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REVIEW

Impacts of coastal realignment on biodiversity. A systematic review and meta-analysis

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Abstract

In the context of climate change and sea-level rise, several types of management are employed, including coastal realignment, which consists in reopening polders to marine intrusions. This intervention induces changes in biodiversity. A systematic review, including a meta-analysis, was carried out to assess the impact of coastal realignment on biodiversity. 4 476 references of published and gray literature were collected from two publication databases, Google Scholar and specialist websites. After a screening process, a database of 255 relevant articles corresponding to 866 studies (one taxon in one site) was constructed. Qualitative data were extracted in order to identify knowledge gaps and clusters. Focusing on the 190 studies with a Before-After-Reference-Intervention experimental design, the risk of bias in studies was assessed. Excluding studies with a high level of bias or with non-extractable data, quantitative data related to abundance and species richness were analyzed from 19 and 24 studies respectively. Study sites are mostly in the USA and the UK, but also in Canada and other European countries. Plants are the main group of taxa studied while mammals, amphibians and reptiles are rarely considered. Similarly, studies focus mainly on species richness and abundance but much less on structural and functional parameters. The species richness of invertebrates and the abundance of fishes and shorebirds seem to increase after realignment, whereas the species richness of plants decreases. No changes in the species richness of birds, fishes and macrocrustaceans, and in the abundance of birds, invertebrates, macrocrustaceans and plants, were found. More research on lesser studied taxa and parameters is encouraged to obtain a broad view on the subject and help with decision-making in coastal-realignment operations by providing them with comprehensive ecological arguments. In order to enhance the reliability and reusability of research in other synthesis projects, it is important that data reporting be improved.

Keywords: Biodiversity; Coastal realignment; Managed realignment; Dyke removal; Dyke breach; Saltmarsh; Restoration; Systematic review

Introduction

Land reclamation, i.e. the draining of marshes on low-lying coasts and estuary shores to make them suitable for agriculture, is an ancient phenomenon in Europe. The Netherlands pioneered this practice as early as the Middle Ages, reclaiming almost 2 000 square kilometers (km^2) of land between the years 1200 and 1665 (Gueben-Venière, 2015). In Western Europe, an area of approximately 15 000 km^2 is the product of the land-reclamation process (Goeldner-Gianella, 2007). The largest areas reclaimed are in the

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Netherlands and Germany (6 000 km^2 in each country), France (1 400 km^2) and the United Kingdom (nearly 1 000 km^2). In France, land reclamation took place on the Channel and Atlantic coasts, where large areas were reclaimed, for example in the Bay of Authie along the Picardy coast. After 1 000 years of reclamation, this process came to a halt at the end of the 20th century. In the reclaimed areas, the inhabitants often live below sea level, exposed to a potential risk of submersion. This risk is now greater in a context of global warming and rising sea levels.

The abandonment of the land reclamation policy has been gradual, after an initial phase of abandonment of certain agricultural polders (Goeldner-Gianella, 2007). In parallel, a process of coastal realignment has been observed for the past twenty-five years, which aims to reopen polders to marine intrusions to achieve "renaturation" or ecological restoration. The limited nature of this policy of coastal realignment, covering to date less than 1% of the land initially reclaimed from the sea, is, however, not negligible. From the 1980s to the 2000s, realignment projects have increased threefold, concerning ever larger areas given that it has been planned, for example, to return entire islands to the sea (e.g. Île Nouvelle in the Gironde estuary in France). Coastal realignment will certainly become unavoidable in the near future, in a context of global warming and rising sea levels (Goeldner-Gianella & Verger, 2009).

"Adapto" is a four-year European Life project currently underway in France that explores on ten pilot sites an array of solutions to counter the impacts of climate change on the French coastline from an ecological, economic and social point of view. Among the ten pilot sites, six have been selected to experiment coastal realignment, taking into account expected changes in the environment due to dike breaches and sea-level rise. Once the realignment is underway, the transition from artificial terrestrial habitats to natural or semi-natural environments with a strong marine influence will necessarily have strong implications for the fauna and flora present on the sites. This question, central to realignment operations, is of interest to the environmental managers of the sites concerned by this type of operation, on an international scale.

To synthesize the evidence on the impacts of coastal realignment on biodiversity, a systematic review of the existing literature was performed. Systematic reviews have become increasingly popular in the field of ecological science, as a tool to assist policy makers and practitioners. They have proven to be very effective in investigating a variety of topics, among them restoration ecology (Andradi-Brown et al., 2013; Ramstead et al., 2012). Here, we were inspired by the guidelines for systematic reviews proposed by the Collaboration for Environmental Evidence (CEE) (Collaboration for Environmental Evidence, 2018). The process involves collecting, screening and critically appraising relevant bibliographies before extracting and analyzing data from the included studies. This method minimizes bias and achieves the greatest degree of transparency and objectivity, so that readers can understand and have confidence in the data and results, while being made aware of the inherent limitations. This systematic review can be of major interest to managers of natural environments involved in coastal-realignment operations, particularly in the context of climate change.

Materials and methods

This systematic review is based on the CEE guidelines (2018), with two exceptions, i.e. (i) the methods were not peer-reviewed and published beforehand and (ii) only one reviewer screened, appraised and extracted the data from the articles.

Review question

The review question is: *What are the consequences for biodiversity (species and habitats) of returning salt or brackish water to an impounded site?* It was structured in key elements specified in Table 1.

Search for articles

A search string was built and validated by a test-list (see Appendix A). The search was carried out in two databases,

Table 1. Elements of the review question "What are the consequences for biodiversity (species and habitats) of returning salt or brackish water to an impounded site?".

Question element	Definition
Population	All non-human wild species (fauna, flora, bacteria), native or not, and habitats.
Intervention	Reintroduction of salt or brackish water via all types of coastal realignment. All origins: managed (deliberate human intervention) or accidental (usually by storms). All techniques: banked realignment (entire embankment removal), breached realignment (creation of one or several breaches), regulated tidal exchange (RTE: lowering of a part of an embankment to make a spillway or reversing freshwater sluices to let the seawater enter), installation of culverts in an embankment or substitution of culverts by larger ones.
Comparator	Temporal comparator: Comparison before and after realignment or monitoring over time of a realigned site. Spatial comparator: Comparison between an impounded ('control') or an unimpounded ('reference') site and a realigned site.
Outcomes	All outcomes related to populations: composition (diversity, abundance, frequency, etc.), structure (sex ratio, age ratio, etc.), function (fertility, growth, mortality, diet, etc.).

Web Of Science Core Collection (WOSCC) (Web of knowledge platform, Clarivate) and Scopus (Elsevier). The search was implemented on 9 and 10 September 2019 on WOSCC and Scopus respectively, without any time-span restriction nor any other restrictions (research area, document types, language, etc.). An additional search for gray literature was carried out on Google Scholar (GS) on 18 and 30 September 2019. Further documents were retrieved from four specialized websites and from specialized organizations and experts contacted directly. See Appendix A for search details.

Article screening and database building

The articles were successively screened for relevance by one reviewer, through a three-step process, i.e. first the titles of all the articles, then the abstracts of the selected articles, then the full text of the remaining articles, according to a list of eligibility criteria presented in Table 2. If there was any doubt about the relevance of an article given the eligibility criteria or due to incomplete information, the article was included in the next step.

A database of the included articles with their bibliographic information (e.g. authors, date) and experimental information (e.g. site history, studied taxa, intervention type, measured outcomes, experimental design) was created (see Appendix C: Sheet 1). If a publication contained several studies, defined here as a monitoring of one taxon in one realigned site (itself being defined by its location and date), each study constituted a specific entry in the database.

Critical appraisal

Studies were critically appraised to assess if there was a risk of bias in their results with respect to the review question. The assessment of the risk of bias was performed in three steps.

First, only studies with sampling before and after realignment, on the realigned site and on the reference site (i.e. an undiked site), were selected at this stage. It includes "BARI" designs (for Before-After-Reference-Intervention) and "BACRI" designs, which are BARI designs with a control site in addition, i.e. a diked site. For BACRI designs, only data pertaining to the reference site were considered. These experimental designs were considered the most robust in view of attributing a change in biodiversity due to realignment. Although similarly robust, studies with sampling before and after realignment, on the realigned site and on the control site (BACI designs) were not retained because the number of studies was too low to implement a meta-analysis.

Then, redundant studies, i.e. studies sharing the same data sets, e.g. because of an annual publication of reports and a final article, were identified and only the one with the most complete dataset was retained.

For the third step, each included study was assigned a level of bias (low, medium or high) according to the four criteria presented in Table 3. In some cases, it was difficult to make an evaluation and the item was assigned as "undefined". Finally, studies were grouped into two categories. If at least one criterion was 'high' or if the four criteria were 'medium' or 'undefined', the study was classified as 'high bias' and excluded from the analysis. All other studies were kept.

Data extraction and meta-analysis

The data for the meta-analysis were extracted from the remaining studies. Only data related to plants, fishes, macrocrustaceans, birds and invertebrates were extracted. Data

Table 2. Eligibility criteria used during the screening process.

Inclusion criteria	• Population: all non-human wild species, native or not, and habitats. • Intervention: return of salt or brackish water via all types of coastal realignment: managed realignment or accidental realignment. Banked realignment, breached realignment, regulated tidal exchange, installation of culverts or substitution of culverts by larger ones. • Outcomes: all types of outcomes: composition (diversity, abundance, frequency, etc.), structure (sex ratio, age ratio, etc.), function (fertility, growth, mortality, diet, etc.). • Context: *in situ* field studies; restoration of a site (i.e. return to a former existing state). • *At the full-text screening stage:* Type of document: field studies, remote sensing; Language of document: French or English
Exclusion criteria	• Population: studies dealing only with abiotic parameters (e.g. nutrients, sediments, hydromorphology, without a link to species or habitat). • Intervention: management without increase in salt or brackish water flow (e.g. only supply of dredged material, terraced marsh restoration, freshwater inflow, etc.). • Context: laboratory experiments, modeling; creation of a site (i.e. change to a state which had never been observed on the site until the experiment). • *At the full-text screening stage:* Type of document: reviews, discussion papers; Language of document: Any language other than French or English.

Table 3. Critical analysis criteria.

Criterion	Description	Level of bias assignment
Sampling protocol	Are the five following pieces of information described: steps undertaken, equipment used, time, duration and location of surveys?	• *High:* No protocol or less than two • *Low:* all the information • *Medium:* all other cases
Type of sampling	Is there randomness in the sampling?	• *High:* non-random sampling • *Medium:* systematic sampling • *Low:* random or complete sampling ("complete" meaning, for example, the whole site is visited and all birds observed are noted)
Sampling method	Is there any change (material, method, sampling location, etc.) between before and after the realignment phase or between the study site and the reference site?	• *High:* change in sampling gear without distinctions in the results • *Low:* no change • *Medium:* all other cases
Repeated measurements	Are the measures repeated before and after the realignment?	• *High:* a single sampling event before and after realignment • *Low:* at least two sampling events before and after the realignment phase • *Medium:* all other cases

relating to mangroves and saltponds were not considered. Only data related to species richness or abundance (number of individuals, cover, frequency, etc.) were extracted, based on text, tables or figures (via WebPlotDigitizer image analysis software (Rohatgi, 2020)). Each study was divided into single cases, with one case corresponding to data for a given species, parameter, and year. For pre-realignment data, when several years were available, the choice was made to extract the data corresponding to the last year before the realignment operations. Post-realignment data were extracted per year post-realignment. If data for a site were available for multiple transects or subsites, they were pooled to calculate means and variances at the site level, according to the Cochrane Combined Group formula (Higgins et al., 2020).

Data analysis differed depending on the studied variable. For abundance, the effect size (ES) was defined as the difference between the standardized mean change for the treatment and reference groups (Morris, 2008):

$$ES = C_T.d_T - C_{ref}.d_{ref} = C_T.\left(\frac{M_{post,T} - M_{pre,T}}{SD_{pre,T}}\right) - C_{ref}.\left(\frac{M_{post,ref} - M_{pre,ref}}{SD_{pre,ref}}\right) \quad (1)$$

with $M_{post,T}$ and $M_{pre,T}$ the post- and pre- means for the treatment group, respectively, $M_{post,ref}$ and $M_{pre,ref}$ the post- and pre- means for the reference group, respectively, $SD_{pre,T}$ and $SD_{pre,ref}$ the standard deviation of the pre- means for the treatment and reference groups, respectively. The correction factor is defined as $C_j = 1 - \frac{3}{4*(n_j-1)-1}$ with n_j the number of samples in the treatment ($j = T$) or the reference ($j = ref$) group. A positive ES indicates an increase in abundance after realignment.

The variance of the effect size was calculated as (Morris, 2008):

$$\sigma^2(ES) = C_T^2.\left(\frac{2(1-\rho)}{n_T}\right).\left(\frac{n_T - 1}{n_T - 3}\right).\left(1 + \frac{n_T.d_T^2}{2(1-\rho)}\right) - d_T^2 + C_{ref}^2.\left(\frac{2(1-\rho)}{n_{ref}}\right).\left(\frac{n_{ref} - 1}{n_{ref} - 3}\right).\left(1 + \frac{n_{ref}.d_{ref}^2}{2(1-\rho)}\right) - d_{ref}^2 \quad (2)$$

with d_T and d_{ref} the standardized mean change for the treatment and reference groups, respectively, n_T and n_{ref} the sample size of the treatment and reference groups, respectively, and ρ (rho) the correlation between pre- and post-intervention data. Because the ρ value was never reported in the studies, a sensitivity analysis with ρ ranging from 0.1 to 0.9 was performed. As it did not challenge the results, only results with ρ=0.5 are presented.

To calculate ES values for abundance, only cases with a paired design, with a number of samples strictly higher than 3 and with complete data (i.e. n_j, $M_{pre,j}$, $M_{post,j}$, $SD_{pre,j}$ with $j = T$ and $j = ref$, by year post-realignment) were kept. Half of the cases had a $SD_{pre,T}$ equal to zero, because some species, especially saltmarsh species, were absent from all sampling plots, making the ES calculation impossible. To keep them in the meta-analysis, $SD_{pre,T}$ was slightly modified, by virtually adding 1 individual to 1 sample before and after realignment. This had the effect of making the calculation possible with a negligible change in $SD_{pre,T}$ and no change in the difference of means.

ES values for abundance were analyzed using random-effects models with the maximum-likelihood estimator. Random effects for species within studies were specified as well as auto-correlated random effects at the species level to take into account the fact that studies reported data at

multiple time points. Four different moderators (fixed effects) were tested in separate models, namely the time difference between the sampling and the realignment, the taxon, the ecology of the species (based on the humidity and salt tolerance for plants, on the feeding characteristics for birds), and the species. For this last model, auto-correlated random effects were specified at the study level instead of the species level, because using species as a moderator precluded adding random effects for it. A single model with all or several of the moderators was not used due to unbalanced data. The meta-analyses were performed using the metafor package (Viechtbauer, 2010) in R statistical software (R Core Team, 2019).

For species richness, the majority of the data corresponded to exhaustive sampling (i.e. without means). Therefore, the ES was defined as:

$$ES = (SR_{post,T} - SR_{pre,T}) - (SR_{post,ref} - SR_{pre,ref}) \quad (3)$$

with $SR_{post,T}$ and $SR_{pre,T}$ the post- and pre- species richness for the treatment group, respectively, $SR_{post,ref}$ and $SR_{pre,ref}$ the post- and pre- species richness for the reference group, respectively. The ES values were calculated only for cases at the taxon level, with complete data (i.e. $SR_{pre,j}$ and $SR_{post,j}$ with $j = T$ and $j = ref$, by year post-realignment). A positive ES indicates an increase in species richness after realignment. The ES values were analyzed using one-way analysis of variance (ANOVA) with the taxon as explanatory variable in R statistical software (R Core Team, 2019).

Results

Database creation

The search retrieved 1 761 articles on WOSCC and 2 221 articles on Scopus. The search on Google Scholar returned 4 295 articles. After removing duplicates, 4 476 articles remained. After the three-step screening process, 227 articles were included in the systematic review. A further 28 articles from additional sources and adherence to the screening process were added to the database, bringing the total to 255 articles. The screening process is shown through a ROSES flow diagram (Haddaway et al., 2017) in Appendix B and all retrieved articles and their inclusion/exclusion decision at each stage are available in Appendix C: Sheet 2. Coding was carried out on 255 articles, corresponding to 866 studies (monitoring of one taxon in one realigned site). All extracted metadata are available in Appendix C: Sheet 3.

Characteristics of the studies

Among the 255 included documents, nearly two thirds corresponded to peer-reviewed articles and 28% to reports. The other documents were theses, book chapters and conference presentations.

Study sites and coastal realignment characteristics

Information on the study site was rarely complete. Therefore, the calculated percentages presented below are relative to the total number of articles for which data were available, in each case.

233 study sites were identified in the 255 articles (38% of sites being present in more than 1 article), half of which were in the United States and 28% in the United Kingdom. The remaining sites were located primarily in Canada and in other European countries (Fig. 1A). In terms of surface area, the majority of sites (nearly 80%) were small sites (<100 ha) and only 3 sites were larger than 1 000 ha (Fig. 1B). Most of the sites were located in estuaries, followed by sites directly facing the sea. Another four corresponded to lagoons.

The history of the sites is rarely detailed, but was supplied more or less precisely for half of them. The earliest impoundment operations in the studies included in this review date back to the 17th and 18th centuries. The increase is then exponential with 21% of the operations carried out in the 19th and 73% in the 20th century, the last being dated 1990 (Fig. 1C). The reasons for building dykes can be multiple for one site. The main reasons are agriculture (66%), road creation (13%), salt production (9%), flood protection and reductions in mosquito populations (6% each), habitat creation for waterfowl (5%) and drilling and dredging activities (2%) (Fig. 1E). Following diking, 80% of sites were isolated from the influence of the sea from less than 1 year to a maximum of 380 years (85 years on average) (Fig. 1D).

Realignment dates span 150 years, with the earliest operation recorded in our study dating from 1874 and the most recent from 2018. 70% of the sites were realigned after the 1990s (Fig. 1C). The origins of the realignment are diverse, deliberate or not, and can be multiple for one site, including ecological restoration (56%), mitigation (13%), flood protection (4%) or accidental (e.g. storm, 30%) (Fig. 1F). Different types of interventions were implemented for realignment, even if the following numbers should be taken with caution because of some discrepancies in information provided for a given sampling site in different articles. In 63% of the sites, a breach in a dike occurred and in 13% the dike was completely removed. At the other sites, culverts (or larger ones) were installed (16%), an obsolete dam preventing water from entering the site was removed (9%), a dam was installed to allow partial entry (7%), and/or the dike was lowered (2%). Additional operations were sometimes performed, including channel excavation (18%), top-soil dredging (8%), planting or seeding (6%), grading (5%), importing dredged material, filling ditches, exporting vegetation and/or agricultural activities such as grazing or mowing (< 5%) (Fig. 1G).

Study populations and outcomes

Of the 866 studies extracted from the 255 articles, about one third considered plants (34% of studies), followed by

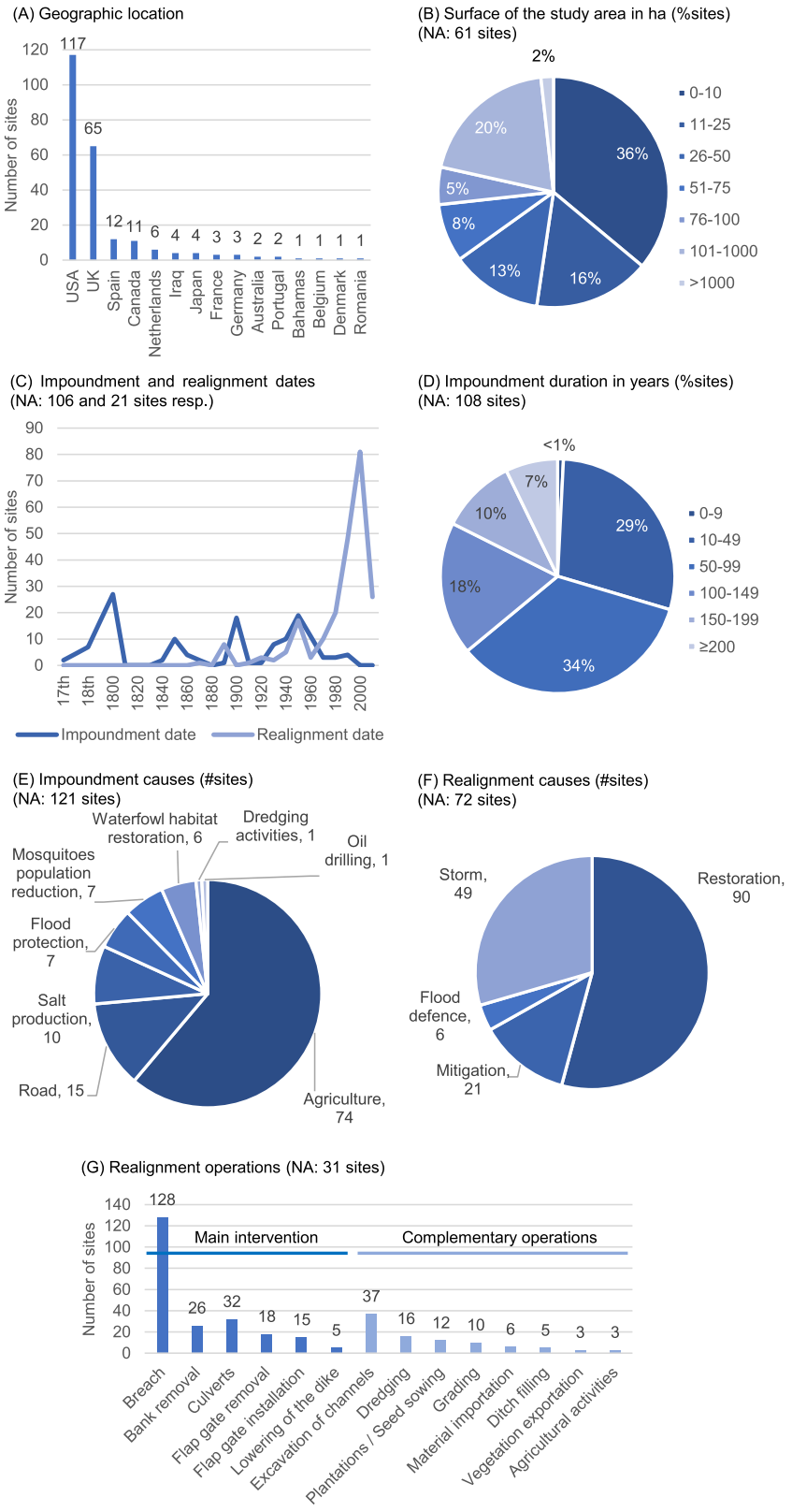

Fig. 1. Characteristics of the studies.
NA: number of sites for which the information is not available (not included in the graphs).

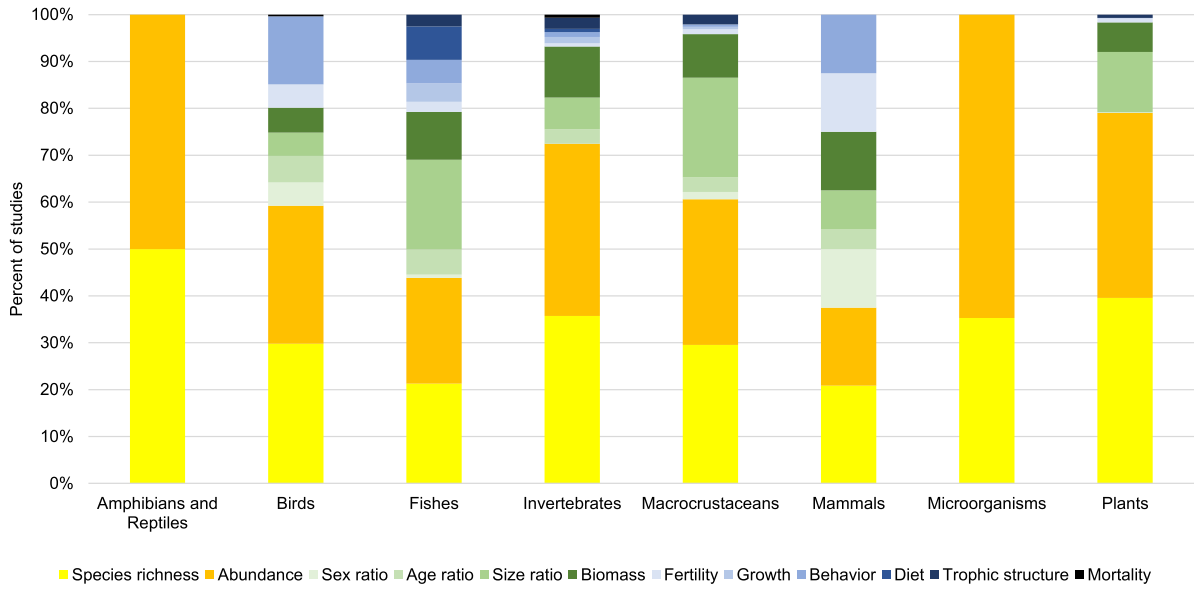

Fig. 2. Studied outcomes by taxon.

fishes (18%), invertebrates (except macrocrustaceans) (14%), birds (10%), macrocrustaceans (7%), microorganisms (mainly bacteria) (3%), mammals (1%), and amphibians and reptiles (<1%). The most recurrent studied species were *Fundulus heteroclitus, Oncorhynchus* spp., *Spartina* spp. and *Phragmites australis*. Habitats were considered in 13% of the studies.

For all taxa, "compositional outcomes" i.e. species richness and abundance were measured in the majority of the studies (>94%). Nearly 40% of the studies focused on a "structural outcome", i.e. size (32%), biomass (20%), age (7%) or sex (3%). "Functional outcomes" were less studied (20% of the studies) and primarily concerned behavior (9%), but also diet (5%), fertility (5%), growth (3%), trophic structure (3%) and mortality (< 1%). It is noteworthy that some criteria were evaluated almost exclusively on specific taxa. For instance, more than 80% of the studies measuring growth and/or diet focused on fishes, and behavioral studies involved birds or fishes in 90% of the cases (Fig. 2).

Study experimental design

Less than 25% of the studies had both a spatial and a temporal comparator, which is considered the most complete experimental design (BACI, BARI, or BACRI design, Table 4).

Control and reference sites are generally adjacent to the study sites (40% and 53% of the studies respectively) or less than 50 km away (27% and 45% resp.) but are sometimes farther than 100 km (18% and 1% resp.). Control sites were of three main types, agricultural land, salt ponds or fresh or brackish marshes mostly invaded by *Phragmites australis*. Reference sites mainly corresponded to salt marshes and mudflats.

Less than a third of the studies included pre-realignement monitoring, generally done during the three years prior to the operations. For 58% of the studies, post-monitoring was implemented in the five years following realignment and did not exceed ten years in the majority of the cases (77%). However, some sites were sampled 100 years after their realignment (2% of the studies).

Risk of bias in the studies

676 studies were excluded because they were without a BARI or BACRI experimental design and 65 because they were redundant. Among the remaining studies, 28 were excluded due to a high level of bias. The status for each article is available in Appendix C: Sheet 4.

Meta-analyses

Some studies were not inluded in the meta-analyses for several reasons, for example a specific context (mangroves,

Table 4. Percentage of studies using different experimental designs Different experimental designs can be implemented. They can involve a temporal comparator (sampling before and after realignment) or not (only after realignment) and/or a spatial comparator (a control site, i.e. a diked site, and/or a reference site, i.e. an undiked site). B: Before; A: After; I: Intervention; C: Control site; R: Reference site. Two studies are not included in this table because it was not clear if there was a temporal comparator.

	No Spatial Comparator	Spatial Comparator		
No Temporal Comparator	AI 17.4%	ACI 0.7%	ARI 45.9%	ACRI 5.4%
Temporal Comparator	BAI 7.8%	BACI 0.7%	BARI 20.6%	BACRI 1.5%

saltponds) or population (mammals, microorganisms, habitats), missing information (e.g. data only for some transects without justification, no data for the reference site), no extractable data (no quantitative data), merging of data from different years, no taxon data for species richness analyses, incompatibilities with Morris' formula for abundance analyses (no paired design or less than 4 samples) (see Appendix B and Appendix C: Sheet 5).

Meta-analyses were performed on 19 studies for abundance, and 24 studies for species richness. All extracted data and ES calculations are available in Appendix C: Sheet 6 and 7.

The following abbreviations are used: CI: Confidence interval, p: p-value.

Abundance

- Moderator: Time (time difference between sampling and realignment)

No statistically significant relationship was found between mean ES and time between the realignment and sampling dates (Slope=−0.007, 95%CI=[−0.016;0.002], $p = 0.132$), indicating no difference in abundance between a site restored a long time ago and a site restored recently, all taxa considered.

- Moderator: Taxon (Five groups: Bird, Fish, Invertebrate, Macrocrustacean, Plant)

Mean ESs were not statistically different from zero except for fishes whose ES was significantly positive (ES=0.697, 95%CI=[0.096;1.298], $p = 0.023$), reflecting a stability in abundance, except for fishes whose abundance rises when a realignment operation has taken place (Fig. 3).

- Moderator: Ecology (Ecological groups based on the feeding characteristics for birds, on the humidity and salt tolerance for plants)

Concerning birds, only shorebirds had a significantly positive ES, indicating an increase in abundance after realignment (ES=1.29, 95%CI=[0.15;2.42], $p = 0.026$). A slight upward trend appeared to occur for waders, but it was not statistically significant (ES=0.45, 95%CI=[−0.78;1.67], $p = 0.474$).

Concerning plants, no statistically significant ES was observed, indicating that no change in abundance between

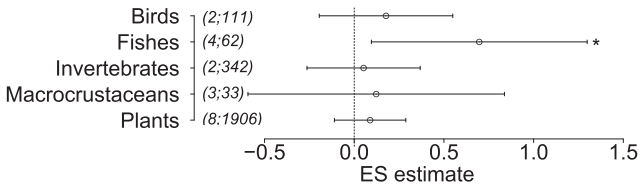

Fig. 3. Effect size estimates for total abundance of selected taxa.
(x;y) : x=number of studies; y=number of cases; * : $p<0.05$; Error bars represent the 95%CI.

before and after realignment was highlighted. Large amplitude, salt-tolerant species and low saltmarsh species seemed to have an increase in abundance, although not statistically significant (ES=0.75, 95%CI=[−0.08;1.58], $p = 0.077$ and ES=0.62, 95%CI=[−0.37;1.62], $p = 0.221$ resp.) (Fig. 4).

- Moderator: Species

For birds, 15 species had a statistically significant ES, positive for 10 of them and negative for 5 of them, indicating an increase or decrease in abundance after realignment, respectively. These results should be taken carefully as they are based on only one study / two cases. Concerning nekton (i.e. fishes and macrocrustaceans), four species exhibited a statistically significant increase in abundance, while five showed a statistically significant decrease. No invertebrate species had a statistically significant ES. 39 plants species had a statistically significant increase in abundance and 31, a decrease. Results are detailed in Figs. 5 and 6 for species with a statistically significant ES, in Appendix D for all species.

Species richness

The species richness mean ES estimate was significantly positive for invertebrates (ES=3.09, 95%CI=[1.49;4.69], $p = 0.0003$) and negative for plants (ES=−0.98, 95%CI=[−1.93;−0.03], $p = 0.040$), indicating an increase and a decrease in species richness for these taxa, respectively (Fig. 7).

Discussion

Knowledge gaps and clusters

A taxonomic bias among studies

Plants and, to a lesser extent, nekton, birds and invertebrates (mainly benthic invertebrates) were the most studied groups, while very few studies concerned mammals, amphibians and reptiles. This may be due to greater difficulties in sampling these groups in occasionally submerged areas, but as mentioned in Troudet et al. (2017), this cannot fully explain taxonomic bias. Other reasons can be given, including an influence of societal interest or an economical dimension (e.g. nekton can be related to recreational and commercial fishing).

Dominance of richness and abundance studies at the expense of other measures of biodiversity

Studies tend to measure species richness and abundance almost systematically. Conversely, structural data (e.g. age and size ratios) and to an even greater degree functional data (e.g. behavior and growth) are less frequently collected. However, size and behavior are sometimes studied, especially for fishes and birds (e.g. Crowther, 2007; Teo &

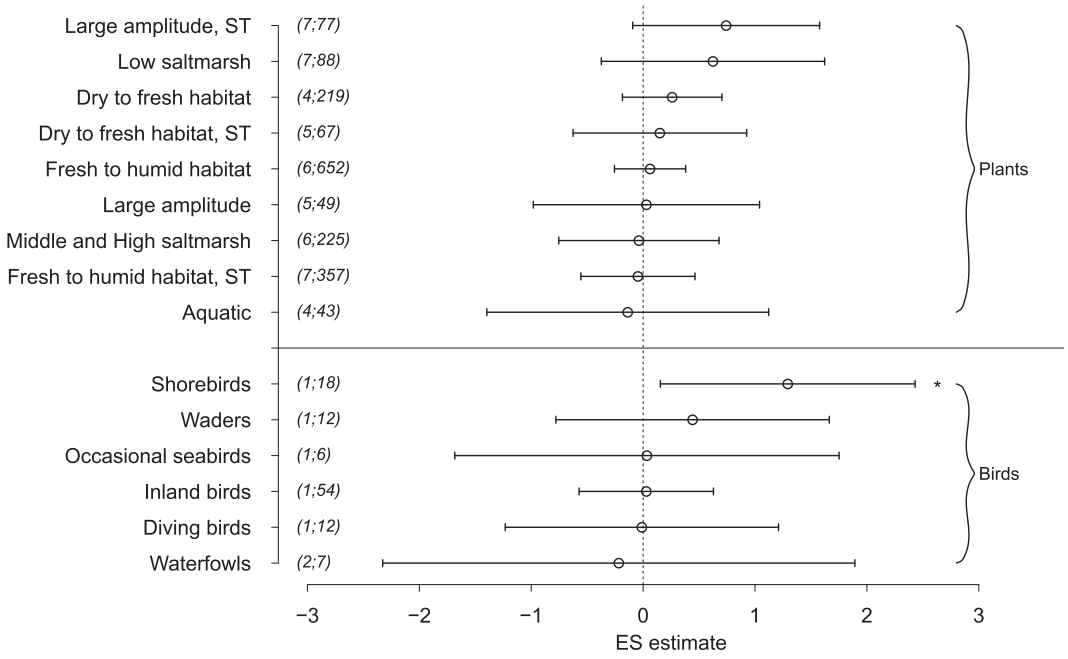

Fig. 4. Effect size estimates for the abundance of ecological groups of birds and plants.
ST = Salt Tolerance
(x;y) : *x*=number of studies; *y*=number of cases; * : $p<0.05$; Error bars represent the 95%CI.

Able, 2003). This may be due to the fact that this type of monitoring is more difficult to set up and requires a greater amount of time, but is recognized as being more reliable for measuring the productivity and vulnerability of an ecosystem (Heemsbergen, 2004; Schleuter et al., 2010; Tilman, 1997). We can only encourage more studies on these criteria as they could provide a more complete picture of the consequences of realignment on the environment.

Lack of long-term monitoring

Another important knowledge gap highlighted by this study concerns long-term monitoring, both before and after coastal realignment. This is unfortunate because such monitoring is crucial both during the pre-restoration phase in order to highlight the stability of the initial situation and to confirm the impact of the intervention (Underwood, 1991), and during the post-restoration phase because some changes may take time to occur (Atkinson et al., 2001; Onaindia et al., 2001).

Impact of coastal realignment on species richness and abundance

We found that realignment induces an increase in the richness of invertebrates and in the abundance of fishes and shorebirds, and a decrease in the richness of plants. The different increases are due to the creation of new habitats (open water, mudflat, saltmarsh), which are used as feeding, spawning or resting areas (Brophy et al., 2013; Raposa, 2002, 2008; Roman et al., 2002). Conversely, a decrease in plants richness is the consequence of the substitution of non-halophyte and non-flood tolerant species by halophyte species (Barkowski et al., 2009; Chang et al., 2016; Sinicrope et al., 1990; White, 2015), which are less diverse (Flowers & Colmer, 2008). These results are in agreement with the BACRI studies. Barkowski et al. (2009), Jacobson (1986) and Matsuda and Kokubu (2016) showed, respectively, a decrease in plants diversity, an increase in the abundance of shorebirds and an increase in the diversity of benthic invertebrates in their realigned sites, while they remained constant in their control and reference sites.

However, some results were more surprising and can be explained by several factors. First, the low number of studies, mainly due to the decision to retain only BARI design and to the high number of imprecise or incomplete studies, decreased the statistical power of the test and can lead to non-significant results. The fact that the ES calculation does not include post-realignment standard deviation can also create artifacts in the results, because a high variability in the post-realignment data is not reflected in the ES formula and the low number of studies cannot attenuate this effect. For example, *Phleum pratense,* in Fig. 6, was reported in only one study, consequently the high effect-size value, due to a high post-realignment mean and variance, is not offset by other studies.

Secondly, studies included in this meta-analysis are short-term, i.e. they reflect only short-term changes, whereas biotic and abiotic parameters may continue to evolve more

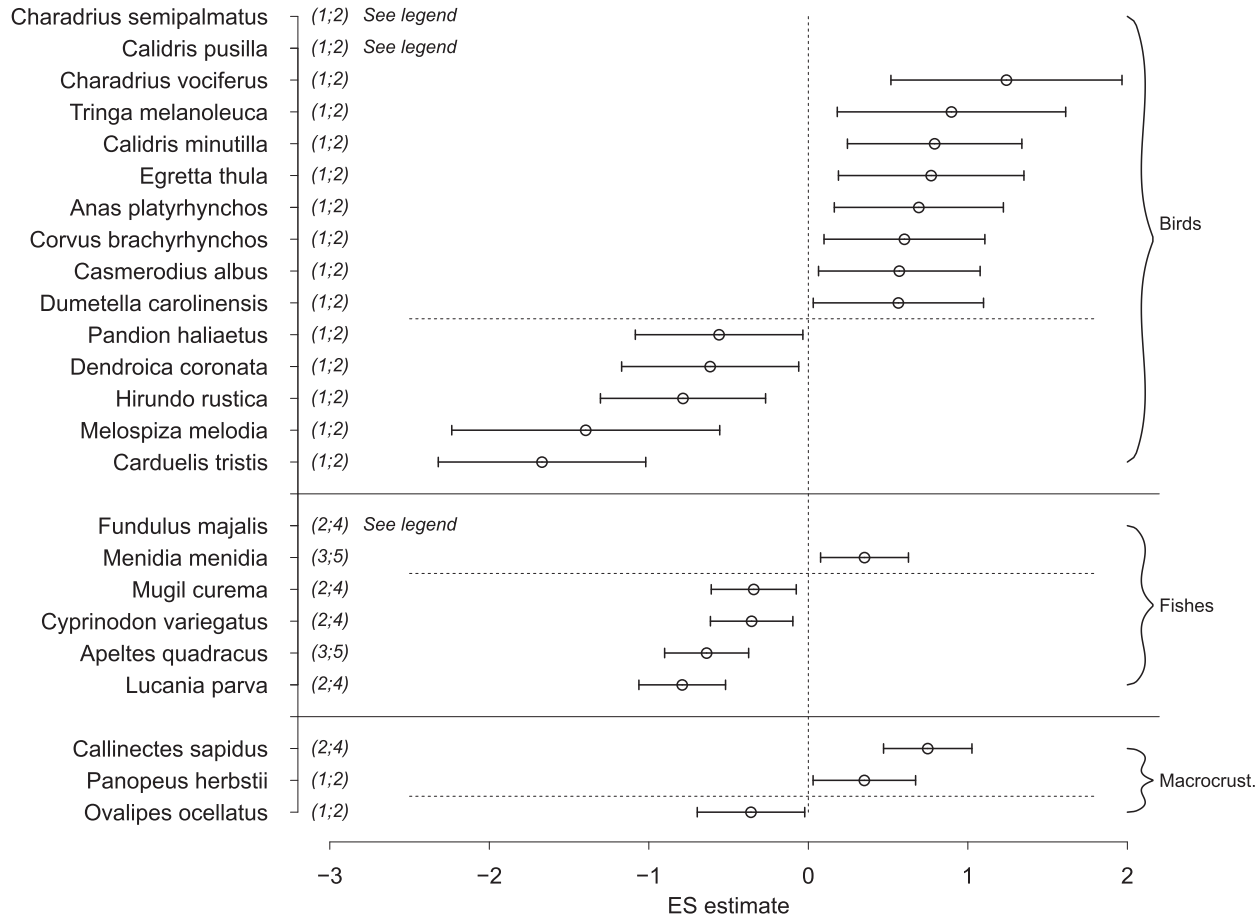

Fig. 5. Effect size estimate of abundance for animal species.

Only those species whose ES is statistically significant are represented in the figure.

For the sake of legibility, some ESs are not represented. Their values are: *Charadrius semipalmatus*: ES=50.498, 95%CI=[34.223;66.773], $p<0.0001$; *Calidris pusilla*: ES=42.915, 95%CI=[28.201;57.629], $p<0.0001$; *Fundulus majalis*: ES=5.832, 95%CI=[5.052;6.612], $p<0.0001$.

(x;y) : x=number of studies; y=number of cases; * : $p<0.05$; Error bars represent the 95%CI.

than ten years after realignment (Gerwing et al., 2020). Thus, the declining numbers of the goose genus *Branta* should be considered with this in mind, as the trend seems to reverse over the long term (10 years) (Bos et al., 2014). On the contrary, there was evidence of an increase in shorebird abundance but on the long term, they may decrease as the mudflats become revegetated (Eertman et al., 2002; Golet et al., 2012; Jacobson, 1986). The development of middle and high marsh species, which do not tolerate frequent flooding, depends on the elevation, i.e. on the sedimentation process, which is slow and can take decades before reaching an equilibrium with sea level (Friess et al., 2012a). Short-term studies may explain the fact that their abundance does not change (Boone et al., 2017; Masselink et al., 2017).

The initial state of a site and the setting of the study site borders also likely affect the results. Flooding a species-poor or a species-rich meadow does not lead to the same change in richness (e.g. Dagley, 1995; Elliott, 2015). Similarly, sampling only flooded areas or also including the non-submerged areas of a site after realignment does not produce the same changes in richness given that glycophyte species disappear in the first, whereas they persist in the second (Chang et al., 2016; Masselink et al., 2017). A site, which is partly under the influence of seawater before realignment (e.g. because of waves overtopping dikes), already hosts, for example, low marsh species and fishes, so realignment does not induce the appearance of such species and the associated increase in richness (Chang et al., 2016). It would be interesting to confirm these last two remarks by analyzing the change in species richness as a function of the proportion of the study site that is subject to the influence of salt water after restoration. However, this data was not always clearly mentioned (or not mentioned at all) in the articles to enable this analysis.

Finally, a compensation effect, either between species or between studies, can induce non-significant results. An increase in fish richness could have been expected, but it

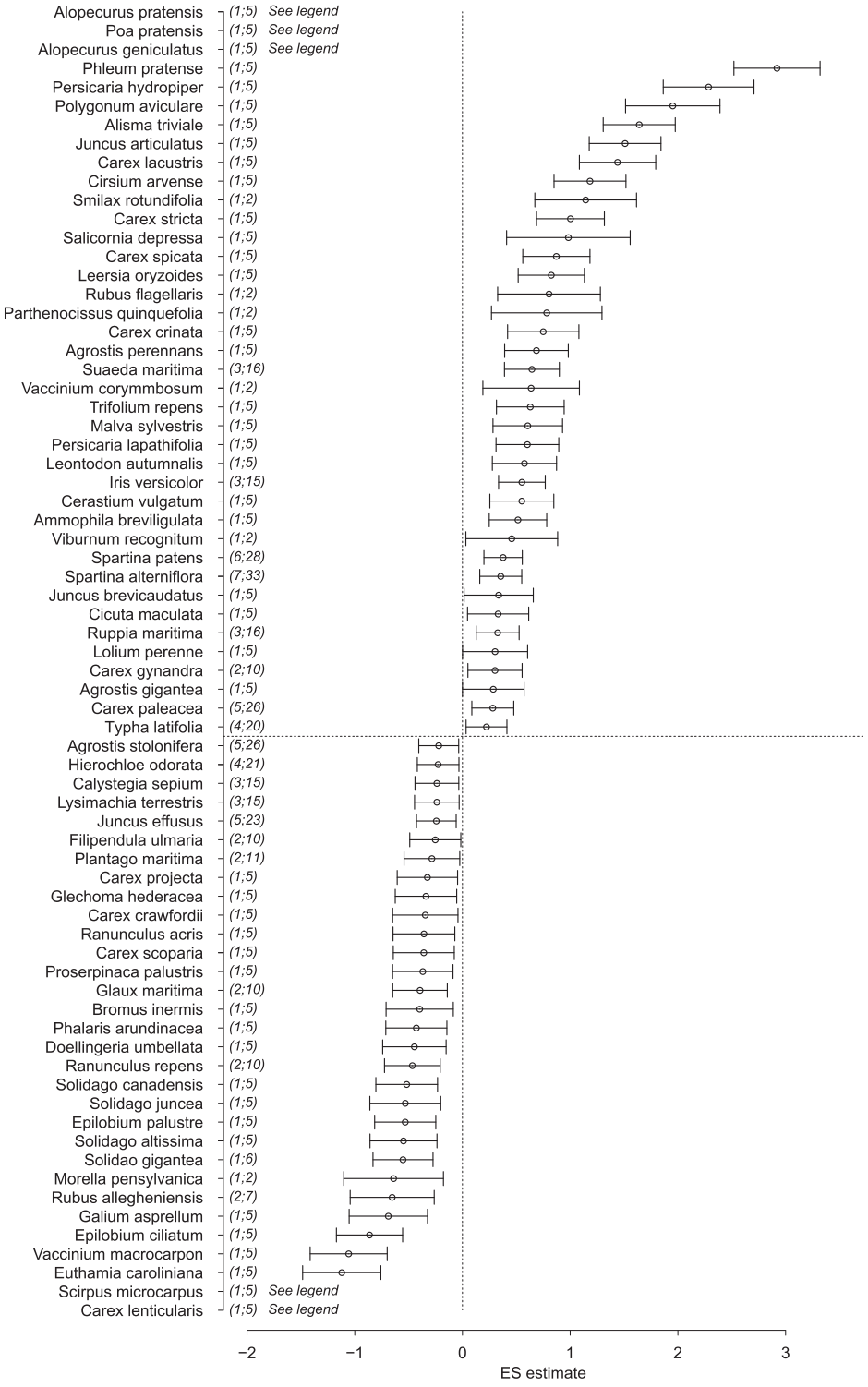

Fig. 6. Effect size estimate of abundance for plant species.

Only those species whose ES is statistically significant are represented in the figure.

For the sake of legibility, some ESs are not represented. Their values are: *Alopecurus pratensis*: ES=15.359, 95%CI=[14.064;16.653], $p<0.0001$; *Poa pratensis*: ES=8.279, 95%CI=[6.754;9.804], $p<0.0001$; *Alopecurus geniculatus*: ES=4.400, 95%CI=[3.812;4.989], $p<0.0001$; *Scirpus microcarpus*: ES=−5.801, 95%CI=[−6.919;−4.697], $p<0.0001$; *Carex lenticularis* : ES=−7.043, 95%CI=[−8.336;−5.749], $p<0.0001$.

(x;y) : x=number of studies; y=number of cases; * : $p<0.05$; Error bars represent the 95%CI.

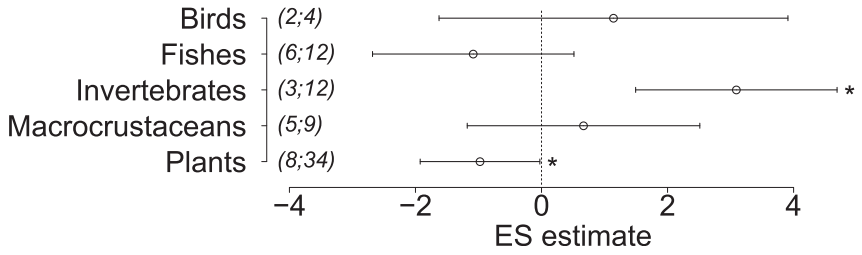

Fig. 7. Effect size estimate for the species richness of selected taxa.
(x;y) : x=number of studies; y=number of cases; * : $p<0.05$; Error bars represent the 95%CI.

was not significant, perhaps due to the fact that some species arrived while others disappeared following realignment, as confirmed by the results per species. Realignment creates new habitats but can also lead to the disappearance of algae, which can be used for refuges, or can increase predation pressures on some species by allowing access to the site to larger fishes or by attracting more fish-eating birds (Raposa, 2008). This compensation can also explain the absence of increases in waders or in waterfowls, e.g. some species such as *Anas platyrhynchos* increase while others like *Branta* species decrease (Bos et al., 2014; Raposa, 2008). Similarly, as mentioned previously, opposite trends may co-exist depending on the initial state of a site and balance each other. However, many other factors, variable from one study or site to another, intervene in the establishment of the new species assemblage, interact together and can lead to different results (e.g. biotic (Brooks et al., 2015; Paramor, 2001), edaphic (Howe et al., 2014; Underwood, 1997), hydric (Schile et al., 2011; White, 2015), geographic (Hinkle & Mitsch, 2005; Mazik et al., 2010; Reading et al., 2008), or anthropic factors (Garbutt et al., 2006; Smith et al., 2009; Spencer et al., 2008). The characteristics of the experimental design can also influence the results (Able et al., 2005; Kimball & Able, 2007) (see Appendix E for a detailed description and further references). It would have been interesting to study the impact of these factors on the effect sizes but the lack of data prevented us from doing so.

Review limitations

Several factors can have an impact on the results of the review and be related either to the research strategy itself or to the articles included in the review.

First of all, we are aware that some relevant articles may be missing in our database. We tried to limit the number of missed articles by implementing the search in two databases, in Google Scholar and by searching complementary sources. However, the search for articles was conducted in English, and only articles in English and French were retained. Even though we ran a search on Google Scholar to retrieve gray literature, it is possible that we missed unpublished reports, which are difficult to find. It is also important to keep in mind that more than 70% of the studies included in the database were excluded from the analysis, in order to keep only studies with a BARI or BACRI sampling design. Although it led us to perform the meta-analysis on a limited subset of studies, this decision was made to assess the consequences of realignment on biodiversity in the most robust way possible, in that these designs are recognized as more accurate than designs with only a spatial or a temporal comparator (Christie et al., 2019; Smokorowski & Randall, 2017).

Some factors in the review limitations are linked to the studies. Because most studies are short-term, long-term changes are not highlighted in the review and this may explain unexpected or non-significant results. The choice of the reference site can be questioned given that some reference sites were old realigned sites and some studies stressed the fact that even after a long time, a realigned site can still change and be different from a site that was never diked (Garbutt & Wolters, 2008; Mossman et al., 2012). The location of reference sites may also be a factor, because many studies used the saltmarsh seaward of the dike as a reference, whereas others stress that lands adjacent to dike are also impacted by realignment (Friess et al., 2012b). Finally, the lack of precision regarding the experimental design (description, consistency) and the data reporting (incomplete, imprecise, not in agreement with the methods) of some articles prevented their use in the analysis. In order to avoid these shortcomings and to produce complete publications which can be reused in meta-analyses, we strongly recommend that the suggestions detailed in Gerstner et al. (2017) be followed.

Conclusion

This review highlights several remarkable points.

- A considerable amount of literature exists on realignment operations. These studies show a change in the species assemblages, including the development of halophilic plants and an increase in the number of fishes and shorebirds. However, knowledge is unevenly distributed among the taxa and certain groups, notably mammals, amphibians and reptiles, remain little studied.
- Although the changes in biodiversity tend to be similar in their general characteristics, the results of realignment are site-specific and depend on many interacting hydric, geographic, biological, and anthropogenic

parameters. The analysis of the results must be carried out with the context and characteristics of the study in mind.
- Monitoring focuses mainly on species richness and abundance, but the structuring of populations and the functioning of ecosystems remain relatively unknown.
- A significant number of studies lack rigor in describing the context of the study, defining the experimental protocol, implementing it and/or reporting the results. However, these are fundamental elements for the analysis of results and it is important to pay more attention to them.
- The studies are generally carried out over the short term (< 5 years) and would benefit from longer duration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.baae.2022.01.009.

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