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# CoAStal and marine waters integrated monitoring systems for ecosystems proteCtion AnD managemEnt

# CASCADE

## Project ID: 10255941

**Priority Axis: Environment and cultural heritage**

**Specific objective: Improve the environmental quality conditions of the sea and coastal area by use of sustainable and innovative technologies and approaches**

# D2.2.9

## Submission of at least 2 open-access peer-reviewed and/or conference papers.

## Part 4

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REVIEW ARTICLE

# Salt marsh restoration: an overview of techniques and success indicators

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## Abstract

Coastal wetlands including salt marshes are among the most productive ecosystems on Earth. They are known for improving the quality of coastal water and provisioning coastal fisheries. However, this ecosystem is under potential threat due to urban coastal land reclamation, limited sediment supply, increased nutrient/eutrophication, and sea level rise. Therefore, restoration efforts to protect the degraded salt marsh habitat are considerably increasing worldwide. In this paper, we present an overview of salt marsh restoration techniques and success indicators. Published scientific literature in English language was collected by searching the most relevant keywords from popular search engines, namely, Google Scholar, Scopus, and Mendeley to get the information about salt marsh restoration techniques and success indicators. This study comprehensively reviewed data from 78 peer-reviewed papers. Results indicated that much of the salt marsh was restored through assisted abiotic strategies (e.g., recovery of tidal exchange, managed realignment, and sediment level amendment). A total of 214 indicators were found, spanning over six major ecological attributes such as structural diversity, ecosystem functions, physical conditions, species composition, external exchange, and absence of threat. Author keywords analysis revealed several hotspots for recent research (e.g., 16 s rRNA, fungi, microbial communities, carbon accumulation, and blue carbon). This paper proposes a model for restoring degraded salt marsh, as well as tracking their success. The information presented here will assist the marine ecosystem restoration practitioners in getting a comprehensive understanding of salt marsh restoration success evaluation.

**Keywords** Restoration ecology · Coastal wetlands · Coastal biological resources · Coastal management · Ecosystem services

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## Introduction

Coastal wetlands such as salt marshes are reported to be among the abundant, accessible, and productive ecosystems on Earth (Gedan et al. 2009; Deegan et al. 2012). Salt marshes are particularly efficient in the sequestration capacity of atmospheric $CO_2$ because of their high rates of primary production (root, shoot, and leaf production) (Chmura et al. 2003; Burden et al 2013; Santini et al. 2019; Poppe and Rybczyk 2021) and relatively low rates of microbial decomposition due to prevailing anaerobic conditions in the surface sediment. Besides, ecosystem functions of salt marsh systems include fishery support as leaves, roots, and stems provide vital shelter and nourishment (Kimball and Able 2007; Billah et al. 2016; Taylor et al. 2018). In addition, several investigations reported their water purifications and nutrient retention capacities (Alvarez-Rogel et al. 2006), coastal protections through sediment stabilization (King and Lester et al. 1995; Koch et al. 2009; Taylor et al. 2019), and biodiversity provision (Costanza et al. 2008).

In spite of great ecological and economic importance, this valuable ecosystem is under threat due to the expansion of urban areas, land reclamation, and inputs of N from the runoff of upland agricultural sites due to fertilizer uses, freshwater influences, enriched groundwater, limited sediment supply, and sea level rise (Gedan et al. 2009; Deegan et al. 2012; Fagherazzi et al. 2019; Liu et al. 2021). Thus, a considerable amount of salt marsh has already been reduced in many parts of the world. In response, substantial restoration efforts are made to rehabilitate salt marsh in many areas of the world (Curado et al. 2014; Chen et al. 2017; Taylor et al. 2019; Xiao et al. 2020).

Ecosystem restoration is becoming an important emerging field of studies within the field of environmental sciences, to mitigate the loss of biodiversity on this planet (Cadier et al. 2020; Airoldi et al. 2021). On March 1, 2019, the United Nations (UN) General Assembly (New York) declared 2021–2030 the "UN Decade on Ecosystem Restoration," to help meet the Sustainable Development Goals (SDGs). This call urges us to reverse the degradation of the planet's ecosystem to achieve sustainable development goals specifically those related to climate change mitigation, poverty eradication, ensuring food security, and protecting biodiversity. In this decade, the world is working to achieve a common goal of preventing, halting, and reversing the degradation of ecosystems worldwide (Cadier et al. 2020). In general, recovery of a degraded site in the coastal system is often challenging because of the dynamic nature of the system and is considered difficult to return to its historical pre-disturbed conditions. Importantly, recent restoration strategies are considering social issues together with the ecological considerations and focused on the multiple goals (e.g., human well-being) ensuring food security and sustainability together with environmental or ecological goals (Crooks et al. 2002; Blott and Pye 2004; French et al. 2005).

To assess the restoration success, it is needed to set the indicator. Selection of restoration indicator is critical as indicators can directly impact on project evaluations. Ideally, the success indicators should be comprehensive, broadly applicable, and not overly labor-intensive. To understand the recovery level of a restored salt marsh compared with natural counterpart, many earlier studies concentrated on the vegetation structures, hydrological conditions, and surface elevations (see review Wolters et al. 2005) but currently, there is an increasing tendency to use functional indicators (e.g., carbon sinks, biomass estimations) to assess the restoration success (Nordström et al. 2014; Poppe and Rybczyk 2021). Hobbs and Norton (1996) suggested using a combination of compositional, structural, and functional attributes to evaluate restoration success.

There are only a few previous review reports describing the evaluation of the success indicators used for ecological restoration. For example, Ruiz-Jaen and Aide (2005) reported the criterion of the restoration success reviewed from the literature published in the "*Restoration Ecology*" from Vols 1–11. Besides, Zhao et al. (2016) provided a general overview of wetland restoration goals and strategies. The authors provided a description of the evaluation of restoration success considering a case study of a degraded estuarine wetland. Moreover, Cadier et al. (2020) have reviewed the indicators used to assess the success of wetland restoration; based on the reviewed indicators, they proposed a *recovery wheel framework* to evaluate restoration success and emphasize the evaluation of functional indicators (e.g., sediment organic matter, carbon sinks, macrobenthic biomass).

However, up until now, there is no comprehensive review that specifically focuses on salt marsh restoration techniques/strategies and success evaluation indicators. Thus, a systematic review of the current information on the restoration techniques and indicators used in the success of the salt marsh restoration is thus of obvious interest. Therefore, the objectives of the present study are to (i) illustrate the current salt marsh restoration techniques and strategies available, (ii) provide indicators to assess the salt marsh restoration success, and iii) describe recent research trends in salt marsh restoration success evaluation schemes.

## Methods

### Search engines

For this systematic review, we searched literature from February 2021 to April 2021, using the major search engines to get available literature in the subject area. The search engines used in this study were as follows: Google Scholar (www.scholar.google.com), Scopus (www.scopus.com), and Mendeley (data.mendeley.com). We did not search Google.com as it came up with many irrelevant pieces of literature. To understand the completeness of the literature search, further search attempt was also taken from "Research Gate," which did not bring any new literature.

### Search terms

For this review, the following English language search terms were used:

**Coastal habitat terms**: coast* OR estuary* OR marsh* OR saltmarsh* OR salt marsh* OR coastal habitat* OR tidal marsh* OR wetland*
**Restoration terms**: restor* OR restoration* OR rehab* OR realignment*
**Monitoring terms**: monitor* OR assess* OR metrics* OR matrices*

These search terms included in the above three categories (coastal habitat, restoration, and monitoring) were combined using the Boolean operator "AND."

### Article screening and article eligibility criterion

For each search in the search engine, literature was screened based on the three criteria: (i) title, (ii) abstract, and (iii) complete manuscript. At first, the title of the literature was studied; if found relevant, then the abstract of the literature was carefully read. Finally, the full text of the literature was studied if the abstract was found relevant. For this systematic review, any literature was considered eligible if it falls within the scope of the following selection criterion:

I) Studies that carried out to assess the restoration success were included for the review.
II) Studies that compared the restored salt marsh with reference, natural sites

A study was excluded from the selection if it appeared to have any of the following characteristics:

i) The studies carried out on a laboratory/ mesocosm base were excluded.
ii) Secondary sources such as reviews were not included in this review.
iii) Studies that did not include any reference site to compare the measured indicators were excluded.
iv) Feasibility studies of salt marsh restoration were not included in this review.

### Data extraction: bibliographic details and restoration techniques

The methods and results section of each eligible paper were carefully read to extract the information. Data were extracted for literature bibliographic details (year of publication, affiliation country of the first author, journal name, and full reference) and restoration details (number of restored sites and reference sites, restoration location, geographical coordinates, species targeted, time/age of restoration, indicators studied).

Information on the salt marsh restoration techniques was extracted from the studies reviewed and nested within the following three major categories proposed by Atkinson and Bonser (2020):

i) Assisted restoration: a combination of "biotic" (e.g., eradication of invasive species, and revegetation mainly through transplantation and seedling) and "abiotic" (e.g., reconstruction of the habitat, control of flood disturbance to create "windows of opportunity" for seed germination).
ii) Natural restoration: to halt and prevent the degradation for example withdrawal of the contamination, water flow restriction, stopping the logging activities, cessation of inappropriate grazing.
iii) Reconstructive restoration: involves both natural restoration and assisted restoration.

### Data extraction: success indicators

We then extracted the indicators used in both restored and reference salt marsh sites for a single paper. Indicators (e.g., fish diversity) were then categorized in sub-attributes (e.g., fauna diversity); sub-attributes were then nested in major ecological attributes (e.g., species composition). For this study, a total of six major ecological attributes were used, namely structural diversity, ecosystem function, species composition, physical condition, absence of threat, and external exchanges following McDonald et al. (2016) (Table 1). These major ecological attributes were further categorized into several sub-attributes. For example, species composition (a major ecological attribute) was divided into six sub-attributes, i.e., nekton composition, fish composition, other macrofauna composition, vegetation composition, microbiota composition, and bird composition.

## Results and discussion

### Number, country, and journal distribution of publications

A total of 78 papers were found eligible based on the eligibility criterion. Studies were mainly concentrated in the USA, with 67% (*n* = 52) of the studies had first author affiliated from the institute at USA, followed by UK (10%, *n* = 8), China (8%, *n* = 6), Spain (6%, *n* = 5), Canada (5%, *n* = 4), Australia (3%, *n* = 2) and Belgium (1%, *n* = 1). The list of 78 papers considered for this study is provided in the supplementary file. These literatures were surveyed restored sites from eight countries, namely USA (*n* = 51), UK (*n* = 8), China (*n* = 6), Spain (*n* = 5), Canada (*n* = 4), Australia (*n* = 2), Italy (*n* = 1), and Belgium (*n* = 1) (Fig. 1); this geographic distribution of study sites does not

**Table 1** List of key ecosystem attributes and sub-attributes category found in the salt marsh restoration project ( modified from McDonald et al. 2016)

| Attribute/description of the attribute | Sub-attribute |
|---|---|
| Absence of threat<br>Halting or cessation of the potential threats (e.g., overgrazing, and contaminations; eradication and control of the invasive species) | • Algal structure<br>• Invasive species structure |
| Physical condition<br>Characteristics of the physical and/or chemical condition of the system | • Surface water physicochemical variables<br>• Pore water and sediment variables<br>• Atmospheric variables |
| Species composition<br>Survey of the existing biotic diversity | • Vegetation composition<br>• Bird composition<br>• Fish composition<br>• Nekton composition<br>• Other macrofauna composition<br>• Microbiota composition |
| Structural diversity<br>Structural diversity is the relationship between species diversity and abundance/growth (e.g., gastropod shell length, fish density) | • Vegetation structure<br>• Bird structure<br>• Fish structure<br>• Nekton structure<br>• Other macrofauna structure<br>• Microbiota structure |
| Ecosystem functions<br>Interactions between biotic and abiotic elements of the salt marsh areas (population dynamics of the marsh fish and/or biomass of the vegetation); | • Primary productivity<br>• Secondary productivity<br>• Food web<br>• Carbon dynamics<br>• Sediment dynamics<br>• Nutrient dynamics |
| External exchange<br>Linkage and connectivity of the salt marsh areas with surrounding systems (e.g., hydrology, gene flows) | • Hydrological connections |

necessarily mean that salt marsh beds are more degraded in those countries but these countries have environmental conservation laws that are generally enforced and sufficient financial capacity to conduct restoration projects. For example, laws and acts related to salt marsh restoration in the USA is Sect. 404 of the Clean Water Act and in Canada, it is "The Environmental Act 1994–95" for coastal and wetland areas. Out of 78 studies, only one study included country of restoration sites (Italy) different than country of first author affiliation (USA; Moseman-Valtierra et al. (2016)).

These studies were reported in different journals ($n=32$ journals), with high contributions from three journals such as "*Restoration Ecology*," "*Estuaries and Coast*," and "*Estuaries*" (Fig. 2a). The earliest study was published in the year 1990s; the number of papers increased sharply after 2002 and the highest number of papers were published in the year 2019 (7 studies) (Fig. 2b); this trend of publication suggests the rapid increasing scholars' interest to investigate the salt marsh restoration success.

## Author keyword analysis: identifying research hotspots

What changes have the keywords undergone throughout time (1990–2021) and what are the recent keywords in the context of salt marsh restoration? To address this question, keyword evolution analysis was performed. An author keyword analysis is a quantitative technique and is used in bibliometrics as keyword provides ideas about the content of the manuscript. Author keywords are useful to understand the theme of the research article and to get the conceptual idea of the boundary of the article (Radhakrishnan et al. 2017; González et al. 2018). Hence, author keyword co-occurrence analysis is a useful tool in bibliometric research to understand the research hotspots in a specific field of study.

In the present investigation, a total of 232 author keywords were extracted for analysis. Author keywords were cleaned reasonably to make them unified through (i) keeping the same meaning (synonymic keywords) of the word, for example, "salt marsh" and "saltmarsh" were uniformly written as "salt marsh" and (ii) singular or plural for example "restoration" and "restorations" were uniformly written as "restoration." For this study, author keyword analysis was performed using keywords cited at least two times (42 keywords) using VOSviewer software (V 1.6.17) and as shown in Fig. 3. In this graphical visualization, the size of the circle is proportional to the number of occurrences of a particular keyword. The thickness of the link between two keywords is

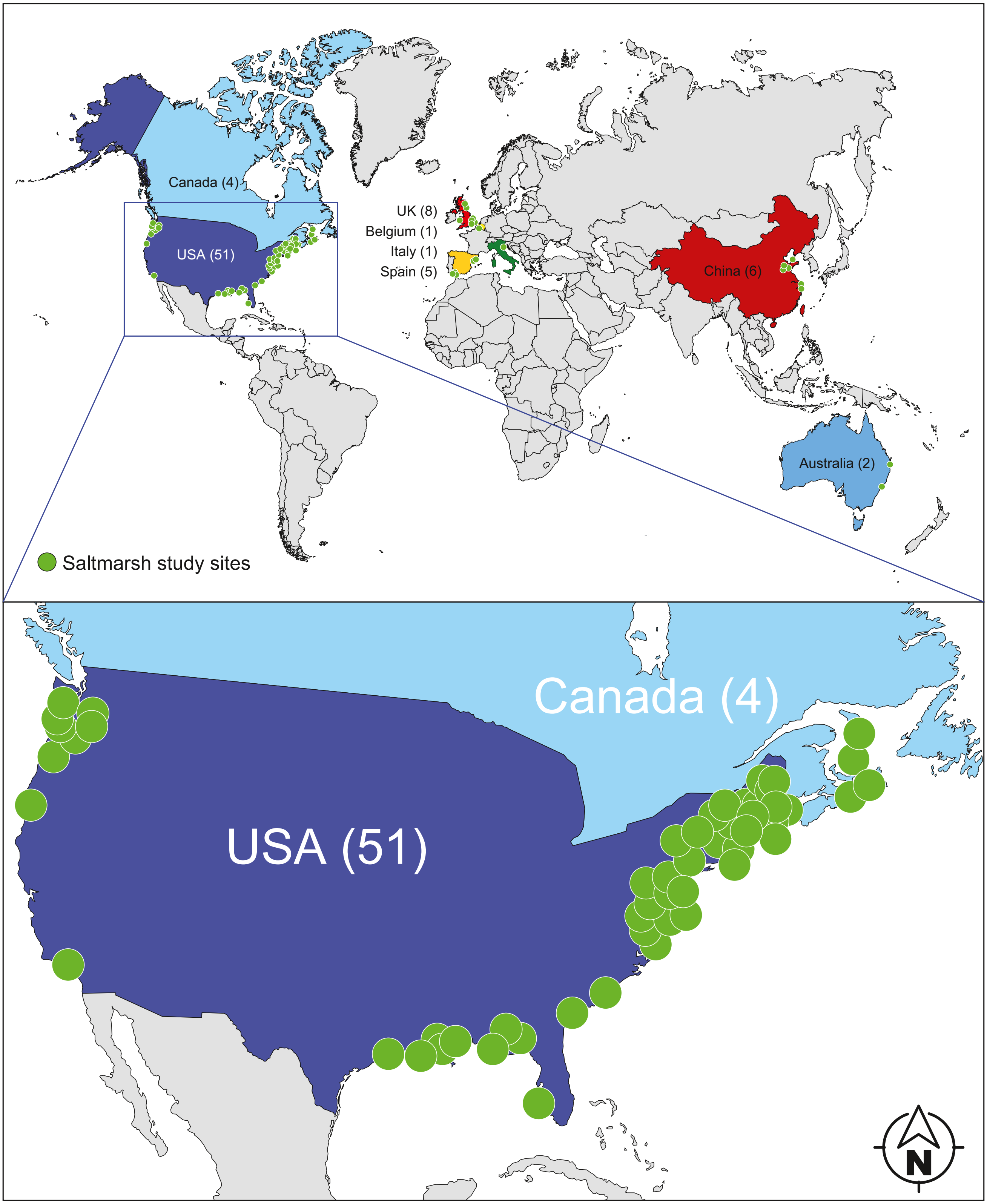

**Fig. 1** Distribution of salt marsh restoration case studies considered in this systematic review

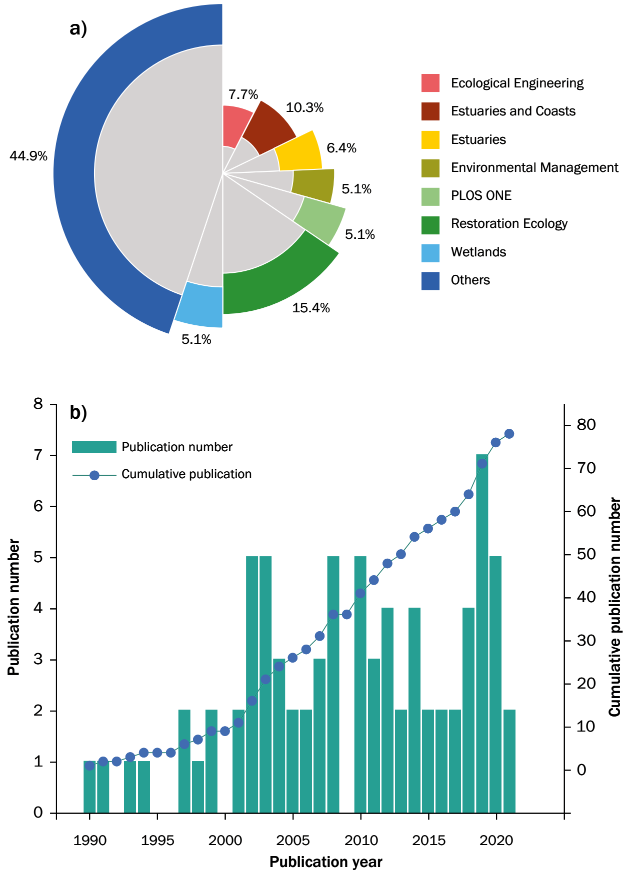

**Fig. 2** Contributions by different journals (**a**) and trends in number of articles published (**b**) on salt marsh restoration throughout the world

proportional to the number of concurrences they have. The circle color of a keyword is corresponding to the average publication year of the published article.

The ten most-cited keywords in our data set are restoration ($n=25$), salt marsh ($n=19$), salt marsh restoration ($n=8$), de-embankment ($n=6$), managed realignment ($n=6$), carbon accumulation ($n=5$), nekton ($n=5$), *Spartina* ($n=5$), succession ($n=5$), biomasss ($n=4$) and *Pharagmites australis* ($n=4$).

Based on Fig. 3, *Melampus*, macroinvertebrate, reference marshes, sampling methods, and *Geukensia demissa* are older in terms of article publication year when they occur, indicating that several earlier investigations (< 2000s) considered macroinvertebrate composition as the key success indicator of salt marsh restoration. On the other hand, keywords such as 16 s rrna, fungi, microbial communities, wetland restoration, carbon accumulation, and blue carbon are most recent in terms of publication year they occur.

The occurrences of keywords such as "fungi," "microbial communities," and "16 s rrna" in the recent papers indicate that there are increasing research interests to understand the microbial compositional differences between restored and natural marshes. Microbial communities, including prokaryotes and fungi are indispensable components of the salt marsh systems and are the driving factors of many ecosystem functioning, for example, carbon and nutrient dynamics (Xio et al. 2020). The microbial process of essential elements especially carbon and nitrogen (C and N) stimulates critical processes within salt marshes either by enhancing productivity and carbon storage or promoting organic matter decomposition. Soil microorganisms are the

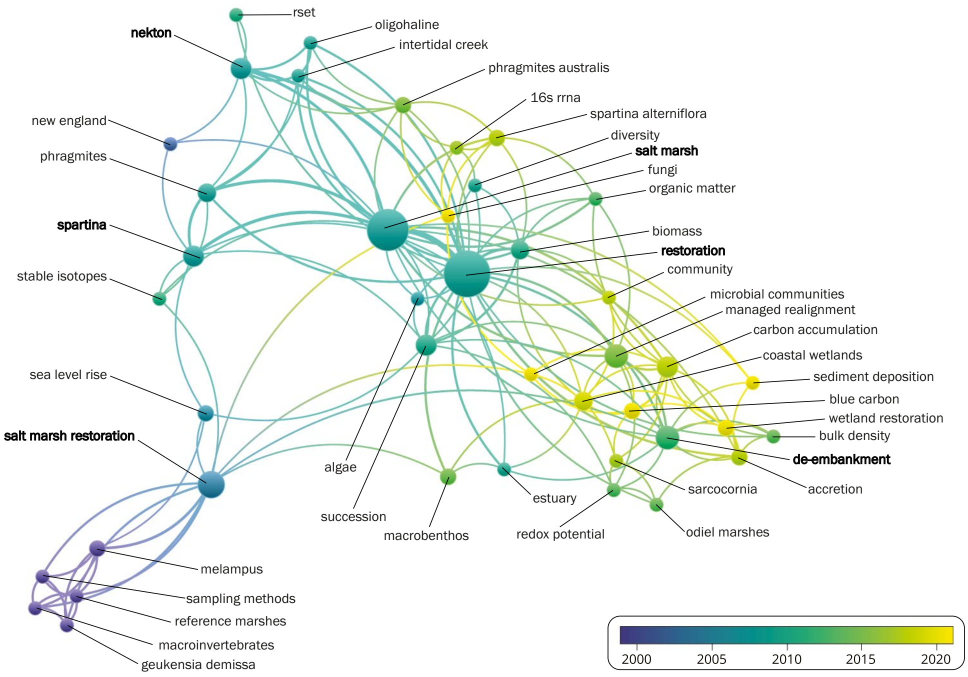

**Fig. 3** Mapping the co-occurrences of author keyword analysis over three decades (1990–2021); color indicates the year when a respective keyword was published in an article

main decomposer of organic matter and during this process (mineralization of organic carbon), excess nutrients (N, P, and S) are eventually released into the salt marsh systems in plant available (bio-available) state.

The growing interest in studying carbon sequestrations in the blue carbon systems is reflected with the occurrences of "blue carbon" and "carbon accumulation" keywords in the recent publications (Fig. 3; Santini et al. 2019; Drexler et al. 2019; Poppe and Rybczyk 2021).

## Restoration techniques

The present study indicated that most of the work carried out abiotic assistance ($n=51$ studies) for restoration techniques, followed by biotic assistance ($n=9$), and mixed of biotic and abiotic ($n=8$) and only a few studies ($n=2$) did not provide the description of the approach attempted for restoration.

Common restoration strategies are illustrated in Fig. 4(a–j). As presented on the result of restoration strategies (Table 2), much of the salt marsh restoration work attempted assisted abiotic techniques. Briefly, such strategy includes various efforts including de-embankment of the existing dike made for the road, reshaping and activating the tidal exchange either constructing and excavating canal or constructing culvert.

In general, restoration techniques attempted in different geographical areas vary due to differences in the causes of marsh degradation/stressors affecting the system (e.g., land reclamation, shoreline erosion, tidal restrictions, and invasive species) (Gedan et al. 2009; Wolanski and Elliott 2015). For example, in the Bay of Fundy, in Canada, a salt marsh is restored by expanding the tidal channel through a culvert construction (Bowron et al. 2011). However, in Northwest Europe, salt marshes are increasingly created by "managed realignment" removing or breaching the dikes either limited or no human interventions (Crooks et al. 2002; Blott and Pye 2004; French et al. 2005; Wolters et al. 2005; Burden et al. 2013, 2019). Besides, in the USA, multiple techniques are often attempted, for example, in North Carolina, salt marshes are created through grading an upland site to intertidal elevations, followed by re-vegetation through planting with *Spartina* spp. and *Juncus roemerianus* (Craft et al. 2002, 2003). In Louisiana, sediment slurries are dispersed in the degraded marshes (relatively shallow areas) that are already subsided due to mainly soil consolidations; in this method with low hydraulic pressure, dredged sediments are dispersed over the marsh surface (Slocum et al. 2005; Schrift et al. 2008). Besides, in the southern New England salt marsh, restoration is mainly focused on the removal of invasive *Phragmites.*

As an example of successful salt marsh restoration, case study is carried out using reconstructing the soil level (assisted abiotic restoration). In 1978, at Davis Bayou area of the Mississippi Sound, two salt marshes (salt marsh island) were created using the dredged sediment derived during the constructions of the boat docks and degraded materials (Ferguson and Rakocinski 2008). The authors also described that to assist the sedimentations, hay-bales were placed in shoreline with wooden stakes. After over 27 years of construction, the success of the restoral has confirmed the presence of typical low marsh plants such as *Spartina alterniflora* and *Juncus romerianus* and macrobenthic composition and structures.

## Indicators recorded to assess restoration success

The present study extracted a total of 214 indicators from the literature data. The list of the indicator with exemplary references is shown in Table 3. The highest number of indicators was reported for structural diversity ($n=70$; 32.7%), followed by ecosystem functions ($n=71$; 33.2%), physical condition ($n=42$; 20%), and species composition ($n=18$; 8%). Absence of threat had the lowest number of indicators ($n=3$; 1%). The number of studies found for different sub-attributes under major ecological attributes is shown in Fig. 5.

The width of the band/node in Fig. 5 is proportional to the number of studies carried out for a respective band/node. The highest number of studies considered ecosystem functioning indicators ($n=43$) to assess restoration success. Besides, indicators related to vegetation structures were most cited ($n = 32$) sub-attributes under structural diversity attributes. Within the ecosystem function attributes, carbon dynamics were most cited ($n=25$) sub-attributes (Fig. 5).

Out of 214 indicators, 26 indicators were found to be cited with at least 5 literatures. These indicators were then visualized through density visualization using VOSviewer software (V 1.6.17) and shown in Fig. 6. Through this visualization, the color of an indicator changes from yellow to red depending on the number of citations it receives. As citations increase, the indicator's hue darkens. For instance, stem density ($n=6$) (yellow) received more citations than water salinity ($n=13$) (red).

In the present study, salt marsh species diversity, vegetation cover biomass (above and below ground), and stem density were appeared as among the dominant indicators in the restoration success evaluation schemes (Fig. 6). This outcome is expected as these indicators are easy to measure and measurements of these attributes are associated with relatively low cost and time.

Among the functional indicators especially, sediment organic matter (SOM), sediment carbon (%), and sediment ntirogen (N) content were frequently cited (Fig. 6); this can be explained by the fact that, in the terrestrial and wetland sediments, these attributes are the key functional measures of the ecosystems. SOM and sediment N content are the

**Fig. 4** Illustration of the major salt marsh restoration strategies reported in the literature

good proxy to understand the energy flow (carbon content) and nutrients (N concentrations) cycles of ecosystems (Craft et al. 2003). There are evidences that N limited the salt marsh above-ground biomass, and therefore succession of vegetation in the restored or created marshes depends on the accumulated N contents in the soil and plant biomass (Van Wijnen and Bakker 1999; Craft 2001). Being a detritus-based ecosystem, salt marsh SOM serves as a food for heterotrophic organisms including deposit-feeding invertebrates and to fuel microbial process like de-nitrifications (through providing labile fractions of the carbon) (Craft 2001).

**Table 2** Restoration strategies, major approach, and description of the approach and exemplary references

| Types of restoration strategies | Major approach | Description | References |
|---|---|---|---|
| Assisted abiotic restoration | Recovery of tidal exchange | Tidal exchange/inundation has been recovered and restored through various means, including culvert constructions, canals and/or channels excavations (Fig. 4a) | Lynum et al (2020); Kimball and Able (2007) |
| | Recovery of sediment characteristics | In order to improve soil characteristics for revegetation effort, rubbles are removed and incorporated with organic mangrove soil (Fig. 4b) | Santini et al (2019) |
| | Managed realignment | Partial or whole scale breaching of coastal defense structures to ameliorate the salt marsh habitat for sustainable biodiversity response. Breaching of dikes is either intended or caused by natural processes, such as erosion, sea level rise, or wave actions/storms (Fig. 4c) | Thom et al (2002); Petillon et al (2014) |
| | Reconstruction of soil levels | Sediment slurry is added to the marsh bed to reduce the flooding-related stress to the salt marsh plants (Fig. 4d) | Jones et al (2019) |
| | Created salt marsh through dredged sediment | In the Venice lagoon, salt marsh beds are created through dredged sediment from the nearby navigation channels and excavation of the barrier (Fig. 4e) | Moseman-Valtierra et al (2016) |
| Assisted biotic restoration | Control of invasive *Phragmites* spp. | Establishment and invasion of the *Phragmites* are eliminated by the large-scale application of herbicide and burning the marsh surface (Fig. 4f) | Able et al (2003) |
| | Control of invasive *Spartina alterniflora* | In the salt marsh of the Yangtze Estuary, invasive *Spartina alterniflora* is removed mainly by herbicide application (Fig. 4g) | Chen et al (2017) |
| Assisted biotic restoration | Recovery of vegetation through revegetation | Usually carried out either transplantation of sediment cores with target salt marsh plant or transplantation of clumps of target salt marsh species from natural populations (Fig. 4h) | Minello and Zimmerman (1993) |
| Reconstructive restoration<br>Reconstructive restoration<br>Reconstructive restoration | Construction of a new lagoon thereby creating new marshes | Construction of a new lagoon and removal of breakwaters, walking paths, connecting roads, and accumulated debris (Fig. 4i) | Cabrera et al (2019) |
| Natural and assisted abiotic restoration | Restriction of the vehicles and sediment level amendment | Exclusions (through fencing in the lagoon) of the recreational vehicles that are destructing the marsh beds through erosions and reconstructions of the soil level to accelerate the re-colonization of the salt marsh (Fig. 4j) | Green et al (2010) |

**Table 3** Indicators used to assess the success of salt marsh restoration

| Name of the major ecological attributes | Sub-ecological attributes, indicators, and exemplary reference |
|---|---|
| Absence of threat | Invasive species height, coverage and macroalgal cover (Raposa 2008) |
| Ecosystem functions | Primary productivity |
| | Root production (Santini et al. 2019); above-ground biomass, root biomass, and rhizome biomass (Schafer et al. 2019); chlorophyll concentration (Howe and Simenstad 2015); algal biomass and biovolume (Zheng et al. (2004); below-ground biomass (Poppe and Rybczyk 2021); seed production and seed density (Erfanzadeh et al. 2010); seed weight (Wolters et al. 2008) |
| | Secondary productivity |
| | Fish foraging performance and fish growth potential (David et al. 2014); nekton biovolume (Burdick et al. 1996); fish growth rate and fish proximate body composition (lipid, dry mass, water base) (Dibble and Meyerson 2012); gastropod biomass (Swamy et al. 2002); gastropod reproductive characteristics (Dibble and Meyerson 2012); zooplankton biomass (Cabrera et al. 2019); macrofauna (fish and decapod biomass) (Rezek et al. 2017); crab biomass (Liu et al. 2020); macrobenthic biomass (Ferguson and Rakocinski 2008) |
| | Food web |
| | Vegetation isotopic signature, suspended organic matter isotopic signature and fish isotopic structure (Wozniak et al. 2006); food web analysis (stable isotope-based (Rezek et al. 2017); trophic structure (stomach content-based) analysis David et al. (2014); mussel isotopic signature (Howe and Simenstad 2015); arthropod food web analysis (Gratton and Deno 2006); infauna trophic structure (Craft et al. 1999); relative abundance of foraging guilds (Lewis and Casagrande 1997) |
| | Carbon dynamics |
| | Water total organic and inorganic carbon (Cabrera et al. 2019); organic carbon content (Drexler et al. 2019); carbon accumulation rate (Drexler et al. 2019); sediment organic matter and greenhouse gases fluxes (Schafer et al. 2019); gross ecosystem production (GEP), net ecosystem $CO_2$ exchange and ecosystem respiration (Wang et al. 2021); soil respiration, organic carbon sequestration rates, organic carbon stocks of above and below-ground biomass (Santini et al. 2019); macro organic matter (Craft et al. 1999); microbial biomass carbon; fine and coarse particulate organic carbon (Xiao et al. 2020); dissolved organic carbon (Cabrera et al. 2019); sediment carbon stock, carbon mineralization rates and sediment C:N ratio (Burden et al. 2013); sediment organic carbon density and % C (Poppe and Rybczyk 2021) |
| | Sediment dynamics |
| | Sediment accretion rate (Drexler et al. 2019); sediment accumulation (Chen et al. 2017) |
| | Nutrient dynamics |
| | Soil nitrogen (Santini et al. 2019); acetylene reduction rates (Moseman-Valtierra et al. 2016); soil P (Craft et al. 1999); soluble reactive phosphate (Cabrera et al. 2019); soil $NH_4$-N and soil $NO_3$-N (Stagg and Mendelssohn 2010); soil $SiO_3$ and soil $PO_4$-P (Lv et al. 2018); Humic substances (Burden et al. 2013), total leaf N (%) (Gratton and Denno 2006); leaf C:N and leaf toughness (Dibble and Meyerson 2014) |
| External exchanges | Maximum flooding depth (Able et al. 2003); shoreline slope (Schulz et al. 2020); daily maximum water level and depth to ground level (Van Proosdij et al. 2010); pore water table (Wang et al. 2021); water depth, surface elevation, inundation period and tidal frequency (Green et al. 2010) |
| Physical conditions | Pore water |
| | Salinity (Bernhard et al. 2012); pH, $Cl^-$, $S^{2-}$, $SO_4^{2-}$, dissolved organic carbon (Wang et al. 2021); $NH_4$ and $NO_2/NO_3$ (Jones et al. 2019) |
| | Sediment characteristics |
| | Soil electrical conductivity and stable aggregate composition (Xiao et al. 2020), soil redox (Curado et al. 2014), sediment porosity, texture, and $Cl^{-1}$ (Kadiri et al. 2011); % sand, pH, bulk density, inman sorting value, water content and soil conductivity (Fearnley 2008); substrate type (Schulz et al. 2020); soil elements e.g., Fe, K, Mg, Mn, Na and S (Stagg and Mendelssohn 2010); soil hardness (Li et al. 2016); soil salinity (Swamy et al. 2002), soil temperature (Schafer et al. 2019); sediment macrodetritus (Rezek et al. 2017) |
| | Atmospheric characteristics |
| | Air temperature, humidity and net radiation (Schafer et al. 2019); light attenuation (Moseman-Valtierra et al. 2016) |
| | Surface water characteristics |
| | Turbidity (Minello and Zimmerman 1993); water conductivity and pH (Schafer et al. 2019); transparency, temperature, salinity, and dissolved oxygen (Able et al. 2004); water total N, P, $NH_4$, and $NO_2/NO_3$ (Cabrera et al. 2019); water cover and land cover (Li et al. 2011) |
| Species composition | Salt marsh diversity (Schulz et al. 2020); diatom diversity (Zheng et al. 2004); bird diversity, bird species richness, nekton composition, and nekton species richness (Raposa 2008); fish assemblages composition and species richness (Van Proosdij et al. 2010); spider species assemblages (Petillon et al. 2014); zooplankton diversity (Cabrera et al. 2019); trematode species composition and richness (Huspeni and Lafferty 2004); invertebrate taxonomic group (Woo et al. 2018); soil fungal community composition and diversity (Xiao et al. 2020); microbial community analysis (Santini et al. 2019); prokaryotic diversity (Lynum et al. 2020) |

**Table 3** (continued)

| Name of the major ecological attributes | Sub-ecological attributes, indicators, and exemplary reference |
|---|---|
| Structural diversity | Vegetation structure<br>Algal abundance (chlorophyll a) (Green et al. 2010); number of target salt marsh species (Wolters et al. 2008); plant relative coverage% (Curado et al. 2014); plant abundance and vegetation height (Van Proosdij et al. 2010); vegetation frequency of occurrence (Thom et al. 2002); stem density (Able et al. 2003); plant standing height (Curado et al. 2014); dead stem density, flowering phonology, germination rate, and insect flower damage (Jones et al. 2019); root density, rhizome density, and leaf area index (Schafer et al. 2019); litter depth (Petillon et al. 2014); seed floatation time (Erfanzadeh et al. 2010); plant coverage (Schrift et al 2008); leaf phenolic concentrations (Dibble and Meyerson 2014) |
| Structural diversity | Bird structure<br>Bird density (Raposa 2008); bird abundance and bird percent cover (Brawley et al. 1998); number of bird nests, abunadance of salt marsh sparrows, abundance of salt marsh specialist bird (Elphick et al. 2015)<br>Fish structure<br>Fish abundance, fish weight at length analysis, fish density, fish otolith measurements, fish age group distribution and fish parasite prevalence (Dibble and Meyerson 2012); fish length frequency distribution (Able et al. 2004)<br>Nekton structure<br>Nekton length (Van Proosdij et al. 2010); nekton density (Raposa 2008); macrofauna (fish and decapods) density and abundance (Minello and Zimmerman 1993)<br>Other faunal structures<br>Spider gut content (Gratton and Deno 2006); bivalve density, gastropod density and shell length (Peck et al. 1994); gastropod and invertebrate occurrences (Fell et al. 1991); mussel growth rate and diet composition (Howe and Simenstad 2015); infauna (polychaete and amphipod) density (Minello and Zimmerman 1993); Density of amphipod, nereid polychaete and benthic invertebrate (Gray et al. 2002); % of trematode prevalence (Huspeni and Lafferty 2004); macroinvertebrate (snails and amphipod) density (Swamy et al. 2002); crab carapace width, sex ratio, molting stage and abundance (Jivoff and Able 2003); crab density (Peck et al. 1994); amphipod individuals (Petillon et al. 2014); herbivory strength, density of crab burrows (Liu et al. 2020); arthropod abundance (Gratton and Denno 2006); macrobenthic functional group (Lv et al. 2018)<br>Microbiota structure<br>Bacterial abundance (Bernhard et al. 2012); mycorrhiza presence in roots (Cooke and Lefor 1990) |

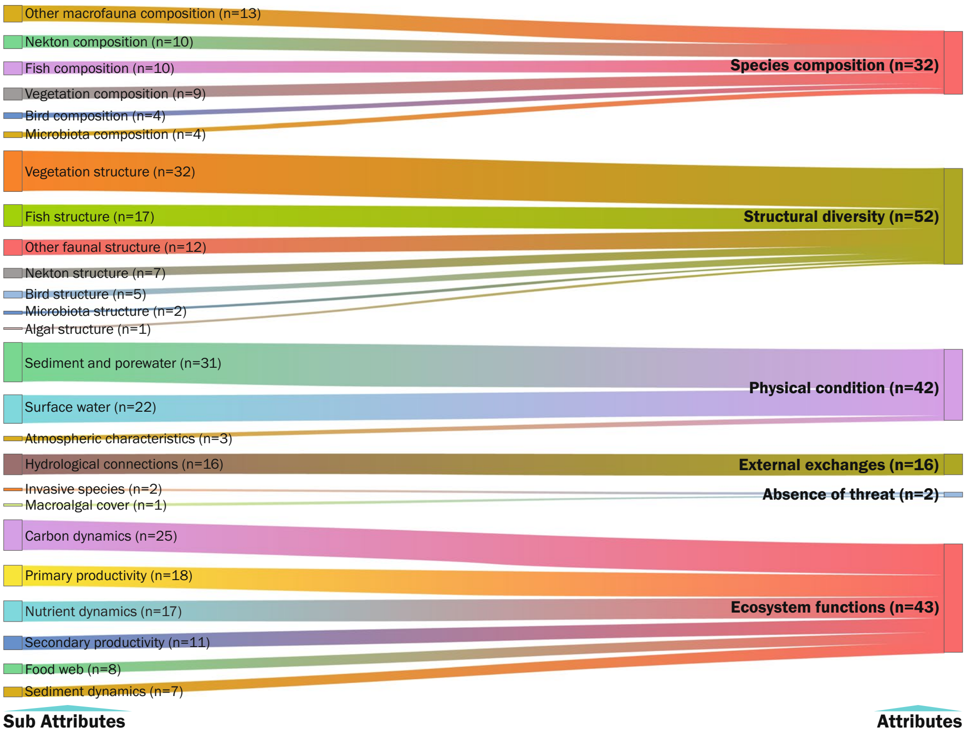

**Fig. 5** Distribution of the number of publications reporting the indicators nested within different sub-attributes and major attributes

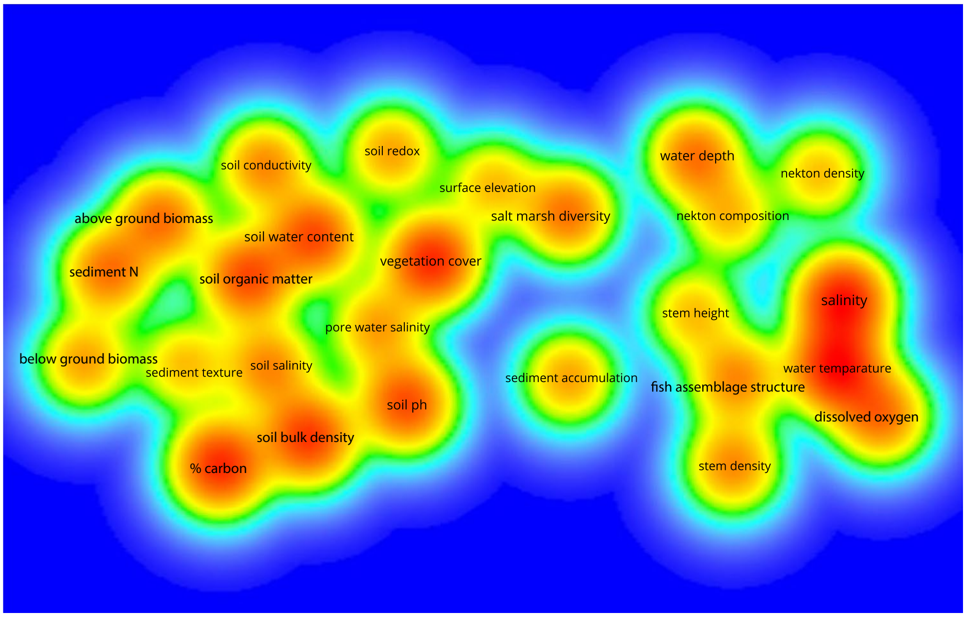

**Fig. 6** Density visualization of most cited 26 indicators (≥ 5 citations). An indicator's color indicates the degree of citations, from red (highest citation) to yellow (lowest citation)

Besides, among the hydrological characteristics, surface water salinity and temperature were appeared to be frequently cited (Fig. 6) as these attributes are easy and inexpensive to measure and considered as the key hydrological factors. Further, high occurrences of fish assemblages structure, nekton composition, and nekton density in Fig. 6 are due to the fact that salt marsh utilization by fish and nekton has long been considered as success indicators (Matthews and Minello 1994; Dionne et al. 1999).

## Success indicators in restored marsh: required time to achieve equivalence level of natural marsh

The time required to achieve an equivalence level of success indicator measured in a restored salt marsh against that measured in a natural marsh is reported (Craft et al. 2002, 2003; Nordström et al. 2014). Almost immediately after hydrological connections, hydrological indicators (especially well water depth, pore water salinity, and sedimentation) achieved equivalence to natural marshes (Burdick et al. 1996; Craft et al. 2003) (Fig. 7). Similarly, some biological responses to restoration especially, fish utilization of salt marsh has also been reported immediately after hydrological connections (Burdick et al. 1996; Simenstad and Thom 1996) (Fig. 7).

It has been reported that vegetation structural attributes (e.g., biomass, density) in the restored marsh require several years to reach equivalency with those measured in natural marsh (Burdick et al 1996; Craft et al. 2003; Fig. 7). For example, a study carried out in a managed realignment site in UK has been reported that within

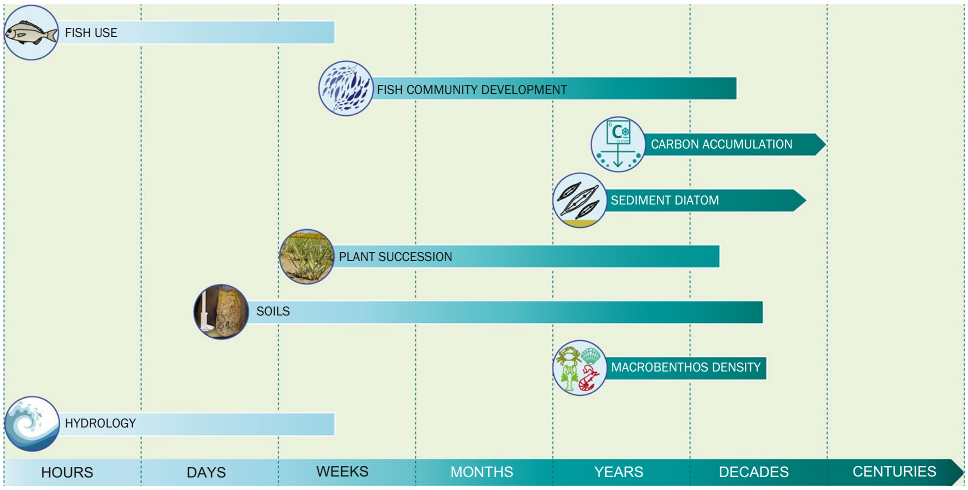

**Fig. 7** Generalized trends in temporal development of success indicators in restored salt marsh ( modified from Burdick et al. 1996)

8 years of restoration, vegetation succession has developed confirming with the presence of *Salicornia* sp. and *Spartina anglica* in the pioneer zone and mid-marsh is abundantly vegetated with *Puccinellia maritime* (Spencer et al. 2008). Macrobenthic density in constructed marsh requires 5–25 years to reach equivalence to natural marsh (Craft et al. 1999, 2003). Besides, SOM in restored marsh requires about 15 years to achieve equivalent level of that measured in the natural marshes; however, N content of the sediment requires 30 years to achieve equivalent level of that measured in the natural marsh (e.g., Craft 2001). Similarly, restored marshes require more than 30 years to reach the same level of sediment diatom similarity as natural marshes (Craft et al. 2003).

Peat development and carbon accumulation in restored marsh may require about a century to reach equivalence to natural marsh (Fig. 7; Burden et al. (2019)). A study carried out in Tollesbury-managed realignment site (UK) showed carbon accumulation rate as 0.92 t C ha$^{-1}$; considering this rate of accumulation, it was predicted that it would take approximately 100 years to recover the carbon sinks similar to natural site (Burden et al. 2019). Similar to their study, Craft et al (2003) projected up to 70 years to recover the soil total organic carbon pool in a restored marsh.

## Conceptual model of suggested salt marsh restoration approach and success evaluation

This paper proposes a model for restoring degraded salt marsh, as well as tracking the success of the restoration (Fig. 8). This model is developed comprising (i) proposed model by Zhao et al. (2016) for wetland restoration monitoring, (ii) results from present study, and (iii) success communication idea provided by Society for Ecological Restoration International Science and Policy Working Group (SER) (SER 2007). After selection of a degraded salt marsh site, damage analysis and field survey could be performed to understand the cause of degradation. After feasibility study, appropriate restoration techniques will be decided and attempted to get a fully recovered, resilient, and functioning system. The available restoration strategies are already provided and discussed in this paper (Fig. 4 and Table 2). The success of salt marsh restoration would be ecologically diagnosed by comparing the success indicators (absence of threat, physical condition, species composition, structural diversity, ecosystem functions, and external exchange; Table 1) between natural sites with the resorted site (Fig. 8).

To communicate the level of success of restoration a "5-star based recovery system" can be applied (following SER 2007). This 5-Star Recovery System tool indicates a

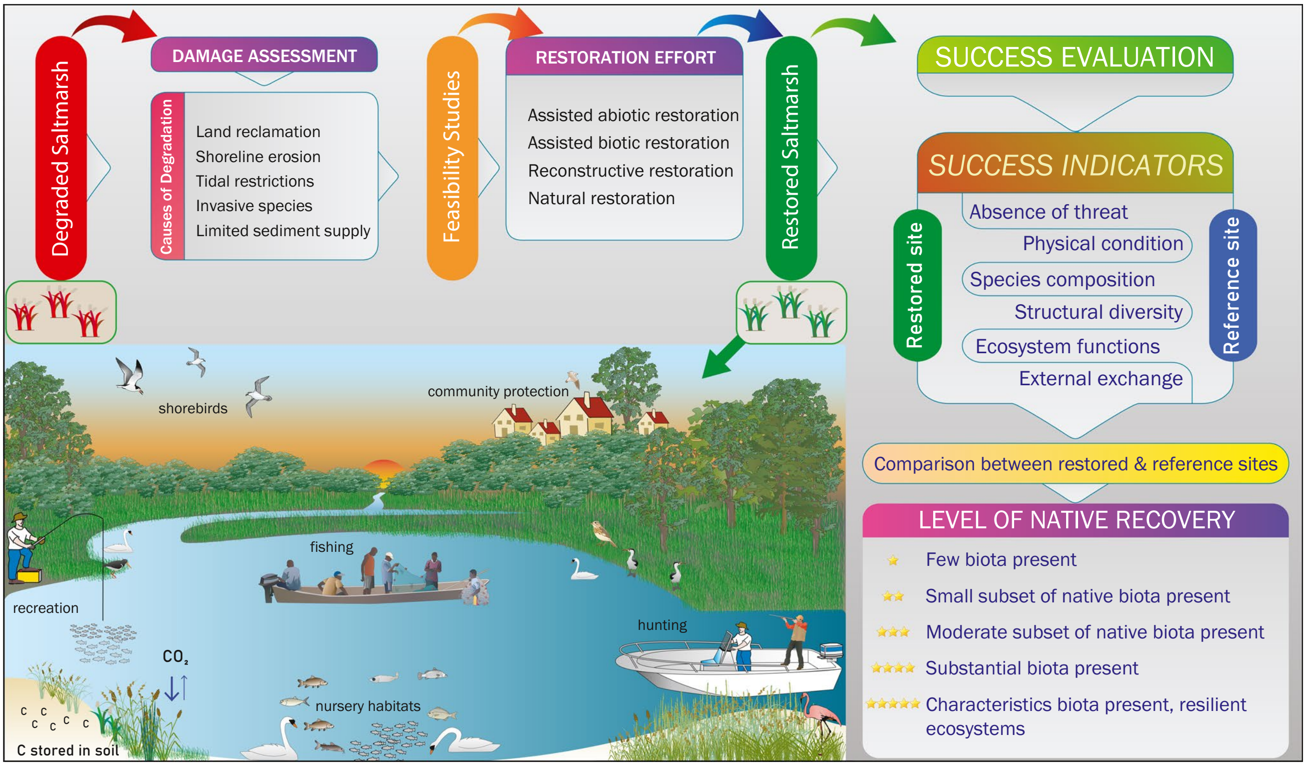

**Fig. 8** Conceptual model of suggested salt marsh restoration approach and success evaluation (Some symbols used in this figure are courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science—ian.umces.edu/symbols/)

1–5 star (*) scale/ranking considering the level of similarity with the reference systems. Based on this 5-star ranking, a restored site will be categorized or assigned to any of the recovery levels (from one star to five stars, with 5 being the highest level of similarity) for overall assessment of the site or assessment of any ecological attributes (structural, species composition, functioning, physical conditions, external exchanges, and absence of threat).

## Conclusions

Even though 50–90% of the marine habitat is reported to be degraded, marine restoration effort is negligible and underdeveloped compared to those carried out inland (Benayas et al. 2009a, 2009b). Restoration of the salt marsh in the degraded habitat not only ensures ecosystem services and supporting biodiversity but also can ensure equity and justice through food security and sustainability. Considerable improvements have been made to restore the degraded salt marsh areas over the last decades. The present systematic review provides comprehensive information about salt marsh restoration strategies and success evaluation indicators used in the previous studies. Success indicators realated to structural diversity  and ecosystem functions are mostly studied; on the other hand, indicators related to the absence of threat (for example, invasive species abundance/presence) are less studied. There is a lack of generalized common success criteria assessment method. The present study suggests a conceptual model for success evaluation. We hope that the data presented here will be of use in designing a study to evaluate the success of wetland restoration.

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**Author contribution** MMB—conceptualization, data exactions, analysis, writing original draft, and editing. MKB—data extractions, visualization, review, and editing. MAI—review and editing. JD—review and editing. ATMRH—review and editing.

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**Data availability** All data generated or analyzed during this study are included in this published article. More detailed data can be provided upon request to the corresponding author.

## Declarations

**Ethical approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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