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Evidence map of crop diversification strategies at the global scale

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ERRATUM

Erratum: Evidence map of crop diversification strategies at the global scale (2019 *Environ. Res. Lett.* **14** 123001)

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During the production process the incorrect version of figure 5 was published. The correct version of figure 5 appears in the following.

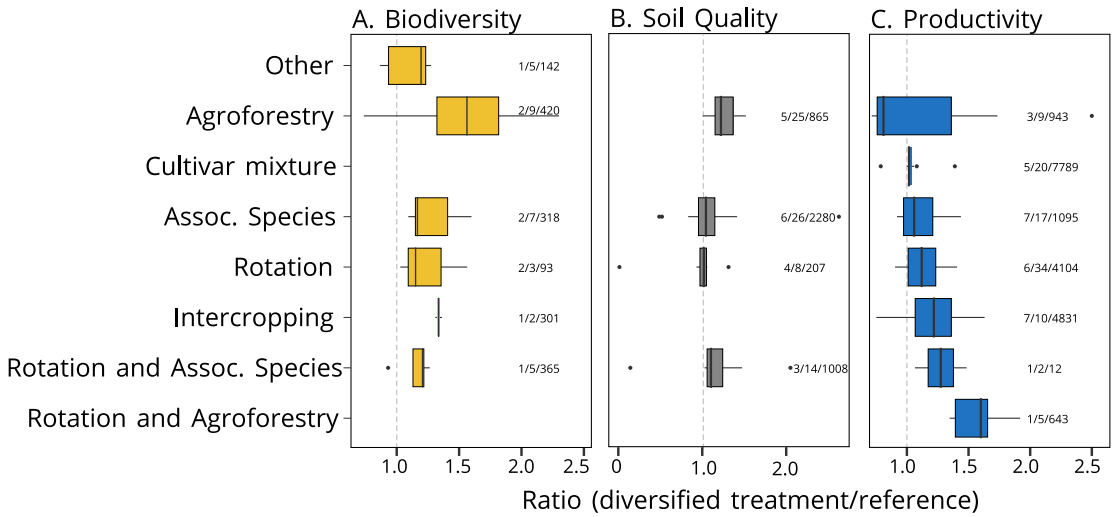

Figure 5. Impacts of crop diversification on biodiversity (yellow), soil quality (gray) and productivity levels (blue). The impacts are quantified with effect sizes (i.e. the ratios of a measurement in a diversified cropping system to its corresponding value in a less diversified cropping system). The number of meta-analyses/effect sizes/individual studies included in each pair strategy*outcome are indicated at the right of the boxplots. When the ratio is greater than 1, the diversified system outperforms the less diversified one for the considered outcome. One extreme ratio measuring the impact of agroforestry on biodiversity is not represented (Ratio = 5.2). In some meta-analyses the effect sizes are computed for a fraction of its total data sample (e.g. per covariate), but only global effect sizes are presented here. Effect sizes corresponding to relative differences are first converted to log ratios, back-transformed to ratios, and then reported in the figure, whereas absolute differences and hedge's distances are not reported here.

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TOPICAL REVIEW

Evidence map of crop diversification strategies at the global scale

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Keywords: agroforestry, cover crop, intercropping, rotation, variety mixture, systematic review, meta-analysis

Supplementary material for this article is available online

Abstract

The diversification of cropping systems encompasses different strategies that may help maintain or enhance the sustainability of agriculture. Thousands of experiments have been carried out around the world since almost five decades to evaluate and compare the performances of various diversification strategies in a wide array of agroecosystems and climates. Although these analyses have been synthesized in a growing number of meta-analyses, the information remains somewhat fragmented. A multicriteria systematic synthesis of worldwide agricultural diversification is still lacking. Here, we review all meta-analyses conducted on crop diversification strategies and produce a detailed overview of their results and of their quality. We identified and analyzed 99 meta-analyses summarizing the results of more than 3700 agronomic experiments on seven crop diversification strategies. Among these strategies, rotation and associated plant species are dominant in the literature followed by intercropping, agroforestry and landscape heterogeneity. Our analysis reveals that rotation and intercropping are associated with yield increases. Agroforestry systematically induces an improvement of biodiversity and soil quality—in particular soil organic carbon. We show that, regardless of the context, a combination of several diversification strategies outperforms any individual strategy. Our review reveals that a significant knowledge gap remains, in particular regarding water use, farmers' profitability, product quality and production stability. Few meta-analyses investigate the performance of landscape heterogeneity and of systems with species other than cereals and pulses. Additionally, we show that most of the meta-analyses studied cannot be considered fully transparent and reproducible. Their conclusions should therefore be interpreted with caution. Our systematic mapping provides a benchmark to guide and improve the relevance and reliability of future meta-analyses in agronomy.

1. Introduction

More sustainable and climate-resilient farming systems are needed to decrease the impact of agriculture on the biosphere and ensure a stable food supply for the coming decades. Addressing these issues by reconsidering the simplification of agro-ecosystems — especially in highly intensified systems which are often based on one or on a limited number of cultivated species — is one pathway explored by farmers and agronomists. To this end, a quantification of the performances of diversified cropping systems in various regions of the world appears particularly useful. However, the wide range of strategies aiming at incorporating agrobiodiversity in cropping systems and the heterogeneity in the quality of the studies hampers a simple synthesis on this subject.

In this context, systematic quantitative reviews (i.e. meta-analyses) provide a framework for summarizing and analyzing numerous and heterogeneous experimental results. Meta-analysis is a transparent and reproducible method which allows to estimate the effects of a treatment (i.e., here the effect of a given crop diversification strategy compared to a less-diversified cropping system). Note that these summary effects can here be useful both for studying the

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consequences of the diversification of simplified systems and of the simplification of diversified systems.

Crop diversification covers a wide range of agricultural practices, from the introduction of one additional crop species in a rotation to the implementation of complex landscape management strategies. In recent decades, an increasing number of meta-analyses has been conducted to estimate the impacts of—most often one—diversification strategy on one or several outcomes related to crop production (e.g. the impact of cultivar mixture on yield), environmental impacts (e.g. the impact of agroforestry on soil carbon) or economic profitability (e.g. the impact of shaded cocoa systems on gross revenue). These meta-analyses differ according to their objectives, the number of primary studies synthesized, their overall quality and also their conclusions. To date, a comprehensive description of the focus, quality and results of meta-analyses assessing crop diversification is lacking.

To make progress, we performed a systematic synthesis of 99 meta-analyses on crop diversification at the global scale. We considered the following types of diversification strategies: agroforestry, associated plant species, cultivar mixture, intercropping, landscape heterogeneity, and rotation (Beillouin *et al* 2019). On this basis, we provide (i) a description of the diversification strategies and outcomes studied worldwide (ii) an analysis and comparison of their results and (ii) and in-depth assessment of the quality of the 99 selected meta-analyses. Incidentally, our review helps to identify knowledge gaps to sketch guidelines for improving future meta-analyses. Our conclusions should provide stakeholders involved in agricultural and environmental policies with evidence on the expected impacts of diversifying simplified cropping systems and on the possible consequences of simplifying diversified systems.

2. Material and methods

2.1. Literature search

The literature search was carried out in peer-reviewed journals and grey literature on May 2018. We queried six databases: Web of Science, CAB abstract, Greenfile, Environment Complete Database, Agricola and Google Scholar. Our 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). No restriction was applied to the date and language of publication in the article title, abstract and keywords, or to the geographical localization of the studies. We also screened the references cited in each selected meta-analysis and those listed in a narrative review (Kremen and Miles 2012). Our literature search was not designed to be representative of existing farming practices but to be representative of publication experimental studies conducted for comparing cropping systems. Because we used a rigorous protocol (see also Beillouin *et al* 2018) to conduct our systematic review, our results are expected to retrieve most of the meta-analyses published on crop diversification.

2.2. Study selection

The initial literature search identified 537 unique candidate meta-analyses of potential interest. Titles and abstracts were screened for eligibility according to the following inclusion criteria: (i) study dealing with at least one crop diversification strategy (defined in table S1 is available online at stacks.iop.org/ERL/14/123001/mmedia), (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). Studies dealing with pure forestry or wood production were excluded. Two hundred twenty-two articles met these criteria. Eligible full-texts articles were then examined according to the same three criteria and 123 articles were removed (41 because of a lack of quantitative result, 72 because of the lack of any defined crop diversification strategy, and 11 because of a lack of control plot). At the end of the screening process, 99 meta-analyses were selected.

2.3. Characterization of the selected meta-analyses and their primary studies

We extracted all effect sizes related to crop diversification in each of the selected meta-analysis. An effect size is defined as a quantitative measure of the effect of a crop diversification strategy compared to a reference cropping system (i.e. less diversified) on one or several outcomes (e.g. crop yield, soil carbon content, biodiversity index, plant disease incidence). For the effect-sizes, let YT and YC be the values of one outcome variable in the diversified treatment and control, respectively. Depending on the considered meta-analysis, the effect size can either be the ratio of YT to YC (or a log ratio, odds ratio) or the difference between YT and YC (standardized or not). Effect sizes corresponding to relative differences were converted to log ratios as exposed in Tang *et al* (2013). A given meta-analysis could report several outcomes for one or several strategies of crop diversification. Also, the reference system could differ between meta-analyses (e.g. monoculture, 2-yr-rotations, etc). In studies evaluating agroforestry yields, only effect sizes measuring crop yields were extracted because tree yields were considered in only a few studies. In studies evaluating rotation yields, only effect sizes measuring yields for one crop were considered—and not yield for the entire rotation.

We also assess the quality of each of the 99 meta-analyses. We considered criteria related to the literature review, data extraction, data analyses, and interpretations. A special emphasis was given to the reproducibility of the results of each meta-analysis. The 20 criteria listed in Beillouin *et al* (2019), and are an adaptation of the ones proposed in several fields of research (Gates 2002, Moher *et al* 2009, Borenstein *et al* 2011, Philibert *et al* 2012). When satisfied, a criterion was scored 1, and 0 otherwise. A global quality score was given by calculating the proportion of criteria met.

We extracted the list of primary studies of each meta-analysis. We characterized each primary study by its country, year of publication, studied species (in the control or the diversified strategy), and all metadata (DOI, references). Seven regions clustering countries were considered: Central and Southern America, Eastern Asia, Western and Eastern Europe, Middle and Southern Africa, Northern and Western Africa, South Eastern Asia, Western, Southern and Central Asia. The list of countries included in each region is available in Text S1.

2.4. Data visualization and statistics

To characterize the meta-analyses, we calculated descriptive statistics and presented contingency tables. We considered the following variables: strategies of crop diversification, type of outcomes (e.g. soil C, yield), year of publication, regions, quality score, and effect sizes. For each of the 20 quality criteria, the differences of quality score between diversification strategies were examined using a binomial *glm* model. The global quality score (over the 20 criteria) was assessed with a linear model with a log transformation.

All analyses and graphical representations were performed through the R software (R Core Team 2013) and package ggplot2 (Wickham 2016). An interactive Data visualization is available at https://cropdiversification.shinyapps.io/Crop_divers/.

3. Results

3.1. A growing number of meta-analyses on crop diversification

Our set of 99 recovered meta-analyses summarize more than 3736 primary studies, 97% of which were published after 1980 (figure 1). The first meta-analysis was published in 1994, but three quarters have been released in the last 6 years (figure 1). Northern America and Europe drain the major part of this research on crop diversification. These regions account for 35% and 22% of the total number of primary studies (figure 2), and 35% and 38% of the authors publishing meta-analyses. The others regions represent individually less than 9% of the number of primary studies and 7% of the authors. South-Eastern Asia- and Polynesia showed the lowest number of primary studies (i.e. 63). Primary studies located in Eastern Asia, South-Central America and Europe were mostly published after 2005 (85%, 60% and 58% respectively) contrary to Northern America, Northern West Africa or Oceania (45%, 44% and 28% respectively).

Rotation and associated plant species (see definition in table S1) are the most investigated diversification strategies (32 and 29 meta-analyses reported at least one effect-size on these interventions, respectively). The other options are represented by half as many reviews: agroforestry (15 meta-analyses), intercropping (14 meta-analyses), and inclusion of heterogeneity at the landscape scale (6 meta-analyses). Cultivar mixture is examined by only 5 meta-analyses. Since the 1960s, the studies originating from Northern America mostly focused on the implementation of rotations (i.e. 4 times the number summarized by other regions—figure 1, figure 2, figure S1). Together with Europe, Northern America also largely contributed to the primary studies on associated plant species (more than 250 and 400 studies resp. versus less than 100 studies produced by the other regions). Agroforestry, on the opposite, is predominantly documented for Africa and Central-South America (figure 1); and, more generally, is the most commonly investigated diversification strategy for many countries in the tropics. Most of the primary studies on agroforestry were published after 2000. Landscape heterogeneity is not frequently studied, most of the few meta-analyses on this subject were published in Europe. Cultivar mixture is a long-time studied strategy and has not seen a recent acceleration in publication.

Fourteen botanical families are analyzed by more than 150 primary studies. However, most meta-analyses focused on the diversification of cropping systems based on cereals and pulses (figure 3). Maize is the most frequently studied crop species in 5 out of 9 world regions —the proportion is particularly high in Africa and Northern America (figure 3). Wheat ranks first in the other 4 regions—the share is notably large in Eastern-Western-Central Asia, and Oceania. Cowpea, pea and sorghum are highly represented in Europe and Africa, millet in Northern and Western Africa, rice in Asia, soybean in America and Eastern Asia and lupin in Oceania. Cocoa is frequently studied in Asia (e.g. in Indonesia), and in a few African countries (e.g. Ghana), and coffee in South America (e.g. Mexico).

3.2. Impact on production and on the environment

Crop yield is the main measure of diversification impact with twice as many meta-analyses (i.e. 50 meta-analyses) as soil quality and biodiversity together (i.e. with 26 and 23 meta-analyses respectively) (figure 4). The effects of diversification on the abundance and distribution of pests and diseases is analyzed in 12 meta-analyses. Finally,

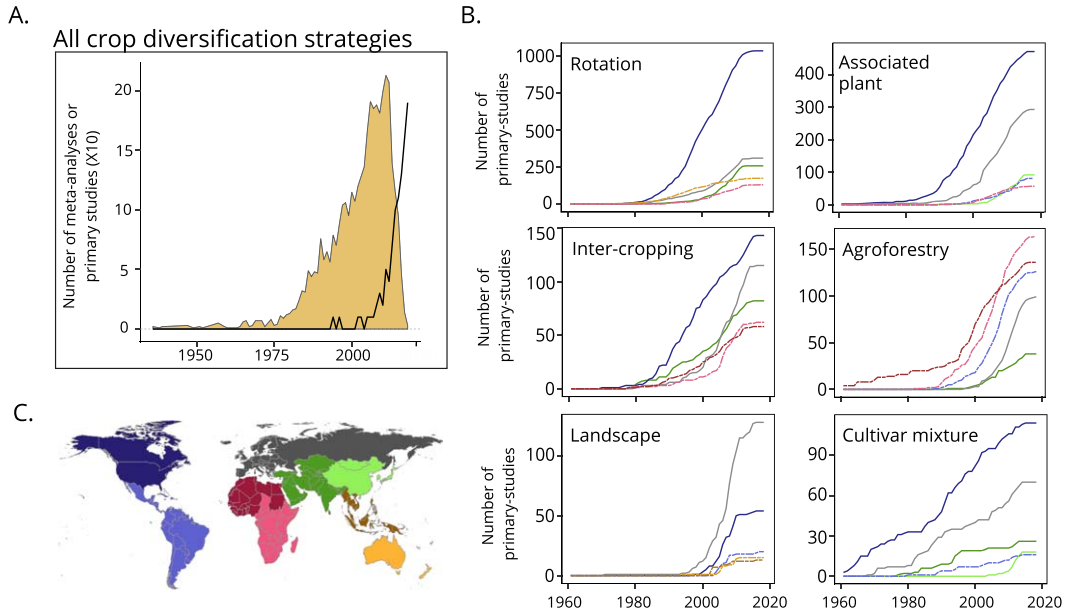

Figure 1. Dynamic of publications of the meta-analyses on crop diversification. Number of meta-analyses (black line) and their primary studies (orange area) by year of publication (A.) with details by strategy and region of the world (B.); The colors of plot B correspond to regions of the world presented in the map (C.). The plots B have different y-scales. Dotted lines correspond to regions South America, North and West Africa, East and South Africa, Oceania, and South Asia.

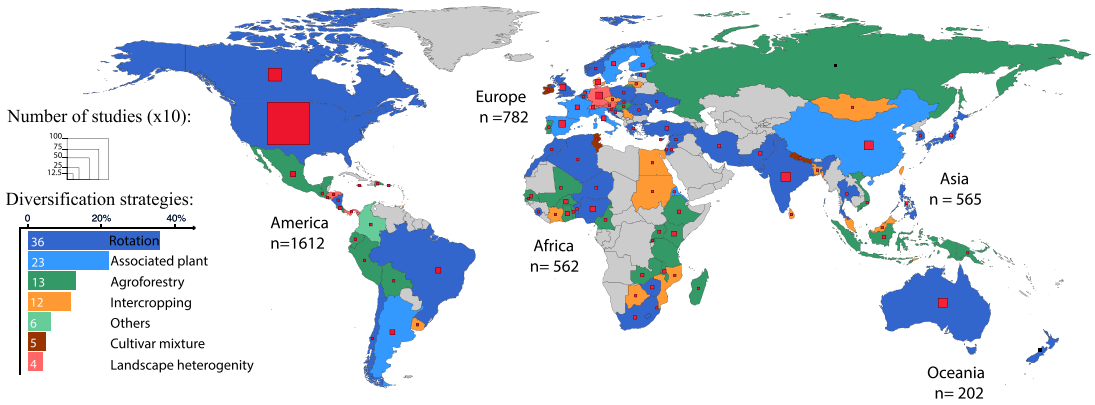

Figure 2. Localization, number and strategies of crop diversification in the 3723 primary studies retrieved from the 99 meta-analyses. The colors of each country indicates the strategy with the largest number of primary sources conducted in that country. The legend is available at the bottom left corner, along with the proportion of each diversification strategies worldwide. Countries with no trials are in grey. The total number of studies in each country is represented with the red square. The total number of primary studies in each region is also indicated.

other outcomes related to production (e.g. input use and product quality) are the focus of a very small number of meta-analyses (3 meta-analyses each, respectively) (figure 4). Environmental outcomes include soil quality (26 meta-analyses), biodiversity (23 meta-analyses), greenhouse gas emission (10 meta-analyses), water quality (7 meta-analyses) and water use (3 meta-analyses). Economic outcomes are mentioned in only 7 meta-analyses (figure 4). We do not observe any temporal trend in the relative importance of the outcomes examined in the literature (figure S3).

All diversification strategies globally benefit biodiversity (figure 5(A)); with more than 75% of the estimated effect sizes showing a positive effect on this outcome. Biodiversity measures increase, in most cases by more than 25%, in agroforestry plots, compared to adjacent less diversified plots. The majority of the effect sizes extracted from the 99 meta-analyses indicates a positive impact on crop yield (figure 5(C)). This effect is robust for almost all diversification strategies. A notable exception concerns agroforestry, that have highly variable yields. However, agroforestry almost systematically positively impacts soil quality (figure 5(B)), in particular soil organic carbon.

We found that combining several crop diversification strategies improves the productive performances

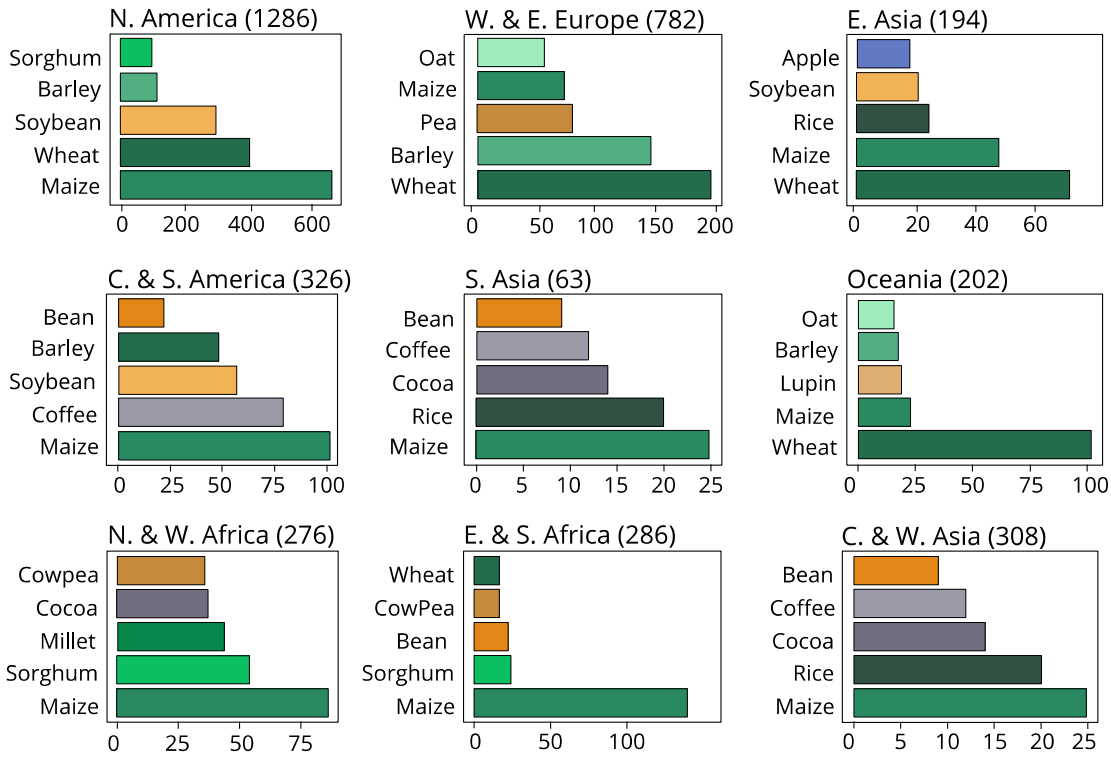

Figure 3. The five most considered species per region in the primary studies. Species are colored by botanical family (green: Graminaea; Orange: Fabacaea; Darkgray: Malavacaea; Lightgray: Rubiacaea; Blue: Rosaceae). The total number of primary studies per region is indicated in brackets. The plots have different x-scales. The species were retrieved in both control and diversified plots in the primary studies included in the meta-analyses. List of countries in each region is given in Text S1.

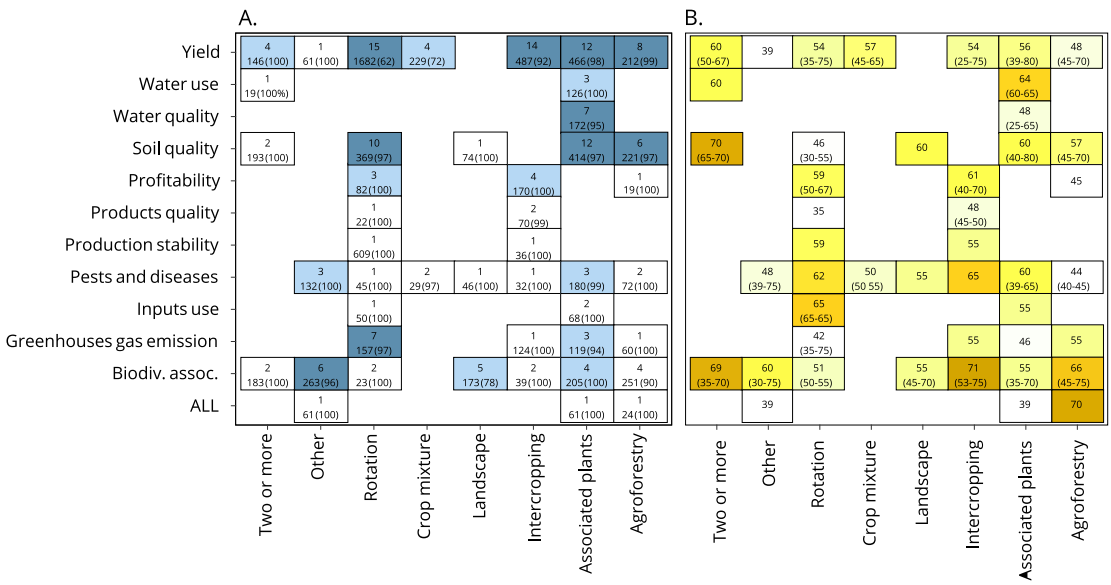

Figure 4. Available evidence (A.) and its reliability (B.) on the impacts of crop diversification for twelve outcomes (y-axis). The numbers of meta-analyses (colors and number at the top of the cells) and of primary studies (number at the bottom of the cells) are reported in A. The percentage of primary studies used in only one meta-synthesis is indicated in parenthesis. An empty cell indicate that no meta-analysis is performed for the particular pair diversification strategy and outcome. The reliability (B.) is characterized by the median quality score of an in-depth assessment of the transparency and reproducibility of each meta-analysis (colors and number at the top of the cells). The score is expressed as a percentage of criteria met (see list of criteria in figure 6). The minimum and maximum quality score of each pair of crop strategy and outcome is given in parenthesis. '2 or more' item correspond to combined diversification strategies. 'All' item correspond to outcome mixing all dimension of performances.

of cropping systems (figure 5(C)). For example, agroforestry or associated plant species (e.g. cover crops) led to higher yield ratios when associated to crop rotations (figure 5(C)).

3.3. Few redundancies between meta-analyses but large knowledge gaps

A small number of outcomes and diversification strategies focus most of the research efforts, e.g.

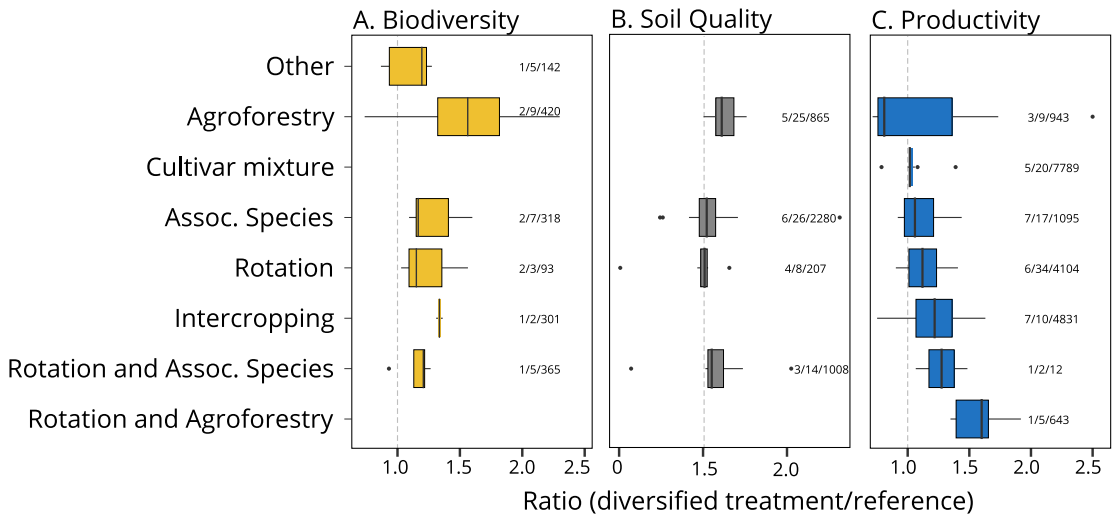

Figure 5. Impacts of crop diversification on biodiversity (yellow), soil quality (gray) and productivity levels (blue). The impacts are quantified with effect sizes (i.e. the ratios of a measurement in a diversified cropping system to its corresponding value in a less diversified cropping system). The number of meta-analyses/effect sizes/individual studies included in each pair strategy*outcome are indicated at the right of the boxplots. When the ratio is greater than 1, the diversified system outperforms the less diversified one for the considered outcome. One extreme ratio measuring the impact of agroforestry on biodiversity is not represented (Ratio=5.2). In some meta-analyses the effect sizes are computed for a fraction of its total data sample (e.g., per covariate), but only global effect sizes are presented here. Effect sizes corresponding to relative differences are first converted to log ratios, back-transformed to ratios, and then reported in the figure, whereas absolute differences and hedge's distances are not reported here.

impacts of rotation, and associated plant species on yield or soil quality; and impacts of intercropping on yield. These topics are each addressed in 10 to 15 meta-analyses, and several hundred primary studies (figure 4(A)). Despite this concentration of meta-analyses on a small number of topics, there is a low level of redundancy between the primary studies of the different meta-analyses. More than 90% of the primary studies are synthetized by only one meta-analysis in all except three cases, i.e. rotation and of variety mixture impacts on yield (redundancy of 37% and 21% respectively), and landscape heterogeneity impacts on associated biodiversity (redundancy of 22%). The mean number of unique primary studies for a given pair outcome*strategy varies between 14 and 609 (figure 4(A)).

Large knowledge gaps remain. Eleven combinations of diversification and outcomes are examined in only one or two meta-analyses, e.g. intercropping, rotation, landscape, mixture and agroforestry impacts on pests and diseases, or intercropping and agroforestry impacts on greenhouse gas emission (figure 4(A)). Products quality, production stability, water quality and use and input use are analyzed for less than three diversification strategies. Among all pairs of impact and strategy, 56% are not considered in any meta-analysis.

3.4. Half of our quality criteria are satisfied on average

Twenty quality criteria, grouped in three categories (literature review and studies selection, statistical analyses, and identification of potential bias) are considered. On average, only 54% of our 20 transparency and reproducibility criteria are satisfied over the 99 meta-analyses (figure 6). Some criteria are satisfied by none the meta-analyses (e.g. protocol publication), while others are met in more than 80% of the studies (e.g. the list of included study). Note that global quality (i.e. the number of criteria met) show a positive but non-significant time trend (figure S3).

Higher quality meta-analyses (with an average score higher than 65%) are the ones analyzing the impacts of associated plants species on pests and diseases, and of agroforestry on associated biodiversity. The effects of rotation or associated plants on greenhouse gas emission and agroforestry on yield showed comparatively a lower average quality score (i.e. below 50%).

In general, the literature review, the study aim, the list of the included studies and the inclusion or exclusion criteria are precisely described. The search strings and the literature database are mentioned in more than 70% of the meta-analyses, although often without sufficient details to repeat the procedure. None of the 99 meta-analyses published a protocol before performing the quantitative synthesis, and almost none provided the list of excluded studies. The results of the meta-analyses are usually accurately described and heterogeneity of the results is often explored, e.g. using environmental covariates. The tools used to perform the analyses (e.g. statistical software, packages) are often mentioned. The authors, however, often failed to present individual effect sizes and their distribution (i.e. effect sizes of primary studies). The dataset is made publicly available in less than 35% of the studies, making posterior check, update or re-use of the database very difficult. Regarding the identification of potential biases, primary studies are weighted according to their accuracy in less than 40% of the cases. The

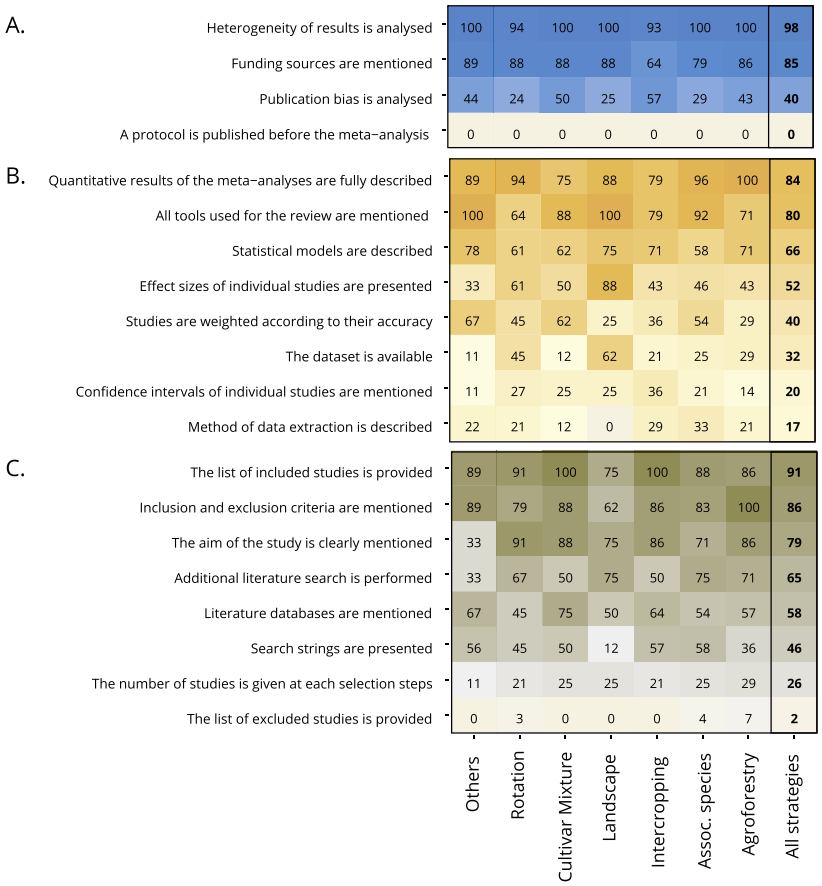

Figure 6. Detailed examination of the transparency and reproducibility of the meta-analyses on crop diversification. Twenty criteria of quality, grouped in three categories ((A). Identification of potential bias, (B). Statistical analyses, (C). Literature review and studies selection) are considered. Results are presented for each pair of strategy and outcome. Numbers correspond to the percentage of meta-analyses satisfying each of the 20 quality criteria. No significant differences of quality score were observed for the combination of items and strategies, except for the strategy 'other' that show significant lower values for item 'The aim of the study is clearly mentioned'.

funding sources are often available, but meta-analyses rarely assess possible publication bias (e.g. through the use of funnel plots). Finally, large variations in the mean quality score are observed across combination of diversification strategies and outcomes (figure 4(B)).

4. Discussion

4.1. Evidence of benefits of crop diversification

Crop diversification is increasingly promoted as a mean to improve the sustainability of agriculture while maintaining a sufficient level of food and feed production (e.g. Lin 2011, Njeru 2013, Bullock *et al* 2017). Ecological and agronomic performance of crop diversification strategies are known to be context dependent (Duru and Therond 2015). However, our systematic synthesis reveals that a large majority of the quantitative estimates reported in the literature support the idea that diversification strategies have positive impacts on production and the environment, particularly in rice, maize and wheat cropping systems, which represent ~34% of the species mentioned in the primary studies. At the global level, these crops contribute nearly 60% of calories and proteins obtained by humans from plants.

More specifically, our results provide strong evidence that crop diversification strategies can increase associated biodiversity. The impact of agroforestry is particularly strong with an increase in biodiversity of more than 25% in most cases. These results are in line with several narrative reviews highlighting the positive impacts of crop diversification on biodiversity (e.g. Kremen and Miles 2012, Rosa-Schleich *et al* 2019).

Our results also reveal that the majority of the extracted effect sizes indicate a positive impact on crop yield, as Rosa-Schleich *et al* (2019). This positive impact on crop production concerns almost all diversification strategies except one, agroforestry, for which productive the performance is more variable. However, agroforestry has almost systematically a positive impact on soil quality, particularly on soil organic carbon. This result confirms that agroforestry could play an important role inmitigating climate change through the sequestration of atmospheric carbon dioxide.

We found that combining several crop diversification strategies, in particular rotation combined with agroforestry or rotation combined with associated plants, improves the productive performances of

cropping systems, as observed by Rosa-Schleich *et al* (2019).

The initial diversification level together with local soil and climate conditions, impact both the performances and the practical recommendations for the implementation of any crop diversification strategy. Initial diversification levels can be very different depending on local contexts. For example, in northern countries, about 80% of the US corn is grown alternating with soybeans and-or wheat while intensive rotation in France include mostly wheat or maize monoculture, or wheat alternating with soybean and-or barley (Mignolet *et al* 2012). The level of diversification can be higher in other situations. Barbieri *et al* (2017) showed that crop rotations are 15% longer in organic systems compared to conventional, mostly to the detriment of cereals. We have referenced all primary studies in a public database (see Beillouin *et al* 2019) to allow all potential users to retrieve local experiments and the characteristics of their cropping systems.

4.2. Knowledge gap

The adoption of diversification strategies by farmers depends on several factors, including their economic profitability and their resilience to adverse climate conditions. Despite a high number of meta-analyses published in the field of economy (Stanley *et al* 2013, Cadotte *et al* 2012), we found very few syntheses on the economic impacts of crop diversification. Local-evidence of impact of crop diversification on the farmer's incomes and risk exist (e.g. Schroth and Ruf 2014, Reed *et al* 2017). Analyses of farmers' income are important as farmers' decision to move toward diversified agricultural systems will be influenced by the ability of the diversification strategy to support the economic resilience of farms (Lin 2011). Diversified agricultural systems could offer solution to maintain production levels under more frequent climate extremes (e.g. drought- Mijatović *et al* 2013), or water resources scarcity (e.g. Lenssen *et al* 2014). Diversified agricultural systems are supposedly able to be more robust to extreme climate conditions (Lin 2011). Meta-analyses assessing the impact of diversification strategies on water use are scarce. A large part of the research efforts focus on the impacts on average productivity of various diversification strategies while production inter-annual variability or product quality are scarcely studied. As already pointed out by Seufert and Ramankutty (2017) regarding organic farming, very few diversification comparisons focus on the total energy, caloric, or protein yield across an entire crop rotation or system. These variables are, however, important for analyzing food security at the farm and regional levels.

Many meta-analyses have been conducted on rotation, intercropping, associated plant species, and agroforestry, but other strategies have been far less analyzed (figure 4). The number of meta-analyses assessing landscape management has recently increased, particularly in Europe, but it remains low compared to other strategies. Data at the landscape scale are in fact more difficult to access (Lortie 2014, Hillebrand and Gurevitch 2016)—on the contrary, for example, for data on rotation (Lorenz *et al* 2013). Note that we did not include meta-analyses assessing the effects of diversification before and after a land-use change due to possible confounding effects, hence reducing the pool of available syntheses on this strategy. Regional specificities explain the number and localization of landscape-scale studies. In Europe, landscapes tend to be characterized by small scale land-use mosaics as opposed to the protection of large wilderness areas, for example in Northern America (Sutherland 2002).

The evidence available regarding agroforestry is also largely context dependent. Most of the existing reviews are based on primary studies that were performed in tropical and subtropical biomes. In many African areas, crops are traditionally cultivated with trees (Kumar and Nair 2004). In sub-Saharan Africa, the proportion of agroforestry reaches 29% of the agricultural land (Coe *et al* 2014) whereas these areas are much smaller in Europe (Den Herder *et al* 2017), despite large potential areas for implementation (Reisner *et al* 2007). In Europe, agroforestry is currently, mainly restricted to areas with unfavorable pedo-climatic conditions (e.g. cold temperatures, drought, the lower altitude mountain regions) that limit the productivity (Mosquera-Losada *et al* 2012). The integration of trees in intensive European or US farming systems need to redesign the cropping systems (Wezel *et al* 2014).

4.3. Quality of the meta-analyses

In line with Philibert *et al* 2012, we show that there is considerable opportunities to improve the quality of meta-analyses conducted in agronomy. On average, 46% of our 20 quality criteria are not met in the 99 meta-analyses (figure 6). All main steps of the reviewed meta-analyses present flaws, with some criteria poorly satisfied for the literature review, the statistical analyses, or the identification of bias. The global quality of meta-analyses seems, however, slowly improving (non-significantly), as in other research fields (El-Rabbany *et al* 2017, Jamshidi *et al* 2018).

The identification of relevant studies is a critical aspect of any systematic review; the non-inclusion of relevant experimentations may result in biased conclusions. Based on data provided, we can hardly assertthe suitability of the data collection methods of any meta-analyses. No meta-analyses meet all eight criteria of the 'literature review and selection' theme. The mention of excluded studies with explicit reasons and exclusion steps is very rare, as already observed in other research fields (11% in Jamshidi *et al* 2018; <1%

in Gates 2002 or Roberts *et al* 2006; a very low CEESAT score for this item in Woodcock *et al* 2017). The search strings and/or database queried are often presented without sufficient details to repeat the procedure as already found in Woodcock *et al* 2017 but not Jamshidi *et al* 2018. Preregistration of full protocols has been proposed as a means to improve transparency and perhaps also to help increase the quality of these studies (Ionnidis *et al* 2016). None of the meta-analyses in our study published or reference an *a priori* protocol, a common problem in different scientific fields (Booth *et al* 2013, Moher *et al* 2015). On the opposite, list the references of primary studies summarized in the meta-analyses is a well-established practice in different domains (e.g. almost 100% in agronomy, 74% according to Jamshidi *et al* 2018).

A transparent presentation of the results is necessary to avoid possible misinterpretation. The statistical models are presented in a majority of the studies (66%), so are the tools employed (e.g. software, packages, functions; 80%). More generally, in agronomy, the impacts of the co-variables on the results are almost always investigated (our study: 98%), unlike in other scientific fields (Gates 2002, Roberts *et al* 2006). Agronomists are, indeed, keen on understanding crop management techniques and environmental characteristics that drive the performances of agro-systems (Philibert *et al* 2012). Here, the reviewed meta-analyses, however, fail to provide a comprehensive description of individual effects-sizes and their uncertainty (i.e. effect sizes of each primary studies) contrary to other fields (Gates *et al* 2002, Woodstock *et al* 2017). The results of the included studies cannot be easily reanalyzed, updated or compiled because of the lack of availability of the dataset (provided in less than 35% of the studies considered here—Philibert evaluated this score to 10% in 2012).

There is potential room for improvement in the statistical analyses of most studies. In agronomy, primary studies are rarely weighted according to their accuracy or quality. In these unweighted analyses, within-and between-study variations are not easily disentangled and heterogeneity may be difficult to analyze properly (Gurevitch *et al* 2018). This also increases the influence of small studies—whose results are often highly variable (Button *et al* 2013). The choice of the method to identify and to score primary studies according to their quality are, however, debated (Greenland and O'rourke 2001). Analyzing potential publication bias seems not to be a common practice, for the time being, in agronomy. Publication bias is perhaps the greatest threat to the validity of meta-analyses results, and must be considered particularly seriously (Rothstein *et al* 2005). Our study, however, indicates some progress in recent years in agronomy (16% of studies analyzed by Phillibert *et al* 2012 met the criteria versus 40% in our study). As a comparison, this criterion is fulfilled in 8% to 34% of the meta-analyses in other fields (Gates 2002, Roberts *et al* 2006, O'Leary *et al* 2016, Jamshidi *et al* 2018). Yet, simple methods exist to evaluate potential publication biases (e.g. fail-safe number, funnel plots, Hillebrand and Gurevitch 2016).

Globally, our results indicate limited transparency and reproducibility of some meta-analyses. Low-quality meta-analyses are strongly criticized (Kirsch *et al* 2008, Pullin and Knight 2012, Ioannidis 2016) and negatively impact the image of usefulness of such method (Whittaker 2010). Our in-depth quality assessment could serve as a benchmark to perform new meta-analyses.

5. Conclusion

Our work presents the first evidence map on crop diversification at the global scale. We provide a global synthesis of 99 meta-analyses and of more than 3700 experimental results assessing seven crop diversification strategies around the world. More than 75% of the estimated effect sizes indicate a positive impact of crop diversification on biodiversity. All diversification strategies except agroforestry showed a positive median impact on crop yield. Agroforestry productive performance is more variable, but present almost systematically positive impacts on soil quality, in particular on soil organic carbon. Estimating product quality, water use and economic performance in diversified systems requires new synthetic quantitative data since these outcomes have only been studied in a small number of meta-analyses. Our analysis also reveals that a large improvement of the quality of the meta-analyses is required, as 46% of our quality criteria are not met in average.

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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 at https://doi.org/10.1016/j.dib.2019.103898.

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