Biodiversity and yield trade-offs for organic farming

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Abstract

Organic farming supports higher biodiversity than conventional farming, but at the cost of lower yields. We conducted a meta-analysis quantifying the trade-off between biodiversity and yield, comparing conventional and organic farming. We developed a compatibility index to assess whether biodiversity gains from organic farming exceed yield losses, and a substitution index to assess whether organic farming would increase biodiversity in an area if maintaining total production under organic farming would require cultivating more land at the expense of nature. Overall, organic farming had 23% gain in biodiversity with a similar cost of yield decline. Biodiversity gain is negatively correlated to yield loss for microbes and plants, but no correlation was found for other taxa. The biodiversity and yield trade-off varies under different contexts of organic farming. The overall compatibility index value was close to zero, with negative values for cereal crops, positive for non-cereal crops, and varies across taxa. Our results indicate that, on average, the proportion of biodiversity gain is similar to the proportion of yield loss for paired field studies. For some taxa in non-cereal crops, switching to organic farming can lead to a biodiversity gain without yield loss. We calculated the overall value of substitution index and further discussed the application of this index to evaluate when the biodiversity of less intensified farming system is advantageous.

1. Introduction

In order to meet the demands of a growing world population (FAO 2019), agriculture must provide sufficient food and raw materials. Agriculture occupies about 38% of the land surface of the Earth (FAO 2019). However, the conversion of land from nature to agriculture has caused and is still causing major biodiversity losses (Robinson & Sutherland 2002; Godfray *et al.* 2010; Tilman *et al.* 2011; Newbold *et al.* 2015). Ensuring sufficient food supply in a sustainable way is a challenge (Godfray *et al.* 2010; Tilman *et al.* 2011; Newbold *et al.* 2015; Ramankutty *et al.* 2018; Seppelt *et al.* 2020). As there is a pressing need to make agriculture less damaging to biodiversity, conservation measures in agricultural landscapes need to be re-considered in a Global Biodiversity Framework (Wanger *et al.* 2020). Shifting from conventional to organic farming has been considered as an option for enhancing agricultural biodiversity (Tuck *et al.* 2014).

Conventional farming with intensive management (e.g. routine application of synthetic pesticides and fertilizers in large crop monocultures) achieves high production, but with serious negative consequences for farmland biodiversity and its associated ecosystem services (Reganold & Wachter 2016; Meemken & Qaim 2018; Ramankutty *et al.* 2018; Beckmann *et al.* 2019). Organic farming, which uses no or only natural pesticides and organic fertilizer, is seen as a more environmentally friendly option (Bengtsson *et al.* 2005; Albrecht *et al.* 2007; Clough *et al.* 2007; Lori *et al.* 2017). Organic farming, has been rapidly increasing worldwide, in many different crops over the last decades (IFOAM 2021). In general, organic farming harbors higher biodiversity but lower yield than conventional farming (Batáry *et al.* 2011; Seufert *et al.* 2012; Tuck *et al.* 2014). Since organic farming has a lower yield per unit area than conventional farming, more land is required for producing the same amount of food (Phalan *et al.* 2011a; Balmford *et al.* 2018; Meemken & Qaim 2018). Thus, additional land from non-crop such as natural and semi-natural habitats need to be converted to organic farmland if the same production is required. As farmland, including organically farmed land, usually harbors lower biodiversity than natural habitats, such conversion likely increases the negative impact of farming on biodiversity (Phalan *et al.* 2011a; Grass *et al.* 2021). Therefore, due to its lower yield, organic farming could reduce and even cancel out the positive effect on biodiversity gain when transferring from conventional farming by reducing natural land. Whether it is worthwhile to switch from conventional to organic farming in terms of the biodiversity gain and yield loss is under debate (Hodgson *et al.* 2010; Phalan *et al.* 2011b; Tscharntke *et al.* 2012; Balmford *et al.* 2018).

While individual studies comparing conventional and organic farming inform us about specific trade-offs between biodiversity gain and yield loss (e.g. Solomou & Sfougaris 2011; Gabriel *et al.* 2013), a meta-analysis that helps us to have a global synthetic understanding of this topic is essential (Gurevitch *et al.* 2018). There are different, stand-alone meta-analyses, which compare either yield (Seufert *et al.* 2012), or biodiversity (Tuck *et al.* 2014) between organic and conventional farming, and showed that results varies among taxa and crop types. Tuck *et al.* (2014) reported that species richness in organic farming is about one-third higher than in conventional farming, but this effect varies among taxa and crop types. For example, plants benefited more from organic farming than birds, arthropods or microbes, whereas cereals exhibited larger differences in biodiversity than non-cereal crops. Seufert *et al.* (2012) found yield in organic farming to be about one-fourth lower than in conventional farming, but it also varies among crop types, with a much larger yield gap in cereal than non-cereal crops.

However, it is still not known whether high yield loss always implies high biodiversity gain, and how such effect differs among different crop types and taxonomic groups. To evaluate whether it is worthwhile to switch from conventional to organic farming we need studies that quantify the effects of organic and conventional farming on both biodiversity and yield. To our knowledge, no such synthesis has been conducted.

Here, we synthesized studies that evaluated both biodiversity and yield for conventional vs. organic farming, to quantify the strengths of trade-offs between biodiversity and yield, to better inform agricultural management decisions. First, we aim to determine whether high yield loss always means high biodiversity gain across studies and how it varies between crop types and taxonomic groups. To achieve this aim, we i) examine the relation of biodiversity gain to yield loss across all studies in our meta-analysis; ii) define a 'compatibility index' to evaluate the overall difference comparing conventional and organic farming based on the relative amount of biodiversity gain and yield loss, and (iii) analyze whether these indices differ between crop types and taxonomic groups, as well as factors that might affect the organic treatments such as agricultural management intensification, climatic zonation, nation and landscape context.

Second, we propose that the biodiversity gain versus yield loss relationship can provide a good basis for deciding whether it is worthwhile to switch from conventional to organic farming including the fact that organic farming may require the conversion of more non-crop habitat to cultivated land. We developed a substitution index, which can be used to infer whether transferring from conventional to organic farming would be more advantageous for biodiversity conservation. We identify the overall value of this substitution index, and test whether it varies between crop types and taxonomic groups.

2. Material and Methods

2.1 Literature search and screening protocol

We focused on studies that measured both biodiversity and yield, within a paired fields/farms setting that compared organic management and conventional management. Within management pairs within each study, biodiversity and yield should always have been measured using the same methods and the same spatial sampling unit, so that proportional increases/decrease comparisons are meaningful. We searched articles in the Web of Science Core Collection database. Search terms used were Topic: (organic* OR agri-environment* OR biodynamic OR agroecolog* OR "ecological agri*" OR ecoagri* OR eco-agri*) AND Topic: (inorganic OR convention* OR “chemical fertilizer*" OR "integrated pest management" OR pesticide* OR insecticide* OR herbicide* OR fungicide*) AND Topic: (yield* OR production* OR productivit*) AND Topic: (biodiver* OR richness OR diversit*) (see Appendix S1 in Supporting Information for details of refinement options). We included all articles published between 1990 and 2021, which resulted in 1396 studies.

In some biodiversity studies, the yield data is only included as background information and not included in the topic field of Web of Science (title + keyword + abstract), hence we missed these studies. The meta-analysis conducted by Tuck *et al.* (2014) focused on the biodiversity comparison between organic and conventional farming, we therefore conducted a full text filtering for all studies used by Tuck *et al.* (2014), which is up to 2011 (Fig. S1), and we subsequently used the same search terms to collect articles from 2011 to 2021. We classified treatments as conventional or organic according to the classification within the study. For studies that did not mention organic farming, we included farming management without chemical pesticide and synthetic fertilizer as the organic treatment. Other managements included in organic are biological pest control (e.g. micro-organisms for insects), physical control (e.g. using hand or grass cutter for weed), organic manure (e.g. dairy manure and green manure) and cover crops (Bengtsson *et al.* 2005; Seufert *et al.* 2012; Tuck *et al.* 2014).

We screened titles and abstracts for performing the first selection, excluding studies that lacked a mean or sample size information for species richness or crop yield, which resulted in a total of 359 articles for full-text assessing. Finally, a total of 75 studies met selection criteria and were used in the analysis (see PRISMA diagram in Fig. S1; see bibliography of the 75 studies in Appendix S2). Locations of these studies were showed in Fig. S2. Detailed reasons of exclusion for the 284 studies are provided in Appendix S3.

2.2 Data extraction and validation

Biodiversity was usually reported as the species richness (i.e. number of species) observed in a temporally and/or spatially defined sample. For studies that only reported biodiversity indices (e.g. Shannon entropy), the values were back-transformed to species richness (see Jost *et al.* 2006). Yield could be reported as grain dry weight per area or per plant. We divided crops into cereals (wheat, oat, barley, rice and maize) and non-cereals (fruits, vegetables, coffee, legumes, forage grass, oil crops, tea, sunflower and cocoa). Studies that only measured the overall yield with a mixture of cereal and non-cereal crops were classified as mixed crops. We classified organisms into five broad taxonomic groups: birds, mammals, invertebrates, microbes and plants. Studies may contain multiple taxonomic groups, crop types, multiple regions or multiple treatments. In the 75 selected studies, we calculated 177 biodiversity comparisons and 175 yield comparisons. Some studies recorded biodiversity for more than one taxonomic group but only one crop type of yield, and vice versa; therefore, 205 paired biodiversity and yield comparisons could be constructed from the 177 biodiversity comparisons and 175 yield comparisons.

We extracted species richness and yield means, standard deviations, and sample sizes either directly from the text and tables or from figures using Getdata 2.26 (Peng *et al.* 2019). Sixteen studies with 55 cases had no standard deviation for biodiversity, and 13 studies with 22 cases had no standard deviation for yield. As the scale of biodiversity, yield and their standard deviation varied between studies, directly imputing missing standard deviation from all dataset would generate inappropriately large values. We therefore first calculated the effect size and the related variances for the studies with variance information, based on which we then imputed the missing variances (van Buuren & Groothuis-Oudshoorn 2011). The missing variances was computed as the average value from 100 imputation chains (Kabacoff 2011).

Considering that organic treatment is poorly defined and context dependent (Seufert *et al.* 2017), we further divided selected studies according to different management practices, climatic zones and locations. Management practices include different intensification levels according to the fertilization and pesticide application following Beckmann *et al.* (2019). Accordingly, two intensification levels, low and medium, were identified for fertilization application and pesticide use (see Appendix S4 for details). We followed Peel *et al.* (2007)'s guidelines and divided our studies into different climatic zones based on their locations. As organic treatment might depend on national regulations (Seufert *et al*. 2017), we divided all studies by nation, categoizing European Union countries as EU. It needs to be noted that due to the lack of sufficient studies, meaningful comparisons might not be possible for all categories. The number of studies for each category was provided in Table S1.

Furthermore, we extracted information on the proportion of arable land at the radius of 1km as a proxy for landscape complexity (Tuck et al. 2014) for respective studies. If the information was not recorded but detailed locations of study sites were available, the proportions of arable land was estimated based on the most recent digital maps from Google Earth. As all of these studies were published after 2005 and were mostly in Europe, where temporal changes in the proportion of arable land at the landscape level are likely minor.

2.3 Effect size

We used log response ratios to compare biodiversity and yield in organic and conventional farming. As effect size for the relative biodiversity in organic and conventional farming (E_b), we used the logarithm of the ratio (R_b) of species richness in the organic (B_o) and conventional (B_c) treatment in each study,

$$E_b = ln(R_b) = ln\left(\frac{B_o}{B_c}\right)$$

Similarly, as effect size for the relative yield (E_y) in the organic and conventional treatment, we used the logarithm of the ratio (R_y) of yield in the organic (Y_o) and conventional (Y_c) fields,

$$E_y = ln(R_y) = ln\left(\frac{Y_o}{Y_c}\right)$$

The corresponding variances, $\sigma^2(E_b)$ and $\sigma^2(E_y)$ are:

$$\sigma^2(E_b) = \frac{\sigma^2_{B_o}}{n_{B_o} * B_o^2} + \frac{\sigma^2_{B_c}}{n_{B_c} * B_c^2}$$

$$\sigma^2(E_y) = \frac{\sigma^2_{Y_o}}{n_{Y_o} * Y_o^2} + \frac{\sigma^2_{Y_c}}{n_{Y_c} * Y_c^2}$$

where $\sigma^2_{B_o}$ and $\sigma^2_{B_c}$ are the variances of B_o and B_c, respectively, and n_{B_o} and n_{B_c} are the corresponding numbers of replicate measurements ; $\sigma^2_{Y_o}$ and $\sigma^2_{Y_c}$ are the variances of Y_o and Y_c, and n_{Y_o} and n_{Y_c} are the corresponding numbers of replicate measurements.

2.4 Compatibility index and substitution index

We propose two indices (illustrated in Fig. 2) to summarize the strength of the trade-off observed between biodiversity and yield when comparing organic management to conventional management. The compatibility index simply contrasts the proportional increase in biodiversity with the proportional decrease of yield – it is high when increasing biodiversity is highly compatible with maintaining yield (and in pure win-win scenarios, see Fig. 2A and Appendix S5 for the inference). The substitution index aims to quantify how comparatively biodiversity-rich a third, unfarmed landcover would have to be, to favor a strategy of conventional farming combined with sparing such unfarmed land. When the substitution index is high, the organic farming is likely to lead to higher overall species-abundance, under certain assumptions (see Fig. 2B). Our compatibility index, $C_{c\text{-}o}$, is defined as

$$C_{c-o} = ln(R_b * R_y) = E_b + E_y$$

It is a heuristic measure which is higher when the biodiversity gain is large compared to the yield penalty when comparing the organic management to the conventional.

The variance of $C_{c\text{-}o}$ is:

$$\sigma^2(C_{c-o}) = \sigma^2(E_b) + \sigma^2(E_y)$$

Intuitively, a positive or high value of $C_{c\text{-}o}$ suggests that the organic farming is effective, demonstrating compatibility of yield with biodiversity on the same land (see Fig. 2A)– but mathematically it does not give a condition for whether this management is the optimal choice for biodiversity (see Fig. 2C).

To clarify the overall losses/gains involved in switching management, we should include the potential biodiversity decrease caused by maintaining overall agricultural yield in any option where yield-per-area is lower. Conversely, it may sometimes be beneficial to conventional farming if this "spares" some land with a high biodiversity value.

Consider an area divided in a proportion conventionally managed agricultural land p and a proportion uncropped land (1-p) (Fig. 1; although N and B are illustrated as blocks, we don't make any assumption about the spatial configuration of these landcovers). Assuming biodiversity in the whole of the area is a weighted average of the biodiversity of its component areas, the total biodiversity would be $p * B_c + (1 - p) * N$ where N is the biodiversity in the natural area. In an area with the same production output from organic farming, the area proportion for agriculture would be $\frac{p}{R_y}$. The biodiversity in this situation would be $\frac{p}{R_y} * B_o + \left(1 - \frac{p}{R_y}\right) * N$.

From the viewpoint of biodiversity maximization, organic farming would be the better solution if:

$$\frac{p}{R_y}B_o + \left(1 - \frac{p}{R_y}\right)N > pB_c + (1-p)N$$

which can be simplified to either:

$$\frac{R_b - R_y}{1 - R_y} > \frac{N}{B_c}$$

in the expected case where the organic farming has lower yield ($R_y < 1$), or the opposite inequality

$$\frac{R_b - R_y}{1 - R_y} < \frac{N}{B_c}$$

in the unexpected case if ever the organic farming has higher yield ($R_y > 1$).

We can furthermore consider the following scenarios where no trade-off actually exists:

1) When $R_y \geq 1$ & $R_b > 1$, i.e. no yield loss but biodiversity gain when comparing conventional to organic farming, then organic farming is always preferred, which can also be considered as a win-win scenario (blue hatched area in Fig. 2B).

2) When $R_y < 1$ & $R_b \leq 1$, i.e. no biodiversity gain but only yield loss, then organic farming cannot be preferred, which can also be considered a lose-lose scenario (red hatched area in Fig. 2B).

Usefully, without knowing N, we set up a substitution index ($S_{c\text{-}o}$) as:

$$S_{c-o} = \frac{R_b - R_y}{1 - R_y}$$

The substitution index measures a threshold for the biodiversity of low-intensive organic farming, to evaluate whether converting to organic farming is worthwhile as extra land would be needed when reaching the same total production. In other words, if the $S_{c\text{-}o}$ is larger than the ratio in biodiversity in non-farmed areas to conventional land, (i.e. N/B_c), then organic farming is preferred. Otherwise, it is not preferred.

The variance of $S_{c\text{-}o}$ is (see Appendix S6 for derivation):

$$\sigma^2(S_{c-o}) = \left(\frac{\sigma^2(R_b)}{(R_b - 1)^2} + \frac{\sigma^2(R_y)}{\left(1 - R_y\right)^2}\right) * \left(\frac{R_b - 1}{1 - R_y}\right)^2$$

2.5 Data analysis

We first conducted a meta-regression to determine linear relationships between the mean effect size of yield ($E_y = ln\ (R_y)$) and biodiversity ($E_b = ln\ (R_b)$) based on the mixed-effects model with the restricted maximum likelihood (REML) and weighted considering the sampling variances (Gurevitch *et al.* 2001; Zuur *et al.* 2009), of which E_b is the independent variable. Because some studies contain multiple cases, we created a hierarchical dependence structure in the model by including study identity and species taxa as a random factor (Peng *et al.* 2019; Wan *et al.* 2020). Analysis was first conducted for the overall dataset, subsequently separate for each taxon group.

Next, we used mixed-effects model with REML in a hierarchical structure to estimate the grand mean biodiversity effect size (E_b), yield (E_y) and compatibility index ($C_{c\text{–}o}$) as well. Mean effect sizes for the different taxa in each crop type were first estimated separately, and then estimated for crop types by merging all taxa, and finally the overall effect size. Birds in the non-cereal crop type only had one study which did not allow us to calculate the between-study variance, thus birds in non-cereal crop were not included in the hierarchical model structure (Chen & Peace 2013). Furthermore, we compared the organic-conventional ratio of biodiversity (R_b), yield (R_y) and the compatibility index ($C_{c\text{–}o}$) for different management intensities, climatic zones and study nations. Comparisons were separated by crop types and taxa, while groups ≤ 3 studies were not compared. Accordingly, meaningful comparisons were possible for low and medium fertilizer intensities for microbes and plants in non-cereal crop species. We further analyzed the correlation between the effect size of biodiversity (E_b), yield (E_y), compatibility index and the proportion of arable land. Correlations were analyzed by meta-regression for each taxon group and overall dataset, again based on the mixed-effects model with REML and weighted according to their variances.

We calculated the value of $S_{c\text{-}o}$ based on the mean of E_b and E_y, for the taxa in each crop types, and then the overall value. Some sub-groups were not used for the $S_{c\text{-}o}$ calculation because they were in the ‘win-win’ or ‘lose-lose’ quadrants (Fig 2B) (only cases with $R_b > 1$ and $0 < R_y < 1$ were analyzed).

Finally, we assessed potential publication bias with funnel plots and a trim-and-fill assessment (Duval & Tweedie 2000). Heterogeneity was assessed with the Q test. Bias corrected equations were used to recalculate all the effect sizes (Appendix S7).

All analyses were conducted in R (version 4.0.3; R Core Team 2020). Package “metafor” (version 2.4-0; Viechtbauer 2010) was used for conducting all meta-analysis models.

The missing variance resulted from missing standard deviation was imputed by package "mice" (version 3.13.0; van Buuren & Groothuis-Oudshoorn 2011). All data were included in Appendix S4.

3. Results

3.1 Biodiversity and yield relationships

Looking at biodiversity gain and yield loss when moving from conventional to organic farming, we found that the majority (111 out of 205 cases) had trade-offs with positive biodiversity gain (i.e. higher biodiversity and lower yield in organic than conventional) and a minority had trade-offs with negative biodiversity gain (15 cases). We found 47 cases of win-win, while 32 cases were lose-lose situation (Fig. 3).

When combining all studies, we found no significant linear relationship between the overall effect sizes (log ratios of organic to conventional farming) for biodiversity and yield ($\beta = -0.03$, SE = 0.03, $P = 0.253$, Fig. 3). Examining the different taxa, there were significant negative linear relationship for microbes ($\beta = -0.26$, SE = 0.12, $P = 0.028$) and plants ($\beta = -0.15$, SE = 0.05, $P = 0.002$), but not for any of the other taxa (Fig. 3).

3.2 Compatibility and substitution index

Overall, the compatibility index ($C_{c\text{-}o}$) was very close to 0 (0.05, 95% CI = -0.05~0.14) (Fig. 4A), while the average response ratios for organic-conventional ratio of biodiversity (R_b) and yield (R_y) were 1.23 and 0.83 (Fig. 4B). The compatibility index of non-cereal crops was positive (0.18, 0.04~0.33), while that of cereal crops was not significantly different from zero (-0.09, -0.19~0.01) (Fig. 4A).

Comparing the different taxa, birds had significantly negative $C_{c\text{-}o}$ values in both cereal and non-cereal crops (Fig. 4A). In contrast, plants had a significant positive mean $C_{c\text{-}o}$ value cereal crops, but no significance for non-cereal crops (Fig. 4A). The ratio of overall biodiversity in non-cereal crops was significantly larger than 1, while the yield was not significantly different from 1 (Fig. 4B). The same trend was observed for microbes and plants in non-cereal crops (Fig. 4B), indicating that a biodiversity gain is compatible with little or no yield loss for those taxa under organic farming.

Comparing different intensities of fertilization application, the organic-conventional ratio of biodiversity (R_b) was higher at medium than low intensity level for non-cereal microbes (Fig. S3). No significant difference for other variables and plants (Fig. S3). There was no significant difference for $C_{c\text{-}o}$ values between different climatic zones for all taxa when looking cereal and non-cereal crops separately, although variation for the ratio of biodiversity and yield observed for certain taxa (Fig. S4). While limited comparisons were available, differences in R_b, R_y and $C_{c\text{-}o}$ were observed among different nations for invertebrates in both cereal and non-cereal crops (Fig. S5). The proportion of arable land negatively correlated with the log ratio of yield (E_y) for microbial studies, and positively correlated with the log ratio of biodiversity (E_b) and the compatibility index ($C_{c\text{-}o}$) for bird studies (Fig. S6). No significant correlation was observed for the overall trend and other taxa (Fig. S6).

The overall mean effect size of the substitution index $S_{c\text{-}o}$ was 2.40 (Table 1). Comparing crop types, the grand mean effect size of $S_{c\text{-}o}$ in cereal crops was 1.98. For non-cereal crops overall, biodiversity increased and there was no yield loss, thus organic farming is preferred for biodiversity conservation in general.

The $S_{c\text{-}o}$ showed high variance between the different taxa and crop species (Table 1). The mean effect size of $S_{c\text{-}o}$ for birds in cereal crops was 1.18, whereas there was no biodiversity gain in non-cereal crops, and thus organic farming was not preferred for bird biodiversity. The value of the $S_{c\text{-}o}$ for microbes in cereal crops was 1.38, whereas there was no yield loss with biodiversity gain in non-cereal crops. The $S_{c\text{-}o}$ for the invertebrates was much lower for cereal crops (1.83) than for non-cereal crops (4.18), while for plants this value was much similar between cereal (3.90) and non-cereal (4.88).

3.3 Publication bias and heterogeneity analysis

The funnel plot and trim-and-fill assessment estimated that there was no sign of bias for $C_{c\text{-}o}$ of each grand mean and group (Fig. S7, S8), except a positive bias for plants in cereal crops (6 estimated missing cases on the left side of the funnel plots) (Fig. S8). The Q test indicated heterogeneity among all study groups, except for birds in non-cereal crops (Table S2).

4. Discussion

Biodiversity gain and yield loss

Our study quantified the trade-off between biodiversity and yield in conventional and organic farming. Previously, meta-analyses compared the conventional and organic (or low intensity) farming independently for either yield or biodiversity (Seufert *et al.* 2012; Tuck *et al.* 2014; Beckmann *et al.* 2019) and hence did not analysis the trade-offs between biodiversity and yield. Here we compared yield and biodiversity differences within paired fields setting to understand whether the strength of the trade-off was consistent, or under what circumstances the trade-off became more extreme.

By examining the relation between biodiversity gain and yield loss across studies, we did not find a significant linear relationship between the effect size of yield and that of biodiversity for switching from conventional to organic farming. Although negative linear relationships between the log response ratios for biodiversity of microbes and plants and yield in organic and conventional farming were observed, there was only a shallow decrease of yield with increasing biodiversity in the organic farming examples. This result indicates that a higher biodiversity gain does not necessarily mean a much greater yield loss. The result is not surprising as both biodiversity loss and yield gain in different studies are influenced by differences in environmental factors such as climatic conditions, surrounding landscapes, study taxa and management strategies (Gomiero *et al.* 2011; Tuck *et al.* 2014; Tscharntke *et al.* 2021). In fact, it is also possible that biodiversity enhances yield through the provision of ecosystem services and hence enables the potential of ecological intensification for food security (Bommarco *et al*., 2013).

The compatibility index that we developed provides a picture of the overall relative size of the biodiversity gain and yield loss. By synthesizing all studies, we found that the index is positive, but close to zero, indicating that the biodiversity gain in organic farming is almost equivalent to the yield loss. This positive effect is mainly driven by the non-cereal crops, where there is no yield loss, while the biodiversity gain is similar for both cereal and non-cereal crops. Organic farming with no yield loss combined with a biodiversity gain supports the organic movement, but this mainly occurs in non-cereal crops (see Fig. 3) to achieve a win-win situation in biodiversity and yield. We found an overall ratio of 1.23 in biodiversity gain comparing organic and conventional farming, which is similar to the 1.34 that Tuck *et al.* (2014) found. Our overall organic to conventional yield ratio (0.83) is similar to that from Seufert *et al.* (2012) (0.75), although Seufert *et al.* (2012) used a much more elaborated sorting of crop types. In other words, our results show that, on average, organic farming has a one-fourth (23%, compared to conventional) gain in biodiversity with a similar cost (20%, compared to organic) in terms of yield decline.

The sub-group analysis showed that biodiversity gain for different taxa in different crops were mostly similar, but with a higher value for plants and a lower value for birds in cereal crops. Higher biodiversity for plants as compared to animals and microbes in organic versus conventional farms has also been reported in other meta-analyses (Bengtsson *et al.* 2005; Batáry *et al.* 2011), which is likely because the effect of herbicides on weeds is larger than the effect of other pesticides and chemical fertilizer on animals and microbes. In addition, the growing crops themselves can be a food resource for animals, whereas crops suppress weeds. The low compatibility value for birds is caused by the low biodiversity gain (not significantly larger than 0) and high yield loss (almost 50% loss in cereal crops, see Fig. 4B), but it needs to be noted that there was only one study of birds. Overall, our results suggest that, when focusing on microbes and plants in non-cereal crops, switching from conventional to organic farming is viable, because the biodiversity gain comes at a cost of little, or no, yield loss.

While more studies are needed, our results suggest that biodiversity and yield trade-off is context-dependent due to the variation of organic treatment. Intermediate intensity of fertilization application in the organic farming may enhance both yield and biodiversity for studies on microbes in non-cereal crops. Although differences were observed in the ratio of biodiversity and yield between organic and conventional farming for certain taxa across climatic zones, no significant difference was found in the compatibility index indicating an overall compromise trade-off for yield and biodiversity. We observed a negative correlation between the proportion of arable land and the log ratio of yield for microbial studies and a positive correlation with the log ratio of biodiversity for birds. Considering the unexpected cases for these taxa, i.e. yield in organic is higher than in conventional farming for microbe studies, while biodiversity in organic is lower than in conventional for birds, results suggest that these extreme cases are likely to occur in landscapes where the proportion of arable land is low. Our results again highlighted the importance of landscape factors in driving the biodiversity-yield trade-off (Tuck *et al.* 2014; Smith *et al.* 2020; Tscharntke *et al.* 2021).

The substitution index and its application

The substitution index ($S_{c\text{-}o}$) that we developed in this study provides an initial view if it is worthwhile to switch from conventional to organic farming in a landscape when the objective is to restore biodiversity while maintaining productivity. The overall mean $S_{c\text{-}o}$ value is about 2.4, which indicates that, on average, organic-farming would be a more effective strategy if the unfarmed lands are less than 2.4-times as biodiverse as conventional farms. This overall value, however, needs to be interpreted with caution, particularly because there are such marked differences between cereal and non-cereal crops.

The mean $S_{c\text{-}o}$ value is about 2.0 for the cereals, which indicates that organic farming is better if non-crop land has a biodiversity less than 2.0 times that of conventional farms.

However, though there are rather few studies that have made this biodiversity comparison, semi-natural areas often exceed this biodiversity threshold, and even uncropped field margins may do so (Hodgson *et al.* 2010; Phalan *et al.* 2011b). Looking at the taxonomic breakdown for cereal crops, birds, microbes and invertebrates showed a low substitution index, indicating that it is easier for non-crop areas to exceed the threshold, whereas plants show a high substitution index.

For non-cereal crops, there is almost no yield loss combined with a biodiversity gain, thus organic farming is the preferred option. However, this conclusion is very sensitive to the large uncertainty in the yield ratio. Whenever we are confident that $R_y>1$ (i.e. yield of organic farms is higher than that of conventional one), organic farming is a reasonable option. When R_y is close to, but less than 1, there is a possibility that conventional farming can be an effective strategy. Sub-group analysis showed large variances of the S_{c-o} for non-cereal crops, and little conformity across taxa. Birds were, even in non-cereal crops, likely favored by conventional farming, while microbes were likely favored by organic farming. Invertebrates and plants showed a high and uncertain threshold for conventional farming (i.e. non-crop areas only beneficial if up to 20-times as biodiverse as conventional farms).

The high variance of the S_{c-o} value that we calculated in this meta-analysis presents a difficulty to directly use the S_{c-o} to guide management and policy-making, because it is always context-dependent. However, by including biodiversity observation from natural habitats, the index provides a window that allows policy-makers and stakeholders to make decisions to choose organic or conventional farming at a local scale. Nonetheless, values might be different for different taxa. For example, in

Mbalmayo Forest Reserve in Cameroon, the ratios of arthropod and bird biodiversity between primary forest and conventional farm are about 1.7 and 4.5 (Lawton *et al.* 1998). Thus, if the $S_{c\text{-}o}$ value for arthropods is larger than 1.7, organic farming strategy could be acceptable, but the value should reach at least 4.5 for bird conservation. The required value might be higher for other locations, for example in the Lore Lindu National Park in Indonesia, where arthropod and bird diversity differences between primary forest to conventional land are about 2.5 and 5 (Schulze *et al.* 2004). In total, the $S_{c\text{-}o}$ provides a tool to evaluate biodiversity and yield trade-off, and can indicate the threshold when the biodiversity of organic-farming is advantageous, despite the extra area it takes up. We fully acknowledge that the value of the $S_{c\text{-}o}$ varies between locations and taxa. Also it is rarely obvious which land -if any- is encroached upon by organic management. Nonetheless, if similar $S_{c\text{-}o}$ values among different regions were observed, then organic farming is more likely preferred for regions with lower species-richness in the remaining non-crop habitats.

When looking at larger scales, the substitution index can be used to address the biodiversity conservation and land-use intensification debates (e.g. Beckmann *et al.*, 2019, i.e. to help the decision makers to address whether a less intensive farming system is more beneficial than an intensive one in terms of yield production and biodiversity conservation (Seppelt *et al.*, 2020). The Biodiversity conservation and land-use intensification trade-off is also related to the "land sparing" vs. "land sharing" debate (Hodgson *et al.* 2010; Godfray & Garnett 2014; Phalan *et al.* 2016; Balmford *et al.* 2018). In the "land sparing" strategy, the agricultural land is intensively used for high yielding agriculture to leave as much land as possible for conserving high biodiversity in natural lands (Green *et al.* 2005; Phalan *et al.* 2011a; Ramankutty *et al.* 2018). In the "land sharing" strategy, the agricultural land is managed extensively and biodiversity-friendly, however, more land is required for achieving the same total production as in intensive agriculture (Fischer *et al.* 2008; Phalan *et al.* 2011a; Kremen 2015). Thus, the substitution index can be interpreted as the minimum threshold for the biodiversity of any spared land (as a multiple of the biodiversity of conventional farmland), which would be needed to render a land-sparing strategy optimal. Therefore, when the substitution index is high it is probably difficult to find spared land rich enough in biodiversity, and so the lower intensity agriculture is likelier to maximize biodiversity. When the substitution index is low, it arguably should be easy to find uncultivated land rich enough in biodiversity, that could be combined with the conventional farming to form a "winning" land-sparing strategy.

Future directions and conclusion

Here we only used species richness and crop yield to evaluate the trade-off for conventional-organic conversion. Species richness could be affected by the observation scales (e.g. sampling effort, Belmaker & Jetz 2011) and should be considered in further study. To investigate other metrics, such as species composition, species abundance and farmer income are also encouraged to provide a more comprehensive understanding of this topic (Baudron *et al.* 2021). Further studies are also needed to examine species according to ecological function or their relationship with humans (e.g. synanthropic or not), and divide crops into more specific crop types. In addition, here we assume a linear species-area relationship, a non-linear relationship may also need to be considered, particularly when extending our substitution to a larger scale (Egan & Mortensen 2012). Furthermore, organic farming is not the only way for farmland biodiversity conservation. Studies are also encouraged to investigate trade-offs between the cost and biodiversity gain of other management in agriculture, such as small and diversified fields for biodiversity-friendly landscapes (Tscharntke *et al.* 2021).

Overall, this study provides (1) a compatibility index to evaluate trade-offs between biodiversity gain and yield loss when switching from conventional to organic farming, and (2) a substitution index to indicate the preferred strategy of conventional to organic farming for maintaining both biodiversity and productivity while considering the impacts of the land claim of agriculture on overall biodiversity. Our results do show the possibility of high biodiversity gain at the cost of little, or no, yield loss when converting from conventional to organic farming in non-cereal crops, indicating that organic farming can be the preferred option to maximize biodiversity. Although the high variance indicates the context-dependency when considering conventional or organic farming, we provided a tool to help local decision makers to address whether a less intensive farming system is beneficial for yield production and biodiversity conservation.

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Table 1. Taxon-and crop-specific substitution index (S_{c-o}) weighted means with 95% confidence intervals in brackets, only calculated for sub-groups where there appears to be the expected trade-off (higher biodiversity and lower yield in lower intensity agriculture). Higher values of the substitution index mean that organic farming is likelier to maximise biodiversity despite the extra land it takes up.

	Cereal	Non-cereal
Bird	1.18 (0.57~1.80)	‘lose’ **R_b <= 1**
Invertebrate	1.83 (1.13~2.51)	4.18 (0.51~7.85)
Microbe	1.38 (0.97~1.78)	‘win’ **R_y >= 1**
Plant	3.90 (2.71~5.09)	4.88 (-9.87~19.63)
Grand mean	**1.98 (1.53~2.43)**	‘win’ **R_y >= 1**
Overall	**2.40 (1.62~3.18)**	

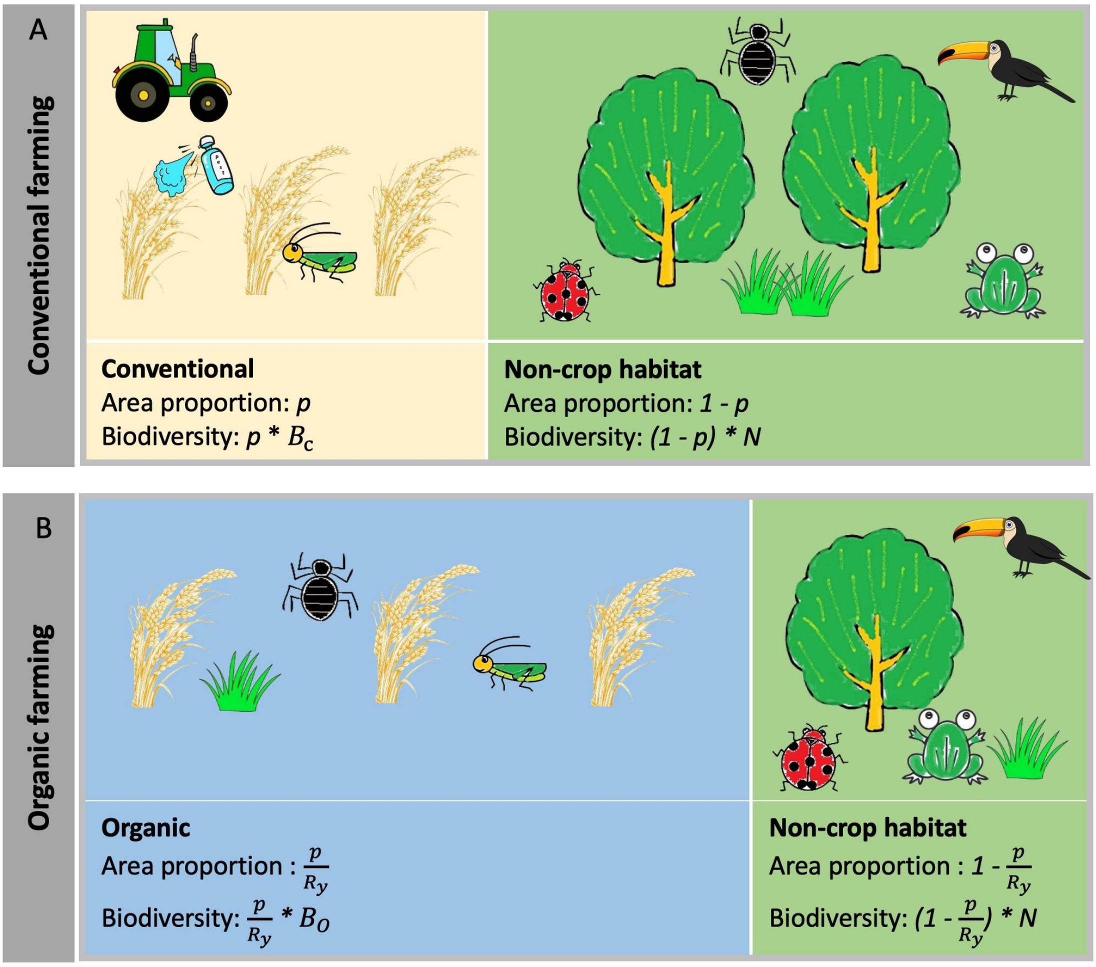

Figure 1. Diagram showing the conventional (A) and organic (B) farming strategies that could reach the same total food production. If land management is to be changed, a factor $1/R_y$ more land is required for the organic farming, or conversely, a fraction of land could be released if the farming is conventional. These uncultivated areas could be in any spatial configuration; we make no assumption about whether they are distributed around the fields/farms themselves, or somewhere separate. Given simplifying assumptions, the formulas for the area and biodiversity of each land component help us to evaluate which strategy results in the highest total biodiversity-abundance.

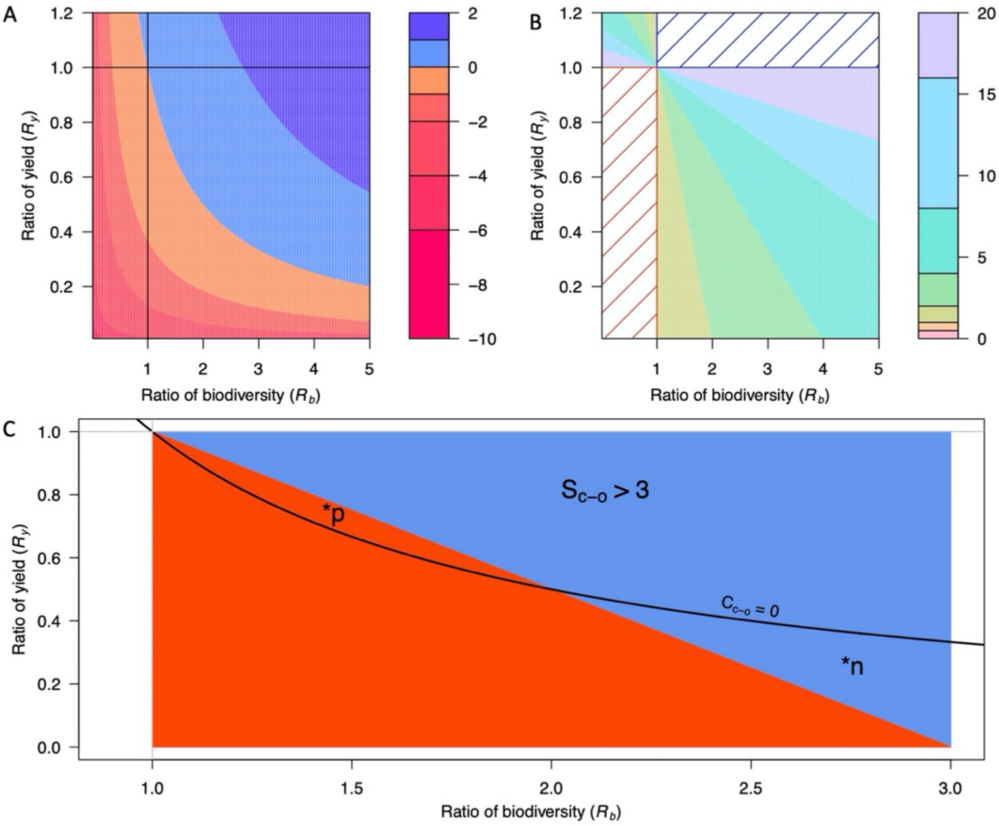

Figure 2. Illustrative diagrams of our two proposed indices which depend on the ratios of biodiversity (R_b) and of yield (R_y) between organic and conventional farming. (A) The compatibility index ($C_{c\text{-}o}$), which is the log ratio of biodiversity and yield (i.e. $E_b + E_y$) when shown by colour zones (truncated at -10 and 2); (B) The substitution index ($S_{c\text{-}o}$) index shown by colour zones (truncated at 1 and 20); the shaded areas in blue and red refer to win-win and lose-lose situations respectively for both biodiversity and yield under organic farming; (C) An example to show how a positive compatibility index ($E_b + E_y > 0$) doesn't necessarily indicate that organic farming is the most efficient conservation strategy. The black curve, where compatibility index = 0, intersects with an example threshold value of $S_{c\text{-}o} = 3$ (background blue where $S_{c\text{-}o} > 3$). Areas labelled *p shows where compatibility index is positive, but conventional farming is preferred; *n shows where compatibility index is negative but organic farming is preferred.

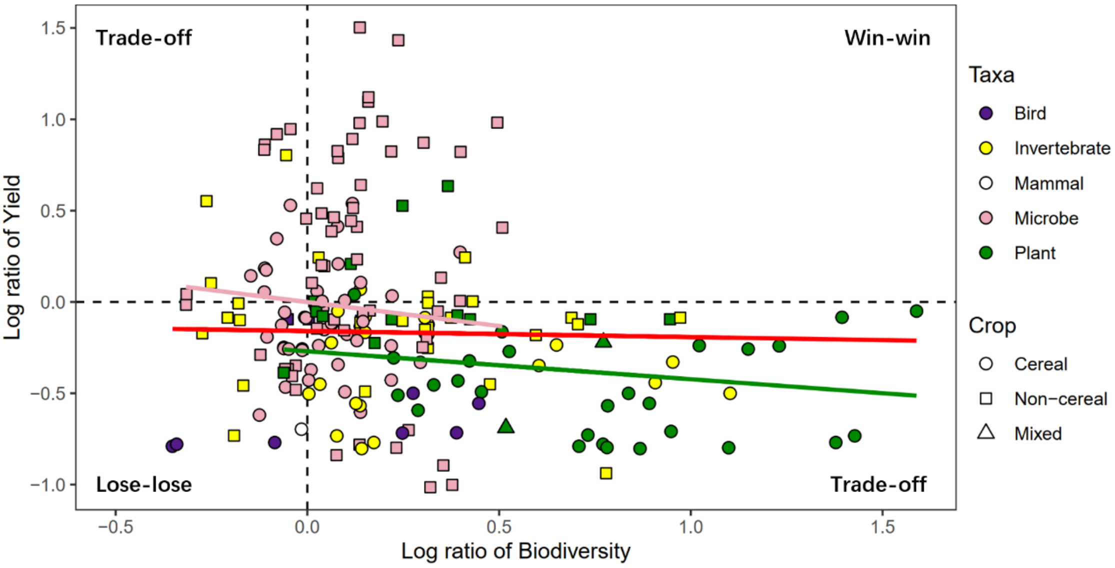

Figure 3. Scatter plot of log yield ratio vs log biodiversity ratio in organic vs conventional farming. Effect sizes were calculated from treatment pairs within studies. The red line shows the overall linear regression (n=205); the pink line refers to the linear regression for microbes (n=100) and the green one for plants (n=43).

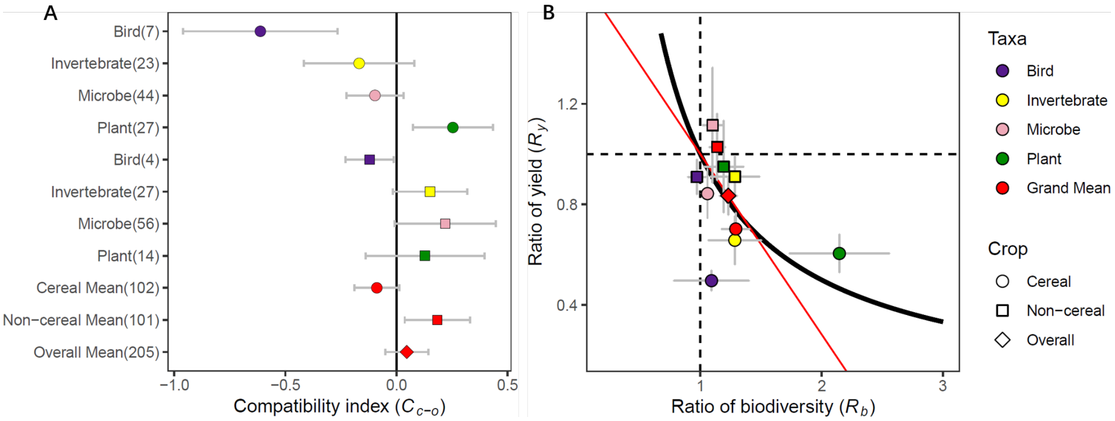

Figure 4. (A) The mean compatibility index (i.e. the contrast in log biodiversity gain and yield loss, $C_{c\text{-}o}$) for all studies and sub-groups; error bars represent 95% confidence intervals; numbers in brackets refer to number of cases. (B) The ratio in yield (R_y) and biodiversity (R_b) between organic and conventional fields for different taxa in different crop types, and for all studies. Dots and error bars show the mean value and 95% CI. The black curve shows where compatibility index $C_{c\text{-}o}$=0; the red line shows where substitution index $S_{c\text{-}o}$ equals its overall mean of 2.4 (see Table 1).