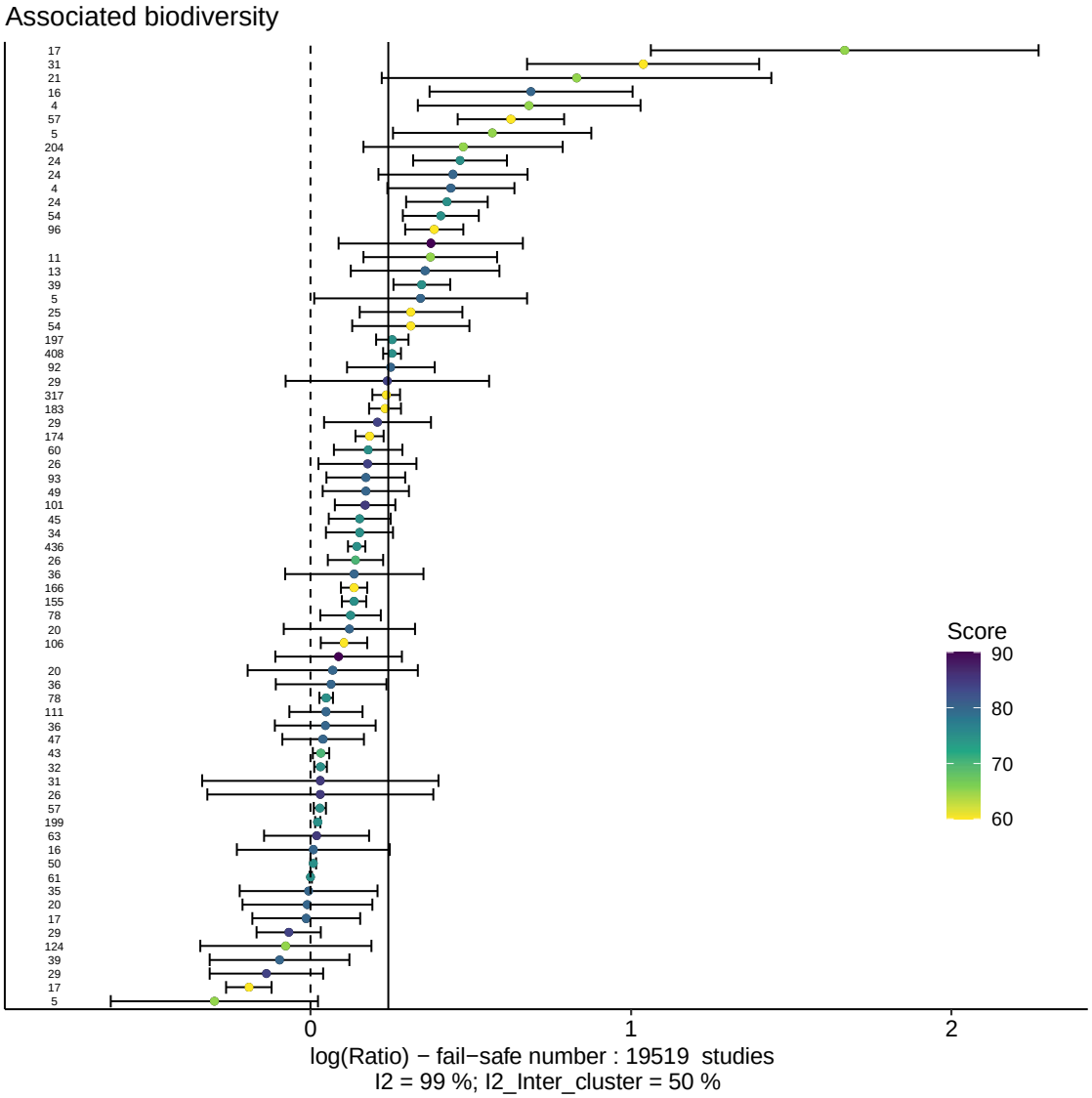


Figure S11. **Forest plot of the impacts the various crop diversification strategies on the soil quality.** Points, and thin lines represent the estimated mean value of the effect, its 95% confidence intervals of individual effect-sizes collated from the primary meta-analyses. Light and dark shaded area represent the 95% confidence and prediction intervals, respectively, calculated with a random effect-model. The number on the left of the plot represent the number of paired-data used to calculate each effect-size in the primary meta-analyses. The colors of the points indicated the quality score of the primary meta-analyses. Effect-sizes are expressed as log(ratio).

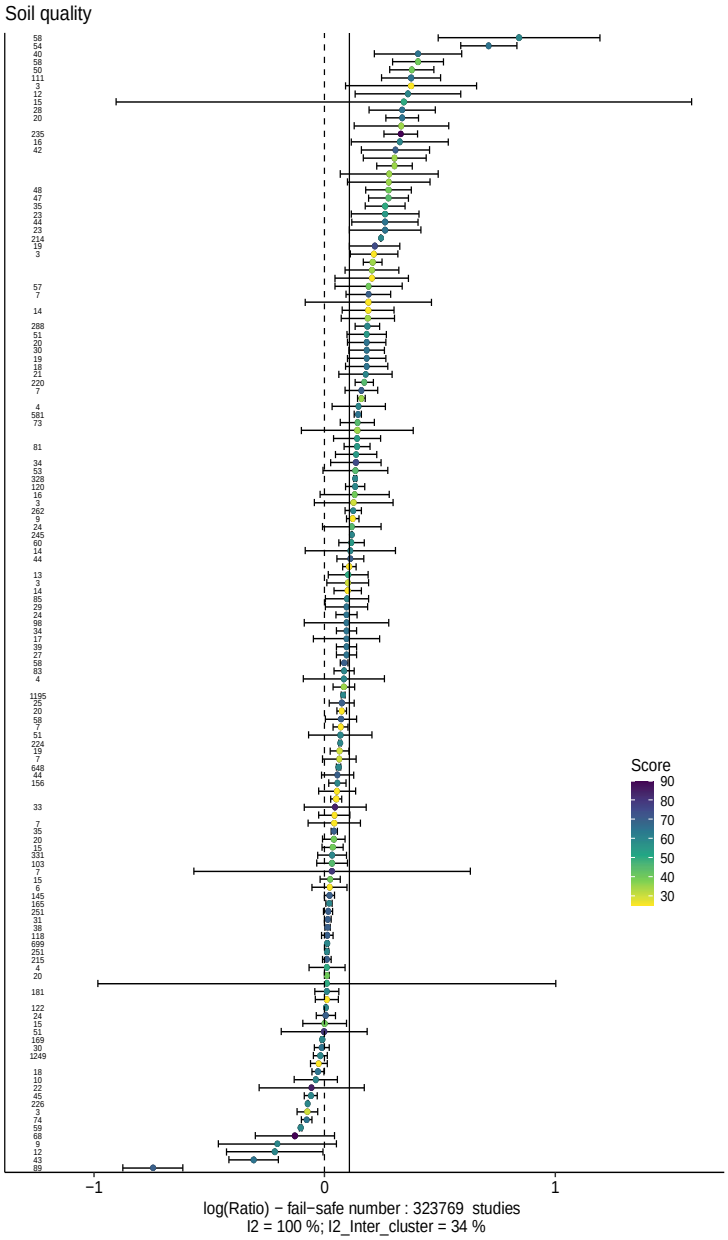


Figure S12. **Forest plot of the impacts the various crop diversification strategies on the water quality.** Points, and thin lines represent the estimated mean value of the effect, its 95% confidence intervals of individual effect-sizes collated from the primary meta-analyses. Light and dark shaded area represent the 95% confidence and prediction intervals, respectively, calculated with a random effect-model of the second-order meta-analysis. The number on the left of the plot represent the number of paired-data used to calculate each effect-size in the primary meta-analyses. The colors of the points indicated the quality score of the primary meta-analyses. Effect-sizes are expressed as log(ratio).

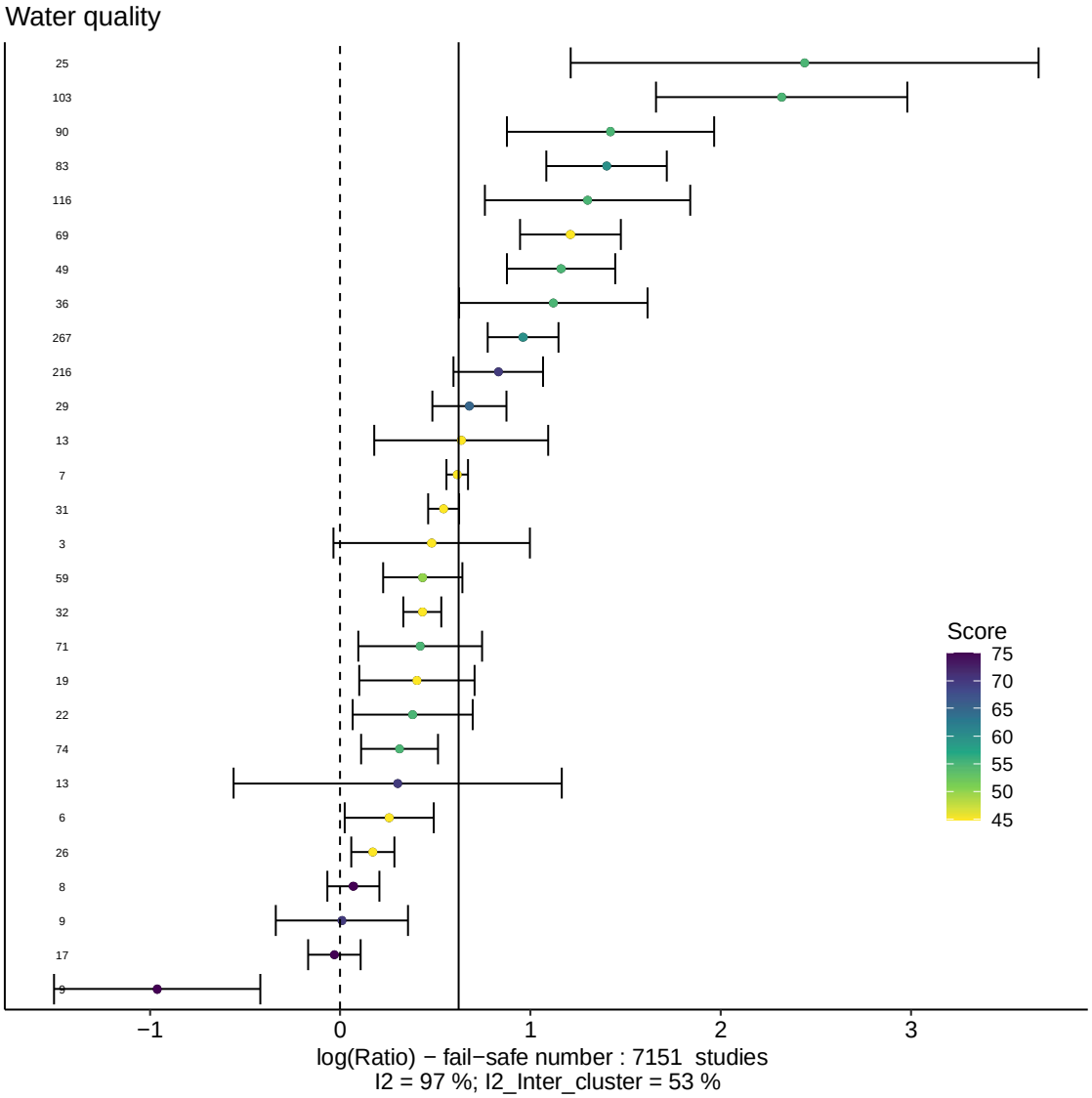


Figure S13. **Estimated impacts the various crop diversification strategies on the soil carbon stock.** Points, thin lines and thick lines represent the estimated mean value of the effect, its 95% confidence intervals, and its 95% prediction intervals respectively. Shaded areas display the distribution of effect-sizes collated from the meta-analyses. The number of meta-analyses and number of paired observations included in each category are displayed in parentheses.

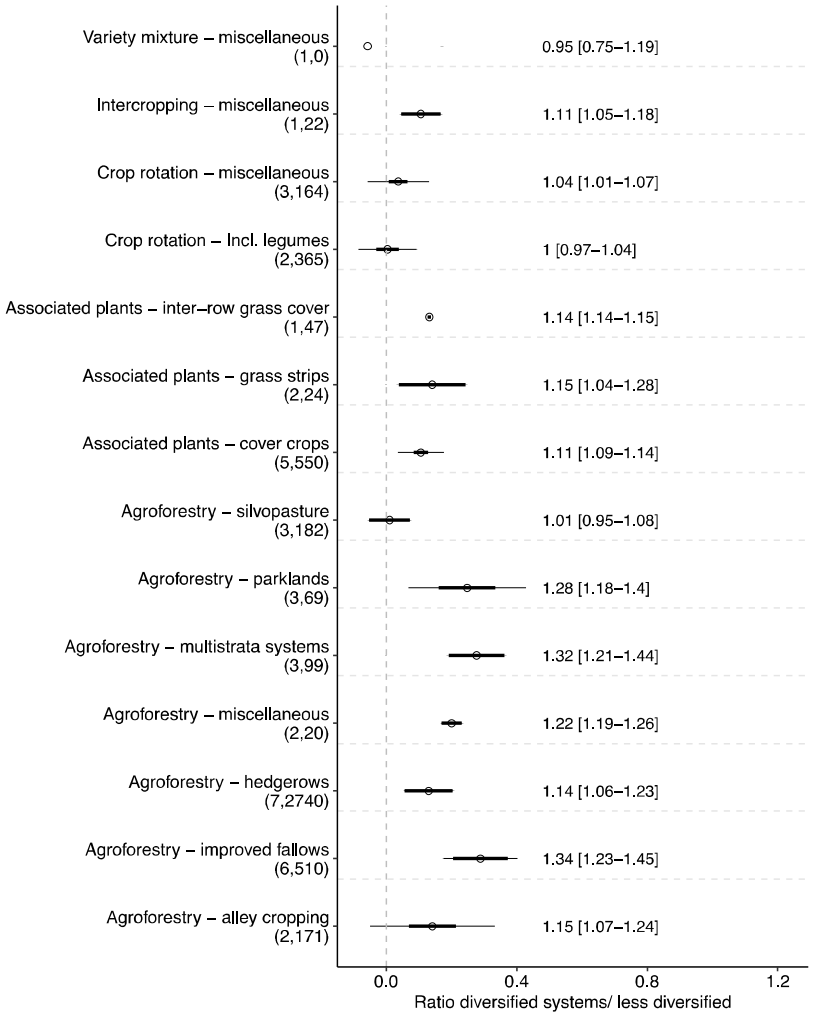


Figure S14. **Flowchart of literature search, screening, selection and characterization of the studies**. Arrows are proportional to the number and the proportion of articles excluded/included at each. Articles initially identified are presented in white. After screening and selection, 83 studies are included in the database (green). Three selection criterions were used at title and abstract and full text screening steps: i) The article synthesizes of several individual studies; ii) The article quantifies the impact of at least one strategy of crop diversification; iii) Control plots are present next to treatment plots. * Only papers reporting (log)ratios (or similar metrics) and presenting indicators of variability were included in the study.

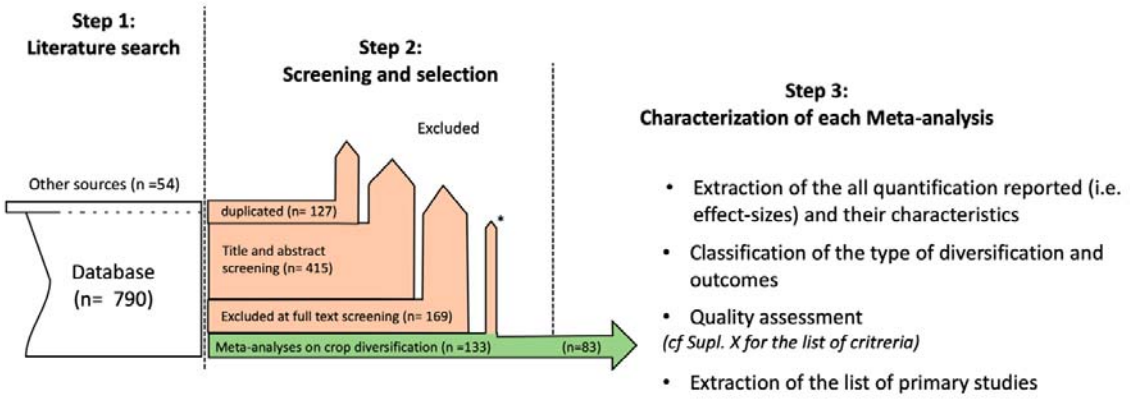


Table S1. **Definition of the crop diversification considered.**

Strategies of crop diversification	Definition and details
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. We further classified agroforestry practices as follows, based on table 1 of *Cardinael et al.,2018* and from *Nair, 2009:* - **Alley cropping**: Fast-growing, usually leguminous, woody species (mainly shrubs) grown in crop fields, usually at high densities. The woody species are regularly pruned and the prunings are applied as mulch into the alleys as a source of organic matter and nutrients. Usually found in tropical regions. Sometimes referred as 'intercropping systems' -**Fallows**: Only sequential agroforestry system considered here. Include both improved and natural fallows - **Hedgerows:** They consist of linear plantation around the fields. They include also shelterbelts, windbreaks and live fences. - **Multistrata systems**: Multistorey combinations of a large number of various trees at high density, and perennial and annual crops. They include home gardens and agroforests. -**Parklands**: Intercropping of agricultural crops or grazing land under low density mature scattered trees. Typical of dry areas like Sahel (e.g. *Faidherbia albida*) - **Shaded perennial-crop systems**: Growing shade-tolerant species such as cacao and coffee under, or in between, overstorey shade trees that can be used for timber or other commercial tree products. - **Silvoarable systems:** Woody species planted in parallel tree rows to allow mechanization and intercropped with an annual crop; usually used for timber (e.g. *Juglans* spp), but also for fuel (e.g. *Populus* spp). Usually low tree density per hectare. Usually found in temperate regions, but not exclusively. - **Silvopastures**: Woody species planted on permanent grasslands, often grazed.

Associated plants species	Plant sown in addition to the main crop for agronomic or environmental purposes (e.g., to manage soil erosion, soil fertility, soil quality, weeds, pests, diseases, biodiversity or nitrate leaching). The associated plant could be harvested or not, permanent or not. We further classified associated plant practices as follows: **-Cover crops:** plants that are planted within fields to cover the soil rather than for the purpose of being harvested. Cover crops may be an off-season crop planted after harvesting the cash crop. **-Grass-strips:** an agroecological infrastructure formed by a linear plant cover, often placed on or near the edge of a field, perpendicular to the slope. Also named buffer strip. **- Inter-row grass cover:** A particular type of cover-cropping, for perennial plantation. The inter-row of the main crops (e.g. vineyard, orchards) are sown with non-harvesting purposes plants. **-in flowers/push/pull plants:** Plants or flowers are sown within fields or at field margin for a behavioral manipulation of insect pests and their natural enemies via the integration of stimuli that act to make the protected resource unattractive or unsuitable to the pests (push) while luring them toward an attractive source (pull) from where the pests are subsequently removed (see cook et al., 2006 for further details)
Cultivar mixture	The simultaneous cultivation in the same field of multiple cultivars of the same species. All cultivars are harvested. The cultivars could differ for many characters including disease resistance or physical characteristics, but have sufficient similarity to be grown together. For further details, see *Wolfe (1985)*.
Intercropping	The simultaneous cultivation in the same field of two or more crops (different species) for all or part of their growth cycle. All crop species are harvested. In this category, we do not include the cultivation with non-woody crops (see Agroforestry category). We further classified intercropping practices as follows (see Brookers et al., 2015 for further details) **-Mixed intercropping:** the plants are grown without any distinct row arrangement, but in an orderly manner. **-Relay intercropping:** the planting of the second crop occur after the first crop has flowered or completed its development or just before harvesting. **-Strip intercropping:** the different plants are grown in strips, allowing crop interactions and independent cultivation.

Rotation	Recurrent succession of a set of selected crops grown on a particular agricultural land each season or each year according to a definite plan. Here, we do not consider as rotation, a system with temporal overlap of two or more crops.

Table S2. Description of available data and their characteristics. Rosenthal's Fail-Safe Number represent the number of additional 'negative' studies (studies in which the intervention effect was zero) that would be needed to increase the P value for the meta-analysis to above 0.05 (*Rosenthal 1979).* The heterogeneity (I2) represent the percentage of the variability in effect estimates that is due to heterogeneity rather than sampling error. The proportion of total variance that can be attributable to within-cluster heterogeneity is indicated in the last column.

Ecosystem services	number of primary meta-analyses	number of effect_sizes	number of paired -data	Rosenthal's Fail-Safe Number	I2	Between cluster_I2
Yield stability	1	4	366	0	NA	NA
Profitability	2	4	120	0	88,20	76,28
Product quality	3	20	1807	9	99,84	22,38
Input use efficiency	4	6	947	812	98,58	48,87
Greenhouse gas emissions reduction	7	13	1299	7257	99,39	NA
Water use	8	25	1346	396	98,76	25,80
Water quality	10	28	1502	7151	97,26	52,93
Associated biodiversity	12	70	4809	19519	99,37	49,85
Pest and disease control	12	59	3081	17866	94,87	32,08
Soil quality	31	142	11911	323769	99,92	33,78
Production	37	113	21352	67958	99,92	35,56

Table S3. Description of quality items.

Description_short	description
A protocol is published before the meta-analysis	An a priori review protocol exists, and can be accessed (e.g., Web address), and, if available, provide registration information including registration number.
The aim of the study is clearly mentioned	The list of criteria used to defined the scope of the study are clearly mentioned PICO : Population, variable response, treatment and control.
Literature databases are mentioned	The study describes the databases in the search.
Additional literature search is performed	Additional research (grey literature?)
Search strings are presented	Are the search string clearly defined? All search terms, so that the exact search is repeatable by a third party
Inclusion and exclusion criteria are mentioned	Description of the criteria used to select articles from the original result list (to ensure repeatability). If additional exclusion motives - these are also detailed (e.g., years considered, language, publication status, date last searched)
The number of studies is given at each selection steps	Detailed summary of studies screened, assessed for eligibility, and included in the review, ideally with a flow diagram. Diagram PRISMA
The list of included studies is provided	The study includes the final list of the references of the selected individual studies used in the meta-analysis
The list of excluded studies is provided	The study includes the list of the excluded studies
Method of data extraction is described	Do the authors explicate how data were extracted from the figures?
The dataset is available	Availability of the original dataset? (In results?)
All tools used for the review are mentioned	Name of the program/package used for statistical analysis
Statistical models are described	Statistical analysis of the database: description (model, effect(s), equation...)
Studies are weighted according to their accuracy	Are individual studies weighted according to their accuracy or quality?
Effect sizes of individual studies are presented	Provide information of the size effect for each individual study includes in the meta-analysis? (table, plot)
Confidence intervals of individual studies are mentioned	Provide information of the confidence interval for each individual study included in the meta-analysis? (table, plot)
Quantitative results of the meta-analyses are fully described	Results: Quantitative information on summary effects (effect estimates and confidence intervals, ideally with a forest plot).
Heterogeneity of results is analysed	Is the heterogeneity analyzed using sensitivity analysis or meta-regression?
Publication bias is analysed	Does the synthesis consider possible publication bias?
Funding sources are mentioned	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.

Additional literature:

Baumer, E.P., Sinclair, J., Hubin, D. and Tomlinson, B., 2009, August. metaViz: Visualizing Computationally Identified Metaphors in Political Blogs. In *2009 International Conference on Computational Science and Engineering* (Vol. 4, pp. 389-394). IEEE.

Brooker, R.W., Bennett, A.E., Cong, W.F., Daniell, T.J., George, T.S., Hallett, P.D., Hawes, C., Iannetta, P.P., Jones, H.G., Karley, A.J. and Li, L., 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytologist*, *206*(1), pp.107-117.

Cardinael, R., Umulisa, V., Toudert, A., Olivier, A., Bockel, L. and Bernoux, M., 2018. Revisiting IPCC Tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems. *Environmental Research Letters*, *13*(12), p.124020.

Cook, S.M., Khan, Z.R. and Pickett, J.A., 2007. The use of push-pull strategies in integrated pest management. *Annual review of entomology*, *52*.

Doi, S.A. and Thalib, L., 2008. A quality-effects model for meta-analysis. *Epidemiology*, pp.94-100.

Duval, S. and Tweedie, R., 2000. A nonparametric "trim and fill" method of accounting for publication bias in meta-analysis. *Journal of the american statistical association*, *95*(449), pp.89-98.

Nair, P.R., Nair, V.D., Kumar, B.M. and Haile, S.G., 2009. Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. *Environmental Science & Policy*, *12*(8), pp.1099-1111.

Rosenthal, R., 1979. The file drawer problem and tolerance for null results. *Psychological bulletin*, *86*(3), p.638.

Wolfe, M., 1985. The current status and prospects of multiline cultivars and variety mixtures for disease resistance. *Annual review of phytopathology*, *23*(1), pp.251-273.