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Top ten priorities for global saltmarsh restoration, conservation and ecosystem service research

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Abstract

Coastal saltmarshes provide globally important ecosystem services including ‘blue carbon’ sequestration, flood protection, pollutant remediation, habitat provision and cultural value. Large portions of marshes have been lost or fragmented as a result of land reclamation, embankment construction, and pollution. Sea level rise threatens marsh survival by blocking landward migration where coastlines have been developed. Research-informed saltmarsh conservation and restoration efforts are helping to prevent further loss, yet significant knowledge gaps remain. Using a mixed methods approach, This paper identifies ten research priorities through an online questionnaire and a residential workshop attended by an international, multi-disciplinary network of 35 saltmarsh experts spanning natural, physical and social sciences across research, policy, and practitioner sectors. Priorities have been grouped under four thematic areas of research: *Saltmarsh Area Extent, Change and Restoration Potential* (including past, present, global variation), *Spatio-social contexts of Ecosystem Service delivery* (e.g. influences of environmental context, climate change, and stakeholder groups on service provisioning), *Patterns and Processes in saltmarsh functioning* (global drivers of saltmarsh ecosystem structure/function) and *Management and Policy Needs* (how management varies contextually; challenges/opportunities for management). Although not intended to be exhaustive, the challenges, opportunities, and strategies for addressing each research priority examined here, providing a blueprint of the work that needs to be done to protect saltmarshes for future generations.

Keywords: saltmarsh conservation and restoration, ecosystem services, global variation, socio-ecological interactions, research priorities.

1. Introduction

Saltmarshes occupy the land-sea interface of sheltered coastlines, providing a diverse set of goods and services including flood and coastal protection, biodiversity conservation, carbon sequestration, pollutant remediation, food provision, and enhancement of human wellbeing (Barbier et al. 2011; Rendón et al. 2019; McKinley et al. 2020). Saltmarshes are found in almost all countries worldwide (Fig. 1); however, their extent and quality have been severely degraded by human activity.

Throughout centuries of disturbance, saltmarshes have been diked and drained for agriculture and land development, used for livestock grazing, and managed for fisheries and aquaculture (Gedan et al. 2009). Major coastal settlements including the global cities of Boston, London and Shanghai were developed on filled or drained coastal wetlands. Over 50 percent of saltmarsh habitat in Europe has been lost to coastal development alone (Airoldi and Beck 2007). Estuarine saltmarshes are particularly vulnerable to impacts from riverine management including alterations to freshwater runoff, sediment, nutrients, heavy metals, and other pollutants (Adams, 2020; Silliman et al. 2009). At global scales, accelerated sea level rise and increasing storm intensity and frequency contribute further to saltmarsh loss from prolonged flooding and erosion (Schuerch et al. 2018). The threat from sea level is considered so severe, that saltmarshes globally may be lost unless considerable efforts are taken to realign the coast (Crosby et al. 2016; Horton et al. 2018; Törnqvist et al. 2020; Saintilan et al. 2022; Ohenhen et al. 2023).

By recognising that marsh degradation threatens critical ecosystem services (Barbier et al. 2011), efforts are underway to protect, restore, and predict how saltmarshes will respond to global change drivers (Murray et al. 2022). Key to this effort is interdisciplinary research to understand how ecosystem services and function vary with marsh characteristics and different socio-environmental contexts (Fig. 2). Despite marshes being one of the most geographically widespread coastal vegetated ecosystems, occurring from the arctic to the tropics (Mcowen et al. 2017), and given the pace at which climate change and anthropogenic activity are degrading especially vulnerable saltmarsh socio-ecological systems worldwide, a rapid shift in research priorities is needed to address the key barriers to a sustainable future for saltmarshes.

Using expert opinion from an international network of multi-disciplinary researchers, policymakers, and practitioners, this paper presents the top ten research priorities in global saltmarsh research to date. For each research priority, we summarise the current state of knowledge and set out how impactful research can support international decision making on marsh conservation, restoration and management in the final section.

2. Methods

Standard approaches for expert identification of research priorities were adopted (as outlined by Sutherland et al. 2013). Initially using a purposive sampling approach (i.e. selecting participants with relevant expertise and knowledge), drawing on the existing network of the project lead partner, and then supplemented through snowball sampling (i.e. individuals recommended to the research team), a multi-disciplinary group of 35 saltmarsh experts from 11 countries and six continents was identified and invited to participate in this study. This team encompassed natural and physical scientists with expertise in saltmarsh oceanography, sediment dynamics, ecological and biological composition, and ecosystem modelling; social scientists with expertise in ecosystem service valuation, governance and public perceptions (Academics $n = 28$); and representatives from saltmarsh governance and management organisations (Practitioners $n = 7$), including five Early Career Researchers from a range of disciplinary backgrounds.

Research questions were identified through a 3-step process. (1) Using an online questionnaire (available in Supp. Materials), delivered through the Survey monkey platform, participants were asked to respond to a number of questions regarding a wide range of issues relating to salt marsh ecosystem services and management. An initial research prioritisation process was carried out through an open question where experts were asked to list 10 priority research questions concerning saltmarsh ecosystem functioning and ecosystem services, with a total of 191 research questions returned. (2) Analysis of the questions resulted in the identification of 15 research themes, with each theme containing between 5 and 33 questions. Data analysis involved thematic coding of the individual responses, using standard qualitative analysis techniques and data reduction processes (Braun, 2006) carried out by three of the research team to ensure the consistency of the thematic coding. (3) A four-day workshop was held in Wales, United Kingdom, in December 2017. The workshop programme included initial context setting presentations from a number of the workshop attendees, with a day and a half allocated to the research prioritisation exercise. To do this, attendees were divided into four multidisciplinary groups, with participants able to self-select their preferred group depending on the themes being discussed, and each assigned 2-4 themes including the original research questions and tasked with firstly discussing and synthesising these themes. Each group then voted to produce a shortlist of 10 key questions per theme, hereafter called research 'priorities'. Experts were each allocated 5 stickers and asked to place these by the research priorities of greatest importance to them, using a colour-based coding of rank importance. The top 10 research priorities were then identified according to the total number of stickers. Since the workshop in 2017, the identified research themes have undergone a subsequent review by the authorship team in 2022 to ensure their ongoing relevance. No changes were made to the identified priorities following this process. This process was carried out in accordance with Cardiff University Ethics Procedures (Approved August 2016),

3. The Top Ten priorities for global saltmarsh research

The top 10 research priorities (RPs) identified are organised into thematic categories (Fig. 3) and discussed below. In each case, we outline current understanding and identify remaining knowledge gaps, alongside suggestions for how these may be addressed through future research.

3.1. Theme 1: Saltmarsh Area Extent, Change and Restoration Potential

RP1: How has the rate of change in saltmarsh areal extent varied globally over time?

Monitoring saltmarsh dynamics, assessing the magnitude of human impacts, and designing appropriate local and regional conservation policy depend on knowledge of areal extent. The extent of saltmarshes has recently been mapped (Worthington et al. 2023), providing a baseline for quantifying variation in ecosystem services, including blue carbon, at a global scale (Macreadie et al., 2019; Mcleod et al. 2011, Pendleton et al. 2012).

Saltmarsh gains appear to have marginally exceeded losses by an estimated 100 km^2 between 1999 and 2019 (Murray et al. 2022). Patterns of marsh expansion and erosion vary between regions. For example, the Mississippi delta lost ~5,000 km^2 of its marshes between 1932 and 2010 (Couvillion et al. 2011), whilst marshes along the China coast expanded by ~8,000 ha between 2010 and 2019 (Chen et al. 2022).

Although changes in saltmarsh extent at the single-marsh scale have been reported especially across Europe and North America (e.g. Bromberg & Bertness 2005, Prahalad 2014), regional-scale studies rarer (Gu et al. 2018; Ladd et al. 2019), and global-scale studies are short-term and coarse resolution (Murray et al. 2022). Studies at these varying scales are necessary as local, small-scale studies of marsh change are not always indicative of larger-scale trends in marsh change. In the UK, for example, high rates of erosion observed along Southeast England coastlines had been up-scaled to predict marsh change across the entire UK to dictate conservation policy (Pye & French 1993), but a later study revealed that northern regions had been stable/expanding (Phelan et al. 2011). Similar variation across scales have been seen in North America (Gedan & Silliman 2005) (Fig. 4), further highlighting the overall importance of this research question.

Understanding the regional variation in saltmarsh areal change at a global scale would be augmented by investigating the regional drivers of change (mostly relative sea-level rise, sediment supply, and reclamation intensity; Spencer et al. 2016). Indeed, relative to vertical/elevational changes, drivers of saltmarsh horizontal/areal changes have been much less studied. However, understanding changes in saltmarsh extent globally and its regional variation cannot be achieved by analysing the recently released UNEP-WCMC global saltmarsh data set due to the absence of a systematic time component (Mcowen et al. 2017). Instead, this could be achieved through a coordinated remote sensing analysis of global saltmarshes and/or by a meta-analysis of existing studies globally. An important advantage of the latter is that it could allow periodic re-estimation of future changes in global saltmarsh extent (e.g., every 10 years). Understanding changes in areal extent will also benefit from the development of new marsh models that are spatially explicit, inclusive of both biophysical and socio-economic processes, and applicable to multiple geographical regions (Fagherazzi et al. 2012, Spencer et al. 2016).

RP2: Where and how can saltmarshes be realistically restored?

In light of historical losses in the extent of saltmarshes worldwide (Gedan et al. 2009), and the growing vulnerability of the marshes that remain (especially to sea level rise; Saintilan et al. 2022), restoration of intertidal areas and the ecosystem services they sustain (Wolters et al. 2005) is now seen as a global priority (Fischer et al. 2020).

To deliver on global habitat restoration goals, areas suitable for restoration must be selected based on cost-benefit analysis of the restoration methods required (Armitage 2021), whether the areas earmarked for restoration have the potential for long-term success and do not interfere with natural marsh expansion-erosion dynamics (Wolters et al. 2005), and the value of ecosystem service and biodiversity benefits likely to emerge from the restored habitat, especially for coastal flood protection (Luisetti et al. 2011) and carbon sequestration (McMahon et al. 2023). Tidally restricted coastal areas may need improved hydrological connectivity (e.g., tidal gates dismantled, or upstream dams/levees removed), while bare, degraded, or eroding marshes may need to be rehabilitated through active transplantation of vegetation, invasive species removal, or construction of wave breaks to stabilise eroding shorelines and create windows of opportunity to facilitate pioneer establishment (Silliman et al. 2009). In all cases, systematic inclusion of positive inter- and intra-species interactions is key to increasing restoration success (Duggan-Edwards et al. 2020). Furthermore, the use and values attributed to the hinterland selected for managed realignment must be considered – low-value biodiversity-poor agricultural land, where removal of dykes and levees would lead to natural recolonisation of saltmarsh, may represent an example of high restoration potential (Waltham et al. 2021).

Further research into multi-decision criteria analyses focused on restoration upscaling strategies is urgently required. This should allow the best performing restoration options to be identified across a large number of selection criteria, including environmental, financial, and social considerations, as well as taking account of the various challenges posed by ongoing climate change. Further, quantifying variation in ecosystem function and service provision in restored or created marshes is an essential conservation priority to demonstrate the efficacy of restoration.

3.2. Theme 2: Spatio-social contexts of Ecosystem Service delivery

RP3: How does ecosystem service delivery vary with key marsh features and climate change?

Given that ecosystem services and benefits do not display a linear relationship with ecosystem area (Barbier et al. 2008; Koch et al. 2009) (i.e. more marsh area does not necessarily equal higher levels of ecosystem services or benefit), quantifying variation in service delivery based on marsh characteristics is crucial for describing how different marshes function within socio-economic systems. For instance, wave attenuation displays a threshold-like relationship with saltmarsh width (Koch et al. 2009), while saltmarshes with a greater extent of high-mid marsh zones may be more suitable for wildlife habitat provisioning by providing suitable bird nesting habitat (Malpas et al. 2013; Sharps et al. 2016). Knowing the relationship between service delivery and area, shape and configuration optimises the selection and prioritisation of saltmarshes for conservation, environmental monitoring, and habitat restoration.

Key marsh features have a particularly strong effect on the role that saltmarshes play in coastal protection. Near the seaward extent of the marsh, saltmarshes alter storm surge water levels as the bulk flow of water is reduced, causing a water surface slope from sea to land on the rising tide and from land to sea on the falling tide (Möller et al. 2014). Depending on the marsh configuration and position along an estuary (Fairchild et al. 2021), this effect can lead to a prolonged residence time of high-water levels at the landward margins of the marsh (Loder et al. 2009) and is therefore likely to vary with saltmarsh area, latitude, width, and volume. Close to the shore, saltmarsh habitat provides resistance to erosion due to surface topography, vegetation cover and the presence of creek systems (Spalding et al. 2014; Spencer et al. 2016). It is not known which saltmarsh features determine erosion resistance, although it has been suggested that sedimentology and root zone characteristics play a key role in this (Crooks & Pye 2000, see also Silliman et al. 2019 and De Battisti et al. 2019), but the role of saltmarshes in slowing down erosion may be context-dependent (e.g., less relevant for open coasts than for semi-enclosed coasts). Questions remain as to how climate change will affect ecosystem services delivery; what will be the extent of saltmarsh loss due to coastal squeeze and sediment deficit (see Schuerch et al. 2018)? How will the scale of saltmarsh change impact ecosystem service delivery (Ladd et al., 2021)? How can we relate changes in saltmarsh area and elevation to functional relationships and loss of ecosystem services? How will changes in species composition and range shifts due to warming and elevated CO_2 influence ecosystem service delivery? And how will shifts in ecosystem type or identity of main foundation species affect services (including the current trend of mangroves changing into saltmarshes with global warming, or vice-versa: Kelleway et al. 2017)? Several of these questions can be investigated by examining the existing variation in structure and function across climatic gradients using a space for time substitution approach (e.g. the latitudinal trend of productivity in the saltmarsh plant *Spartina alterniflora*: Kirwan et al. 2009 or the use of standardised litter to assess decomposition Mueller et al. 2018). Another approach could be to reconstruct ecosystem service change by studying contrasting sites and then map the ecosystem services of the area. Models could then be used to simulate the environmental conditions of the area in the future and map the projected ES distribution.

There has been an increase in the number of modelling and empirical tests of different climate change drivers on saltmarsh ecology and geomorphology (see for example Gedan & Bertness 2009, Kirwan & Mudd 2012; Smith et al, 2022). Yet, while some drivers such as sea level rise have been studied intensively, and temperature increasingly, others such as drought and elevated CO_2 need further investigation.

RP4: How are saltmarsh ecosystem services valued amongst different groups across the globe?

The interest and values ascribed to specific saltmarsh ecosystem services vary widely between groups (e.g. policy makers, land owners, civil society, Indigenous peoples) (Granek et al., 2010; McKinley et al., 2020a; Thomas et al., 2022; Rendon et al., 2022; Burdon et al., 2022; Rahmen et al,. 2023). Recognizing, describing, and embracing the plurality of stakeholder values facilitates improved engagement of diverse actors, support meaningful management negotiations and enhance the legitimacy and public acceptability of resulting decisions and management (Roca and Villares, 2012; Simpson et al., 2016). Understanding stakeholder values of saltmarsh ecosystem services, therefore, has clear implications for governance and management at local, (sub)-national and international scales (Loft et al., 2015). An analysis of these values on a global scale could also shed light on the underlying anthropogenic factors attributing to the current decline in saltmarsh coverage (Garcia Rodrigues et al., 2017).

There has been considerable research into the importance of saltmarshes and their monetary and non-monetary value for *provisioning* (Luisetti et al., 2014), *regulating* (e.g. Beaumont et al., 2014; Himes-Cornell et al., 2018), *supporting* (e.g. Laffaille et al., 2005; Barbier et al., 2011) and *cultural* services (Jobstvogt et al., 2014). These techniques provide a means of communicating saltmarsh ecosystem services values and may influence perceptions (Granek et al., 2010), and even policy (e.g. HM Government, 2011; ONS, 2021). In comparison, there has been considerably less stakeholder research to determine how different ecosystem services are valued across different groups within or between countries. Instead, this has often been approached in a case-specific fashion to document how priorities, and use and non-use values, diverge according to stakeholder interests and dependencies on saltmarsh ecosystems (McKinley et al., 2020b). Research has drawn from a range of social science methodologies and tools, such as questionnaires (McKinley et al., 2020b) and choice experiments (Bauer et al., 2004; Voltaire et al., 2017), focus groups (Souse et al., 2013), participatory mapping (Burdon et al., 2022; Rova et al., 2015), multimodal qualitative methodologies (Roberts et al. 2021) and prioritisation exercises (Carollo et al., 2013). It is important to be cognisant that such research reflects a snapshot in time, whereas in reality, these values are dynamic (Santana-Cordero et al. 2016), and values may shift through stakeholder engagement activities.

To date, research into stakeholder perceptions and values of saltmarsh ecosystem services is arguably fragmented in terms of the representation of geographies, temporal variation, types of services and stakeholders. Despite recent efforts (McKinley et al., 2020b), to support future management and policy there is a need for a global, robust means to document, assess and monitor the ways in which stakeholder values differ across spatio-temporal scales and identify underlying factors shaping these differences. Moreover, such research could help address knowledge gaps, such as private sector engagement with blue carbon, how this aligns to stakeholder objectives across various sectors and where this interest is located. Moving forwards, it is vital that saltmarsh research continues to embrace the social sciences within the wider research agenda.

RP5. What are the cultural ecosystem services of saltmarshes and what factors drive spatial-temporal variation in these services and benefits?

Cultural ecosystem services (CES) are typically related to activities and practices (e.g. recreation) and symbolic, emotional, mental-cognitive and spiritual engagement with ecosystems (Milcu et al. 2013). They provide benefits to human wellbeing (Russell et al., 2013; Martin et al., 2016), contributing to identities (e.g. heritage, social bonds, transformative memories), experiences (e.g. spiritual, aesthetic, thrill), and capacities (e.g. health, knowledge, skills) (Church et al. 2014; Fish et al. 2016).

Research highlights the role of CES in providing material and intangible benefits in coastal (e.g. Brown and Hausner, 2017) and marine habitats (Jobstvogt et al., 2014; Liquete et al., 2013), focussing mainly on mangroves and seagrasses (Himes-Cornell et al., 2018). The limited literature addressing saltmarsh CES shows that stakeholders tend to attribute high rankings to tourism and recreation (Cabral et al. 2014; Hutchinson et al., 2012), but rarely consider sense of experience (Thomas et al., 2022; Carollo et al., 2013; da Silva et al., 2014; Christie and Rayment, 2012) and spiritual and inspirational benefits (McDonald, 2003; Church et al. 2014). Aspects of wellbeing such as physical and mental health provided by coastal habitats have been studied (Wheeler et al., 2012; Gascon et al., 2017), but similar human benefits provided by saltmarshes have not been frequently reported although there are examples of recent work on this by Thomas et al. (2022), Rendon et al. (2019) and McKinley et al. (2022).

The influence of social and economic drivers on delivery of CES is varied and complex, with studies showing that some activities, such as land reclamation, negatively affect the provision of marine cultural ecosystem services (Rocha et al., 2015; Garcia Rodrigues et al., 2016), while others like saltmarsh grazing may contribute positively to biodiversity protection (Ford et al., 2012; Sharps et al., 2016), which in turn can influence some aspects of wellbeing (e.g. Fairchild et al. 2022; McKinley et al., 2021), and tourist attraction (van Zenten et al., 2016). Clearly, there is a need for indicators (Church et al., 2014; Atkins et al., 2015; Broszeit et al., 2017) to elucidate the linkages between CES and wellbeing benefits of saltmarshes, and their spatial and temporal variability, currently rarely explored (Santana-Cordero et al., 2016). Some examples of these links in coastal and marine landscapes are emerging (Potts et al., 2014;

Wang et al., 2017a; Saunders et al., 2015; Burdon et al., 2017), but further work is required to advance decision-making (Kenter et al. 2016) and support the science-policy-practice interface (McKinley et al., 2018; Drakou et al., 2018) in a way that takes account of these complexities. Some recent advancements have been made by Burdon et al (2019; 2022) who have identified benefits of coastal and marine ecosystems and linked them to beneficiaries through developing place-based participatory mapping approaches to support local decision making. It is recommended that an international effort to elucidate the underlying factors that shape saltmarsh CES across spatial-temporal scales is made, in particular focussing on: 1) varying governance and management approaches; 2) differences in cultural values and social norms; 3) awareness and use of saltmarshes; 4) differences in biodiversity and culturally important species; and 5) seasonality and climatic variation.

3.3. Theme 3: Patterns and processes in saltmarsh functioning

RP6: What are the global drivers of saltmarsh ecosystem structure and function?

Successful management, restoration and conservation of saltmarshes hinge upon our ability to identify which abiotic (e.g., temperature, tides, sea level rise, precipitation, nutrient cycling, and sedimentation rates) and biotic processes (e.g. dispersal and species interactions, organic production) drive variation in their structure and function. Saltmarsh ecosystem functioning refers to the activities of microbes, plants, and animals and their effects of the movement energy between biotic and abiotic ecosystem compartments (e.g., living tissues vs, organic and inorganic nutrient pools, Naeem et al. 1999). Explicitly linked to carbon sequestration, improvement of water quality through nutrient uptake, and support of coastal fisheries and livestock, marsh ecosystem functions are often assessed by measuring stocks or biomass of microbes, plants, and animals and by measuring rates of decomposition, plant productivity, or nitrogen uptake carbon, within saltmarsh soils, microbes, primary producers, and higher trophic levels (e.g. Barbier et al. 2011). Conceptual, qualitative, and quantitative models forecasting how saltmarsh communities, and their ecosystem functions, will respond to anticipated shifts in these drivers are especially important in the face of climate change factors such as increased tidal inundation with sea level rise, enhanced variability in river discharge, rising temperatures, and changes in species assemblages due to fisheries management, invasive species, and range shifts.

Saltmarshes have served as a model system for understanding material and energy flows for more than half a century. Physical stressors (e.g. inundation time, temperature) and resource availability regulate much marsh primary and secondary production and internal recycling (e.g., Valiela and Teal 1979, Dai and Wiegert 1997), while the presence of consumers and filter-feeders (e.g., Daleo et al. 2015), consumer diversity (e.g., Hensel and Silliman 2013), and invasive species (e.g., Hacker and Dethier 2006) can support ecosystem regulation. Species interactions and community composition varies with diversity, density, and stability of plant, animal and microbial assemblages, creating a major knowledge gap in how changes to these communities mediates the performance and maintenance of individual and multiple ecosystem functions (Baker et al. 2021, Lafage et al. 2021).

Due to the within-marsh scale of much of this research, our understanding of how physical processes and dispersal connect or isolate saltmarsh communities at larger scales (i.e., meta-community dynamics), and the consequences of connection/isolation levels for marsh structure, stability and functions, remains context dependent (e.g. Waltham et al. 2021). In particular, the roles of ocean currents, estuarine circulation, river discharge and marsh geomorphological features in controlling plant and animal propagule exchange in saltmarshes remain largely unexplored. This lack of knowledge regarding the 'supply side' of saltmarsh ecology impedes the ability to predict how species' range shifts (e.g., mangrove encroachment into saltmarshes, expansion of invasive green crabs, arrival of new colonists; but see Kimball & Eash-Loucks 2021) and fluctuations in climatic conditions (e.g., El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) cycles) may influence saltmarsh species' composition and genetic diversity. Finally, rigorous evaluation of the effects of stochastic processes on saltmarsh communities is rare and our understanding of microbial community dynamics (i.e., turnover and diversity) remains quite limited.

RP7: How can integration of biological processes into physical models improve understanding of saltmarsh dynamics?

Saltmarsh vegetation closely interacts with its abiotic environment through feedback mechanisms between hydrodynamics, sediment dynamics and vegetation growth (Murray et al., 2008; Fagherazzi et al., 2012; Saco and Rodriguez, 2013). Such interactions are further complicated by plant-animal interactions such as predation and grazing of vegetation by domestic livestock (Silliman and Bertness 2002, Fairchild et al. 2021). Integration of physical and biological processes in models can simplify these often-non-linear interactions and improve their management. Biophysical interactions are often studied in isolation as saltmarsh vertical accretion (Morris et al. 2002; Mudd et al., 2009) or the effects of vegetation on hydrodynamics (Leonard and Luther, 1995, Bouma et al., 2007). Integrating small-scale interactions into landscape-scale models is needed (Ibáñez et al., 2014) especially in relation to long-term abiotic change.

The integration of biological and physical processes in models so far has been achieved in the following ways:

a) Conceptual models have been proposed specifically to understand critical transitions between the tidal flat and the vegetated saltmarsh state (Marani et al., GRL 2007; Balke et al., 2014) or cyclic behaviour of lateral marsh dynamics (Bouma et al. 2016, van de Koppel et al., 2005). Simple metrics have been developed based on such models to predict saltmarsh change (Balke et al. 2014, Ganju et al., 2017).

b) Empirical/physical models in engineering flumes are used to study the effect of vegetation on flow and wave attenuation (Nepf, 1999; Vandenbruwaene et al., 2011). This has been important to validate numerical models and to quantify the coastal protection function (Möller et al., 2014).

c) The minimum requirement to numerically model water flow through the marsh canopy is the use of an overall drag coefficient as a function of vegetation biomass (Baptist et al., 2007, see also van Veelen et al. 2020 for integration of plant flexibility). Vegetation can also be modelled as rigid cylinders with a specific stem density, length and diameter (Fagherazzi et al., 2012; Saco and Rodriguez, 2013). Direct capture by vegetation stems, change in settling velocity, and direct organic production have also been related to biomass (Morris et al., 2002; D'Alpaos et al., 2007).

Models describing the coupled evolution of landforms and biota are rapidly being developed; however, most of the existing models are studying the effects of vegetation on abiotic processes and less so the effects of physical processes on saltmarsh biota. Models should be developed that go beyond specific environmental conditions (e.g. tidal range, species or sediment type) and include other vital information, such as data on biogeochemical processes, as well as potentially including relevant social and economic data so that system change can be accounted for within management decisions.

RP8: Do invasive marsh species contribute to ecosystem services and how does this contribution vary globally?

The effect of invasive primary producers and animals has been quantified in saltmarshes around the world and vary in both impact and manageability. Invasive grasses can spread rapidly by outcompeting native grasses and colonising denuded habitats (Bertness et al. 2002, Ayers et al. 2004), while invasive mammals and wildfowl species can modify marsh structure and functioning (Isaac-Renton *et al.* 2010, Hensel et al 2021) by decreasing aquatic habitat quality through fouling and compaction of sediment, reducing biodiversity, or altering biogeochemical processes (Levin et al. 2006, An et al. 2007, Gedan et al. 2009). Given these deleterious effects, there has been huge investment in time and money to monitor, prevent and eradicate invasive species (Roberts and Pullin 2008), with good examples of success (Rohmer et al. 2014, Adams et al. 2016), but eradication attempts often have had little long-term success over large spatial scales, and full recovery of functioning and species diversity can take a century (Garbutt and Wolters 2008, Pétillon et al. 2014). More recent work has shown that invasive species, in certain contexts, can increase coastal ecosystem services by vegetating bare ground, stabilising unstable edges, or building marsh elevation. For example, invasives (or hybrids) can expand or create new marshes suitable for reclamation (An et al. 2007, Kennedy et al. 2018), filter pollutants (Shutes 2001, Lee 2003), resist sea level rise with increased accretion rates (Rooth and Stevenson 2000) and sequester more carbon than native species (Liao et al. 2007, Kennedy et al. 2018).

To generate new ideas for alternative management of invasive non-native species, a more thorough assessment of invasive species impacts in marshes is required, including investigating impacts on many ecosystem services and weighing that in terms of a cost benefit analysis for different management scenarios at various geographical scales. We must determine both the positive and negative effects on functioning that invasives and natives have on both individual services as well as integrative indices (i.e. multifunctionality), and how these might vary in response to climate change, to properly estimate which ecosystem services are being delivered or hindered. Importantly, measurements should span multiple spatial scales (i.e. plot level, whole marsh level, and regional) to properly map marsh wide service provision. Second, scientists, managers, stakeholders and citizens must work together to identify the most important ecosystem services to conserve in a given region (Smeaton et al., 2022). For example, whilst some marshes lose biodiversity-rich habitats when invaded by *Phragmites australis,* low lying saltmarshes facing rapid sea level rise may benefit from increased accretion rates typically provided by this invader (Rooth and Stevenson 2000). In the Mississippi Delta (Louisiana, USA), *P. australis* has stabilised the river levees, and thus its recent dieback is causing major concerns (Cronon et al., 2020).

Lastly, managers must explicitly weigh the short- and long-term cost and value of their marshes under different invasive species management regimes. Total eradication is difficult, expensive, and could weaken the overall services that a given marsh can provide. Partial eradication (e.g. containing an invasive plant to a certain marsh zone) could maximize functioning provided by both invasive and native species. More research is needed to design effective ways of measuring services to better inform local habitat managers the scales at which invasive species may affect ecosystem goods and services provision in native marshlands.

3.4. Theme 4: Management and Policy Needs

RP9. What are the challenges and opportunities to the effective management of saltmarsh ecosystem services?

Recent years have seen the conservation, management and restoration of saltmarshes prioritised at national levels and through international means such the Convention on Wetlands of International Importance (Ramsar Convention 1971) and the United Nations Convention on Biological Diversity (CBD 2000). Still, local and regional drivers of coastal governance and management make the trade-offs between conservation and management of saltmarsh ecosystem services complex. These trade-offs can be dramatic, such as the complete loss of saltmarsh habitat and associated services for development; or more subtle, such as the trade-off between grazing of livestock and fisheries maintenance. Furthermore, there is a need for more research on the barriers and enablers of large-scale coastal wetland restoration if coastal restoration efforts are to be upscaled as part of adaptation/mitigation strategies against climate impacts.

Across the globe, opportunities exist to plan, design, and implement various management tools based on ecosystem service frameworks to achieve sustainable management, including marine spatial planning, ecosystem-based management, and integrated coastal zone management (Post and Lundin 1996, Granek et al. 2009, Foley et al. 2010, EU 2014). Many of these planning and management processes have recommended saltmarsh restoration through the use of managed realignment, or the removal of barriers and flooding of reclaimed land. These activities have been supported by positive cost benefit analyses (Turner et al. 2007, Luisetti et al. 2011); however, these analyses rarely include economic values for regaining coastal protection, fisheries, tourism and recreation, or carbon sequestration. Understanding how these services and benefits may trade off against each other is an important, yet complicated, aspect of future restoration efforts. To address this, some management strategies include “bundling” of ecosystem services as a way of minimizing trade-offs and maximizing services (Raudsepp–Hearne et al. 2010, Lester et al. 2013). For example, UK saltmarshes are widely grazed for both agricultural purposes and are used as a conservation tool to enhance floral and faunal biodiversity (Bouchard et al. 2003). Floral and faunal species richness is generally maximized under light grazing regimes, although care needs to be taken when calculating stocking densities to account for effects of spatial and temporal variation in livestock activity (Sharps *et al.* 2017). Grazing may also have a positive effect on saltmarsh carbon sequestration, depending on a complex interaction of stocking density, grazer type, saltmarsh zone, seasonality, factors associated with geographic location and other abiotic parameters (Davidson et al. 2017).

Another management tool, Payments-for-Ecosystem-Services (PES), provides an incentive-based mechanism promoting sustainable management of natural resources (Lau 2013). Despite the variety of ecosystem services provided by saltmarshes, their potential inclusion in PES schemes has not been maximised globally. Considering the valuable climate regulation service that saltmarshes provide, there is significant potential to establish PES markets, engaging third parties through corporate social responsibility schemes, for example, to help finance saltmarsh management and ensure continuing provision of services (Muenzel and Martino, 2018). There is a need, however, to test the effective of PES approaches to ensure their feasibility in different environmental, geographical, social and economic contexts and to explore such management tools and opportunities of effective management of saltmarshes, especially in the light of increasing calls for saltmarsh habitat creation and restoration.

RP10: What management actions can be used to enhance the protective function of saltmarshes?

Saltmarshes have long been recognised as highly valuable in terms of contributing to coastal protection (Gedan et al. 2011; Temmerman et al. 2013, Fairchild et al. 2021) by *i)* attenuating waves reaching the flood-defence behind the marsh (Möller et al. 1999), *ii)* reducing storm surges (Loder et al. 2009) and *iii)* by minimizing coastal erosion (Feagin et al. 2009; Wang et al. 2017b).

When comparing various coastal ecosystems, marshes come out as highly efficient in attenuating waves due to their high position in the intertidal (Bouma et al. 2014). Wave attenuation by marsh vegetation is the result of the interaction of the vegetation structure with the orbital water motion. This effect is typically the strongest for stiff and dense vegetation (Bouma et al. 2005, 2010) for the time that the water-level is relatively low compared to the vegetation, typically expressed as Hw/Hp-ratio (water depth at high tide to average height of the tallest 33% of plant stems: Yang et al. 2011). This wave attenuation by the vegetation is important in that it allows the marsh to accrete sediment (Bouma et al. 2005). This results over time in an elevated bio-geomorphic marsh platform. During the rare extreme conditions for which flood defences have been designed, with high water levels and high waves, the marsh vegetation may significantly contribute to wave attenuation (Möller et al. 2014). However, as vegetation progressively flattens and breaks, the capacity of the vegetation to attenuate waves reduces (Möller et al. 2014; Vuik et al. 2017). However, the resistance of plants may depend on various characteristics (Schoutens et al. 2020), which can differ between and within species and over time (Schulze et al. 2019). Fortunately, the marsh platform is highly erosion resistant (Möller et al. 2014; Spencer et al. 2016), so that the "plant-built" biogeomorphic elevated marsh platform remains effective in attenuating the wave loads reaching the flood defence (Vuik et al. 2017).

Compared to wave attenuation, the effect of marshes on storm-surge water-levels is much less studied and the effects less clearly defined, although existing studies suggest the effect is important (Loder et al. 2009; Fairchild et al. 2021). It has been well recognized that marshes can strongly reduce erosion caused by storm events, with the roots binding the sediment (Lo et al, 2017; De Battisti et al., 2010). However, in the long-term this does not prevent marshes from lateral erosion. Cyclic dynamics, with alternating phases of lateral erosion and lateral expansion, have been recognised as an inherent property of natural minerogenic saltmarshes (van de Koppel et al. 2005). The rate of erosion is affected by *i)* landscape setting, with the length of the fetch as main driver, *ii)* sediment type, with mud-content being the main driver, and *iii)* plant species, with root biomass as main driver (Lo et al. 2017; Wang et al. 2017b, Ford et al. 2016). On top of this, management measures such as cattle grazing may influence directly and indirectly marsh erodibility (by altering sediment compaction and plant traits, respectively; Elschot et al. 2015; Pagès et al. 2019) whereas human influences like eutrophication may enhance erodibility (Deagan et al. 2012). The marsh erosion-rate is more determined by the average wave conditions than (rare) extreme storm events, as average wave conditions can have greater impact by being present all the time (Leonardi et al. 2016).

Given that coastal engineering structures are typically designed and built for a lifespan of 50 years, decisions require in-depth understanding of the long-term marsh dynamics to include them as integral part of the flood defence (Bouma et al. 2014). To manage the foreshore tidal flats fronting a marsh seems a promising way forward to manage lateral marsh dynamics, and thereby the marsh width (Hu et al. 2015). The management choice will strongly depend on the tidal prism and specific setting of a marsh. While wave attenuation across marsh surfaces is fairly well understood, predictability of lateral dynamics and aboveground biomass of marshes as key contributions to coastal protection needs further attention.

4. Conclusion and recommendations

With both the UN Decade of Ocean Science for Sustainable Development (2021-2030) and the UN Decade of Ecosystem Restoration (2021-2030) as a political and research backdrop, the paper presents an overview of co-identified current research priorities for saltmarsh conservation and management (summarised in Table 1).

Table 1. Recommendations on the practical steps that can be taken by researchers, policymakers, and practitioners to address each of the top ten research priorities identified by expert opinion.

Research Priority	Suggested Research Activities
RP1: How has the rate of change in areal extent varied globally over time?	Produce robust calculations of global saltmarsh extent change from the 2023 baseline (Worthington et al. 2013) using satellite data and where possible, aerial photography, historical mapping and traditional ecological and Indigenous knowledge.
RP2: Where and how can saltmarshes be realistically restored?	Construct validated restoration potential maps (appropriate to restoration techniques available) that incorporate key biotic/ecological, geomorphic, and social factors known to influence the long-term success of saltmarsh restoration schemes
RP3: How does ecosystem service delivery vary with key marsh features and climate change?	Construct validated maps of ecosystem service function and value, drawing on various sources of information and evidence, including traditional and Indigenous knowledges to map and evaluate variations in ecosystem service delivery.
RP4: How are saltmarsh ecosystem services valued amongst different groups across the globe?	Integrate social science methodologies into saltmarsh research programmes to support evaluation of the ecosystem services delivered by saltmarshes globally. Develop a global database of ecosystem service valuations (including monetary and non-monetary) which can be used to support management and restoration of saltmarshes.
RP5. What are the cultural ecosystem services of saltmarshes and what factors drive spatial-temporal variation in these services and benefits?	Prioritise understanding of the importance of the CES provided by saltmarshes, including the design of valuation tools which include the diverse values which can be attributed to CES. Use participatory methods and future scenarios to validate how CES values may fluctuate with changes in saltmarsh extent to support restoration and conservation initiatives.
RP6: What are the global drivers of saltmarsh ecosystem structure and function?	Map connectivity between saltmarshes and other habitats (e.g. mudflats) to better understand how they might impact each other. Develop validated models to explore how inputs from both the land and seaward side of saltmarshes impact their extent and ecosystem function and service provision.
RP7: How can integration of biological processes into physical models improve understanding of saltmarsh dynamics?	Produce validated models which integrate a wide range of parameters, including biogeochemical data, to evaluate system change and its impacts on saltmarshes.
RP8: Do invasive marsh species contribute to ecosystem services and how	Develop longitudinal monitoring programmes for assessing the extent and impact of INNS on saltmarshes.

Research Priority	Suggested Research Activities
does this contribution vary globally?	Produce evaluation approaches which take account of INNS and recognise their potential for both positive and negative contributions to ecosystem function.
RP9. What are the challenges and opportunities to the effective management of saltmarsh ecosystem services?	Develop understanding of the barriers and enablers associated with saltmarsh restoration, including social acceptability of initiatives within local communities. Design and test PES schemes to support saltmarsh conservation and management.
RP10: What management actions can be used to enhance the protective function of saltmarshes?	Explore options that maximise flood risk mitigation by saltmarshes within a Nature-based Solutions framework through field observations, flume experiments, and numerical models at plant to coastal cell scales.

By drawing on multiple disciplines, saltmarshes are further recognised as complex socio-ecological systems, which require a truly transdisciplinary research agenda to respond to the extreme changes and pressures facing these fragile and vulnerable ecosystems. The research agenda sets out an initial blueprint of research priorities for both managers and policymakers at international, national, regional and local scales, providing a foundation to support the development of future research programmes globally. While a valuable and much needed starting point, it is important to emphasise that this is not an exhaustive nor conclusive list. Saltmarsh research must and will continue to evolve in response to a rapidly changing social, economic, ecological and cultural global context. Emerging fields of research (such as forecasting of climate change effects on ES) and new tools (e.g. the use of non-invasive monitoring, such as eDNA and drones to monitor saltmarsh biodiversity) indeed provide opportunities to address many of the research questions outlined and support global conservation and management of saltmarshes.

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Figure 1. Worldwide cover of intertidal salt marshes (redrawn and updated from Mcowen et al. 2017).

Figure 2. A) Illustration of general context-dependency of appropriate ecosystem management interventions to ensure continued delivery of functional ecosystems from which beneficial services flow. B) Example of how a particular ecosystem service, coastal protection by salt marshes, depends on three key contextual factors, in this case, exposure, tidal range and degree of human development.

Figure 3. Research Priorities for future saltmarsh research.

Figure 4. Drastic saltmarsh losses and gains. A) Reclaimed areas in coastal China (note the figure for 2010-2020 is planed reclamation). B) Trends in annual suspended-sediment loads of Mississippi River at Tarbert Landing, Mississippi. C) Trends in relative mean sea level (relative to the most recent Mean Sea Level datum established by CO-OPS) at Cedar Key, FL. D) Coastal development around a salt marsh in North Carolina. E) Sinking salt marshes in the Mississippi Delta. F) Conversion of coastal forests into salt marshes in New Jersey, due to saltwater intrusion. Data sources and photo credits are to be added.

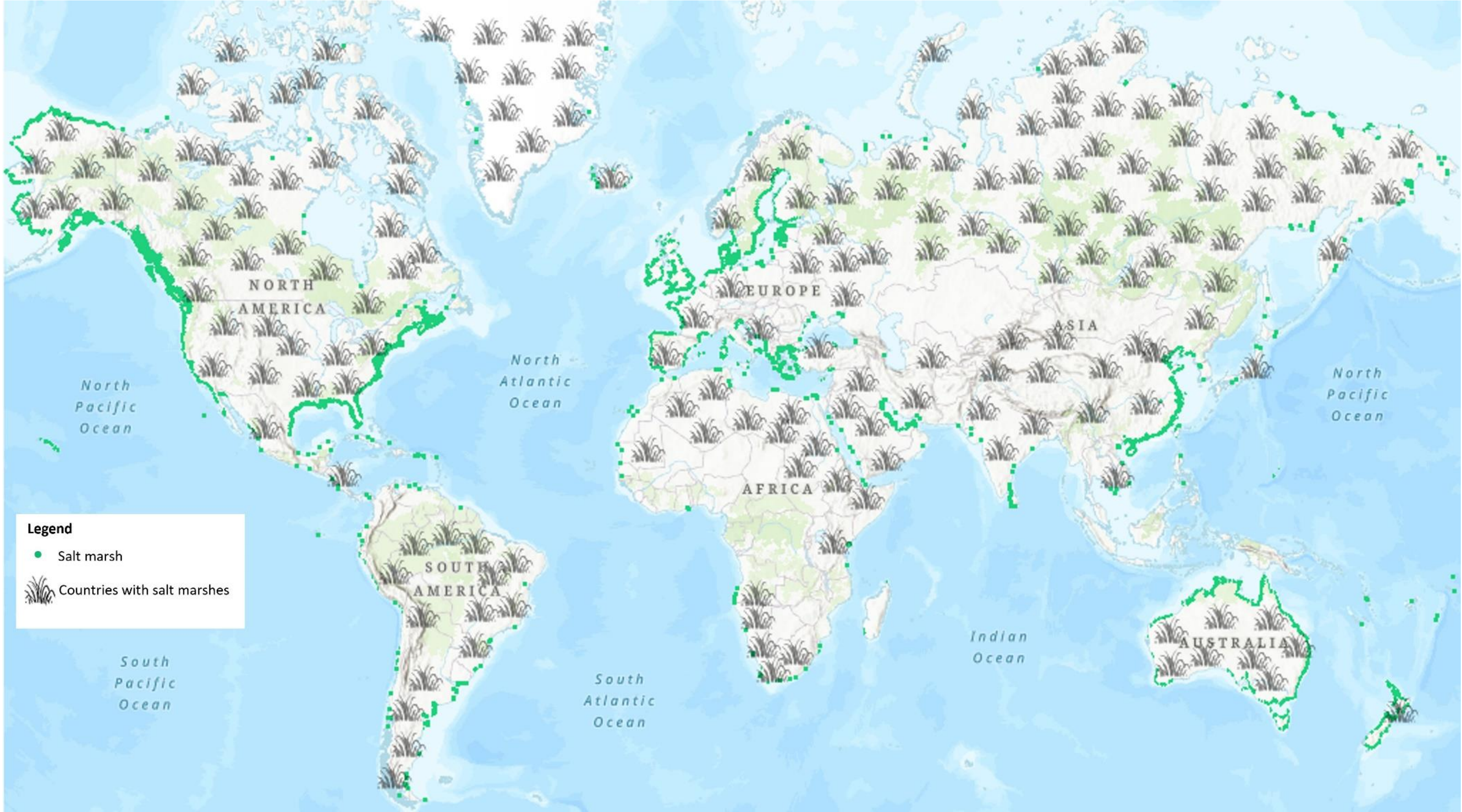

Fig. 1. Pétillon, McKinley et al.

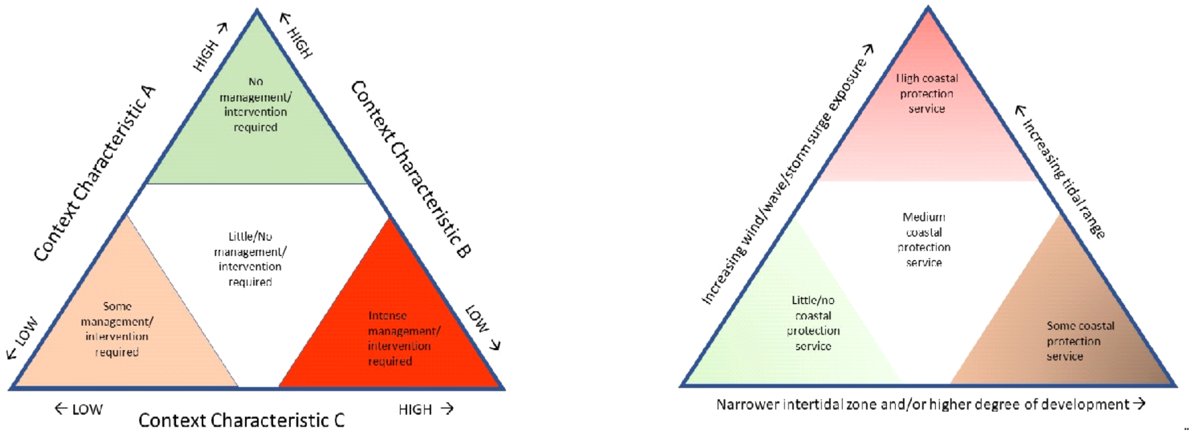

Fig. 2. Pétillon, McKinley et al.

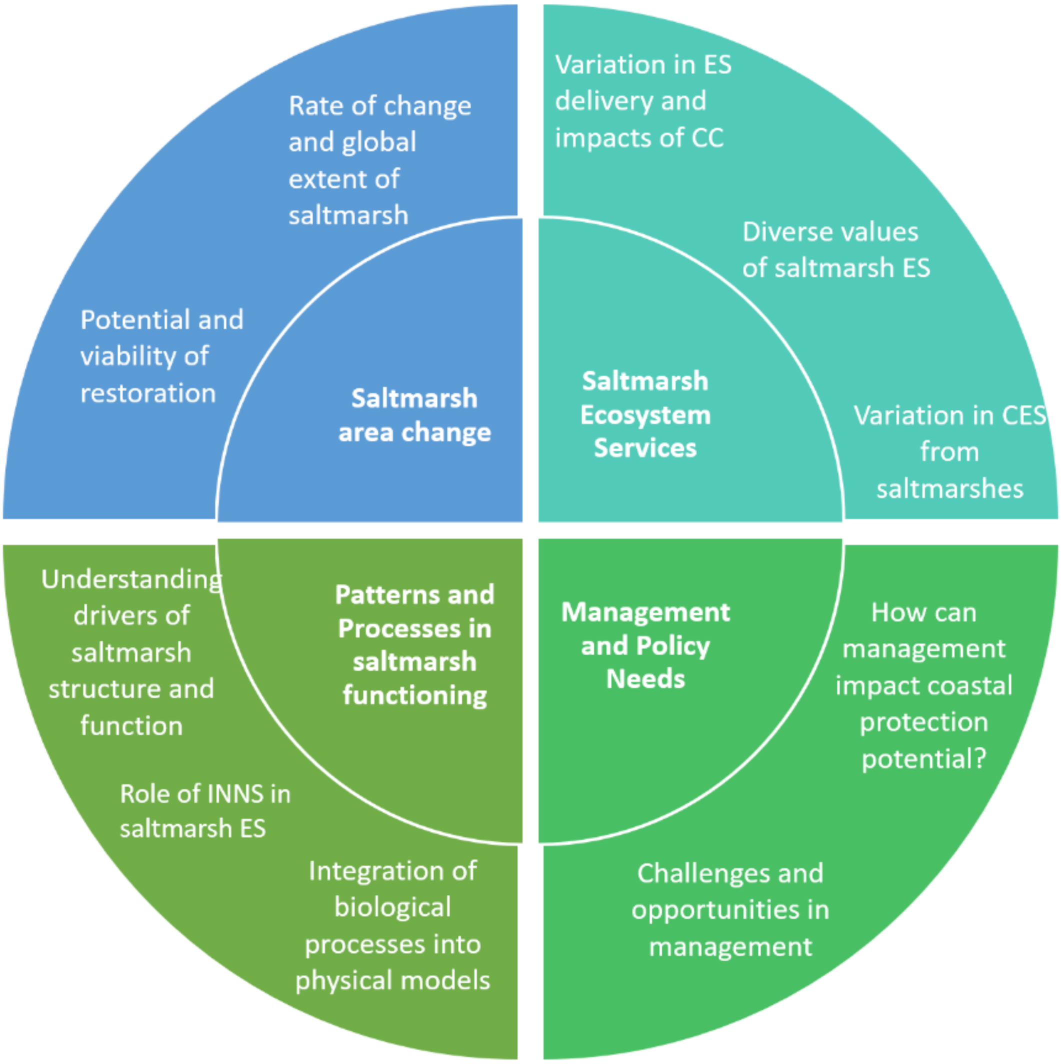

Fig. 3. Pétillon, McKinley et al.

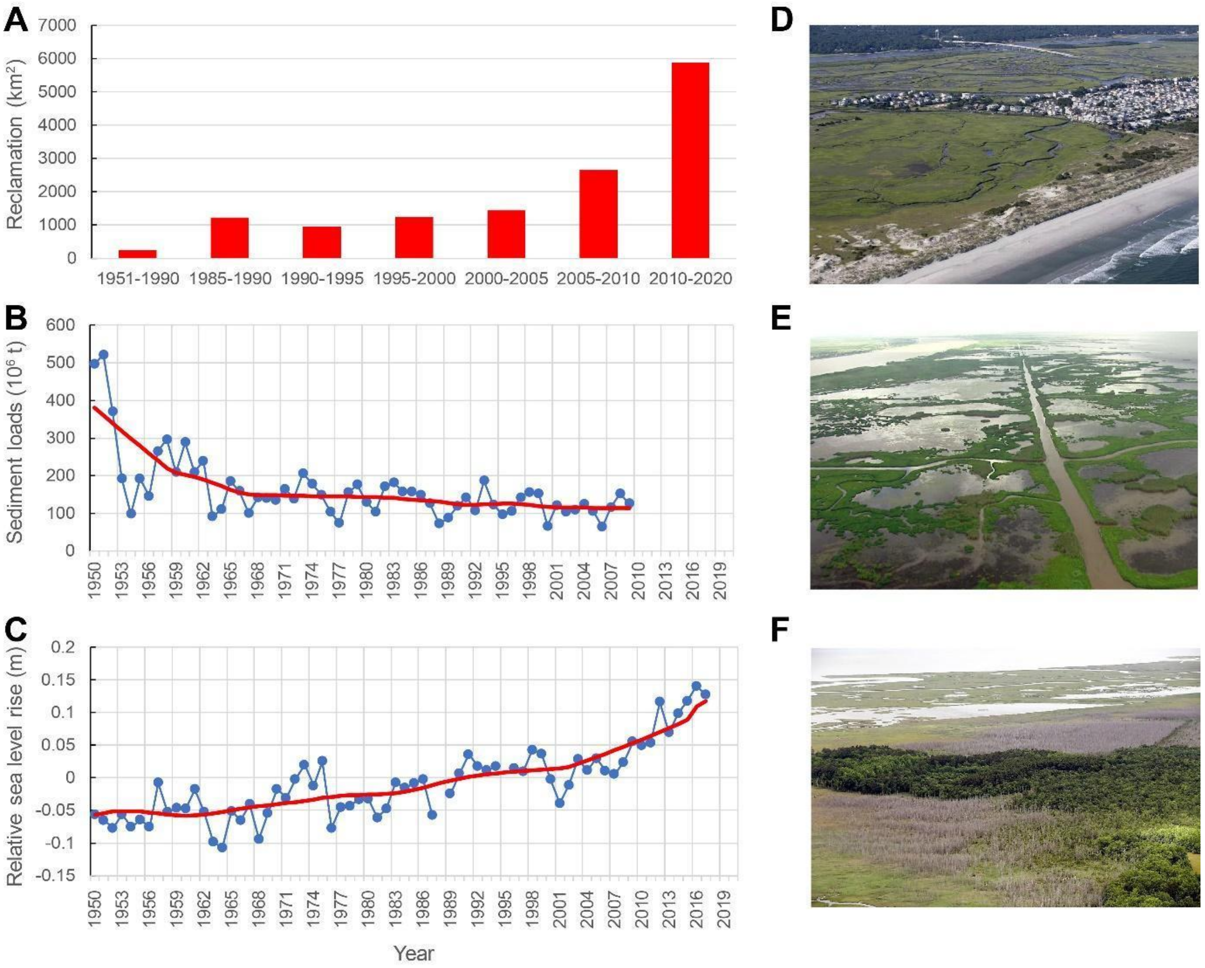

Fig. 4. Pétillon, McKinley et al.