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*Review*

# Evolution and Effectiveness of Salt Marsh Restoration: A Bibliometric Analysis

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**Abstract:** Salt marshes play a critical role in supporting water quality, erosion control, flood protection, and carbon sequestration. Threats from climate change and human activities have prompted global restoration initiatives. We analyzed restoration efforts worldwide from 1978 to 2022, using the Web of Science database and SciMAT mapping tool. After a PRISMA screening to identify methodologies, success rates, and key indicators, a total of 62 publications underwent detailed analysis, to increase knowledge on the best practices to employ in future restoration interventions and evaluation of their effectiveness. The research reveals a growing interest in ecosystem dynamics, biodiversity, anthropogenic impacts, and ecosystem services. Assisted interventions emerged as the predominant restoration method, employing 15 indicators across vegetation, sediment, fauna, and water, each one using different metrics for the intervention evaluation based on how good the outcome of the interventions described in the reviewed studies met the desired result. Our analysis suggests that combining natural interventions such as managed realignment with reconnection to tidal waters, along with long-term monitoring of vegetation, fauna, and water indicators such as sedimentation and erosion rates, plant cover and biomass, as well as fauna diversity and density, leads to the most successful outcomes. We provide valuable insights into best practices for future restoration interventions, offering guidance to future practitioners and policymakers based on a comprehensive review of the scientific literature, contributing to the resilience of these vital ecosystems, and ensuring effective restoration actions in the coming years.

**Keywords:** ecological restoration; coastal management; salt marshes; ecosystem services

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## 1. Introduction

Coastal ecosystems, such as salt marshes, present great complexity due to the interconnection of different processes (physical, chemical, and biological), and habitat diversity [1]. As vital connections between land and sea, where saltwater and freshwater mix, these habitats deliver essential ecological functions and provide a wide range of ecosystem services [2,3]. Salt marshes contribute to the maintenance and improvement of water quality and provide protection against erosion and floods, and carbon sequestration, services valued at 188 EUR/ha/year [4] and 65.57 EUR/t$CO_2$ [5], respectively. In Portugal, for instance, salt marsh ecosystem services values (including provisioning, supporting, regulating, and cultural) were estimated for several transitional systems ranging from 5 to 6 EUR/$m^2$/y [6].

Due to their location, however, salt marshes have been impacted by human activities such as urban development, pollution discharges, dredging, and other factors that alter their habitats and hydrodynamics. For instance, the loss of coastal marshland has a direct impact on biodiversity and consequently on the supply of fish biomass to the aquaculture and fisheries sectors [7]. To reverse this eminent and widespread biodiversity loss, ecosystem restoration has been highly advocated to meet the Sustainable Development Goals (SGDs) of the UN 2030 Agenda for Sustainable Development, particularly those related to climate change mitigation (SGD 13) and conservation of marine resources (SGD 14). Generally, the recovery of a degraded coastal site poses significant challenges due to the dynamic nature of the system, making it difficult to revert to its original undisturbed conditions. Notably, contemporary restoration approaches are incorporating social considerations alongside ecological factors, focusing on multiple objectives such as human well-being to ensure food security and sustainability, in addition to environmental or ecological goals [8–11].

Despite the growing recognition of salt marshes as important zones for maintaining essential ecosystem services, their restoration has been carried out for decades using relatively simple techniques like seeding and transplantation of plants to the area to be restored [12]. Also, the desertion of human interference proposed in 1997 by Bakker et al. [13] to let the salt marshes evolve naturally was short-lived due to ineffective vegetation recovery after the natural tidal cycles have been altered. More recently, it was perceived that the selection of the restoration method should consider several factors like the site degradation level, the resources available, the desired result, and the time. As highlighted in Zhao et al. (2016) [14], the three main methodologies of coastal wetland restoration are (1) active restoration, when humans control and interfere methodically to reestablish the ecosystem processes and improve the community structure; (2) passive restoration, with the removal of the elements jeopardizing the well-functioning of the wetland such as levees or dams that interfere with the water flow, usually less expensive and potentially giving more resilience to the restored area although taking more time to fully achieve the desired results; and (3) creation, which consists of the conversion of upland or subtidal habitats into new, previously non-existent wetlands, usually by building an artificial structure to trap sediment. More recently, a new approach to the wetlands restoration has been taken with the introduction of nature-based solutions (NbS) [15]. It can be briefly described as an umbrella term that congregates the sub-categories "green infrastructure"—built or engineered to improve resilience to climate impacts—and "Natural infrastructure"—use of existing or restoring natural landscapes [16]. It thus relies less on artificial structures to face the challenges of carbon sequestration, erosion protection, and conservation of biodiversity, and makes use of the ecosystem services to solve these issues. Assessing the success of restoration efforts requires the establishment and careful selection of indicators as they directly influence project evaluations. Ideally, success indicators should be comprehensive, widely applicable, and user-friendly [11]. While earlier studies predominantly examined vegetation structures, hydrological conditions, and surface elevations to understand the recovery of a restored salt marsh compared to its natural counterpart, there is a growing trend toward utilizing functional indicators (e.g., carbon sinks and biomass estimations) as well to evaluate restoration success [17]. For instance, Cadier et al. (2020) [18] conducted a review and assessment of the ecological outcomes of coastal wetlands restoration, concentrating on indicators used to evaluate ecosystem recovery and success in restoration projects. Bertolini and Mosto (2021) [19] emphasized the significance of coastal wetland restoration and conservation for climate change mitigation and adaptation, particularly focusing on the potential of coastal wetlands in carbon storage and enhancing their resilience to sea level rise. Zhao et al. (2016) [14] highlighted the importance of evaluating the success of restoration projects, establishing a success indicator system, and addressing the challenges and opportunities in wetland restoration and management. Additionally, the study underscored the significance of coastal wetland restoration in mitigating climate change, conserving biodiversity, and providing valuable ecosystem services. Billah et al. (2021) [11] reviewed salt marsh restoration strategies, success evaluation indicators, and the impact of restoration efforts on ecosystem development, plant and animal communities, sediment dynamics, and carbon accumulation. The study aims to provide insights into the importance of restoring degraded salt marsh areas for ecosystem services and biodiversity, as well as to assist marine ecosystem restoration practitioners in understanding salt marsh restoration success evaluation. Xiang and Cao (2024) [20] focused on analyzing the research on blue carbon sinks using bibliometric analysis and visualization software to identify the main characteristics, temporal and spatial distribution, and thematic evolution trends of blue carbon research. Despite previous studies focusing on salt marsh restoration techniques and success evaluation indicators, few focused on assessing the types of techniques that perform the best and what indicators were used to measure their effectiveness. Regardless of some extensively studied salt marshes, there are gaps in geographical coverage, especially in countries with limited funding. These nations could gain insights from prior studies, pinpointing the factors that led to the success or failure of previous procedures. By adapting methodologies based on lessons learned, these countries could address challenges more efficiently. Additionally, the varied metrics used to assess the success of restoration efforts in different studies hinder comparability.

This review aims to (i) point out the distribution, trends, and hot topics concerning salt marsh restoration projects over the years and identify the possible paths regarding future research and interventions; (ii) identify the main techniques applied in previous restorations projects; and (iii) evaluate the effectiveness of each technique used by the analysis of the outputs described in each work and compiling the given indicators and metrics used. This holistic approach not only sheds light on the current state of salt marsh restoration but also guides towards optimized strategies for future interventions, resulting in more successful conservation actions.

## 2. Methods

*Literature Search and Analysis*

For this review, the terms "article" and "review article", in English language, were used to collect the relevant bibliography in the online database Web of Science (www.webofscience.com, accessed on 27 February 2023), up to the year 2022. Aware of the possibility of many restoration interventions not being published or listed in the database used, grey literature, non-published papers, or unpublished data were intentionally not included, to ensure reliability of the results. To search for the largest number of scientific papers concerning the topic of "salt marsh restoration", and to extract the information about the location, type of restoration and the consequent output, the following search term was used: TS = ((*saltmarsh** OR (*salt* AND *marsh**) OR (*tidal* AND *marsh**)) AND (*restor** OR *rehab** OR *recover**)). The geo-temporal visualization of the work produced in this research field and general themes, as well as their evolution over the decades, was subsequently conducted using keywords and h-index analysis. To improve data consistency and remove noise from the analysis, a deduplication process was applied, grouping words and expressions that represent the same concept [21]. To better visualize the themes evolution, years were grouped into 3 main periods, as follows: before 2000; from 2001 to 2010; and from 2011 to 2022.

The distribution of publications through the different countries was plotted using data extracted from the "Countries/Regions" category in the "Analyze Results" tool in Web of Science (Figure 2A–C).

A bibliometric analysis was conducted to assess the evolution of the main subjects related to salt marsh restoration over the years. This analysis involved exploring authors' keywords with the *SciMAT* software package v1.1.04—*Science Mapping Analysis Tool* [22]. The bibliometric analysis performed in *SciMAT* enabled a visualization of the evolution of the addressed themes in a more general manner. The conceptual map of research themes (Figure 3) and strategic maps for each period (Figure 4) were extracted from the software outputs to enhance visualization and interpretation of the results. However, for a more specific evaluation of the practical work undertaken within the theme of restoring salt marshes, the overall research was then screened using the *PRISMA* approach [23]. The objective was to narrow down the set of publications, allowing for an assessment of the methodology employed, success rates, and the indicators and metrics used. Publications that did not specify the type of intervention and/or the metrics used to evaluate restoration success were excluded from the analysis. The steps utilized in the *PRISMA* screening process are summarized in Table 1.

**Table 1.** Summary of the exclusion and inclusion criteria followed in the *PRISMA* screening.

| Number of Papers Excluded (From Total 2852) | Reason for Exclusion | Number of Papers Remaining |
|---|---|---|
| 1837 | Not representing the restoration of salt marshes as the focus of the work; having a greater focus on mangroves or genetic or theoretical studies. | 1015 |
| 645 | Studies in the laboratory/mesocosm or mapping work/data collection with a view to a potential restoration action. | 370 |
| 224 | Did not refer to a restoration project carried out by the authors or identified in the publication. | 146 |
| 94 | Did not describe in the methodology the type of intervention that was carried out, or the indicators used to evaluate the success | 62 |

The way in which different types of interventions are distributed and their resulting outcomes in salt marsh restoration projects offer valuable insights into the effectiveness and challenges involved in restoring these ecosystems. Each restoration project was grouped by the method applied and type of intervention (Figure 6, Table 3), and to reduce the degree of inconsistency and misinterpretation, we used the three-category framework proposed by Atkinson and Bonser (2020) [24], adapted from the "International Principles and Standards for the Practice of Ecological Restoration": (1) assisted restoration: a combination of "biotic" (e.g., invasive species removal, and revegetation mostly performed with transplantation and seedlings) and "abiotic" (e.g., habitat reconstruction, control of flood disturbance to promote seed germination); (2) natural restoration: cease and prevent the degradation (e.g., retreat of contamination, stopping logging activities, cessation of grazing); and (3) reconstructive restoration: combines both natural restoration and assisted restoration. The success of the intervention was measured by taking into consideration the outcomes and conclusions described in the publication. Interventions that, based on the evaluation of the metrics used, achieved a positive outcome, or met the objective of the restoration were considered successful, in contrast to those that failed to present a positive outcome or meet the goal of the intervention. Those that met some goals but were unsuccessful in delivering important expected outcomes were considered limited, and those that, based on the evaluation of the metrics used, did not give a significant positive outcome were labelled as inconclusive.

For each restoration project, indicators and metrics used to evaluate the success of the operation were identified. Similar terminology and synonyms were grouped together for a more precise analysis, and each metric used was grouped in the corresponding indicator group. The information was compiled into several tables (Table 2A–D), each one for a different scope of observation ("sediment", "vegetation", "fauna", and "water"). For each identified metric, the number of publications (*N*) that used that reference as a metric was counted. The data on indicators used provide insights into the key aspects that are considered and monitored during restoration efforts (Table 2A–D, Figure 7).

**Table 2.** (**A**) Indicators and metrics used to evaluate the success of the restoration projects grouped by observation scope (sediment). (**B**) Indicators and metrics used to evaluate the success of the restoration projects grouped by observation scope (vegetation). (**C**) Indicators and metrics used to evaluate the success of the restoration projects grouped by observation scope (fauna). (**D**) Indicators and metrics used to evaluate the success of the restoration projects grouped by observation scope (water).

| (A) | | | |
|---|---|---|---|
| **Scope** | **Indicators** | **Metrics** | ***N*** |
| Sediment | Sediment dynamics | Sedimentation rate | 10 |
| | | Erosion rate | 4 |
| | | Soil aeration | 1 |
| | | Elevation | 19 |
| | | Critical erosion velocity | 1 |
| | | Mass eroded | 1 |
| | | Vertical accretion | 5 |
| | Sediment characteristics | Bulk density | 9 |
| | | Granulometry | 4 |
| | | Clay percentage | 1 |
| | | Silt percentage | 2 |
| | Hydrodynamics | Flooding duration | 2 |
| | | Flooding frequency | 1 |
| | | Drainage | 1 |
| | | Percentage time drained | 1 |
| | | Percentage time flooded | 3 |
| | Physicochemical characteristics | pH | 6 |
| | | Conductivity | 3 |
| | | Redox potential/Eh | 6 |
| | | Greenhouse gas fluxes | 1 |
| | | Salinity | 7 |
| | | Water content | 8 |
| | Nutrients | Pore water nutrients | 1 |
| | | Soluble reactive phosphorus (SRP) | 1 |
| | | Total dissolved nitrogen (TDN) | 1 |
| | | Extractable dissolved organic carbon (DOC) | 1 |
| | | Potentially mineralizable nitrogen (PMN) | 1 |
| | | Extractable ammonium (NH4-N) and nitrate (NO3-N) | 1 |
| | | Total phosphorus (P) | 1 |
| | | Total nitrogen (N) | 1 |
| | | Total carbon (C) | 1 |
| | | Nutrient concentrations | 2 |

**Table 2.** *Cont.*

| (A) | | | |
|---|---|---|---|
| **Scope** | **Indicators** | **Metrics** | ***N*** |
| | Biological | Chlorophyll *a* | 1 |
| | | Carbohydrates | 1 |
| | | Organic matter | 12 |
| | | Microbial biomass nitrogen (MBN) | 1 |
| | | Microbial biomass carbon (MBC) | 1 |
| | | Loss on ignition | 1 |
| **(B)** | | | |
| **Scope** | **Indicators** | **Metrics** | ***N*** |
| Vegetation | Abundance | Colonization | 7 |
| | | Cover | 22 |
| | | Vegetation change | 1 |
| | | Species density | 5 |
| | | Species richness | 4 |
| | | Diversity | 15 |
| | | Seedling counts | 2 |
| | | Emergence rate | 1 |
| | | Stem density | 2 |
| | | Shoot density | 1 |
| | Plant characteristics | Stem high | 2 |
| | | Plant height | 3 |
| | | Seed length | 1 |
| | Health and growth | Health | 3 |
| | | Growth rate | 8 |
| | | Belowground biomass | 8 |
| | | Aboveground biomass | 6 |
| | | Biomass | 1 |
| | | Survival rate | 7 |
| | Processes | Seed production | 2 |
| | | Dead stems | 1 |
| | | Live stems | 1 |
| | | Productivity | 1 |
| | | Grazing intensity | 1 |
| | | Photosynthetic rates | 1 |
| | | Entrapped seeds | 1 |
| | | Stomatal conductance | 1 |
| | | Leaf nitrogen | 1 |
| | | Ellenberg indicator values (EIVs) | 1 |

**Table 2.** *Cont.*

| (C) | | | |
|---|---|---|---|
| **Scope** | **Indicators** | **Metrics** | ***N*** |
| Fauna | Abundance | Abundance | 6 |
| | | Colonization | 1 |
| | | Biomass | 5 |
| | | Density | 7 |
| | | Diversity | 7 |
| | | Species richness | 6 |
| | Food web | δ13C, δ15N, and δ34S isotope values | 1 |
| | Characteristics | Growth rate | 2 |
| | | Size | 1 |
| | | Sex ratio | 1 |
| | | Molting stage | 1 |
| | | Habitat utilization | 2 |
| **(D)** | | | |
| **Scope** | **Indicators** | **Metrics** | ***N*** |
| Water | Water dynamics | Wave energy | 1 |
| | | Water table | 1 |
| | | Tidal hydrology | 3 |
| | | Discharge | 1 |
| | | Depth | 3 |
| | | Wave high | 1 |
| | Physicochemical characteristics | Dissolved oxygen | 1 |
| | | pH | 1 |
| | | Salinity | 4 |
| | | Temperature | 1 |
| | | Bottom-water salinity | 1 |
| | | Surface-water temperature | 1 |
| | | Chloride concentration | 1 |
| | | Seston concentration, Chl α, and C/N Ratio | 1 |
| | | Sulfide concentration | 1 |
| | | Sulphate concentration | 1 |
| | | Dissolved organic carbon (DOC) | 1 |
| | | Suspended sediment concentrations (SSC) | 1 |
| | | Secchi depth | 1 |

# 3. Results and Discussion

## *3.1. Bibliometric Analysis*

### 3.1.1. Publications by Periods

The literature search yielded a total of 2852 publications, with the earliest one dating back to 1978. More than four decades after the first publications on salt marsh restoration, there has been a notable increase in the number of publications, indicating a growing interest in the field. The trend in the number of publications over time is depicted in Figure 1. From 1978 to 2000, only 278 papers were identified in the Web of Science output, as not all work conducted was published or appeared in a journal not indexed in online databases. The number of publications more than doubled in the subsequent period (2001 to 2010), reaching 674 publications, and continued to rise, totaling 1900 publications for the final period under consideration (2011 to 2022). As expected, the total number of citations (including self-citations) also increased over the time periods studied. Articles published in the first and second periods exhibited a higher citation rate. In contrast, articles published in the third period demonstrated a significantly lower citation rate. This discrepancy may be attributed, on one hand, to the fact that these articles were published more recently, thus having had fewer opportunities for citation up to this point. On the other hand, it was also during the third period that studies were conducted on a wider range of topics, resulting in more specific articles. Consequently, there is a tendency to cite articles that are more focused on specific subjects, potentially diminishing the overall breadth of each paper's citation potential (Figure 1).

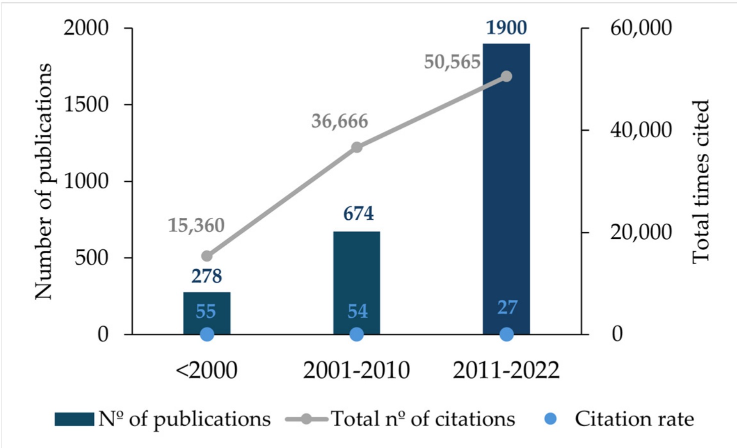


**Figure 1.** Distribution of the number of publications, total number of citations, and citation rate across the three studied periods.

### 3.1.2. Publications by Country

The distribution of salt marshes worldwide is widespread. A recent study collected data from 99 countries, mapping salt marshes across 43 countries and territories, totaling 5,495,089 hectares [25]. Despite their global distribution, most marsh restoration studies are concentrated in the United States (US), followed by Europe [26].

The first period (<2000) was dominated by the United States with 179 publications corresponding to 70.2% of the total published articles (Figure 2A). The second most prolific country was the United Kingdom (UK) with 19 publications (7.5%), followed by Australia and the Netherlands, both with 15 (5.9% of the participation in salt marsh restoration research). Australia possesses a particular richness of wetlands in its territory, which may lead to a division in research between salt marshes and mangroves. This could explain the relatively low percentage of studies regarding this subject when compared to the United States. As far as most of the European countries (Denmark, France, Germany, Italy, Portugal, and Spain) are concerned, they contributed with 25 publications to 11.8% of the total number (Figure 2A).

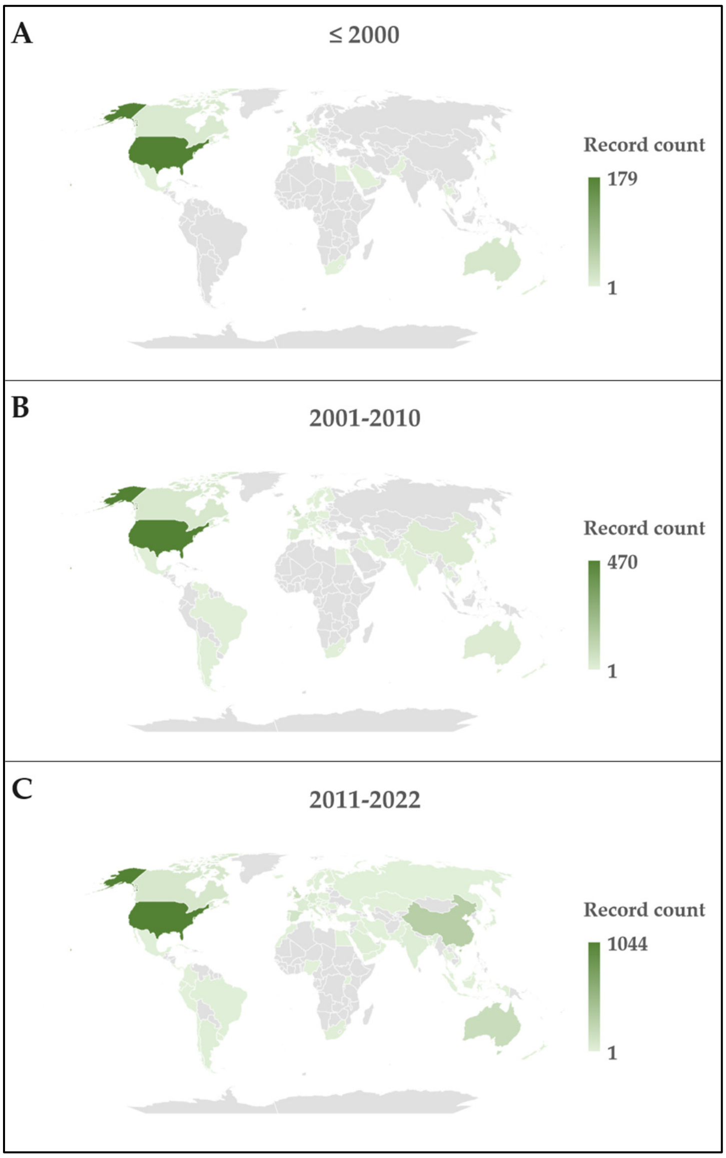


**Figure 2.** Distribution of publications through the different countries by periods ((**A**): <2000; (**B**): 2001–2010; (**C**): 2011–2022).

From 2001 to 2010 (second period), the US maintained the first position with 470 publications (69.8% of the total publications), followed by the UK with 64 (9.5%) and Canada with 34 (5.1%). An investment effort of the European countries towards research of wetlands restoration can be observed, with the UK being the more productive country, followed by the Netherlands (4.5%) and Spain (3.6%) (European contribution with a total number of 197 publications) (Figure 2B).

Although China had already shown interest in this research field during the second period of analysis, it was from 2011 to 2022 (third period) that the research effort became more evident, marked by a significant increase in the number of publications (319; 16.5% of the total). This led to a decrease in the percentage of publications from the US (down to 54%). European countries contributed to a total of 760 publications, with the UK being the most productive with 171 (8.9%), followed by Spain with 118 (6.1%). Australia and Canada also increased their research in salt marsh restoration, raising their participation percentages to 185 (9.6%) and 83 (4.3%), respectively (Figure 2C).

3.1.3. Analysis of Contents

Clear evolution is evident in the research themes addressed over time in the various studied periods, although most of them are related. This points to a growing interest in the restoration of salt marshes. Figure 3 shows the conceptual map of the themes (spheres sized by publication count) and the relation between them (the more related, the thicker the line), obtained with *SciMAT* analysis.

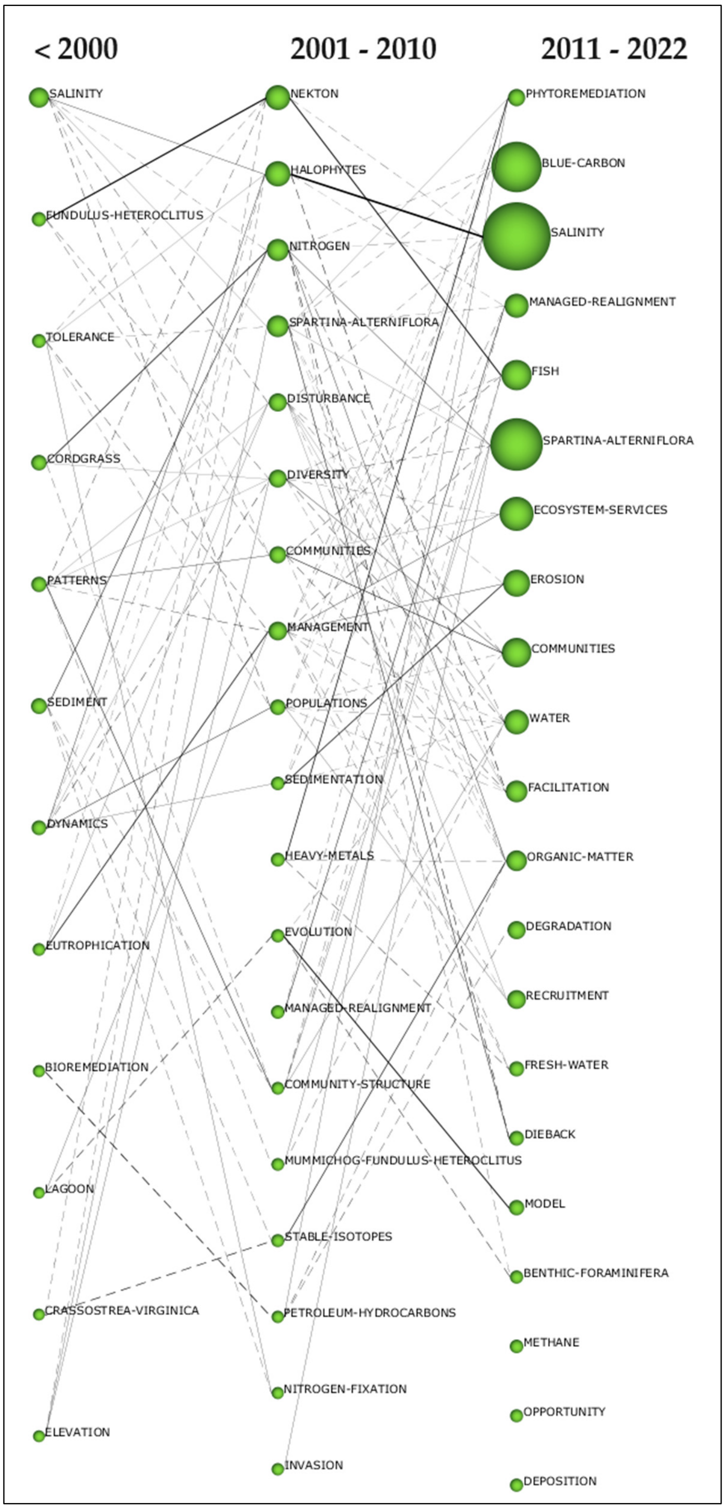


**Figure 3.** Conceptual map of the research themes (spheres sized by publications count) and the relation between them (the more related, the thicker the line).

The keywords from the first period (<2000) (Figure 3) indicate a focus on understanding the impacts of salinity levels on salt marsh ecosystems, including the tolerance of species such as *Fundulus heteroclitus* and the role of cordgrass (*Spartina* sp.) in the salt marsh ecosystem. Topics such as "Sediment dynamics" and "Elevation" suggest research on the evolution and changes in elevation, as well as the movement of sediment in response to sea level rise. This is important because the increasing movement of salt water into the humid zones of brackish and fresh water affects coastal balance [27]. Together with erosion and habitat loss, as the salt marshes become inundated more frequently and for longer periods, the changes in vegetation communities start to occur, with plants adapted to higher elevations being replaced by species better suited to the new conditions [28]. "Eutrophication" and "Bioremediation" indicate concerns about nutrient enrichment and the potential use of natural processes to mitigate the impact of pollution in the environment. The presence of keywords such as "Lagoon" suggests an interest in the interactions between salt marshes and other related estuarine systems, and "*Crassostrea virginica*" appears as an indicator of environmental health and its significance for ecosystem services, including water filtration and coastal protection, and for the maintenance of the coastal habitats. Additionally, it serves as a valuable species for aquaculture activities.

The second period (2001–2010) exhibited a widening of the research focus, with an expanded set of research topics (Figure 3). The inclusion of "Nekton", "Halophytes", and "Nitrogen" suggests a greater emphasis on biodiversity and nutrients in habitats. Keywords related to "Disturbance", "Communities", and "Diversity" indicate increased attention to the responses of communities to ecosystem disturbance. "Management" and "Managed realignment" highlight a growing interest in the development of new restoration strategies. "Managed realignment" is a common method of salt marsh restoration used across UK and Europe usually by allowing tidal water to inundate previously protected or degraded land, most of the time by breaching or removing existing barriers and coastal defenses, enabling the regeneration of salt marsh vegetation and the recovery of the associated fauna. In addition to the ecological benefits, managed realignment contributes to the coastal defense absolving the wave energy and reducing the impacts of erosion, and the engagement of stakeholders helps the projects to benefit both the environment and the local community. The emergence of keywords such as "Heavy metals", "Stable isotopes", "Petroleum hydrocarbons", and "Invasion" suggests concern about the impacts on salt marshes from anthropogenic sources, namely, the presence and analysis of threatening pollutants in the salt marsh system.

The keywords from the third period (2011–2022) reveal a shift in research interests and indicate the emergence of new topics, as well as the evolution of previous topics in salt marsh restoration research (Figure 3). For instance, "Phytoremediation" and "Blue carbon" indicate a focus on exploring the potential of salt marsh vegetation to remove pollutants such as metals and persistent organic pollutants, as well as to sequester carbon from the atmosphere. This highlights their role as valuable ecosystems for mitigating environmental pollution and addressing climate change. In fact, salt marshes provide crucial ecosystem services, including pollution filtration, sediment trapping, carbon sequestration, and wave and storm surge protection. Through their dense vegetation and sediment composition, salt marshes act as natural filters, trapping and biodegrading pollutants from water flow. They also serve as sediment traps, capturing soil and pollutants [29] carried by tidal currents and runoff, thus preventing contamination downstream. Additionally, salt marshes are effective at storing carbon dioxide from the atmosphere [30], primarily through the accumulation of organic matter in their sediments, contributing to long-term climate change mitigation. Moreover, their dense vegetation acts as a protective barrier against wave energy and storm surges [31], mitigating coastal erosion and inland flooding, and providing resilience against climate change-induced sea level rise and extreme weather events.

The inclusion of "Fish", "Erosion", and "Ecosystem services" indicates the vital role of salt marshes in supporting fisheries, coastal protection, and other valuable ecosystem services. Keywords such as "Water", "Freshwater", and "Dieback" highlight concerns about changes in water fluxes and the impacts of freshwater inputs. “Model” suggests a growing adoption of modelling approaches in salt marsh studies, encompassing various fields such as marsh dating and sediment studies, as evidenced by references to “Benthic foraminifera” and “Deposition”. Additionally, it reflects investigations into the biochemical characteristics of the environment and greenhouse gas dynamics, as indicated by references to “Methane”.

Overall, the evolution of themes suggested by the keywords in salt marsh restoration research from 1978 to 2022 reveals a progression from elemental studies on salinity, sediment dynamics, and bioremediation to a more holistic understanding of ecosystem dynamics, biodiversity, human impacts, and ecosystem services.

In *SciMAT*, research themes are designated by density, the internal strength of the network, centrality, and the interaction among the networks. Figure 4A–C show the strategic maps for each period, where each sphere represents one theme, and its size indicates the number of articles. To better interpretate these diagrams, a quadrant-by-quadrant analysis [22] was conducted, considering (i) Quadrant Q1: Motor themes, important for the development of the research field; (ii) Quadrant Q2: Themes well developed; (iii) Quadrant Q3: Emergent or declining themes; (iv) Quadrant Q4: Basic and transversal themes, nevertheless not well developed. Results are detailed below by quadrant.

(i) Motor themes, important for the development of the research field (Q1): During the first period (Figure 4A), the keywords in this quadrant included some of the base knowledge for the development of salt marsh restoration research, such as “Salinity”, “*Fundulus heteroclitus*”, “Tolerance”, and “Cordgrass”. Salinity is a crucial factor influencing salt marsh flora and fauna. Understanding the tolerance of species like *F. heteroclitus* (mummichog) to salinity levels helps comprehend fauna responses to a changing environment. Cordgrass, another keyword in this quadrant, is one the most frequently found species in the salt marsh ecosystem. In the second period (Figure 4B), the keywords in Q1 included “Nekton”, “Halophytes”, “Nitrogen”, “*Spartina alterniflora*”, “Diversity”, and “Heavy metals”. The ecological health of salt marshes can be assessed by measuring nekton. Halophytes, such as *Spartina alterniflora* (smooth cordgrass), being salt-tolerant plants, are vital components of salt marsh ecosystems. The keywords “Nitrogen” and “Heavy metals” emphasize the significance of nutrients and pollution in salt marshes, respectively. The third period (Figure 4C) included “Salinity”, “Phytoremediation”, “Blue carbon”, “Fish”, “Facilitation”, and “Degradation”. Salinity, once again, plays a key role in determining the distribution of species in the ecosystem. Phytoremediation indicates the growing interest in using salt marsh vegetation for environmental restoration and pollution mitigation. Blue carbon highlights the importance of these ecosystems in carbon sequestration. The role of fish in ecosystem functioning, species interactions, and the impacts of degradation on salt marsh health are also highlighted here.

(ii) Themes well developed (Q2): The first period (Figure 4A) included the keyword “Bioremediation”, which highlights the capacity of salt marsh vegetation to remove contaminants and improve water quality. Additionally, “Sediment”, represents a well-established research theme associated with salt marshes, encompassing concepts such as deposition, erosion, accretion, and responses to sea level rise (SLR). The second period’s (Figure 4B) keywords are “Managed realignment”, referring to the intentional alteration of coastal areas to restore or create salt marsh habitats. Also present are “Mummichog *Fundulus heteroclitus*”, and, focusing on the impacts of petroleum pollution and the role of nitrogen-fixing organisms in salt marshes, “Petroleum hydrocarbons”, and “Nitrogen fixation”. The third period’s (Figure 4C) keywords, “Managed realignment,” “Recruitment,” “Dieback,” “Benthic foraminifera,” and “Methane” fall into this quadrant. “Recruitment” stresses the interest in understanding the colonization dynamics of salt marsh species, while “Dieback”, signifies the decline and loss of salt marsh vegetation. “Benthic foraminifera” and “Methane” may illustrate research interest on the microbial communities and methane production in salt marsh sediments.

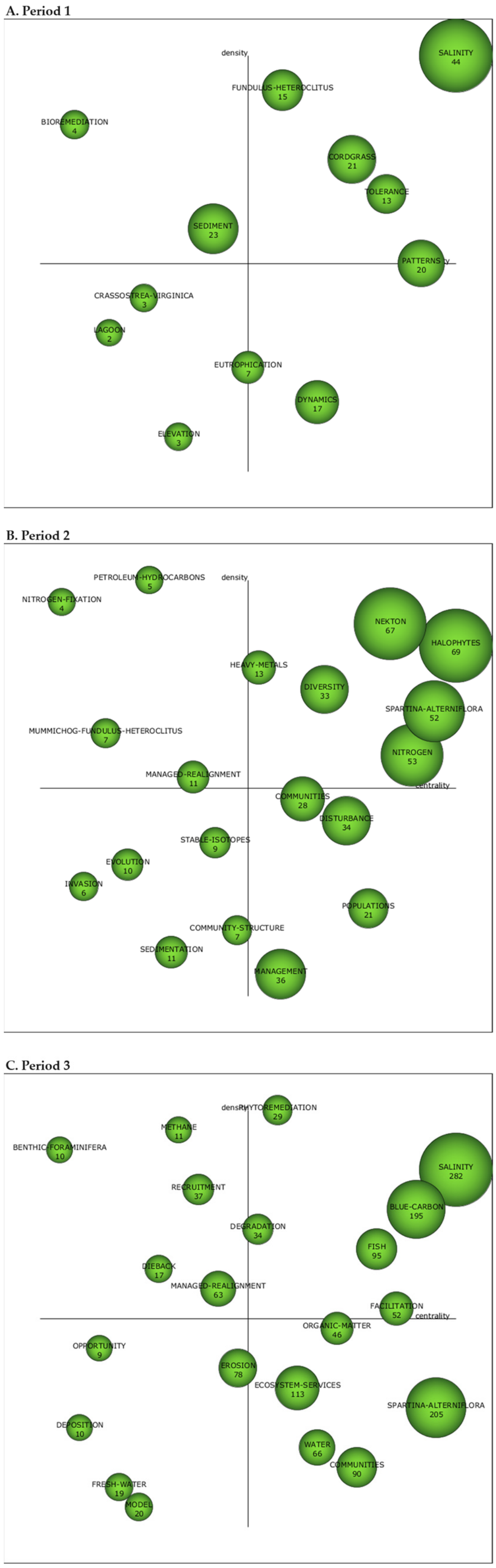


**Figure 4.** Strategic maps for each period. (**A**): period 1 (<2000); (**B**): period 2 (2001–2010); and (**C**): period 3 (2011–2022).

(iii) Emergent or declining themes (Q3): In the first period (Figure 4A), the keywords "*Crassostrea virginica*" (Eastern oyster), "Lagoon," and "Elevation" fall into this quadrant. *C. virginica* suggests an emerging interest in Eastern oyster populations in estuarine ecosystems due to the potential restoration benefits of oyster reefs in salt marsh ecosystems. "Lagoon" and "Elevation", while related to salt marsh studies, may indicate a decline in recent research or a shift to other areas of interest in the field. The second period's (Figure 4B) keywords, "Sedimentation", "Evolution", "Community structure", "Stable isotopes", and "Invasion", fall into this quadrant, representing the ongoing research interest in assessing the response of salt marsh and living communities to sea level rise. In the third period (Figure 4C), the keywords "Fresh water", "Model", "Erosion", "Opportunity", and "Deposition" fall into this quadrant. "Freshwater" represents an emerging topic, indicating a growing interest in understanding the impacts of freshwater inputs on salt marshes. Models and other tools used to simulate and predict the behavior and response of salt marsh ecosystems are another emergent topic essential to an effective management strategy. Due to their centrality, "erosion" may represent a topic that has likely been extensively studied in the past but may be experiencing a decline in research interest.

(iv) Basic and transversal themes, nevertheless not well developed (Q4): In the first period (Figure 4A), the keyword "Dynamics" is classified in this quadrant, possibly related to some aspects of sediment or salt marsh communities that need further research. The second period's (Figure 4B) keywords "Disturbance", "Communities", "Management", and "Populations" are classified in this quadrant. "Disturbance" in the ecosystem may refer to a wide a range of topics, such as extreme events, pollution, or habitat alteration, and understanding their impacts on salt marshes is essential for effective restoration and management. "Communities", "management", and "populations" represent broad themes with the potential for further research. In the third period (Figure 4C), the keywords "*Spartina alterniflora*", "Ecosystem services", "Communities", "Water", and "Organic matter" are classified in this quadrant. *Spartina alterniflora* (smooth cordgrass) is a dominant plant species in many salt marshes, and further research may be needed to implement management actions. "Ecosystem services", "Communities", "Water", and "Organic matter" are themes that require further investigation as they are key elements related to salt marshes.

#### 3.1.4. Bibliometric Analysis after PRISMA Screening

A total of 62 research papers were analyzed in detail after the PRISMA screening to better describe the types of methodology, success rate, and indicators and metrics used in salt marsh restoration projects. The distribution of publications across different countries was plotted using the data extracted from the category "Countries/Regions" from the "Analyze Results" tool in Web of Science (Figure 5).

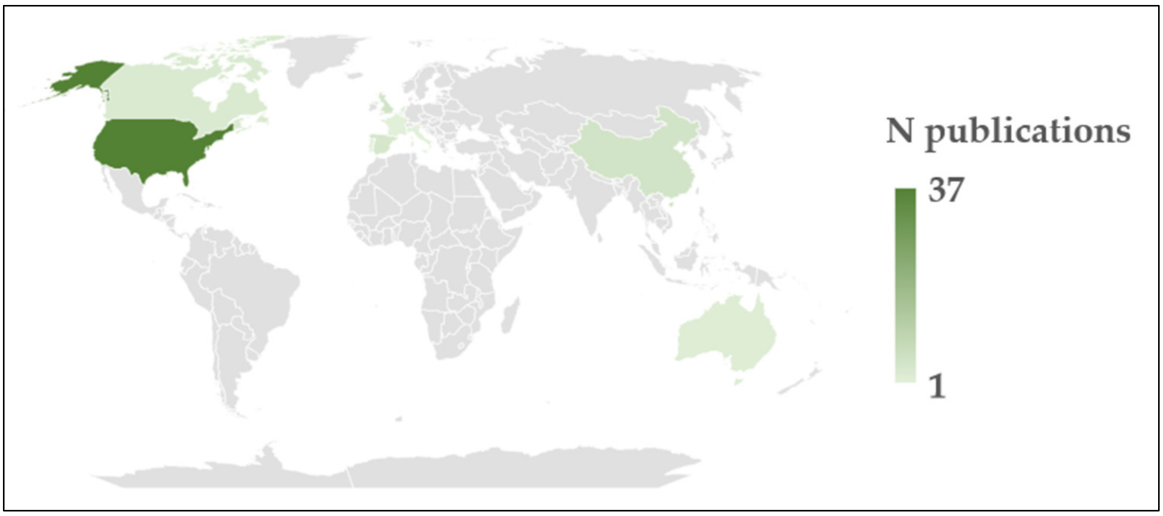


**Figure 5.** Distribution of publications through the different countries after *PRISMA* screening.

The United States (US) stands out with the highest number of papers (37), indicating substantial activity in salt marsh restoration research and a high level of involvement in coastal habitat preservation and conservation. China follows closely with five papers, suggesting a significant commitment to salt marsh restoration efforts. Canada and Spain also stand out in allocating resources to study and implement restoration projects, as both are well represented with three and four research papers, respectively. Australia, the Netherlands, and the UK each have two papers, showcasing a moderate level of involvement in salt marsh restoration research. Belgium, France, Italy, and Portugal have a lower number of papers, with one each, which does not necessarily imply a lack of interest in the topic since various factors can contribute to the reduced number of outputs.

The data in Figure 6 indicate a range of approaches in salt marsh restoration, with assisted interventions being the most prevalent, followed by natural and reconstructed interventions.

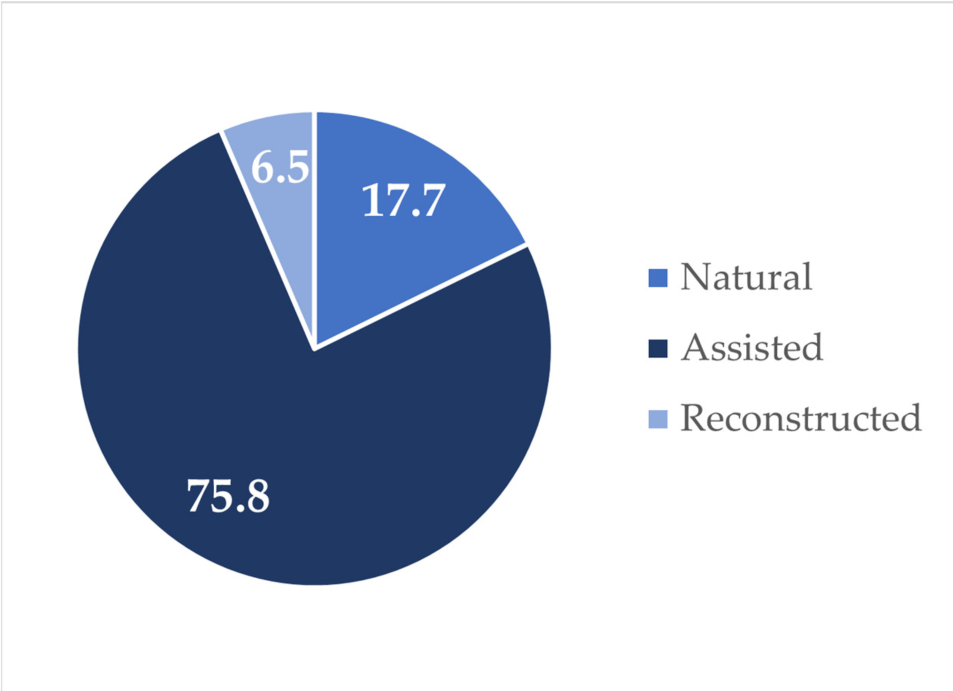


**Figure 6.** Approaches in salt marsh restoration: percentage (%) of natural, assisted, and reconstructed interventions.

Assisted interventions represent most of the work carried out, comprising 75.8% of the projects, with a total of 47 occurrences. Natural interventions account for 17.7% of the projects, with a total of 11 occurrences. Reconstructed interventions make up a smaller proportion, at 6.5% of the projects, with a total of four occurrences (Figure 6). The dominance of assisted interventions suggests a significant emphasis on active human intervention in salt marsh restoration efforts, involving various methods such as planting vegetation, restoring hydrological conditions, or implementing management strategies, with human assistance often considered necessary to achieve the effectiveness of restoration projects. The presence of natural interventions is noteworthy, representing nearly a quarter of the projects. This approach restores tidal and sedimentation patterns, facilitating the colonization of vegetation, and emphasizing the recognition of the resilience and recover capacity of salt marsh ecosystems. The low percentage of reconstructed interventions (Figure 6) may be a consequence of the need for resource-intensive work and engineering efforts.

The choice of intervention type may depend on various factors, including site characteristics, restoration goals, and available resources. It is important to evaluate the effectiveness and long-term sustainability of different intervention approaches to ensure the successful restoration and conservation of salt marsh ecosystems.

"Vegetation" is the most frequently monitored indicator, accounting for 42.3% of the projects, with a total of 47 occurrences (Figure 7). This shows the importance of vegetation in salt marsh ecosystems and its role in the success of restoration projects. Monitoring vegetation helps assess the establishment, growth, and diversity of plant species in the restored salt marsh areas.

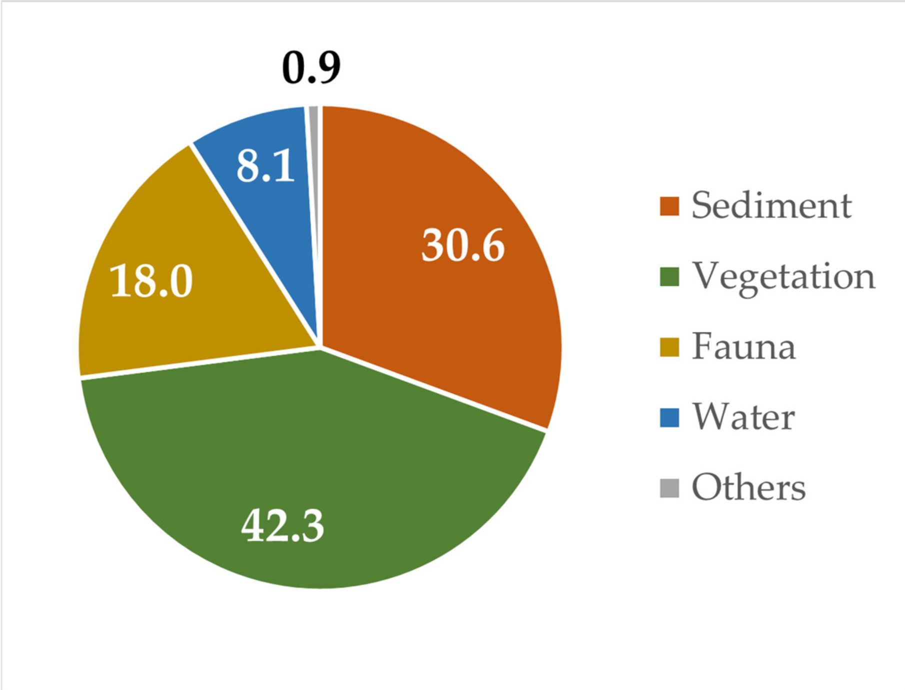


**Figure 7.** Indicators used in salt marsh restoration: percentage (%) of sediment, vegetation, fauna, water, and others.

"Sediment" is another important indicator, representing 30.6% of the projects with 34 occurrences. Monitoring sediment aids in evaluating the effectiveness of restoration activities related to sediment deposition and erosion. "Fauna" monitoring accounts for 18.0% of the projects, with 20 occurrences (Figure 7). This indicator focuses on assessing the presence, abundance, and diversity of animal species in the restored salt marsh habitats, providing insights into the success of restoration efforts in creating suitable habitats capable of supporting life. "Water" is another essential indicator monitored in 8.1% of the projects, with nine occurrences. The "Others" category represents 0.9% of the projects, with one occurrence (Figure 7), and includes additional indicators and parameters less commonly monitored that do not fall into the previous categories, being irrelevant for the scope of this review.

A further investigation was conducted to explore the distribution of indicators used in the three categories of restoration identified by Atkinson and Bonse (2020) [24]. The three charts in Figure 8 present the indicators used in natural, assisted, and reconstructive salt marsh restoration projects. "Vegetation" monitoring appears as a key indicator across all three types, being the most frequently monitored indicator in natural salt marsh restoration projects, representing 37.5% of the projects, 40.0% in assisted restoration projects, and 50.0% in reconstructive restoration projects. "Sediment" monitoring is the second most used indicator in the three categories of restoration, accounting for 37.5% in reconstructive restoration, 35.3% in assisted restoration, and 20.8% in natural interventions, sharing the second place with "water" monitoring. "Fauna" monitoring is employed in all three types of restoration projects, although with varying occurrences. It represents 16.7% of natural projects, 17.6% of assisted interventions, and 12.5% of reconstructive interventions. "Water" monitoring, although less frequent, plays a role in both natural and assisted interventions, with 20.8% of natural projects and 7.1% of assisted interventions. The

"Others" category represents a small portion of the projects, comprising 4.2% of natural interventions, including additional monitoring parameters.

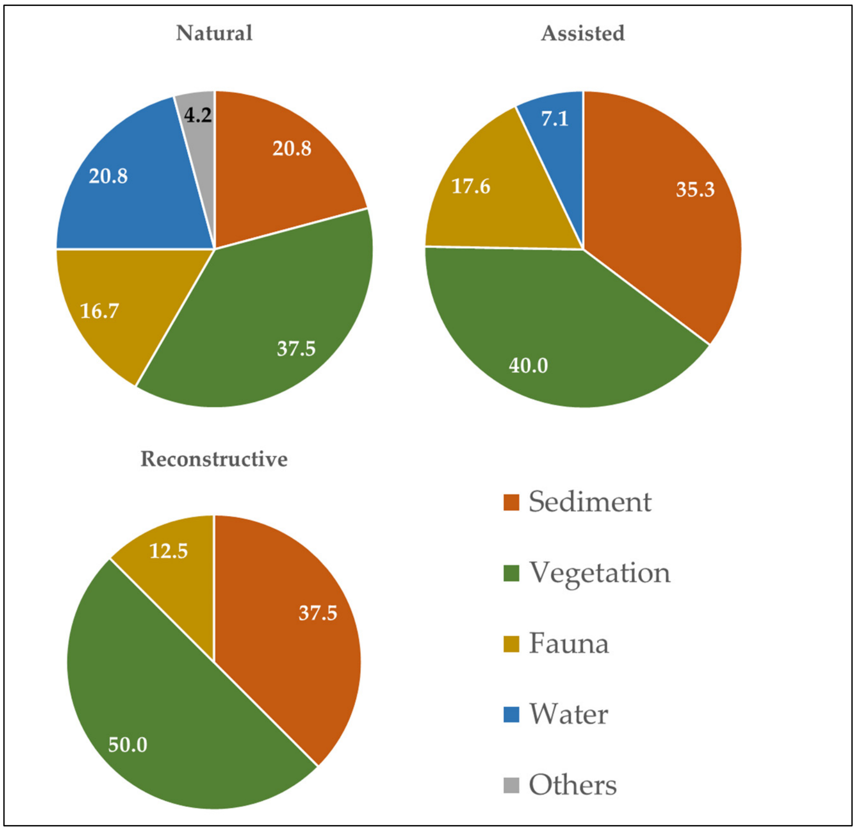


**Figure 8.** Indicators used in natural, assisted, and reconstructive salt marsh restoration: percentage (%) of sediment, vegetation, fauna, water, and others.

*Natural interventions*, such as the removal of tidal restrictions, invasive species, and the reconnection of salt ponds or hay farms, have demonstrated success in promoting the recovery of salt marsh habitats (Table 3). These interventions focus on removing barriers and disturbances to restore the original ecosystem condition. The high success rate of these interventions suggests that allowing for natural processes to return can effectively support the restoration and growth of salt marsh vegetation and promote suitable habitat conditions. The restoration of tidal dynamics, including tidal restriction removal, conversion of breached salt ponds/salt hay farms, tidal flow restoration, and reconnection through breaching/levee removal projects, has all demonstrated high success rates in achieving the desired outcomes (Table 3). Regarding environmental cleanup techniques, projects to remove anthropogenic debris deposited by storms have been successful, indicating the capability to clean up and remove debris caused by storms. This highlights the importance of environmental cleanup efforts in preserving ecosystem health. Additionally, infrastructure management techniques, including both the neglected artificial drainage system and dam removal projects, have achieved high success rates, indicating that proper management and maintenance of infrastructure play critical roles in maintaining a healthy ecosystem. Ecological management techniques, such as both grazing reduction and managed realignment projects, have been successful in preserving the ecosystem (Table 3).

**Table 3.** Different types of restoration techniques and respective success evaluation.

| Typology | Group | | *N* | Success | Failure | Limited | Inconclusive |
|---|---|---|---|---|---|---|---|
| Natural | Restoration of tidal dynamics | Tidal restriction removal | 1 | 1 | | | |
| | | Breached salt ponds/salt hay farm conversion | 2 | 2 | | | |
| | | Tidal flow restoration | 2 | 2 | | | |
| | | Reconnection by breaching/levee removal | 2 | 2 | | | |
| | Environmental cleanup | Storm-deposited anthropogenic debris removal | 1 | 1 | | | |
| | Infrastructure management | Artificial drainage system neglected | 1 | 1 | | | |
| | | Dam removal | 1 | 1 | | | |
| | Ecological management | Grazing reduction | 1 | 1 | | | |
| | | Managed realignment | 1 | 1 | | | |
| Assisted | Tidal exchange and hydrological management | Regulated tidal exchange (RTE) system | 1 | | | 1 | |
| | | Increased tidal flushing | 1 | | | 1 | |
| | | Low tide increased flooding | 1 | 1 | | | |
| | | Automated hydraulic control gates | 1 | 1 | | | |
| | Ecological restoration and management | Invasive species removal | 4 | 4 | | | |
| | | Vegetation transplants | 13 | 9 | 1 | 2 | |
| | | Oyster reefs built | 1 | 1 | | | |
| | | Living shoreline design that couples breakwalls and oyster restoration structures | 1 | 1 | | | |
| | Sediment Management | Sediment fence construction | 1 | | | | 1 |
| | | Sediment addition | 11 | 8 | 1 | 1 | |
| | | Dredged material removal | 1 | 1 | | | |
| | | Thin-layer sediment placement (TLP) | 3 | 1 | | 2 | |
| | | Sediment alginate amendment in plant transplants | 1 | | | 1 | |
| | Geomorphological and habitat enhancement | Tidal creeks excavation | 2 | 1 | | 1 | |
| | | Large-scale biodegradable artificial reefs | 1 | 1 | | | |
| | | Geomorphological reconstruction of surfaces | 1 | 1 | | | |
| | | Marsh terracing | 1 | 1 | | | |
| | | Runnel installations | 1 | 1 | | | |
| | | Experimental gabion stone and clay-filled terraces | 1 | 1 | | | |
| | | Microtopographic structures construction | 1 | 1 | | | |
| | Control and management of vegetation | Herbicide use | 1 | 1 | | | |
| Reconstructive | Tidal marsh construction and restoration | Constructed tidal marshes | 1 | 1 | | | |
| | | New salt marsh created after the removal of buildings and slurry material | 1 | 1 | | | |
| | Soil engineering and revegetation | Soil engineering procedures and revegetation | 1 | | | 1 | |
| | | Native vegetation planted | 1 | 1 | | | |

*Assisted intervention* techniques (Table 3) such as sediment addition, vegetation transplants, and tidal creek excavation, have shown promising results in facilitating the establishment of vegetation, improving sedimentation, and creating suitable habitats for different species. Despite some limited outcomes, these techniques indicate that certain factors may limit their effectiveness. Tidal exchange and hydrological management techniques: The regulated tidal exchange (RTE) system and increased tidal flushing techniques did not yield the expected outcomes and present some limitations. Masselink et al. (2017) [32] conclude that self-regulating tidal gates can be a valuable technique for intertidal habitat creation where there is significant flood risk, but realistic expectations are crucial for achieving a perennial salt marsh community. Additionally, Buchsbaum et al. (2006) [33] found, through vegetation and nekton analysis, that four years after the restoration took place, the salt marsh was still adjusting to hydrologic changes. On the other hand, the low tide increased flooding and automated hydraulic control gate techniques have shown success, indicating positive outcomes in managing tidal exchange and hydrological processes. Ecological restoration and management techniques (Table 3): Invasive species removal has been successful in all four projects, emphasizing the importance of controlling and eliminating non-native species. Vegetation transplants have shown mixed outcomes, with nine successes, one failure due to the inadequate protection against wave energy [34], and two limited results, with significant functional differences between young artificial marshes and older natural marshes [35]. The vegetation restored does not completely match the functionality of the natural area, particularly lacking in material accretion [36]. The construction of oyster reefs and the design of living shorelines coupling break walls and oyster restoration structures have both been successful in promoting ecological restoration. Sediment management techniques (Table 3): Sediment fence construction has inconclusive results. After one and three years, along the edge of the salt marsh, vegetation coverage was higher compared with the control area, but the differences were not significant [37]. Sediment addition projects have shown most of the success, although there is one limited and one failed outcome. After the sediment application, the vegetation cover and invertebrate abundance declined, with the site not recovering after one year [38], indicating the need for further investigation into the factors affecting sediment management. Too much sediment can result in reduced ecological function [39]. Dredged material removal has been successful in the single reported project. Thin-layer sediment placement (TLP) has shown mixed results, with one success and two limited outcomes. The addition of 10 cm of sand to pots planted with *Spartina alterniflora* and *Spartina patens* resulted in fewer stems than controls for *S. patens* after 2 months [40]. Moreover, Ford et al. (1999) [41] found that thin-layer deposition of dredged material was effective at restoring and maintaining marsh elevation after 1.5 years, but the success of the restoration was dependent on open water sediment deposits being completely stabilized after plant colonization. The use of sediment alginate amendment in plant transplants has limited success, suggesting the existence of a threshold level of sediment organic matter above which alginate addition does not favor transplanted *S. alterniflora* [42].

Geomorphological and habitat enhancement techniques (Table 3): Tidal creek excavation has one success and one limited outcome, indicating a lack of effectiveness. Large-scale biodegradable artificial reefs, geomorphological reconstruction of surfaces, marsh terracing, runnel installations, experimental gabion stone and clay-filled terraces, and microtopographic structures construction have all been successful, showcasing their effectiveness in promote habitat conservation and restoration. Regarding the control and management of vegetation group of techniques, the use of herbicides has been successful in controlling vegetation. However, it is important to consider the potential impacts from herbicide use on the ecosystem.

*Reconstructive interventions* (Table 3), including constructed tidal marshes and native vegetation planting, offer opportunities to create new salt marsh areas or restore degraded habitats. The success of these interventions relies on careful engineering and revegetation efforts to promote the establishment of a healthy ecosystem. Despite the reduced number of studies in the selected research papers for this type of intervention, the positive outcomes observed highlight their potential for restoring salt marsh ecosystems. Regarding the tidal marsh construction and restoration group of techniques, the construction of tidal marshes as well as the creation of a new salt marsh after the removal of buildings and slurry material, was successful, indicating that this technique has been effective in creating new salt marsh habitats. Additionally, in soil engineering revegetation techniques, soil engineering procedures have limited outcomes, with the retained sediment falling short of expectations and difficulties in the colonization of vegetation in brackish and tidal water [43]. However, native vegetation planting has a success rate of 100%, indicating that this approach has been effective in establishing and promoting the growth of plant species crucial for ecosystem functions and biodiversity in these ecosystems.

Overall, combining natural, assisted, and reconstructive interventions, tailored to the specific needs of each site, may increase the chances of successful restoration outcomes. By identifying the benefits and limitations of different techniques, researchers and stakeholders can make informed decisions and implement effective restoration strategies.

## 4. Conclusions

Salt marsh restoration projects have been increasing with promising results in improving ecosystem recovery, protect biodiversity, and maintaining and promoting relevant ecosystem services. The geographic coverage of the works carried out initially began in a more restricted area, mainly in the US, but gradually spread to other parts of the globe, gaining notoriety in regions such as China and some parts of Europe. The evolution of the topics covered suggests a growing interest in ecosystem dynamics, biodiversity, anthropogenic impacts, and ecosystem services.

Assisted interventions correspond to the most used methodologies, despite the growing interest in more natural approaches. The success of restoration efforts is influenced by numerous factors, such as the techniques used, the site location, the correct management of the sediment and water, as well as a good handling of invasive species, with vegetation-related indicators being the most used to evaluate the success of restoration. However, different studies use different indicators and evaluate different metrics, making comparisons between studies difficult due to the lack of a standard procedure. The compilation of methodologies, indicators, and metrics used in this review will certainly help researchers in future projects to select good practices from past investigations, avoid repeating the same mistakes, and promote the implementation of a standard system for evaluating restoration effectiveness, making it easier to compare among others. Long-term monitoring studies are needed to better evaluate the success and sustainability of restoration projects, as well as test the resilience of the restored areas to the interventions performed.

Assessing the economic value of ecosystem services provided by salt marshes and their socioeconomic benefits, such as improved water quality, recreational activities, and tourism, can help decision-makers prioritize their restoration. Additionally, it is important for researchers to collaborate with local communities, which have a better understanding of the areas to be restored and the changes that have occurred over time. The transfer of knowledge from academics to stakeholders and decision-makers is a key factor for the success of projects, as it relies on sharing the best practices and lessons learned, leading to the application of the most innovative techniques at our disposal.

From a sustainability viewpoint, adopting a multidisciplinary approach and integrating restoration efforts into policy and management frameworks will certainly help preserve salt marshes and the services they provide for generations to come.

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