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Quantifying the impacts of ecological restoration on biodiversity and ecosystem services in agroecosystems: A global meta-analysis

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ABSTRACT

Landscape transformation due to agriculture affects more than 40% of the planet's land area and is the most important driver of losses of biodiversity and ecosystem services (ES) worldwide. Ecological restoration may significantly reduce these losses, but its effectiveness has not been systematically assessed in agroecosystems at the global level. We quantitatively meta-analyzed the results of 54 studies of how restoration actions reflecting the two contrasting strategies of land sparing and land sharing affect levels of biodiversity and ES in a wide variety of agroecosystems in 20 countries. Restoration increased overall biodiversity of all organism types by an average of 68%. It also increased the supply of many ES, in particular the levels of supporting ES by an average of 42% and levels of regulating ES by an average of 120% relative to levels in the pre-restoration agroecosystem. In fact, restored agroecosystems showed levels of biodiversity and supporting and regulating ES similar to those of reference ecosystems. Recovery levels did not correlate with the time since the last restoration action. Comparison of land sparing and land sharing as restoration strategies showed that while both were associated with similar biodiversity recovery, land sparing led to higher median ES response ratios. Passive and active restoration actions did not differ significantly in the levels of biodiversity or ES recovery. Biodiversity recovery positively correlated with ES recovery. We conclude that ecological restoration of agroecosystems is generally effective and can be recommended as a way to enhance biodiversity and supply of supporting and regulating ES in agricultural landscapes. Whether a land sharing or land sparing strategy is preferable remains an open question, and might be case dependent. Moreover, it is unclear whether crop production on restored land can meet future food production needs.

1. Introduction

Croplands and pastures occupy approximately 40% of the Earth's terrestrial surface, making them the largest land use types on the planet (Foley et al., 2011). Agricultural expansion and intensification result in loss of biodiversity (Tscharntke et al., 2012) and reduction of the variety and levels of ecosystem services (ES), which are benefits that people obtain from ecosystems (Millennium Ecosystem Assessment (MEA), 2005). Converting land for agricultural use leaves some provisioning ES unaffected and improves other provisioning ES (e.g., food and fiber) (Rey Benayas and Bullock, 2012), while at the same time reducing land available to supply other supporting, regulating and cultural ES (Bullock et al., 2011; Pilgrim et al., 2010; Raudsepp-Hearne et al., 2010a, 2010b). MEA (2005) found that, over the last 50 years, the supply of 15 of the 24 ES analyzed have decreased, including biological pest control and pollination. Growth in global income and population are projected to continue in the next decade, leading to predictions of continued growth in demand for agricultural products around the world. Growth in food requirement may be as high as 70% by 2050 (Bruinsma, 2009), though other authors have estimated that future demand can be met with no further increase in agricultural land (Foley et al., 2011).

This highlights the importance of finding management alternatives to reconcile agricultural production with the maintenance

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or enhancement of levels of biodiversity and ES in agricultural landscapes. Ecological restoration seems well-suited to accomplish this goal (Wade et al., 2008). Restoration efforts aim to recover the characteristics of an ecosystem, such as biodiversity and supply of ES, that have been degraded, damaged, or destroyed, usually as a result of human activity (SER, 2004; see this source for definition of concepts). Evidence suggests that ecological restoration works: for instance, a meta-analysis of 89 studies assessing the effects of restoration of a broad range of ecosystem types around the world found that it increased biodiversity by an average of 44% and ES levels by an average of 25% (Rey Benayas et al., 2009). Similarly, other ecological restoration meta-analyses in more specific ecosystem types such as forests (e.g., Felton et al., 2010; Ilstedt et al., 2007) and wetlands (Meli et al., 2014) have reported increases in biodiversity and/or supply of ES. Two examples of large-scale ecological restoration programs are the Atlantic Forest Restoration Pact, which aims to restore 15 million ha of degraded lands in the Brazilian Atlantic Forest by 2050 (Calmon et al., 2011), and the Sloping Land Conversion Program in China, in which steeply sloping and marginal land has been retired from agricultural production since 1999 in order to promote forest and grassland cover (Yin and Zhao, 2012). These initiatives align with international agreements such as the Action Plan for 2020 published by the Convention on Biological Diversity (CBD), which aims to restore at least 15% of the world's degraded ecosystems (CBD, 2012).

Given that a large proportion of degraded, damaged, or destroyed ecosystems are agricultural land, some studies have sought to assess whether ecological restoration can increase biodiversity and supply of ES specifically in agroecosystems (e.g., Aviron et al., 2011; Pöyry et al., 2004; Pykala, 2003; Wade et al., 2008; Wang et al., 2011). Each of these studies, however, has been limited to specific ecosystems, leaving open the question of whether ecological restoration is effective for agroecosystems on a global scale. Therefore, it is necessary to analyze case studies across a broad range of agroecosystems in order to identify global trends in ecological restoration outcomes.

This issue is particularly important because two contrasting strategies are widely used to enhance biodiversity and supply of ES in agroecosystems (Rey Benayas and Bullock, 2012). Land sharing, often called wildlife-friendly farming, advocates conserving and improving the levels of biodiversity and ES of the farmed environment; in contrast, land sparing advocates dividing the land area into separate areas for farming and for maximizing biodiversity and supply of ES other than agricultural production (Green et al., 2005; Phalan et al., 2011). While the restoration actions implemented under a land sharing or land sparing strategy seem to differ more in scale or extent than in type, the two strategies can have profoundly different implications for land use planning, particularly for defining restoration targets, indicators of restoration success, the site of restoration actions, and specific actions that should be taken (Fig. 1).

The two strategies are typically implemented through either passive or active restoration. Passive restoration implies the removal of degrading factors and most frequently involves secondary succession following abandonment of agricultural land in areas formerly used for crop or livestock farming. Active restoration involves actions such as adding in desired plant species and amending the soil, which also drive secondary succession. While previous studies have evaluated one or more of these measures for specific agroecosystem restoration projects, such as forests (Rey Benayas et al., 2008), species-rich grasslands (Pywell

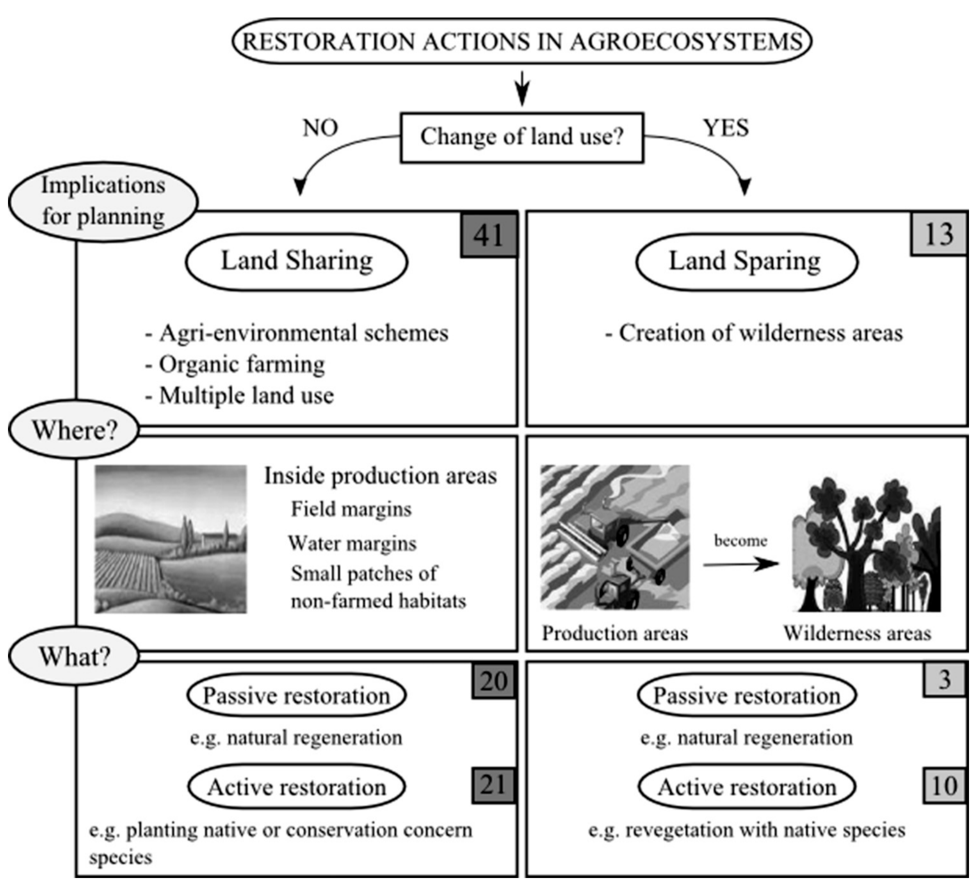

Fig. 1. Framework of restoration strategies (land sharing or land sparing) and specific restoration actions (passive or active) identified in the agroecosystems in our meta-analysis. Numbers in boxes indicate how many articles for each strategy and action were included.

et al., 2002), and heathlands (Pywell et al., 2011), we are unaware of studies systematically assessing their effectiveness across a range of ecosystems.

The aim of the present study was to quantitatively assess how ecological restoration affects biodiversity and supply of ES in a broad range of agroecosystems around the world through meta-analysis of individual case studies from the peer-reviewed literature. Our goal was to examine (1) to what extent restoration efforts can recover biodiversity and ES levels in degraded agroecosystems; (2) whether restoration outcomes are affected by factors such as restoration strategy (land sparing vs. land sharing), type of restoration actions (passive vs. active), the time since the last restoration action (restoration age), or climate type (temperate vs. tropical); and (3) whether biodiversity recovery correlates with ES recovery. We hypothesized that restoration of agroecosystems results in the recovery of biodiversity and ES supply, and that this recovery increases with restoration age. We also expected biodiversity recovery to positively correlate with ES recovery based on the biodiversity–ecosystem function theory (Cardinale, 2012; Hector and Bagchi, 2007; Isbell et al., 2011). The results of this study may help guide land use planning in agricultural activities and the achievement of the CBD's targets for 2020.

2. Methods

2.1. Literature search

We systematically searched the ISI web of knowledge database, which provides access to peer-reviewed studies, on 17 April 2012. We searched without any restriction on publication year using the following combination of terms: [((ecosystem or environment*) and (biodiversity or good* or service* or function*) and (restor* or re-creat* or rehabilitat* or enhance*) and (farm* or crop* or agro* or pasture* or grass*))]. We refined the search to include only the subject areas "environmental sciences ecology", "agriculture", "plant sciences", "biodiversity conservation", "forestry", "water resources", "biotechnology and applied microbiology", "entomology", "zoology", "food science and technology" and "microbiology", which resulted in 1590 articles. We examined the title and abstract of each of these articles to identify those likely to report the information necessary to meet all inclusion criteria for our analysis. To be included in our meta-analysis, studies had to focus on an agroecosystem (cropland or pasture) or agricultural landscape and report the following information:

1) quantitative assessment of passive restoration (natural regeneration) or active restoration in terms of variables related to biodiversity and/or the supply of one or more major types of ES, defined as supporting, provisioning, regulating, and cultural (MEA, 2005);
2) one or more comparisons involving different states of the agroecosystem, such as the reference ecosystem (prior to conversion into an agroecosystem), converted ecosystem (after agricultural activity or intensive grazing and before restoration), and restored ecosystem (after restoration); and
3) sample size and variance estimates.

2.2. Data extraction and database building

Fifty-four studies were identified that met the criteria listed above, yielding 141 comparisons used in our meta-analysis (see below; Table A1, Supplementary data). We constructed a database in which rows contained observations and columns contained the properties of those observations (Table A1, Supplementary data). For each study, we extracted data that were available in the text, tables or graphics on the variables used to measure the impacts of restoration (response variables). Each measurement was recorded as a separate row in the database, even when the measurements came from the same study. To avoid possible problems of non-independence of within-study data, measurements were recorded separately only when the original study assumed spatially independent conditions within the same study site.

We extracted data on the country where the study took place, type of agroecosystem, the main degradation factors, the time since completion of the last restoration action (restoration age), overall climate (temperate or tropical), and the specific restoration action(s) implemented. We categorized the restoration actions according to whether they reflected a land sharing or land sparing strategy. We considered a restoration action to reflect a land sharing strategy when it did not exclude agricultural production (e.g., conversion to organic farming or creating hedgerows that affected a small portion of the agroecosystem). We considered a restoration action to reflect a land sparing strategy when it impeded agricultural production at the field level and involved a relatively large area (e.g., abandonment of farmed fields; Rey Benayas and Bullock, 2012). We further categorized the restoration actions as passive or active. Passive actions were those involving only the removal or reduction of degrading factor(s), such as organic farming and secondary succession following farmland abandonment. Active actions were actions going beyond removal of degrading factors.

Measures of biodiversity assessed species abundance, richness or diversity, as well as growth or biomass of organisms in the agroecosystems. Different biodiversity variables were used for different types of organisms (Table A2, Supplementary data). For ES, we used measured variables that are proxies or indicators of ES supply. ES variables were classified according to the main groups defined by the MEA (2005). Studies in our meta-analysis reported data on regulating and supporting ES. Regulating ES are benefits obtained from the regulation of ecosystem processes, while supporting ES are necessary for the production of other ES (Table A3, Supplementary data). Very few studies reported on provisioning ES (see below), while none reported on cultural ES.

From the 54 selected studies, we extracted 153 observations; however, the following six ES were represented by very few observations and so were not included in the analysis: nutrient mineralization (two observations from one study), primary productivity (three observations from two studies), nutrient retention (one observation from one study), soil biological quality (two observations from one study), crop production (three observations from three studies) and water regulation (one observation from one study). Finally, 141 observations were included in the meta-analysis and assigned as coming from either a temperate climate (131 observations, 50 studies) or a tropical climate (10 observations, four studies), as reflecting either a land sparing strategy (31 observations, 13 studies) or a land sharing strategy (110 observations, 41 studies), and as involving either passive restoration (60 observations, 23 studies) or active restoration (81 observations, 31 studies). Restoration age was reported by 39 studies for 109 observations.

2.3. Statistical analysis

In meta-analysis, effect sizes are extracted from individual studies and pooled to calculate an overall effect size with associated statistical significance (Hedges et al., 1999). The studies in our meta-analysis varied substantially in what ecosystem states they compared as well as in what response variables they used or how they measured them. Therefore we used response ratios (RRs) to quantify the effects of restoration on levels of biodiversity and ES relative to a control. We calculated RRs of the restored agro-ecosystems relative to reference ecosystems [ln(Rest/Ref)] and relative to converted ecosystems [ln(Rest/Con)] for each measure of biodiversity and ES extracted from the studies.

We expected most response variables to correlate positively with biodiversity or with the supply of a particular ES; for example, we predicted greater biomass to be associated with a higher level of the supporting ES "primary productivity". However, we expected some response variables to correlate negatively with supply of ES; for example, we predicted that greater concentration of a soil contaminant or nutrient would be associated with lower levels of supporting ES. In these cases we inverted the sign of the RR (Table A1, Supplementary data).

We performed separate analyses to compare restored and converted ecosystems and to compare restored and reference ecosystems (Rey Benayas et al., 2009; Meli et al., 2014). A categorical, random-effect meta-analysis model was used to calculate mean effect sizes assuming random variation among observations; 95% confidence intervals were calculated around the mean effect sizes using bootstrapping with 999 iterations (Rosenberg et al., 2000). Effect size estimates were considered significantly different from zero if their 95% confidence intervals did not include zero.

To check for publication bias, we calculated Rosenthal's fail-safe number (Rothstein et al., 2005), which indicates how many studies reporting zero effect size would need to be added to the meta-analysis to render the observed effect statistically insignificant. We obtained a fail-safe number of 968,268, suggesting no publication bias in our meta-analysis. We also checked for publication bias using funnel plots (Fig. A1, Supplementary data) (Ellis, 2010). RR calculations and statistical analyses were performed using MetaWin 2.0 (Rosenberg et al., 2000).

To examine whether restoration outcomes are affected by factors such as restoration strategy and type of restoration action and restoration age, we performed non-parametric Kruskal–Wallis tests to compare RRs relating restored ecosystems to converted ones for different restoration strategies (land sparing vs. land sharing) and types of restoration actions (passive vs. active). We also performed Spearman's rank correlation to compare RRs for different restoration ages; for this analysis, we aggregated biodiversity and ES observations before calculating RRs for different restoration ages in order to ensure adequate sample size. Since our sample included only four studies in tropical areas, we decided not to examine whether restoration outcomes are affected by climate.

To examine whether biodiversity recovery correlates with ES recovery, we used the Spearman rank coefficient to quantify the correlation between biodiversity RRs and ES RRs in comparisons of restored and converted ecosystems. We used only RRs from the 16 studies that evaluated both biodiversity and supply of ES, and we treated each of these studies as an independent sample. When the same study measured biodiversity or supply of ES using multiple variables, the related RRs were averaged to generate an overall RR for biodiversity and an overall RR for supply of ES for each study, thereby minimizing the risk of pseudo-replication. We also pooled data for all the major ES types into the same overall RR for supply of ES, thereby ensuring adequate sample size (Rey Benayas et al., 2009; Meli et al., 2014). We could not examine the correlation between biodiversity RRs and ES RRs in comparisons of restored and reference ecosystems since the relevant data came from only three studies. Correlation analyses and Kruskal–Wallis tests were performed using R 3.0.2 (R, 2012).

To evaluate possible pseudo-replication effects, we used an approach similar to that in other ecology meta-analyses (Vilá et al., 2011; Meli et al., 2014): we calculated the mean RR for each of the three largest categories (e.g., supporting ES, regulating ES and biodiversity) using only one randomly selected effect size from each study. These mean RRs were similar to the mean RRs obtained when all effect sizes from each study were included (i.e., the differences were not statistically significant; Table A4, Supplementary data), as the bias-corrected 95% bootstrap confidence interval of the reduced dataset overlapped with that of the complete dataset. Therefore we retained our full dataset.

3. Results

3.1. Overview of analyzed studies

The 54 studies included were conducted in 20 countries: 39 in Europe, five in America, four in Africa, four in Oceania and two in

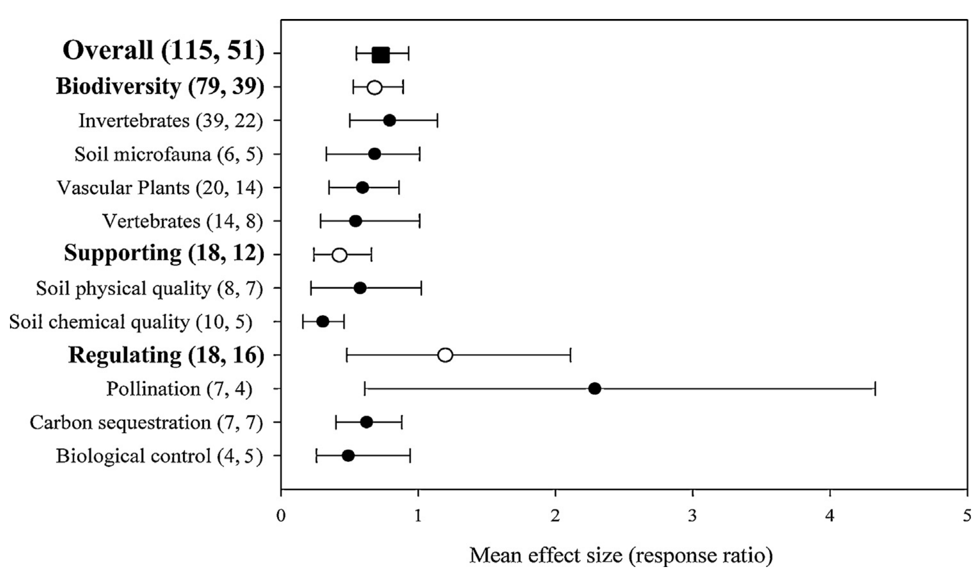

Fig. 2. Mean effect size (response ratio) for levels of biodiversity and of supporting and regulating ES in restored agroecosystems relative to converted ones assessed across the primary studies. Bars around the means denote bias-corrected bootstrap 95% confidence intervals. Mean effect size is significantly different from zero if the 95% confidence interval does not include zero. The first and second numbers in parentheses indicate, respectively, how many comparisons and how many studies were included in each calculation.

Asia. The studies included a variety of cropland and pasture systems: herbaceous crops (28 studies), woody crops (8 studies) and grassland (18 studies). The main degradation factors were agricultural intensification, such as increased use of agrochemicals, crop monocultures, irrigation and high-yielding crop varieties; and agricultural expansion, with the concomitant fragmentation of natural and semi-natural habitats. The mean restoration age was 10 years (sd, 8 years; min, 1 year; max, 61 years).

Approximately 80% of studies in our meta-analysis were based on a land sharing strategy and the remainder on a land sparing strategy (Fig. 1). While both types of studies employed a variety of restoration actions, they favored active restoration to passive restoration. Restoration based on land sharing focused on modifying field and water margins and on generating small conservation areas at the expense of small production areas. Restoration based on land sparing relied mostly on creating new wilderness areas through revegetation with native species (Fig. 1).

3.2. Effects of restoration on biodiversity and supply of ES

Overall, biodiversity and levels of both supporting and regulating ES were 73% higher in the restored state of agroecosystems than in the converted state (Fig. 2). Restoration enhanced overall biodiversity of all organism types by 68%, ranging from 54% for vertebrates to 79% for invertebrates; the recovery levels for soil microfauna and vascular plants fell within the same range (Fig. 2). Restoration actions associated with the greatest increases in biodiversity were creating patches/strips of wildflowers, creating habitats on riparian margins and on the edges of crop fields, organic farming, and revegetating with native species (detailed results not shown).

Restoration also increased the supply of supporting and regulating ES (Fig. 2). Supply of supporting ES increased by an average of 42%, with the following increases for individual ES: soil physical quality (57%) and soil chemical quality (30%). Supply of regulating ES was 120% higher in restored agroecosystems than in converted ones, with the difference between restored and converted areas greatest for pollination (228%), followed by carbon sequestration (62%) and biological control (49%). Restoration actions associated with the greatest increases in ES levels were creating habitats on the edges of crop fields, organic farming and revegetating with native species (detailed results not shown). Biodiversity and levels of supporting and regulating ES as measured by RRs were not significantly different between restored agroecosystems and reference ecosystems assessed across the primary studies (Fig. 3).

3.3. Effects of restoration strategy, type of restoration action and restoration age on restoration outcomes

Analyses to determine the effect of restoration strategy, type of restoration action and restoration age on the effectiveness of ecological restoration were inconclusive. Kruskal–Wallis analysis showed that land sparing and land sharing strategies were associated with significantly different ES RRs relating restored agroecosystems to converted ones (Table 1). In fact, the median associated with the sparing strategy was more than 2-fold higher than the median associated with sharing. On the other hand, the means were not so different and the standard deviations were relatively large. In the case of biodiversity RRs, the differences between strategies were not significant (Table 1).

The two types of restoration actions were not associated with significant differences in supply of ES or in biodiversity (Table 1). Contrary to what we expected, restoration age did not correlate with either biodiversity or ES RRs ($r = -0.12$, $p = 0.267$, $n = 78$).

3.4. Relationship between biodiversity and ES recovery

Only 16 of the 54 studies measured the effects of ecological restoration on levels of both biodiversity and ES. These studies involved primarily habitat creation and organic farming. Biodiversity recovery positively correlated with ES recovery in comparisons of restored and converted ecosystems (Fig. 4), meaning that restoration of agroecosystems was associated with simultaneous recovery of biodiversity and supply of supporting and regulating ES.

4. Discussion

4.1. Recovery of biodiversity and ES levels

Our meta-analysis of a wide variety of agroecosystems across the globe suggests that agroecosystem restoration is usually successful for enhancing biodiversity and supply of ES other than

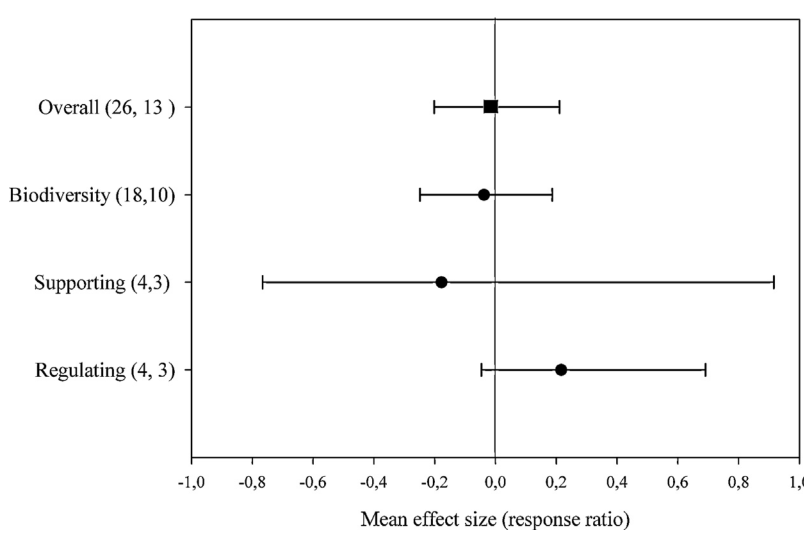

Fig. 3. Mean effect size (response ratio) for levels of biodiversity and of supporting and regulating ES in restored agroecosystems relative to reference ecosystems (i.e., prior to conversion to agroecosystem) assessed across the primary studies. Bars around the means denote bias-corrected bootstrap 95% confidence intervals. Mean effect size is significantly different from zero if the 95% confidence interval does not include zero. The first and second numbers in parentheses indicate, respectively, how many comparisons and how many studies were included in each calculation. Data on biodiversity for specific organism types and on different types of ES were pooled due to small sample size.

Table 1
Effects of restoration strategy and type of restoration action on response ratios (RR) of ecosystem services and biodiversity relating restored agroecosystems to converted ones.

Statistics	Ecosystem services				Biodiversity			
	Land sharing	Land sparing	Active restoration	Passive restoration	Land sharing	Land sparing	Active restoration	Passive restoration
Chi-squared	4.61		1.36		1.49		2.88	
p	0.03		0.24		0.22		0.08	
n	16	16	19	13	79	5	45	39
Median RR	0.20	0.50	0.36	0.24	0.41	1.09	0.41	0.36
Mean RR	1.10	0.66	1.17	0.46	0.68	0.84	0.90	0.41
sd of RR	2.08	0.44	1.86	0.51	0.87	0.48	1.06	0.31

agricultural production and may be an effective approach for achieving CBD goals for 2020. However, the available evidence leaves open the question of whether the increased use of restoration actions will support adequate crop production for global needs, especially since restoration practices often give lower agricultural yields than more intensive methods (Azadi et al., 2011; Foley et al., 2011).

Restoration improved biodiversity to roughly the same extent for all organism types examined. An increase in diversity, though by itself insufficient for ensuring high ecosystem functioning (Callaway, 2005), is usually interpreted as an indication that the structure and resilience of the agroecosystem are recovering (Holt-Giménez, 2002; Swift et al., 2004). However, further studies are needed to clarify whether and how such biodiversity enhancement indicates that the compositions of flora and fauna have fully recovered. The complexity of analyzing biodiversity enhancement is well illustrated by the case of organic farming. Nearly half (47%) of the studies in our meta-analysis evaluated the effects of organic farming on biodiversity. Several reviews and meta-analyses of these effects have concluded, consistent with our findings, that organic farming has overall positive effects on biodiversity (Bengtsson et al., 2005; Gomiero et al., 2011; Hole et al., 2005; Tuck et al., 2014), and that these effects can interact with landscape characteristics such as heterogeneity and scale (e.g., field level vs. landscape level) effects (Bengtsson et al., 2005; Rundlöf et al., 2010; Winqvist et al., 2011). At the same time, in contrast to our findings, some of these existing reviews have concluded that organic farming increases the population size of some taxa more than others (Hole et al., 2005; Tuck et al., 2014), and that it may even reduce the population size of certain taxa (Birkhofer et al., 2014).

Restoration increased the levels of all supporting and regulating ES. Very few studies reporting levels of provisioning ES after agroecosystem restoration (e.g., crop production) met our inclusion criteria, so they were not part of our meta-analysis. Agroecosystems typically seek to maximize the supply of this type of ES (e.g., providing grains, meat and fiber). Therefore analyzing the trade-offs and synergies among levels of provisioning, supporting and regulating ES is crucial for selecting the most appropriate indicators to quantify restoration outcomes (Laterra et al., 2012; Naidoo et al., 2008). Indeed, assessing how restoration affects levels of provisioning ES is key to assessing how well it can reconcile farmland production with biodiversity and supply of ES in agricultural landscapes (Wade et al., 2008).

The cost of agroecosystem restoration is another important factor to take into account when assessing its effectiveness (Aronson et al., 2010; De Groot et al., 2013), yet we found that only three of the 54 studies addressed this issue. Demonstrating a positive cost–benefit relationship for restoring levels of biodiversity and ES in agroecosystems may help support worldwide efforts to accomplish CBD's targets for 2020.

4.2. Context dependence of restoration effectiveness

We found that, based on non-parametric analysis, a restoration strategy of land sparing led to a significantly greater recovery of ES levels than a strategy of land sharing. However, the two contrasting strategies led to similar increases in biodiversity, though a trend

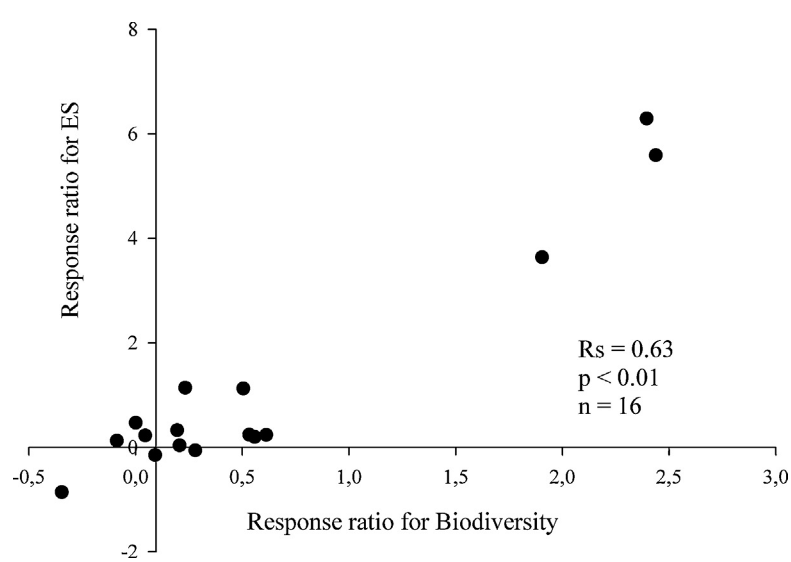

Fig. 4. Spearman rank (Rs) correlation between response ratios for biodiversity and ES levels in restored agroecosystems relative to converted ones.

was observed in which land sparing was associated with higher biodiversity. These findings should be interpreted with caution because the statistical inference is based on medians, whereas the means for the two strategies are rather similar and their deviations are large, particularly for the sharing strategy. In addition, the studies examining land sparing systematically differed in several respects from those examining land sharing. In our meta-analysis, most sites that were restored using a land sparing strategy, which ranged in size from 5 ha to >1000 ha, were much larger than the sites restored through land sharing, which usually measured <0.5 ha (e.g., a field-level scale). Furthermore, most restorations based on land sparing in our meta-analysis relied primarily on active or passive revegetation, and outcomes were assessed using exclusive soil-related response variables (e.g., carbon sequestration). In contrast to our finding of similar biodiversity recovery for both restoration strategies, Phalan et al. (2011) found land sparing to be more effective for restoring densities of bird and tree species in Ghana and India in the face of habitat degradation due to food production. The trend in our data supports this, but a much larger sample is needed to gain a reliable global picture.

The fact that we failed to obtain unambiguous results for the comparison of land sharing and land sparing strategies despite including a relatively large number of studies highlights the difficulties in assessing ecological restoration of agroecosystems. It also underscores the practical and philosophical benefits of seeing the two strategies not as mutually exclusive alternatives but as complementary approaches that can be combined to maximize biodiversity and supply of ES (Rey Benayas and Bullock, 2012). For example, while it may be necessary to choose between these strategies at each individual site, both can be applied at various sites within the same degraded landscape according to an integrated land management strategy.

Our comparison of active and passive types of restoration actions suggests that both types may lead to similar increases in biodiversity and ES supply in agroecosystems. This result is consistent with that obtained by Morrison and Lindell (2011) for bird habitat quality following active and passive restoration in Costa Rica. Since passive restoration is generally less costly than active restoration, the former may be a feasible alternative to enhance biodiversity and ES other than crop production in agroecosystems.

We were unable to compare the effects of specific restoration actions on recovery of biodiversity and ES levels because we identified only a small number of studies using the land sparing strategy. Nevertheless, our meta-analysis identified at least five restoration actions that seem particularly effective. One of these actions is creating habitats in field margins, which seems quite successful and costs little to implement (Pywell et al., 2006). Most of these five effective actions follow the land sharing strategy and have already been widely implemented in large-scale environmental programs, such as agri-environment schemes in Europe (Kohler et al., 2008). This suggests the feasibility of implementing these restoration actions in real-world situations governed by political considerations, beyond the simplicity of scientific experiments. On the other hand, the effectiveness of agri-environment schemes for biodiversity conservation in Europe remains controversial (Kleijn and Sutherland, 2003; Kleijn et al., 2006) and so should be the focus of future research.

As 70% of the studies in our meta-analysis and 132 out of 142 observations corresponded to temperate areas, we were unable to compare the recovery of biodiversity and supply of ES in temperate vs. tropical agroecosystems. Rey Benayas et al. (2009) found that restoration of terrestrial biomes led to 10-fold greater biodiversity and 100-fold greater levels of ES in tropical climates than in temperate ones, but these differences may not apply to agroecosystems. Like the present study, other global meta-analyses contained a preponderance of data from temperate regions (Meli et al., 2014). This highlights the need for more ecological restoration research in tropical regions, such as the study by De Beenhouwer et al. (2013), who assessed the impact of cacao and coffee agroforestry management on biodiversity and supply of ES.

Recovery of biodiversity and ES levels did not correlate with restoration age, similar to other findings (Meli et al., 2014; JMRB, unpublished data). While this may reflect the limited variation in the average restoration age (10 years) in the studies that we analyzed, it may also suggest that successful agroecosystem restoration requires less time than in other ecosystems such as wetlands, where full recovery takes several decades (Moreno-Mateos et al., 2012). Further research should examine this issue.

4.3. Correlation of biodiversity recovery and ES recovery

We found that levels of biodiversity and ES recovery after restoration of degraded agroecosystems positively correlated, similar to findings in a meta-analysis of a wide range of ecosystems around the world (Rey Benayas et al., 2009). This result may at least partially reflect the fact that our analysis did not include measurements of primary productivity variables and the fact that, particularly in agroecosystems, lower productivity is usually associated with higher levels of biodiversity (e.g., Verhulst et al., 2004). Understanding this correlation has important consequences not only for restoration science but also for economics, government policy and social welfare (Naidoo et al., 2008). Thus further research is urgently needed into the poorly understood relationship between biodiversity and ES supply (De Groot et al., 2010). For example, future studies should explore how to optimize the synergy between biodiversity and ES supply when designing management and conservation programs involving restoration (Meli et al., 2014).

5. Conclusions

Our study is the first global, quantitative meta-analysis to show that ecological restoration of agroecosystems improves biodiversity and levels of supporting and regulating ES by an average of 73%. In fact, biodiversity recovery positively correlated with recovery of ES supply. The available evidence therefore strongly supports using agroecosystem restoration in sustainable land use planning. However, our study does not provide clear answers to the questions of whether restoration outcomes are better with a land sharing or land sparing strategy, whether outcomes are better with active or passive restoration actions, or how much such restoration reduces food production. Our results suggest that the answers to these questions may be strongly case-dependent. A wide range of specific restoration actions appears to be effective, and they can be combined as required by the socioeconomic and political context of the ecological restoration. Understanding the optimal mix of actions will require as diverse an evidence base as possible, pointing to the need for more studies in regions like South America, where we did not identify any agroecosystem restoration studies. Restoration effects did not differ significantly as a function of restoration age, and the preponderance of studies in temperate climates highlights the need for more restoration research in tropical areas. Our meta-analysis supports the ability of ecological restoration to enhance biodiversity and ES supply in agricultural landscapes, and highlights important directions for future research to explain and optimize restoration outcomes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2015.01.009.

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