Nature Communications
Supplementary Online Material

Assessing the success of marine ecosystem restoration using meta-analysis

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Figures of the main text: methodology and scripts used

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- **Figure 4** generated in the script called "**glmm_PRD_v2.R**"
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- **Figure S1-A** generated using Excel
- **Figure S1-B** generated in the script called "**Figure_PRD_v1.ipynb**"
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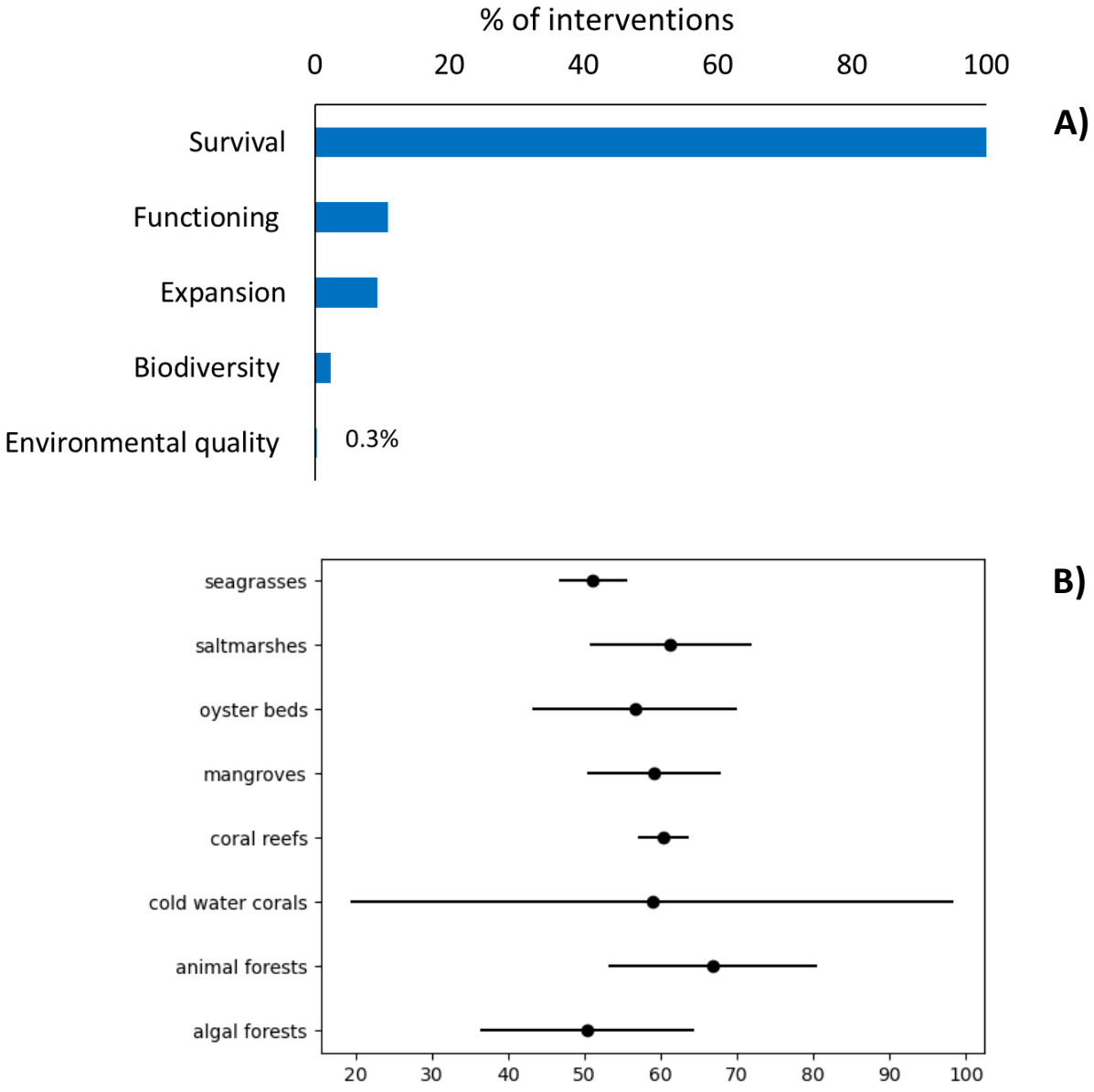

Figure S1. (A) Indicators of success reported in the literature collected (n= 764 case studies) and (B) confidence intervals of restoration success (95%) for the different habitats from descriptive statistics based on the data reported in the box plots of the Figure 2 (n= 759 case studies, excluding 5 studies that did not report the success percentage).

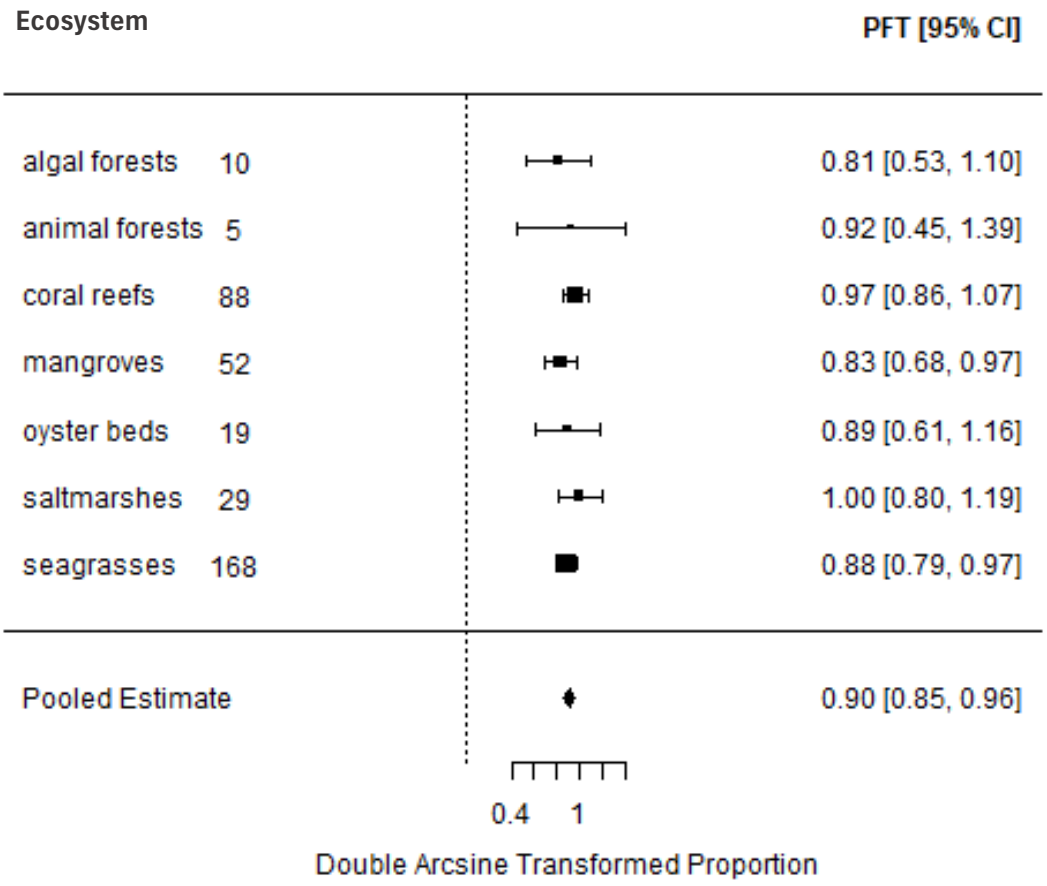

Figure S2: Results of the meta-analysis of survival of restored marine habitat conducted by taking the survival percentage as the effect size. To develop multilevel mixed-effects models, we normalized the proportions by applying the Freeman-Tukey Double arcsine transformation. The proportions were calculated using the spatial extent as the sample size, and the product of spatial extent and success rate as the estimated event count. The visualization shows the point estimate of the observed percentage of survival (effect size) for the different habitat types (n=371) with the corresponding confidence interval, the point estimate is surrounded by a square whose size is determined by the weight of the effect size. Cold-water corals are not reported in this forest plot due to the low number of observations.

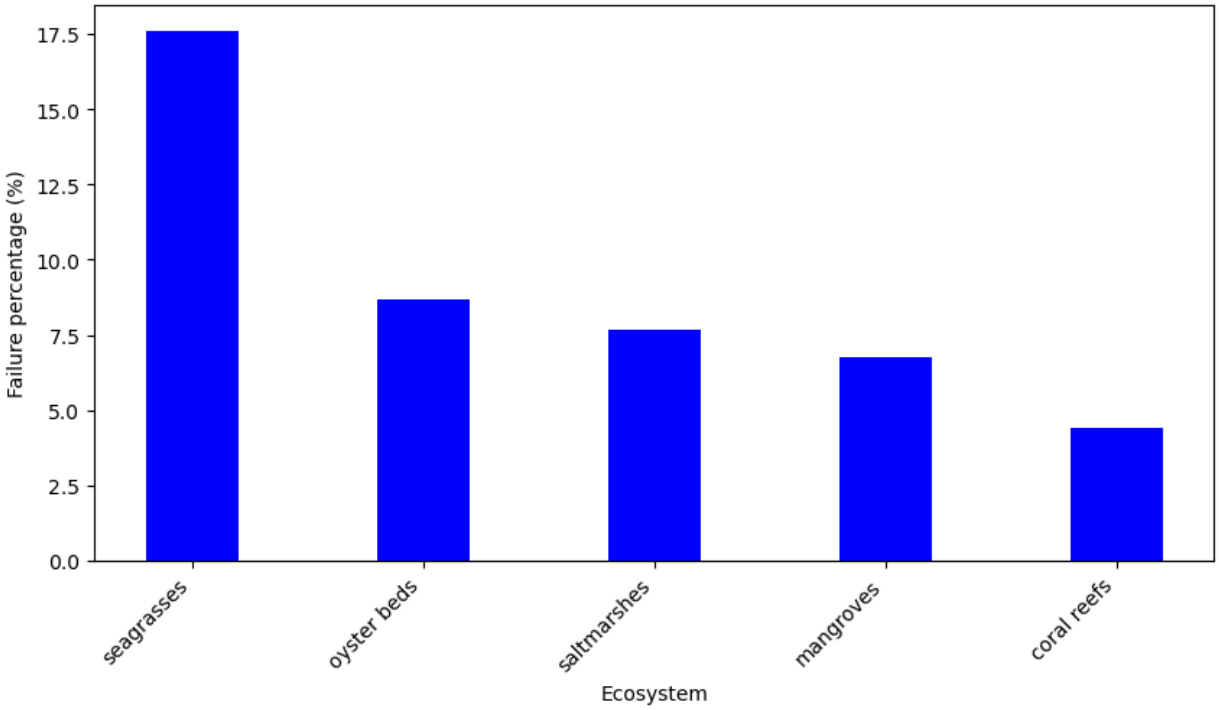

Figure S3. Bar plot representing the number of failed restoration interventions (survival = 0%) per each habitat type/ecosystem (n= 759 case studies). Some habitats (e.g., cold-water corals/deep sea and animal forests/coralligenous) are not reported as no case of complete failures have been reported so far.

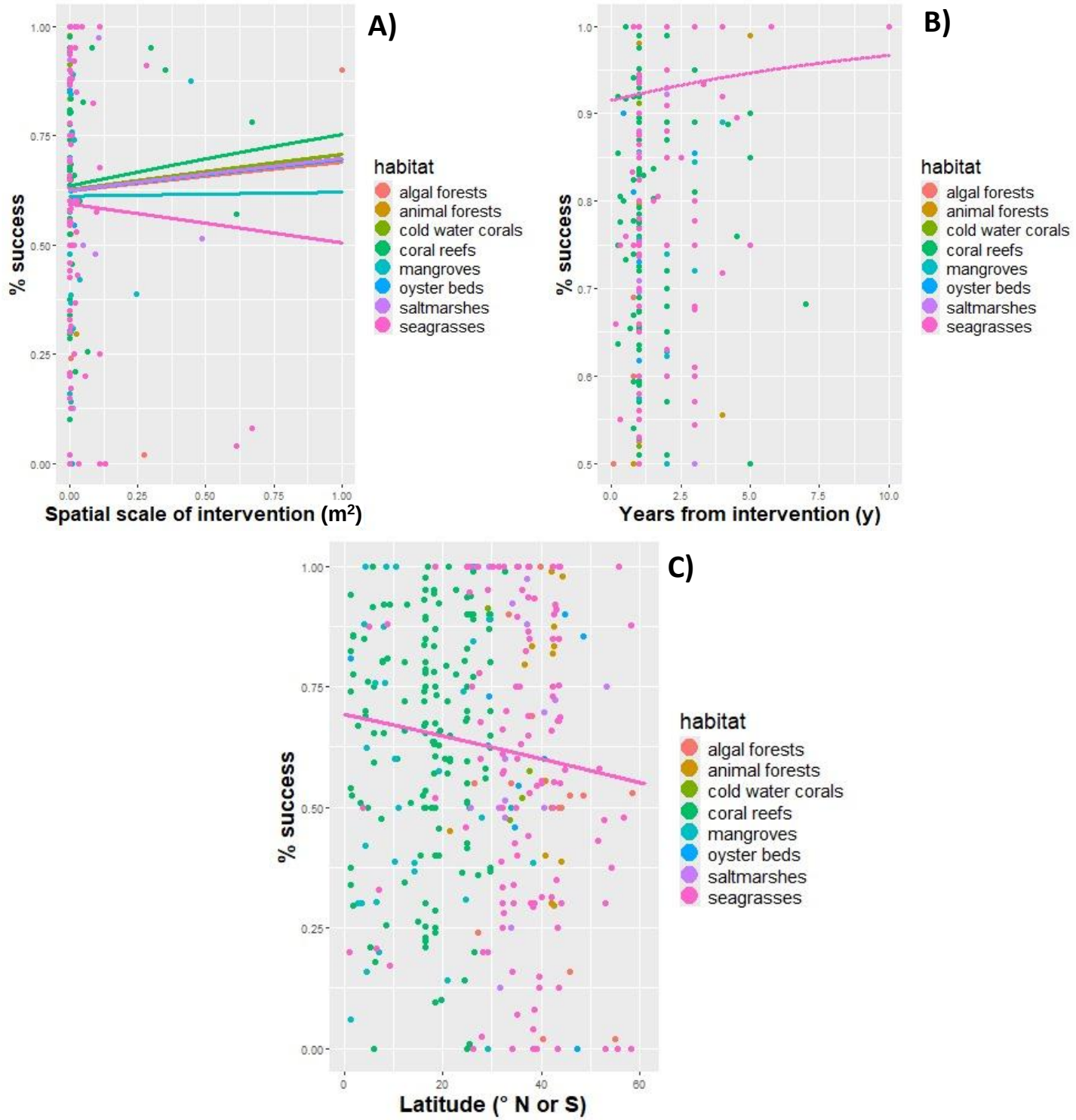

Figure S4. Scatter plots representing the distribution of the survival percentage and corresponding predicted values calculated using linear mixed models (multilevel models), considering different variables (i.e., spatial scale, years and latitude). Reported are: A) Scatter plot of effects of the spatial extent of intervention (surface areas normalized to the largest scale of intervention, data restricted to spatial scales <120,000 m^2); p-value: 0.80 not significant (n= 185 case studies).; (B) Scatter plot of the number of years after the restoration intervention (here we used a cut off < 10 yrs, to avoid outliers from 10 to 60 yrs) ; p-value: 0.62; not significant (n= 271 case studies); (C) Scatter plot of the effects of latitude: range: 0°-59°; p-value: 0.20; not significant (n= 362 case studies)..

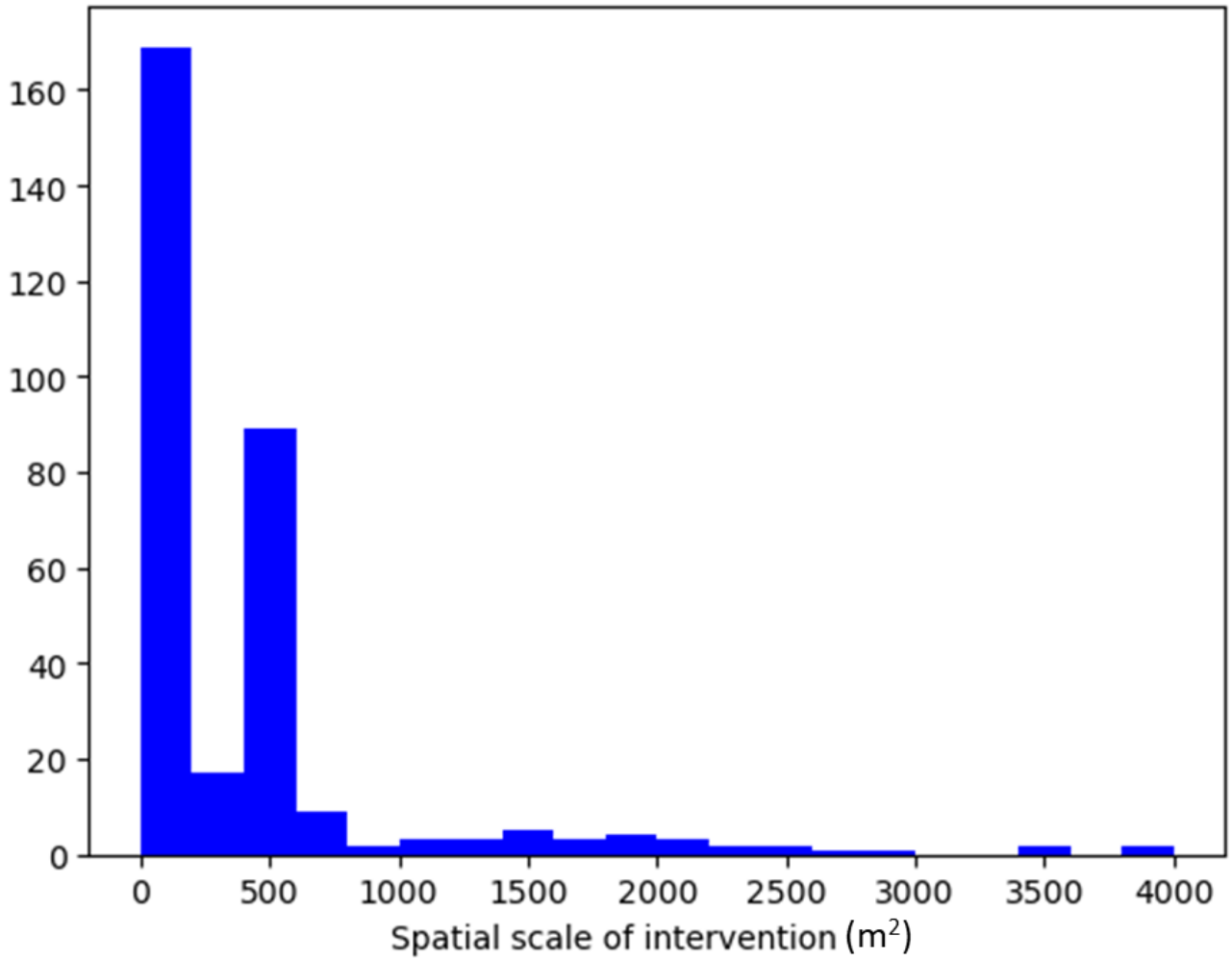

Figure S5. Histogram plot summarizing the number of restoration interventions with a spatial extent ≤ 4,000 m^2 (n= 317 case studies).

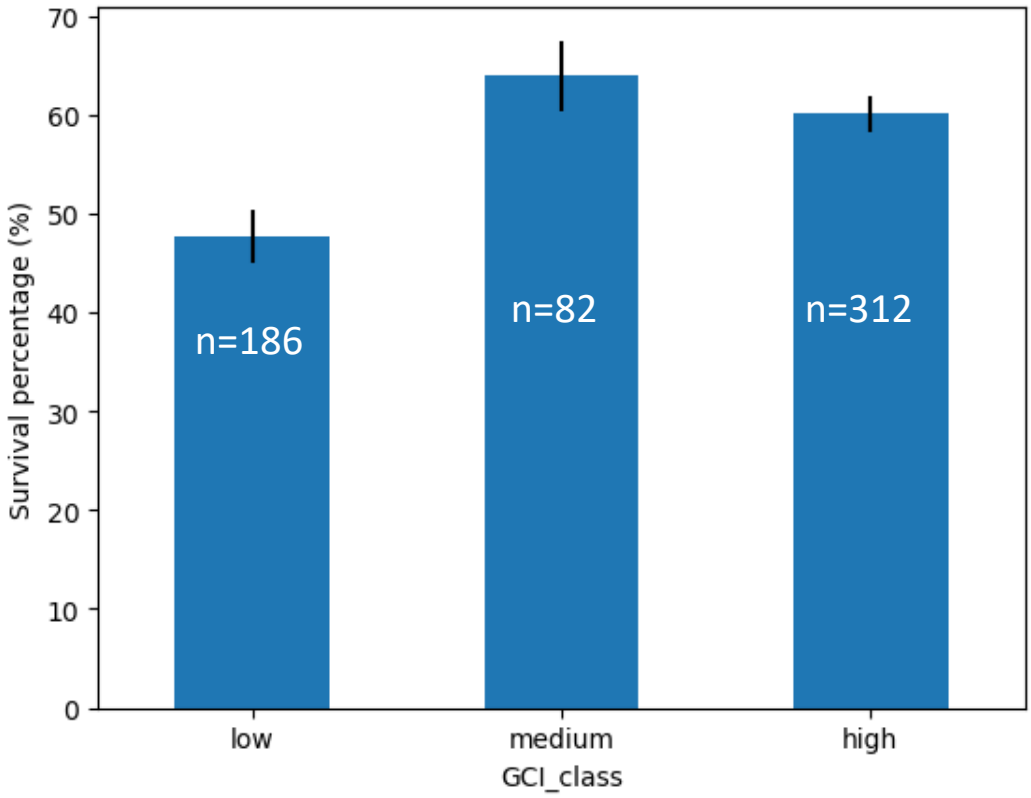

Figure S6. Average success rates of marine restoration interventions on the whole data set (without using cut offs) conducted in areas characterized by "low", "medium", and "high impact" as defined according to the global impact index (n=580). Bars represent survival percentage ± Standard errors. Significant differences were found between low vs medium and low vs high impact conditions (both ANOVA, $p<0.05$; n= 580 case studies). No significant differences were observed for interventions carried out in medium and high impact conditions.

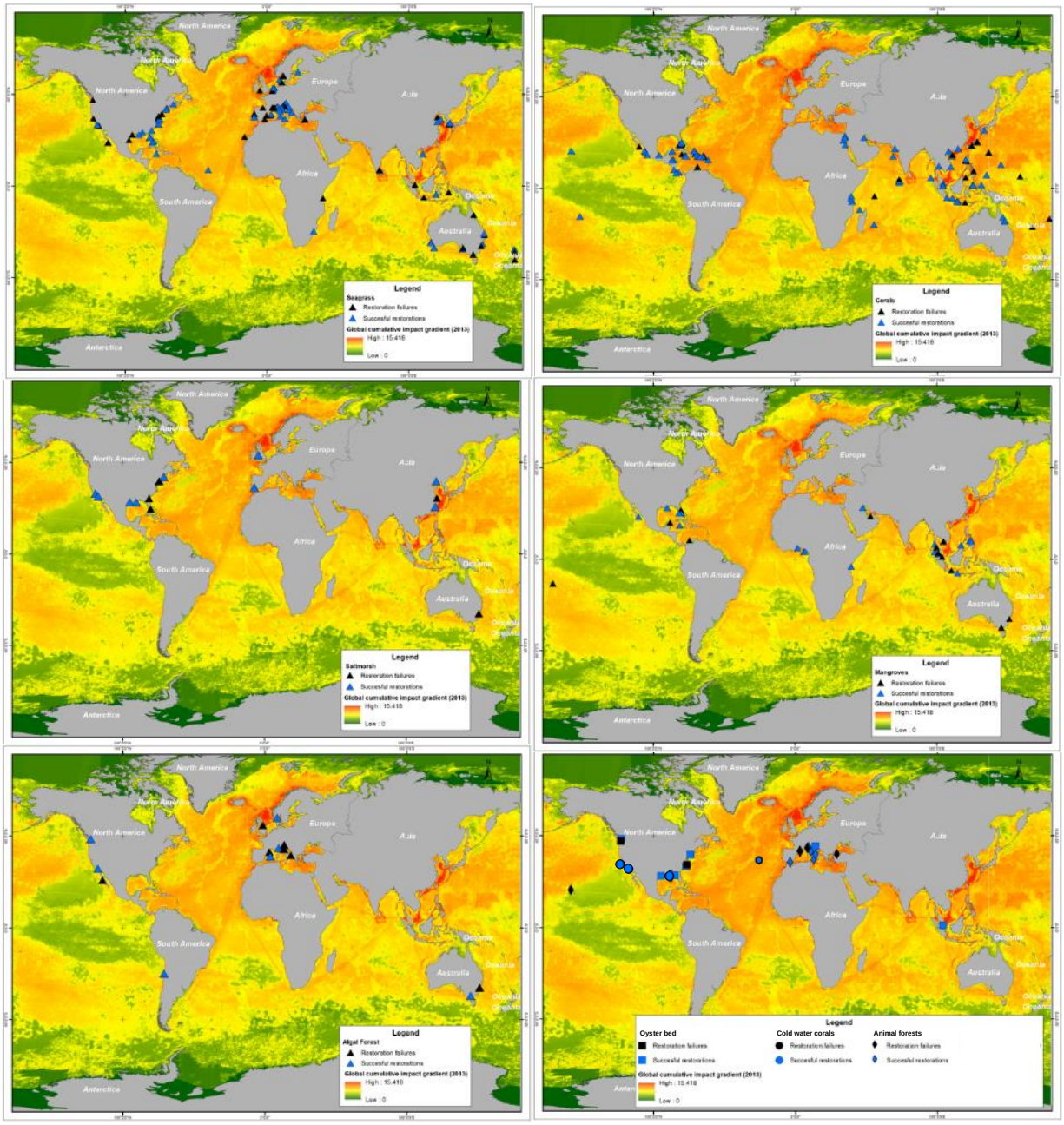

Figure S7. Global distribution of marine restoration interventions and their overlaps with cumulative impacts (Web Map from ArcGIS). Reported are: seagrasses and corals (upper panel: left and right respectively); saltmarshes and mangroves (central panel: left and right); macroalgal forests and other habitat types (i.e., oyster beds/ cold-water corals/animal forests (lower panel: left and right). We calculated the Global cumulative impact index using available raw data (from Halpern et al. 2015) and ranges from 0 to 15.4. This index reports values > 4.02 as representative of high impact, values from 2.74 to 4.02 for medium impact, and values < 2.74 for low impact areas (*sensu* Halpern et al. 2015). Restoration success (blue symbols) indicates survival ≥50%; restoration failures (black symbols) indicate survival < 50% and includes also the complete failures (i.e., survival = 0%). Mapping of cumulative impacts onto marine habitats at spatial scales that do not necessarily reflect accurately the local level of pressures/stressors nonetheless enables comparison of levels of impacts across different geographic regions of interest.

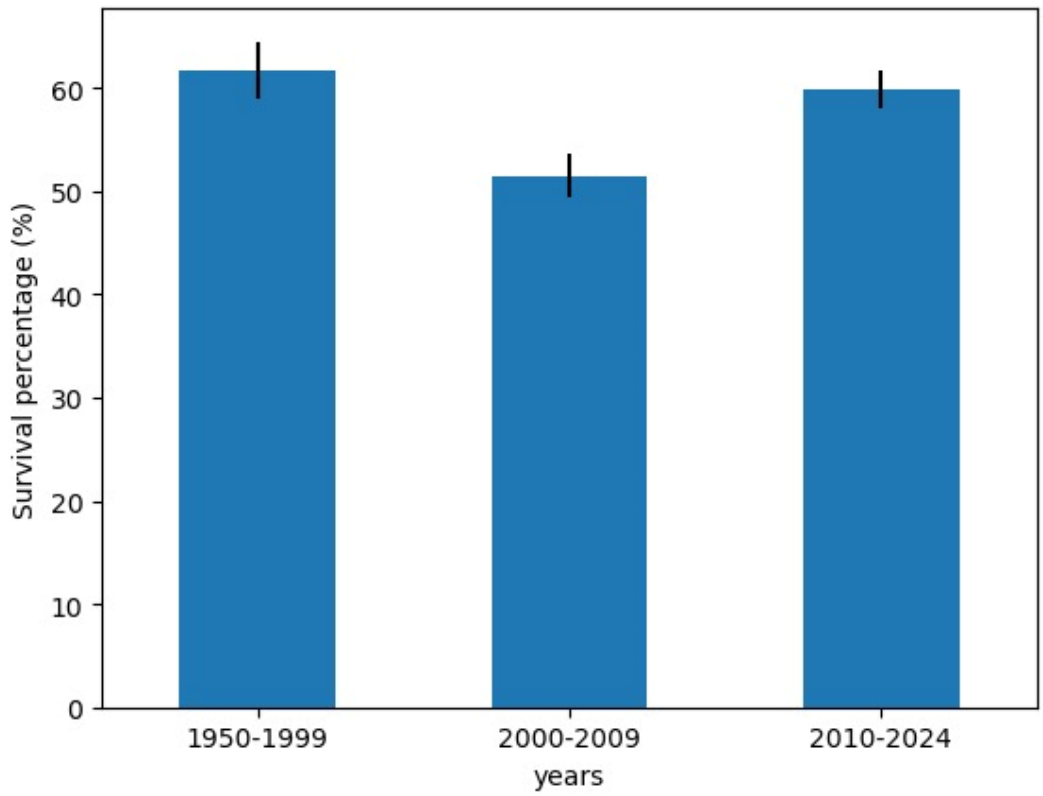

Figure S8. Average success rates of marine restoration interventions conducted between 1950 and 1999 (n=153) to more recent periods (2000-2009, n=283; and 2010-2024, n=303). Bars represent ± Standard errors. Sampling periods did not differ statistically in terms of survivial percentage, except for the comparison of the periods 1950-1999 vs 2010-2024, and 2000-2009 vs 2010-2024, both ANOVA $p<0.05$).

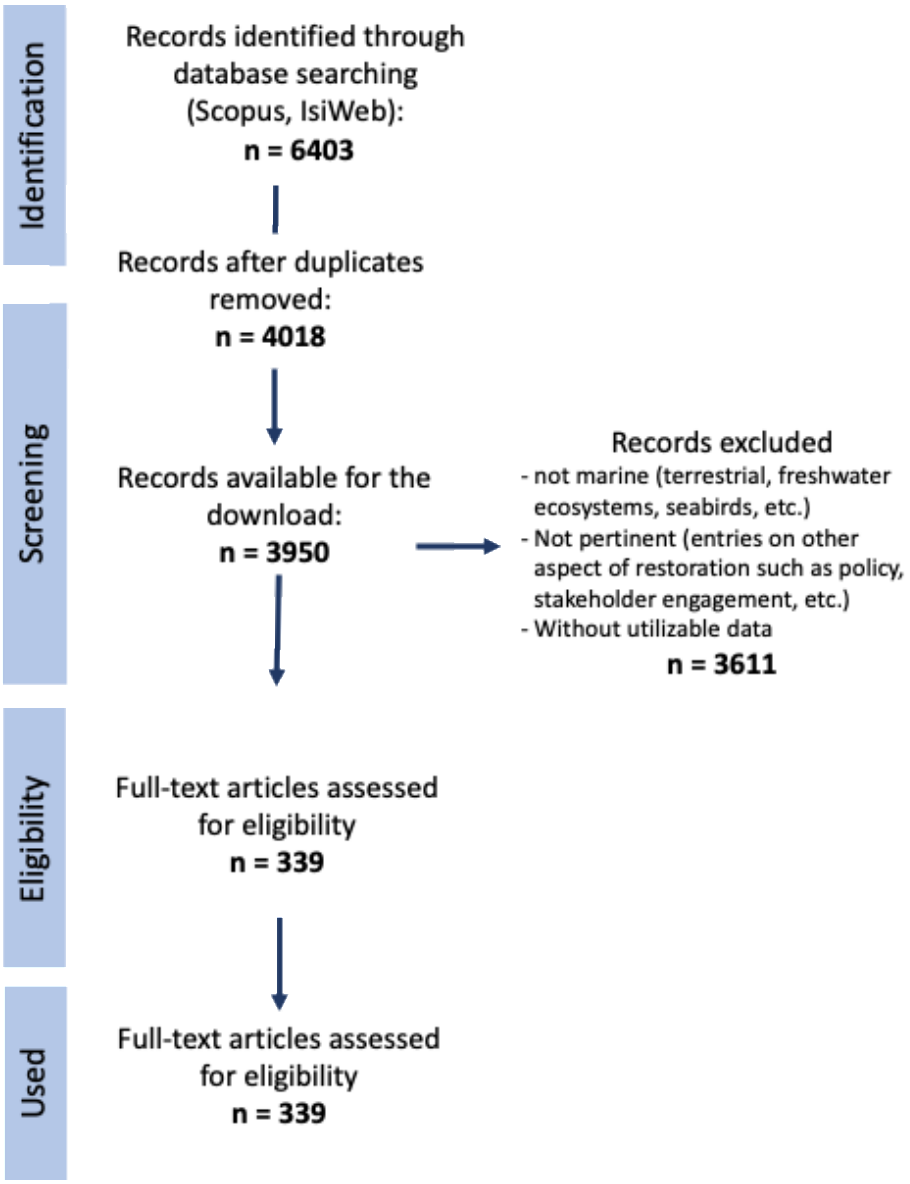

Figure S9. PRISMA flowchart of steps taken to identify and select eligible articles for systematic review and meta-analysis of the data.

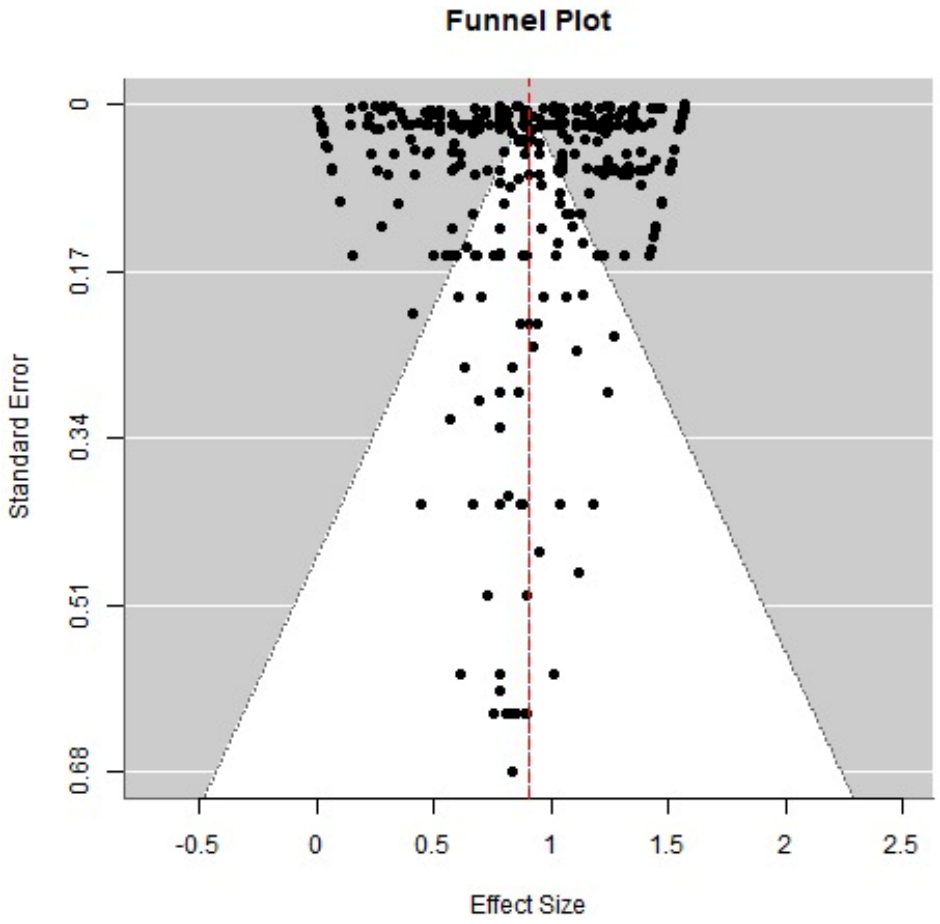

Figure S10: Freeman-Tukey double arcsine-transformed proportion against standard error (n=371). Egger's regression test indicated the lack of publication bias (p-value = 0.913).

Table S1. Results of the literature survey. Reported are the number of documents obtained from search on Scopus and ISI Web of Knowledge (all languages), list of words selected and results of the selection after the criteria for exclusion.

		N. entries	
Literature survey	ISI documents	2461	
	Scopus documents	3942	
	Tot documents	**6403**	
	Repeated entries	2385	
	Tot documents considered	**4018**	
Exclusion criteria	Not available	68	not available for the download
	Not marine	1056	referring to terrestrial, freshwater species/habitat/ecosystem
	Not pertinent	2267	not referring to active restoration intervention, rather to conservation or other aspects of restoration
	does not report useful data	288	referring to active restoration but not reporting useful data
	Data set	**339**	

Table S2. Data extraction and code book.

Biogeographic region	contains a reference to the biogeographical area where the study was conducted
Country	contains the name of the country where the study was conducted
Site	contains the name of the site where the study was conducted
Latitude	contains the number of the latitude, expressed as decimal degrees, indicating where the study was conducted
Longitude	contains the number of the longitude, expressed as decimal degrees, indicating where the study was conducted
Latitudinal gradient	contains the absolute value of the latitude, expressed as decimal degrees, indicating where the study was conducted (this field was calculated and is only contained in the csv used for analysis).
Global cumulative impact	contains the value of the Global Cumulative Impact Index estimated in the area where the study was conducted
Ecosystem	contains the name of the ecosystem type restored in the corresponding intervention
Intervention year	contains the year in which the restoration intervention took place
Intervention extention	contains the value of m2 corresponding to the area restored in the intervention
Delta years	contains the number of years corresponding to the time interval between the date of the intervention and the date of the monitoring check (this field was calculated and is only contained in the csv used for analysis).
survival_perc	contains the percentage of the restored area that survived in the time interval between the date of the intervention and the date of the monitoring check
Success (>50%)	contains a code indicating if the intervention with a survival percentage >50% is long term or short term (see "codebook" sheet)
References	contains the bibliographical references of the work from which the data were extracted
Estimate ID	contains the numbers used to distinguish each sample within the same reference (this field was calculated and is only contained in the csv used for analysis)

Annex 1

Checklist PRISMA-EcoEvo reporting all items considered in systematic review and meta-analysis.

Checklist item	Sub-item number	Sub-item	Reported by authors?
Title and abstract	1.1	Identify the review as a systematic review, meta-analysis, or both	yes
	1.2	Summarise the aims and scope of the review	yes
	1.3	Describe the data set	yes
	1.4	State the results of the primary outcome	yes
	1.5	State conclusions	yes
	1.6	State limitations	no
Aims and questions	2.1	Provide a rationale for the review	yes
	2.2	Reference any previous reviews or meta-analyses on the topic	yes
	2.3	State the aims and scope of the review (including its generality)	yes
	2.4	State the primary questions the review addresses (e.g. which moderators were tested)	yes
	2.5	Describe whether effect sizes were derived from experimental and/or observational comparisons	yes
Review registration	3.1	Register review aims, hypotheses (if applicable), and methods in a time-stamped and publicly accessible archive and provide a link to the registration in the methods section of the manuscript. Ideally registration occurs before the search, but it can be done at any stage before data analysis.	no
	3.2	Describe deviations from the registered aims and methods	not applicable
	3.3	Justify deviations from the registered aims and methods	not applicable
Eligibility criteria	4.1	Report the specific criteria used for including or excluding studies when screening titles and/or abstracts, and full texts, according to the aims of the systematic review (e.g. study design, taxa, data availability)	yes
	4.2	Justify criteria, if necessary (i.e. not obvious from aims and scope)	yes
Finding studies	5.1	Define the type of search (e.g. comprehensive search, representative sample)	yes
	5.2	State what sources of information were sought (e.g. published and unpublished studies, personal communications)	yes
	5.3	Include, for each database searched, the exact search strings used, with keyword combinations and Boolean operators	yes
	5.4	Provide enough information to repeat the equivalent search (if possible), including the timespan covered (start and end dates)	yes
Study selection	6.1	Describe how studies were selected for inclusion at each stage of the screening process (e.g. use of decision trees, screening software)	yes
	6.2	Report the number of people involved and how they contributed (e.g. independent parallel screening)	no
Data collection process	7.1	Describe where in the reports data were collected from (e.g. text or figures)	yes
	7.2	Describe how data were collected (e.g. software used to digitize figures, external data sources)	yes
	7.3	Describe moderator variables that were constructed from collected data (e.g. number of generations calculated from years and average generation time)	yes
	7.4	Report how missing or ambiguous information was dealt with during data collection (e.g. authors of original studies were contacted for missing descriptive statistics, and/or effect sizes were calculated from test statistics)	yes
	7.5	Report who collected data	no
	7.6	State the number of extractions that were checked for accuracy by co-authors	yes
Data items	8.1	Describe the key data sought from each study	yes
	8.2	Describe items that do not appear in the main results, or which could not be extracted due to insufficient information	yes
	8.3	Describe main assumptions or simplifications that were made (e.g. categorising both 'length' and 'mass' as 'morphology')	yes
	8.4	Describe the type of replication unit (e.g. individuals, broods, study sites)	yes
Assessment of individual study quality	9.1	Describe whether the quality of studies included in the systematic review or meta-analysis was assessed (e.g. blinded data collection, reporting quality, experimental versus observational)	yes
	9.2	Describe how information about study quality was incorporated into analyses (e.g. meta-regression and/or sensitivity analysis)	yes
Effect size measures	10.1	Describe effect size(s) used	yes
	10.2	Provide a reference to the equation of each calculated effect size (e.g. standardised mean difference, log response ratio) and (if applicable) its sampling variance	yes

	10.3	If no reference exists, derive the equations for each effect size and state the assumed sampling distribution(s)	not applicable
Missing data	11.1	Describe any steps taken to deal with missing data during analysis (e.g. imputation, complete case, subset analysis)	yes
	11.2	Justify the decisions made to deal with missing data	yes
Meta-analytic model description	12.1	Describe the models used for synthesis of effect sizes	yes
	12.2	The most common approach in ecology and evolution will be a random-effects model, often with a hierarchical/multilevel structure. If other types of models are chosen (e.g. common/fixed effects model, unweighted model), provide justification for this choice	yes
Software	13.1	Describe the statistical platform used for inference (e.g. R)	yes
	13.2	Describe the packages used to run models	yes
	13.3	Describe the functions used to run models	yes
	13.4	Describe any arguments that differed from the default settings	yes
	13.5	Describe the version numbers of all software used	yes
Non-independence	14.1	Describe the types of non-independence encountered (e.g. phylogenetic, spatial, multiple measurements over time)	yes
	14.2	Describe how non-independence has been handled	yes
	14.3	Justify decisions made	yes
Meta-regression and model selection	15.1	Provide a rationale for the inclusion of moderators (covariates) that were evaluated in meta-regression models	not applicable
	15.2	Justify the number of parameters estimated in models, in relation to the number of effect sizes and studies (e.g. interaction terms were not included due to insufficient sample sizes)	no
	15.3	Describe any process of model selection	no
Publication bias and sensitivity analyses	16.1	Describe assessments of the risk of bias due to missing results (e.g. publication, time-lag, and taxonomic biases)	yes
	16.2	Describe any steps taken to investigate the effects of such biases (if present)	no
	16.3	Describe any other analyses of robustness of the results, e.g. due to effect size choice, weighting or analytical model assumptions, inclusion or exclusion of subsets of the data, or the inclusion of alternative moderator variables in meta-regressions	no
Clarification of post hoc analyses	17.1	When hypotheses were formulated after data analysis, this should be acknowledged	not applicable
Metadata, data, and code	18.1	Share metadata (i.e. data descriptions)	yes
	18.2	Share data required to reproduce the results presented in the manuscript	yes
	18.3	Share additional data, including information that was not presented in the manuscript (e.g. raw data used to calculate effect sizes, descriptions of where data were located in papers)	yes
	18.4	Share analysis scripts (or, if a software package with graphical user interface (GUI) was used, then describe full model specification and fully specify choices)	yes
Results of study selection process	19.1	Report the number of studies screened	yes
	19.2	Report the number of studies excluded at each stage of screening	yes
	19.3	Report brief reasons for exclusion from the full text stage	yes
	19.4	Present a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-like flowchart (www.prisma-statement.org)	yes
Sample sizes and study characteristics	20.1	Report the number of studies and effect sizes for data included in meta-analyses	yes
	20.2	Report the number of studies and effect sizes for subsets of data included in meta-regressions	no
	20.3	Provide a summary of key characteristics for reported outcomes (either in text or figures; e.g. one quarter of effect sizes reported for vertebrates and the rest invertebrates)	yes
	20.4	Provide a summary of limitations of included moderators (e.g. collinearity and overlap between moderators)	no
	20.5	Provide a summary of characteristics related to individual study quality (risk of bias)	no
Meta-analysis	21.1	Provide a quantitative synthesis of results across studies, including estimates for the mean effect size, with confidence/credible intervals	yes
Heterogeneity	22.1	Report indicators of heterogeneity in the estimated effect (e.g. I2, tau2 and other variance components)	yes
Meta-regression	23.1	Provide estimates of meta-regression slopes (i.e. regression coefficients) and confidence/credible intervals	no
	23.2	Include estimates and confidence/credible intervals for all moderator variables that were assessed (i.e. complete reporting)	yes

	23.3	Report interactions, if they were included	not applicable
	23.4	Describe outcomes from model selection, if done (e.g. R2 and AIC)	not applicable
Outcomes of publication bias and sensitivity analyses	24.1	Provide results for the assessments of the risks of bias (e.g. Egger's regression, funnel plots)	yes
	24.2	Provide results for the robustness of the review's results (e.g. subgroup analyses, meta-regression of study quality, results from alternative methods of analysis, and temporal trends)	no
Discussion	25.1	Summarise the main findings in terms of the magnitude of effect	yes
	25.2	Summarise the main findings in terms of the precision of effects (e.g. size of confidence intervals, statistical significance)	yes
	25.3	Summarise the main findings in terms of their heterogeneity	no
	25.4	Summarise the main findings in terms of their biological/practical relevance	yes
	25.5	Compare results with previous reviews on the topic, if available	yes
	25.6	Consider limitations and their influence on the generality of conclusions, such as gaps in the available evidence (e.g. taxonomic and geographical research biases)	yes
Contributions and funding	26.1	Provide names, affiliations, and funding sources of all co-authors	yes
	26.2	List the contributions of each co-author	no
	26.3	Provide contact details for the corresponding author	yes
	26.4	Disclose any conflicts of interest	yes
References	27.1	Provide a reference list of all studies included in the systematic review or meta-analysis	yes
	27.2	List included studies as referenced sources (e.g. rather than listing them in a table or supplement)	no