

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

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

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71

72 **Abstract**

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

92

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

95

96

97 **1. Introduction**

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

104 Throughout centuries of disturbance, saltmarshes have been diked and drained for
105 agriculture and land development, used for livestock grazing, and managed for fisheries and
106 aquaculture (Gedan et al. 2009). Major coastal settlements including the global cities of Boston,
107 London and Shanghai were developed on filled or drained coastal wetlands. Over 50 percent
108 of saltmarsh habitat in Europe has been lost to coastal development alone (Airoidi and Beck
109 2007). Estuarine saltmarshes are particularly vulnerable to impacts from riverine management
110 including alterations to freshwater runoff, sediment, nutrients, heavy metals, and other
111 pollutants (Adams, 2020; Silliman et al. 2009). At global scales, accelerated sea level rise and
112 increasing storm intensity and frequency contribute further to saltmarsh loss from prolonged
113 flooding and erosion (Schuerch et al. 2018). The threat from sea level is considered so severe,
114 that saltmarshes globally may be lost unless considerable efforts are taken to realign the coast
115 (Crosby et al. 2016; Horton et al. 2018; Törnqvist et al. 2020; Saintilan et al. 2022; Ohenhen
116 et al. 2023).

117 By recognising that marsh degradation threatens critical ecosystem services (Barbier et al.
118 2011), efforts are underway to protect, restore, and predict how saltmarshes will respond to
119 global change drivers (Murray et al. 2022). Key to this effort is interdisciplinary research to
120 understand how ecosystem services and function vary with marsh characteristics and different
121 socio-environmental contexts (Fig. 2). Despite marshes being one of the most geographically
122 widespread coastal vegetated ecosystems, occurring from the arctic to the tropics (Mcowen et
123 al. 2017), and given the pace at which climate change and anthropogenic activity are degrading
124 especially vulnerable saltmarsh socio-ecological systems worldwide, a rapid shift in research
125 priorities is needed to address the key barriers to a sustainable future for saltmarshes.

126 Using expert opinion from an international network of multi-disciplinary researchers,
127 policymakers, and practitioners, this paper presents the top ten research priorities in global
128 saltmarsh research to date. For each research priority, we summarise the current state of

129 knowledge and set out how impactful research can support international decision making on
130 marsh conservation, restoration and management in the final section.

131

132 **2. Methods**

133 Standard approaches for expert identification of research priorities were adopted (as outlined
134 by Sutherland et al. 2013). Initially using a purposive sampling approach (i.e. selecting
135 participants with relevant expertise and knowledge), drawing on the existing network of the
136 project lead partner, and then supplemented through snowball sampling (i.e. individuals
137 recommended to the research team), a multi-disciplinary group of 35 saltmarsh experts from
138 11 countries and six continents was identified and invited to participate in this study. This team
139 encompassed natural and physical scientists with expertise in saltmarsh oceanography,
140 sediment dynamics, ecological and biological composition, and ecosystem modelling; social
141 scientists with expertise in ecosystem service valuation, governance and public perceptions
142 (Academics $n = 28$); and representatives from saltmarsh governance and management
143 organisations (Practitioners $n = 7$), including five Early Career Researchers from a range of
144 disciplinary backgrounds.

145

146 Research questions were identified through a 3-step process. (1) Using an online questionnaire
147 (available in Supp. Materials), delivered through the Survey monkey platform, participants
148 were asked to respond to a number of questions regarding a wide range of issues relating to
149 salt marsh ecosystem services and management. An initial research prioritisation process was
150 carried out through an open question where experts were asked to list 10 priority research
151 questions concerning saltmarsh ecosystem functioning and ecosystem services, with a total of
152 191 research questions returned. (2) Analysis of the questions resulted in the identification of
153 15 research themes, with each theme containing between 5 and 33 questions. Data analysis
154 involved thematic coding of the individual responses, using standard qualitative analysis
155 techniques and data reduction processes (Braun, 2006) carried out by three of the research team
156 to ensure the consistency of the thematic coding. (3) A four-day workshop was held in Wales,
157 United Kingdom, in December 2017. The workshop programme included initial context setting
158 presentations from a number of the workshop attendees, with a day and a half allocated to the
159 research prioritisation exercise. To do this, attendees were divided into four multidisciplinary
160 groups, with participants able to self-select their preferred group depending on the themes
161 being discussed, and each assigned 2-4 themes including the original research questions and
162 tasked with firstly discussing and synthesising these themes. Each group then voted to produce

163 a shortlist of 10 key questions per theme, hereafter called research ‘priorities’. Experts were
164 each allocated 5 stickers and asked to place these by the research priorities of greatest
165 importance to them, using a colour-based coding of rank importance. The top 10 research
166 priorities were then identified according to the total number of stickers. Since the workshop in
167 2017, the identified research themes have undergone a subsequent review by the authorship
168 team in 2022 to ensure their ongoing relevance. No changes were made to the identified
169 priorities following this process. This process was carried out in accordance with Cardiff
170 University Ethics Procedures (Approved August 2016),

171

172 **3. The Top Ten priorities for global saltmarsh research**

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

177

178 **3.1. Theme 1: Saltmarsh Area Extent, Change and Restoration Potential**

179

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

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

186 Saltmarsh gains appear to have marginally exceeded losses by an estimated 100
187 km² between 1999 and 2019 (Murray et al. 2022). Patterns of marsh expansion and erosion
188 vary between regions. For example, the Mississippi delta lost ~5,000 km² of its marshes
189 between 1932 and 2010 (Couvillion et al. 2011), whilst marshes along the China coast
190 expanded by ~8,000 ha between 2010 and 2019 (Chen et al. 2022).

191 Although changes in saltmarsh extent at the single-marsh scale have been reported
192 especially across Europe and North America (e.g. Bromberg & Bertness 2005, Prahalad 2014),
193 regional-scale studies rarer (Gu et al. 2018; Ladd et al. 2019), and global-scale studies are short-
194 term and coarse resolution (Murray et al. 2022). Studies at these varying scales are necessary
195 as local, small-scale studies of marsh change are not always indicative of larger-scale trends in
196 marsh change. In the UK, for example, high rates of erosion observed along Southeast England

197 coastlines had been up-scaled to predict marsh change across the entire UK to dictate
198 conservation policy (Pye & French 1993), but a later study revealed that northern regions had
199 been stable/expanding (Phelan et al. 2011). Similar variation across scales have been seen in
200 North America (Gedan & Silliman 2005) (Fig. 4), further highlighting the overall importance
201 of this research question.

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

215

216 **RP2: Where and how can saltmarshes be realistically restored?**

217 In light of historical losses in the extent of saltmarshes worldwide (Gedan et al. 2009), and the
218 growing vulnerability of the marshes that remain (especially to sea level rise; Saintilan et al.
219 2022), restoration of intertidal areas and the ecosystem services they sustain (Wolters et al.
220 2005) is now seen as a global priority (Fischer et al. 2020).

221 To deliver on global habitat restoration goals, areas suitable for restoration must be
222 selected based on cost-benefit analysis of the restoration methods required (Armitage 2021),
223 whether the areas earmarked for restoration have the potential for long-term success and do not
224 interfere with natural marsh expansion-erosion dynamics (Wolters et al. 2005), and the value
225 of ecosystem service and biodiversity benefits likely to emerge from the restored habitat,
226 especially for coastal flood protection (Luisetti et al. 2011) and carbon sequestration
227 (McMahon et al. 2023). Tidally restricted coastal areas may need improved hydrological
228 connectivity (e.g., tidal gates dismantled, or upstream dams/levees removed), while bare,
229 degraded, or eroding marshes may need to be rehabilitated through active transplantation of
230 vegetation, invasive species removal, or construction of wave breaks to stabilise eroding

231 shorelines and create windows of opportunity to facilitate pioneer establishment (Silliman et
232 al. 2009). In all cases, systematic inclusion of positive inter- and intra-species interactions is
233 key to increasing restoration success (Duggan-Edwards et al. 2020). Furthermore, the use and
234 values attributed to the hinterland selected for managed realignment must be considered – low-
235 value biodiversity-poor agricultural land, where removal of dykes and levees would lead to
236 natural recolonisation of saltmarsh, may represent an example of high restoration potential
237 (Waltham et al. 2021).

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

245

246 **3.2. Theme 2: Spatio-social contexts of Ecosystem Service delivery**

247

248 **RP3: How does ecosystem service delivery vary with key marsh features and climate** 249 **change?**

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

260 Key marsh features have a particularly strong effect on the role that saltmarshes play in
261 coastal protection. Near the seaward extent of the marsh, saltmarshes alter storm surge water
262 levels as the bulk flow of water is reduced, causing a water surface slope from sea to land on
263 the rising tide and from land to sea on the falling tide (Möller et al. 2014). Depending on the
264 marsh configuration and position along an estuary (Fairchild et al. 2021), this effect can lead

265 to a prolonged residence time of high-water levels at the landward margins of the marsh (Loder
266 et al. 2009) and is therefore likely to vary with saltmarsh area, latitude, width, and volume.
267 Close to the shore, saltmarsh habitat provides resistance to erosion due to surface topography,
268 vegetation cover and the presence of creek systems (Spalding et al. 2014; Spencer et al. 2016).
269 It is not known which saltmarsh features determine erosion resistance, although it has been
270 suggested that sedimentology and root zone characteristics play a key role in this (Crooks &
271 Pye 2000, see also Silliman et al. 2019 and De Battisti et al. 2019), but the role of saltmarshes
272 in slowing down erosion may be context-dependent (e.g., less relevant for open coasts than for
273 semi-enclosed coasts). Questions remain as to how climate change will affect ecosystem
274 services delivery; what will be the extent of saltmarsh loss due to coastal squeeze and sediment
275 deficit (see Schuerch et al. 2018)? How will the scale of saltmarsh change impact ecosystem
276 service delivery (Ladd et al., 2021)? How can we relate changes in saltmarsh area and elevation
277 to functional relationships and loss of ecosystem services? How will changes in species
278 composition and range shifts due to warming and elevated CO₂ influence ecosystem service
279 delivery? And how will shifts in ecosystem type or identity of main foundation species affect
280 services (including the current trend of mangroves changing into saltmarshes with global
281 warming, or vice-versa: Kelleway et al. 2017)? Several of these questions can be investigated
282 by examining the existing variation in structure and function across climatic gradients using a
283 space for time substitution approach (e.g. the latitudinal trend of productivity in the saltmarsh
284 plant *Spartina alterniflora*: Kirwan et al. 2009 or the use of standardised litter to assess
285 decomposition Mueller et al. 2018). Another approach could be to reconstruct ecosystem
286 service change by studying contrasting sites and then map the ecosystem services of the area.
287 Models could then be used to simulate the environmental conditions of the area in the future
288 and map the projected ES distribution.

289 There has been an increase in the number of modelling and empirical tests of different
290 climate change drivers on saltmarsh ecology and geomorphology (see for example Gedan &
291 Bertness 2009, Kirwan & Mudd 2012; Smith et al, 2022). Yet, while some drivers such as sea
292 level rise have been studied intensively, and temperature increasingly, others such as drought
293 and elevated CO₂ need further investigation.

294

295 **RP4: How are saltmarsh ecosystem services valued amongst different groups across the** 296 **globe?**

297 The interest and values ascribed to specific saltmarsh ecosystem services vary widely between
298 groups (e.g. policy makers, land owners, civil society, Indigenous peoples) (Granek et al.,

299 2010; McKinley et al., 2020a; Thomas et al., 2022; Rendon et al., 2022; Burdon et al., 2022;
300 Rahmen et al., 2023). Recognizing, describing, and embracing the plurality of stakeholder
301 values facilitates improved engagement of diverse actors, support meaningful management
302 negotiations and enhance the legitimacy and public acceptability of resulting decisions and
303 management (Roca and Villares, 2012; Simpson et al., 2016). Understanding stakeholder
304 values of saltmarsh ecosystem services, therefore, has clear implications for governance and
305 management at local, (sub)-national and international scales (Loft et al., 2015). An analysis of
306 these values on a global scale could also shed light on the underlying anthropogenic factors
307 attributing to the current decline in saltmarsh coverage (Garcia Rodrigues et al., 2017).

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

326 To date, research into stakeholder perceptions and values of saltmarsh ecosystem services
327 is arguably fragmented in terms of the representation of geographies, temporal variation, types
328 of services and stakeholders. Despite recent efforts (McKinley et al., 2020b), to support future
329 management and policy there is a need for a global, robust means to document, assess and
330 monitor the ways in which stakeholder values differ across spatio-temporal scales and identify
331 underlying factors shaping these differences. Moreover, such research could help address
332 knowledge gaps, such as private sector engagement with blue carbon, how this aligns to

333 stakeholder objectives across various sectors and where this interest is located. Moving
334 forwards, it is vital that saltmarsh research continues to embrace the social sciences within the
335 wider research agenda.

336

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

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

345 Research highlights the role of CES in providing material and intangible benefits in coastal
346 (e.g. Brown and Hausner, 2017) and marine habitats (Jobstvogt et al., 2014; Liqueste et al.,
347 2013), focussing mainly on mangroves and seagrasses (Himes-Cornell et al., 2018). The
348 limited literature addressing saltmarsh CES shows that stakeholders tend to attribute high
349 rankings to tourism and recreation (Cabral et al. 2014; Hutchinson et al., 2012), but rarely
350 consider sense of experience (Thomas et al., 2022; Carollo et al., 2013; da Silva et al., 2014;
351 Christie and Rayment, 2012) and spiritual and inspirational benefits (McDonald, 2003; Church
352 et al. 2014). Aspects of wellbeing such as physical and mental health provided by coastal
353 habitats have been studied (Wheeler et al., 2012; Gascon et al., 2017), but similar human
354 benefits provided by saltmarshes have not been frequently reported although there are
355 examples of recent work on this by Thomas et al. (2022), Rendon et al. (2019) and McKinley
356 et al. (2022).

357 The influence of social and economic drivers on delivery of CES is varied and complex,
358 with studies showing that some activities, such as land reclamation, negatively affect the
359 provision of marine cultural ecosystem services (Rocha et al., 2015; Garcia Rodrigues et al.,
360 2016), while others like saltmarsh grazing may contribute positively to biodiversity protection
361 (Ford et al., 2012; Sharps et al., 2016), which in turn can influence some aspects of wellbeing
362 (e.g. Fairchild et al. 2022; McKinley et al., 2021), and tourist attraction (van Zenten et al.,
363 2016). Clearly, there is a need for indicators (Church et al., 2014; Atkins et al., 2015; Broszeit
364 et al., 2017) to elucidate the linkages between CES and wellbeing benefits of saltmarshes, and
365 their spatial and temporal variability, currently rarely explored (Santana-Cordero et al., 2016).
366 Some examples of these links in coastal and marine landscapes are emerging (Potts et al., 2014;

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

378

379 **3.3. Theme 3: Patterns and processes in saltmarsh functioning**

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

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

398 Saltmarshes have served as a model system for understanding material and energy flows
399 for more than half a century. Physical stressors (e.g. inundation time, temperature) and resource
400 availability regulate much marsh primary and secondary production and internal recycling

401 (e.g., Valiela and Teal 1979, Dai and Wiegert 1997), while the presence of consumers and
402 filter-feeders (e.g., Daleo et al. 2015), consumer diversity (e.g., Hensel and Silliman 2013), and
403 invasive species (e.g., Hacker and Dethier 2006) can support ecosystem regulation. Species
404 interactions and community composition varies with diversity, density, and stability of plant,
405 animal and microbial assemblages, creating a major knowledge gap in how changes to these
406 communities mediates the performance and maintenance of individual and multiple ecosystem
407 functions (Baker et al. 2021, Lafage et al. 2021).

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

422

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

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

434 interactions into landscape-scale models is needed (Ibáñez et al., 2014) especially in relation
435 to long-term abiotic change.

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

- 438 a) Conceptual models have been proposed specifically to understand critical transitions
439 between the tidal flat and the vegetated saltmarsh state (Marani et al., GRL 2007; Balke
440 et al., 2014) or cyclic behaviour of lateral marsh dynamics (Bouma et al. 2016, van de
441 Koppel et al., 2005). Simple metrics have been developed based on such models to
442 predict saltmarsh change (Balke et al. 2014, Ganju et al., 2017).
- 443 b) Empirical/physical models in engineering flumes are used to study the effect of
444 vegetation on flow and wave attenuation (Nepf, 1999; Vandenbruwaene et al., 2011).
445 This has been important to validate numerical models and to quantify the coastal
446 protection function (Möller et al., 2014).
- 447 c) The minimum requirement to numerically model water flow through the marsh canopy
448 is the use of an overall drag coefficient as a function of vegetation biomass (Baptist et
449 al., 2007, see also van Veelen et al. 2020 for integration of plant flexibility). Vegetation
450 can also be modelled as rigid cylinders with a specific stem density, length and diameter
451 (Fagherazzi et al., 2012; Saco and Rodriguez, 2013). Direct capture by vegetation
452 stems, change in settling velocity, and direct organic production have also been related
453 to biomass (Morris et al., 2002; D'Alpaos et al., 2007).

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

461

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

464 The effect of invasive primary producers and animals has been quantified in saltmarshes around
465 the world and vary in both impact and manageability. Invasive grasses can spread rapidly by
466 outcompeting native grasses and colonising denuded habitats (Bertness et al. 2002, Ayers et al.
467 2004), while invasive mammals and wildfowl species can modify marsh structure and

468 functioning (Isaac-Renton *et al.* 2010, Hensel *et al.* 2021) by decreasing aquatic habitat quality
469 through fouling and compaction of sediment, reducing biodiversity, or altering biogeochemical
470 processes (Levin *et al.* 2006, An *et al.* 2007, Gedan *et al.* 2009). Given these deleterious effects,
471 there has been huge investment in time and money to monitor, prevent and eradicate invasive
472 species (Roberts and Pullin 2008), with good examples of success (Rohmer *et al.* 2014, Adams
473 *et al.* 2016), but eradication attempts often have had little long-term success over large spatial
474 scales, and full recovery of functioning and species diversity can take a century (Garbutt and
475 Wolters 2008, Pétilion *et al.* 2014). More recent work has shown that invasive species, in
476 certain contexts, can increase coastal ecosystem services by vegetating bare ground, stabilising
477 unstable edges, or building marsh elevation. For example, invasives (or hybrids) can expand
478 or create new marshes suitable for reclamation (An *et al.* 2007, Kennedy *et al.* 2018), filter
479 pollutants (Shutes 2001, Lee 2003), resist sea level rise with increased accretion rates (Rooth
480 and Stevenson 2000) and sequester more carbon than native species (Liao *et al.* 2007, Kennedy
481 *et al.* 2018).

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

498 Lastly, managers must explicitly weigh the short- and long-term cost and value of their marshes
499 under different invasive species management regimes. Total eradication is difficult, expensive,
500 and could weaken the overall services that a given marsh can provide. Partial eradication (e.g.
501 containing an invasive plant to a certain marsh zone) could maximize functioning provided by

502 both invasive and native species. More research is needed to design effective ways of
503 measuring services to better inform local habitat managers the scales at which invasive species
504 may affect ecosystem goods and services provision in native marshlands.

505

506 **3.4. Theme 4: Management and Policy Needs**

507

508 **RP9. What are the challenges and opportunities to the effective management of saltmarsh** 509 **ecosystem services?**

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

521 Across the globe, opportunities exist to plan, design, and implement various management
522 tools based on ecosystem service frameworks to achieve sustainable management, including
523 marine spatial planning, ecosystem-based management, and integrated coastal zone
524 management (Post and Lundin 1996, Granek et al. 2009, Foley et al. 2010, EU 2014). Many of
525 these planning and management processes have recommended saltmarsh restoration through
526 the use of managed realignment, or the removal of barriers and flooding of reclaimed land.
527 These activities have been supported by positive cost benefit analyses (Turner et al. 2007,
528 Luisetti et al. 2011); however, these analyses rarely include economic values for regaining
529 coastal protection, fisheries, tourism and recreation, or carbon sequestration. Understanding
530 how these services and benefits may trade off against each other is an important, yet
531 complicated, aspect of future restoration efforts. To address this, some management strategies
532 include “bundling” of ecosystem services as a way of minimizing trade-offs and maximizing
533 services (Raudsepp–Hearne et al. 2010, Lester et al. 2013). For example, UK saltmarshes are
534 widely grazed for both agricultural purposes and are used as a conservation tool to enhance
535 floral and faunal biodiversity (Bouchard et al. 2003). Floral and faunal species richness is

536 generally maximized under light grazing regimes, although care needs to be taken when
537 calculating stocking densities to account for effects of spatial and temporal variation in
538 livestock activity (Sharps *et al.* 2017). Grazing may also have a positive effect on saltmarsh
539 carbon sequestration, depending on a complex interaction of stocking density, grazer type,
540 saltmarsh zone, seasonality, factors associated with geographic location and other abiotic
541 parameters (Davidson *et al.* 2017).

542 Another management tool, Payments-for-Ecosystem-Services (PES), provides an
543 incentive-based mechanism promoting sustainable management of natural resources (Lau
544 2013). Despite the variety of ecosystem services provided by saltmarshes, their potential
545 inclusion in PES schemes has not been maximised globally. Considering the valuable climate
546 regulation service that saltmarshes provide, there is significant potential to establish PES
547 markets, engaging third parties through corporate social responsibility schemes, for example,
548 to help finance saltmarsh management and ensure continuing provision of services (Muenzel
549 and Martino, 2018). There is a need, however, to test the effectiveness of PES approaches to ensure
550 their feasibility in different environmental, geographical, social and economic contexts and to
551 explore such management tools and opportunities of effective management of saltmarshes,
552 especially in the light of increasing calls for saltmarsh habitat creation and restoration.

553

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

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

561 When comparing various coastal ecosystems, marshes come out as highly efficient in
562 attenuating waves due to their high position in the intertidal (Bouma *et al.* 2014). Wave
563 attenuation by marsh vegetation is the result of the interaction of the vegetation structure with
564 the orbital water motion. This effect is typically the strongest for stiff and dense vegetation
565 (Bouma *et al.* 2005, 2010) for the time that the water-level is relatively low compared to the
566 vegetation, typically expressed as Hw/Hp-ratio (water depth at high tide to average height of
567 the tallest 33% of plant stems: Yang *et al.* 2011). This wave attenuation by the vegetation is
568 important in that it allows the marsh to accrete sediment (Bouma *et al.* 2005). This results over
569 time in an elevated bio-geomorphic marsh platform. During the rare extreme conditions for

570 which flood defences have been designed, with high water levels and high waves, the marsh
571 vegetation may significantly contribute to wave attenuation (Möller et al. 2014). However, as
572 vegetation progressively flattens and breaks, the capacity of the vegetation to attenuate waves
573 reduces (Möller et al. 2014; Vuik et al. 2017). However, the resistance of plants may depend
574 on various characteristics (Schoutens et al. 2020), which can differ between and within species
575 and over time (Schulze et al. 2019). Fortunately, the marsh platform is highly erosion resistant
576 (Möller et al. 2014; Spencer et al. 2016), so that the “plant-built” biogeomorphic elevated
577 marsh platform remains effective in attenuating the wave loads reaching the flood defence
578 (Vuik et al. 2017).

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

595 Given that coastal engineering structures are typically designed and built for a lifespan of
596 50 years, decisions require in-depth understanding of the long-term marsh dynamics to include
597 them as integral part of the flood defence (Bouma et al. 2014). To manage the foreshore tidal
598 flats fronting a marsh seems a promising way forward to manage lateral marsh dynamics, and
599 thereby the marsh width (Hu et al. 2015). The management choice will strongly depend on the
600 tidal prism and specific setting of a marsh. While wave attenuation across marsh surfaces is
601 fairly well understood, predictability of lateral dynamics and aboveground biomass of marshes
602 as key contributions to coastal protection needs further attention.

603

604 **4. Conclusion and recommendations**

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

609

610 **Table 1.** Recommendations on the practical steps that can be taken by researchers, policymakers,
 611 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.

612

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

626

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633

634

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1197 **Figure 1.** Worldwide cover of intertidal salt marshes (redrawn and updated from Mcowen et
1198 al. 2017).

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1200 **Figure 2.** A) Illustration of general context-dependency of appropriate ecosystem management
1201 interventions to ensure continued delivery of functional ecosystems from which beneficial
1202 services flow. B) Example of how a particular ecosystem service, coastal protection by salt
1203 marshes, depends on three key contextual factors, in this case, exposure, tidal range and degree
1204 of human development.

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1206 **Figure 3.** Research Priorities for future saltmarsh research.

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1208 **Figure 4.** Drastic saltmarsh losses and gains. A) Reclaimed areas in coastal China (note the
1209 figure for 2010-2020 is planned reclamation). B) Trends in annual suspended-sediment loads
1210 of Mississippi River at Tarbert Landing, Mississippi. C) Trends in relative mean sea level
1211 (relative to the most recent Mean Sea Level datum established by CO-OPS) at Cedar Key,
1212 FL. D) Coastal development around a salt marsh in North Carolina. E) Sinking salt marshes
1213 in the Mississippi Delta. F) Conversion of coastal forests into salt marshes in New Jersey, due
1214 to saltwater intrusion. Data sources and photo credits are to be added.

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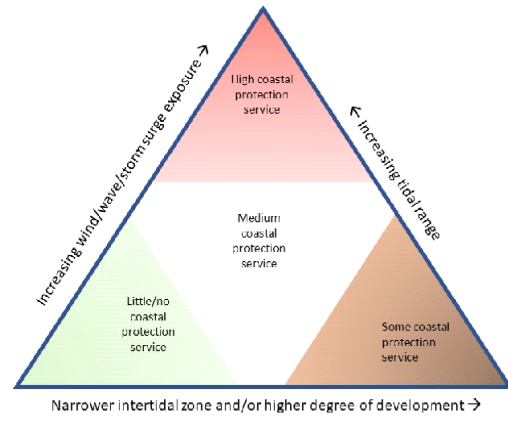
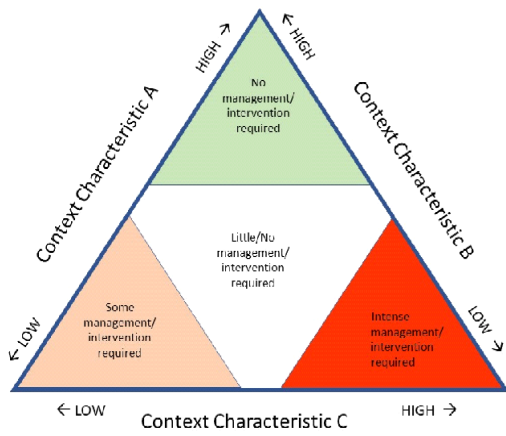
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Fig. 1. Pétilion, McKinley et al.

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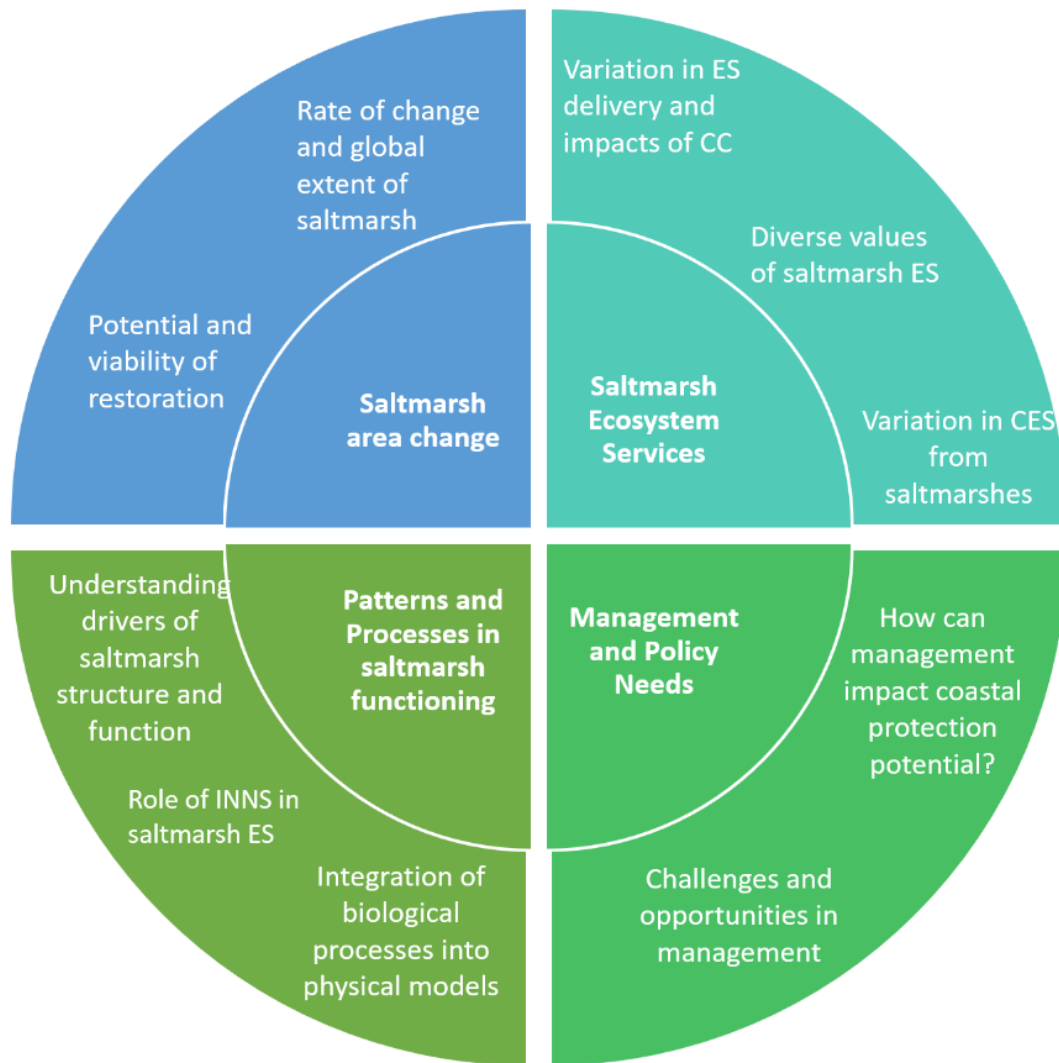
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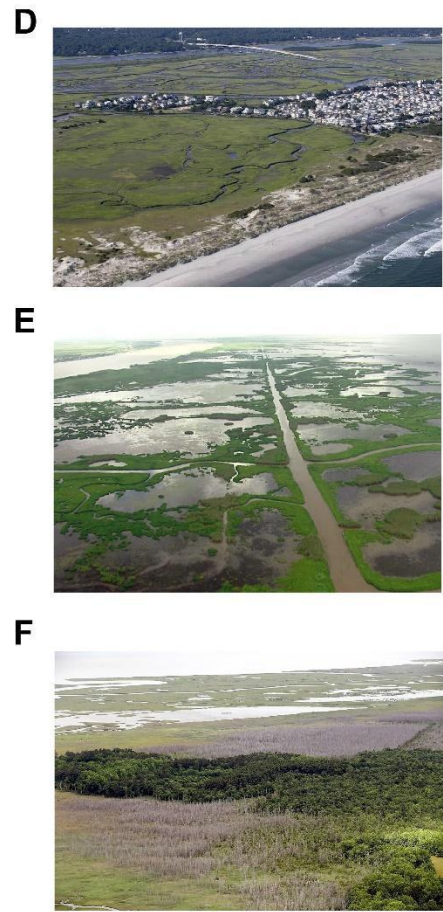
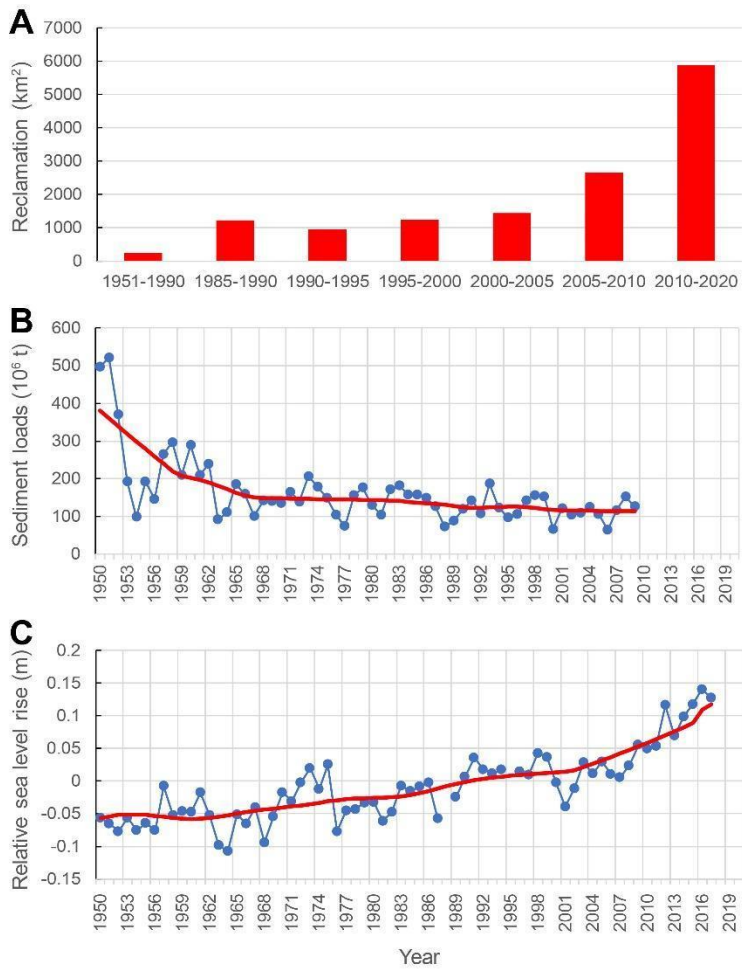
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Fig. 2. Pétilion, McKinley et al.



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Fig. 3. Pétilion, McKinley et al.



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Fig. 4. Pétillon, McKinley et al.