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1 **Maintaining Tropical Beaches with Seagrass and Algae: A Promising Alternative to**
2 **Engineering Solutions**

3

4 Running head: Maintaining beaches with seagrass and algae

5

6 Authors:

7 Rebecca K. James (MSc) Department of Estuarine and Delta Systems, NIOZ Royal Netherlands
8 Institute for Sea Research and Utrecht University, Korringaweg 7, 4401 NT Yerseke, The
9 Netherlands. Rebecca.james@nioz.nl

10 Rodolfo Silva Casarín (Dr.), Instituto de Ingeniería, Universidad Nacional Autónoma de
11 México, Circuito Escolar s/n, Edificio 5, Mexico City, 04510, Mexico.

12 rsilvac@iingen.unam.mx

13 Brigitta I. van Tussenbroek (Dr.), Unidad Académica de Sistemas Arrecifales-Puerto Morelos,
14 Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México,
15 Prolongación Avenida Niños Héroes S/N, Puerto Morelos, Quintana Roo 77580, Mexico.

16 vantuss@cmarl.unam.mx

17 Mireille Escudero-Castillo (Dr.), Instituto de Ingeniería, Universidad Nacional Autónoma de
18 México, Circuito Escolar s/n, Edificio 5, Mexico City, 04510, Mexico.

19 mescudero@iingen.unam.mx

20 Ismael Mariño-Tapia (Dr.), Departamento de Recursos del Mar, Cinvestav, km 6 Carretera
21 Antigua a Progreso, Cordemex, 97310, A.S.P. 73, Mérida, Yuc., Mexico.

22 imarinotapia@gmail.com

23 Henk A. Dijkstra (Prof. Dr. ir.), Institute for Marine and Atmospheric research Utrecht,
24 Department of Physics, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The
25 Netherlands. h.a.dijkstra@uu.nl

26 René M. van Westen (MSc.), Institute for Marine and Atmospheric research Utrecht,
27 Department of Physics, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The
28 Netherlands. r.m.vanwesten@uu.nl

29 Julie D. Pietrzak (Prof. Dr.), Department of Hydraulic Engineering, Delft University of
30 Technology, Stevinweg 1, 2628 CN Delft, The Netherlands. J.D.Pietrzak@tudelft.nl

31 Adam S. Candy (Dr.), Department of Hydraulic Engineering, Delft University of Technology,
32 Stevinweg 1, 2628 CN Delft, The Netherlands. A.S.Candy@tudelft.nl

33 Caroline A. Katsman (Assoc. Prof. Dr.), Department of Hydraulic Engineering, Delft
34 University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands.
35 c.a.katsman@tudelft.nl

36 Carine G. van der Boog (MSc.), Department of Hydraulic Engineering, Delft University of
37 Technology, Stevinweg 1, 2628 CN Delft, The Netherlands.
38 c.g.vanderboog@tudelft.nl

39 Riccardo E. M. Riva (Dr.), Department of Geoscience and Remote Sensing, Delft University of
40 Technology, Stevinweg 1, 2628 CN Delft, The Netherlands. R.E.M.Riva@tudelft.nl

41 Cornelis Slobbe (Dr. ir.), Department of Geoscience and Remote Sensing, Delft University of
42 Technology, Stevinweg 1, 2628 CN Delft, The Netherlands. D.C.Slobbe@tudelft.nl

43 Roland Klees (Prof. Dr), Department of Geoscience and Remote Sensing, Delft University of
44 Technology, Stevinweg 1, 2628 CN Delft, The Netherlands. r.klees@tudelft.nl

45 Johan Stapel (Dr.), Caribbean Netherlands Science Institute, L.E. Saddlerweg, St Eustatius,
46 Caribbean Netherlands. johan.stapel@cnsi.nl

47 Tjisse van der Heide (Dr.), Department of Coastal Systems, NIOZ Royal Netherlands Institute
48 for Sea Research and Utrecht University, P.O. Box 59, 1790 AB Den Burg, Texel, The
49 Netherlands. tjisse.van.der.heide@nioz.nl

50 Marieke M. van Katwijk (Dr.), Department of Environmental Science, Institute for Water and
51 Wetland Research, Faculty of Science, Radboud University Nijmegen, Heyendaalseweg 135,
52 6525 Nijmegen, The Netherlands. M.vanKatwijk@science.ru.nl

53 Peter M. J. Herman (Prof. Dr.), Department of Hydraulic Engineering, Delft University of
54 Technology, Stevinweg 1, 2628 CN Delft, The Netherlands. peter.herman@deltares.nl

55 Tjeerd J. Bouma (Prof. Dr.), Department of Estuarine and Delta Systems, NIOZ Royal
56 Netherlands Institute for Sea Research and Utrecht University, Korringaweg 7, 4401 NT
57 Yerseke, The Netherlands. tjeerd.bouma@nioz.nl

58

59 **Corresponding author:** Rebecca K. James, rebecca.james@nioz.nl, 0031 113 577 491

60

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66

67 **Abstract**

68 Tropical beaches provide coastal flood protection, income from tourism and habitat for ‘flag-
69 ship’ species. They urgently need protection from erosion, which is being exacerbated by
70 changing climate and coastal development. Traditional coastal engineering solutions are
71 expensive, provide unstable temporary solutions and often disrupt natural sediment transport.
72 Instead, natural foreshore stabilization and nourishment may provide a sustainable and
73 resilient, long-term solution. Field flume and ecosystem process measurements along with
74 data from the literature, show that sediment stabilization by seagrass in combination with
75 sediment-producing calcifying algae in the foreshore, form an effective mechanism for
76 maintaining tropical beaches worldwide. The long-term efficacy of this type of nature-based
77 beach management is shown at a large scale by comparing vegetated and unvegetated coastal
78 profiles. We argue that preserving and restoring vegetated beach foreshore ecosystems offers
79 a viable, self-sustaining alternative to traditional engineering solutions, increasing the
80 resilience of coastal areas to climate change.

81

82 **Introduction:**

83 Beaches are key ecosystems in coastal zones, making up 31% of the world’s shoreline in ice-
84 free regions of the world (Luijendijk et al. 2018). They have a vital role in flood defence,
85 provide a source of income as a tourist attraction, and are essential habitats for various tropical
86 “flag-ship” species, such as sea turtles and sea birds (Defeo et al. 2009). Beach erosion,
87 however, has become a major global problem, with a recent analysis showing that 24% of the
88 world’s sandy beaches experience chronic erosion (Luijendijk et al. 2018). The development of
89 human infrastructure along the coast and waterways (Fig. 1a-c) has led to the rapid loss of
90 natural systems that accumulate and stabilize sediment - such as coastal dunes, seagrass

91 meadows and mangroves - disrupting the regular pathways of sediment transport (Feagin et al.
92 2015; Luijendijk et al. 2018). Moreover, the combination of sea level rise with increasing storm
93 occurrence and intensity will exacerbate beach erosion in the future (Defeo et al. 2009; Nicholls
94 & Cazenave 2010). This is of great concern for many tropical areas, which typically have a high
95 dependency on beaches for flood safety, and also economically for local tourism (red shading
96 in Fig. 1d). For example, Caribbean islands together received over 23 million tourist visitors in
97 2015, creating a revenue of 26.5 billion USD (UNWTO 2016). On average, 23% of the gross
98 domestic product (GDP) of countries within the Caribbean is obtained from tourism (Fig. 1d),
99 with most tourists being attracted by the sandy beaches. Cost effective solutions to prevent or
100 mitigate beach erosion are thus urgently needed for the long-term economic sustainability in
101 these countries (Secretary-General 2016; Morris et al. 2018).

102 Many tropical countries lack the infrastructure and finances to undertake engineering solutions
103 for beach protection. Hence, beaches continue to disappear into the sea, increasing the
104 vulnerability of coastal areas to flooding, and threatening coastal structures and beach tourism
105 (Fig. 1b). Where there are sufficient resources, two schemes of coastal engineering strategies
106 are used to counter beach erosion: hard and soft (Finkl & Walker 2005; Castelle et al. 2009;
107 Stive et al. 2013; Silva et al. 2016), both incurring a high capital cost. Hard coastal defence
108 schemes are employed to mitigate wave attack and reduce local erosion (Fig. 1a; Ranasinghe
109 and Turner 2006; Ruiz-Martínez et al. 2015; Walker, Dong and Anastasiou 1991). Such
110 physical barriers typically inhibit the natural sand transport pathways, thereby depleting sand
111 from neighbouring areas (Ranasinghe & Turner 2006; Ruiz-Martínez et al. 2015; Luijendijk et
112 al. 2018). Soft defence schemes, such as beach or foreshore nourishments, have recently
113 become more popular (Fig. 1c; Bishop et al. 2006; Castelle et al. 2009; Ruiz-Martínez et al.
114 2015; Stive et al. 2013). Although effective, soft engineering requires continuous maintenance,
115 resulting in repeated smothering and disturbance of the natural beach communities (Bishop et

116 al. 2006; Defeo et al. 2009) and neighbouring ecosystems (e.g. coral reefs). In the long-term,
117 nourishments can alter beach grain characteristics (Hanson et al. 2002), which can potentially
118 cause permanent changes to the benthic community (Bishop et al. 2006).

119 By combining experimental field measurements with data from the literature, we demonstrate
120 that the combination of foreshore stabilization by seagrass and natural foreshore nourishment
121 by calcifying macroalgae can provide long-term maintenance of tropical beaches. In general,
122 foreshore nourishment (both natural or engineered) is effective in beach protection, as a shallow
123 foreshore reduces wave attack on the beach (Hanson et al. 2002; Christianen et al. 2013).
124 Because a natural foreshore stabilization-and-nourishment regime requires no maintenance and
125 operates gradually over long timescales with locally-produced sediment, it offers a cost-
126 effective and sustainable alternative to human-engineered solutions. Comparing unique long-
127 term beach profiles of vegetated, transitioning and unvegetated coasts illustrate the
128 effectiveness of this approach.

129

130 **Natural foreshore nourishment by vegetation: sediment stabilization and production**

131 Shallow inter- and sub-tidal foreshores of natural tropical sandy beaches are predominately
132 composed of locally produced calcium carbonate (CaCO_3) sediments. These carbonate
133 sediments are biogenically produced and need to be continually captured and retained within
134 the foreshore for a beach to resist erosion and remain stable, something that seagrass is
135 extremely effectively at achieving.

136

137 With a newly developed portable flume, designed to be used in the field, the ability of different
138 vegetation types (bare, vegetated with only calcifying macroalgae, sparse seagrass: 50% cover
139 of *T. testudinum*, and dense seagrass: 100% cover of *T. testudinum*) to stabilize sediment was

140 measured directly within Galion Bay, St Martin (Caribbean). Regulating the speed of two
141 motor-driven propellers allowed the flow velocity within the flume tunnel to be modified (see
142 photo in Fig. 2a, and further methods in Suppl. 1). The point at which the surface sediment
143 began to move was recorded as the threshold shear velocity. We found that in bare areas and
144 areas with only calcifying macroalgae, the coarse carbonate sediments (median grain size: 337
145 μm , SE = 33) that are present in these areas start eroding already at flow speeds caused by
146 moderate breezes (i.e. a wind of 10 m s^{-1} can cause flow speeds of 0.2 m s^{-1} within shallow
147 areas (Hughes 1956)). However, where a sparse cover of seagrass is present, the sediment is
148 finer (median grain size: 297 μm , SE = 17) as the protected seagrass canopy promotes fine
149 grains to settle (De Boer 2007), but the flow required to erode the carbonate sediment doubles.
150 And when *T. testudinum* seagrass cover is dense, the sediment is finer again (median grain size:
151 129 μm , SE = 7), but remains stable at flows stronger than 1.0 m s^{-1} (Fig. 2a); the maximum
152 flow velocity of the flume. These flume results were confirmed by the seven times longer
153 retention time of stained sediment that was placed in dense seagrass beds as compared to bare
154 areas, in a high uni-directional flow environment within Galion Bay, and the four times higher
155 retention time in a wave-exposed area (Fig. 2b).

156

157 Although relatively few studies have directly measured the sediment stabilizing effect of
158 seagrass (Scoffin 1970; Widdows et al. 2008), the available literature widely supports our
159 findings. For example, Christianen et al. (2013) found that even low density, heavily grazed
160 seagrass meadows significantly reduce sediment erosion in Indonesia. A global review by
161 Potouroglou et al., (2017) shows an average accretion rate of $5.33 \text{ mm year}^{-1}$ occurring within
162 seagrass meadows compared to adjacent unvegetated areas that experience an average erosion
163 rate of $21.3 \text{ mm year}^{-1}$. Seagrasses reduce erosion and cause sediment accretion by stabilizing
164 the sediment with their root-rhizome mat (Potouroglou et al. 2017), and by attenuating water

165 flow and waves. Hansen & Reidenbach (2012) reported that dense seagrass canopies of *Zostera*
166 *marina* can attenuate flow velocity by 70-90%, whereas Fonseca & Cahalan (1992) showed a
167 wave energy reduction of 34-44% for four varying species of seagrass, including *T. testudinum*.
168 Flow and wave attenuation cause sediment particles to settle and reduces their resuspension,
169 while additionally, seagrass leaves can bend over the sediment surface, further stabilizing the
170 sediments. For a beach to remain stable over the long-term, however, a continuous supply of
171 sediment is required to offset any erosion that occurs during storm events or from seaward
172 currents that may transport unprotected sediment out of the beach system.

173

174 The breakdown and erosion of nearby coral reefs can provide a large contribution of sediment
175 when the reefs are present (Chave et al. 1972; Hallock 1981). Another sediment contributor is
176 calcifying macroalgae from the Halimedaceae family, which are composed of 70-90% CaCO₃
177 (van Tussenbroek & Van Dijk 2007). Because they grow directly within and adjacent to
178 seagrass meadows on tropical beach foreshores, the sediment they produce is deposited where
179 it is most valuable for providing a natural foreshore nourishment. This sediment production
180 does vary significantly depending on the season, species and their abundance, however, the fast
181 growth and rapid turn-over rates mean that the average sediment production reported for
182 *Halimeda* spp. growing within seagrass meadows in the Pacific region is 337 g_{dwt} CaCO₃ m⁻²
183 year⁻¹ (SE = 70, n = 10) (Suppl. 2; Garrigue 1991; Merten 1971; Payri 1988), and in Caribbean
184 region, 166 g_{dwt} CaCO₃ m⁻² year⁻¹ (SE = 93, n = 8) (Suppl. 2; Armstrong and Miller 1988;
185 Freile 2004; Multer 1988; Neumann and Land 1975; van Tussenbroek and Van Dijk 2007;
186 Wefer 1980). Although this average rate contributes less than 0.28 (Pacific) and 0.15 mm
187 (Caribbean) of sediment to the bed level per year (assuming a dry bulk density of 1.08 g per
188 cm³), the deposition of this CaCO₃ occurs directly within the foreshore where seagrass is
189 present. The algae-produced sediment is therefore immediately captured and retained within

190 the beach foreshore ecosystem by the seagrass, thereby supplying a continuous and natural
191 nourishment.

192

193 **Engineering and natural nourishment as contrasting management regimes**

194 We postulate engineering solutions and natural foreshore nourishment as contrasting
195 management regimes, each having its own positive feedback (Fig. 3a). The engineered regime,
196 where there is an unvegetated disturbed foreshore ecosystem with little or no biogenic sand
197 production and highly mobile sediments. Such a regime results in a beach vulnerable to erosion,
198 and therefore, requires regular engineering nourishments of the beach foreshore system to
199 maintain its form. The alternative regime, a natural self-sustaining foreshore ecosystem with
200 seagrass and calcifying macroalgae fronting a stable beach, which forms a self-stabilizing and
201 self-nourishing system.

202 The combined sediment-stabilization by seagrass and sediment-production by calcifying algae
203 yields a biologically-driven landscape with self-maintaining feedbacks. Specifically, by
204 attenuating waves, preventing excessive erosion, and replenishing lost sediments, seagrass
205 meadows and calcifying algae together create a self-reinforcing loop (Maxwell et al. 2017).
206 Stable sediment has been shown to be a main requirement for the long-term persistence of
207 seagrass meadows (Reise & Kohlus 2008; Christianen et al. 2014; Suykerbuyk et al. 2016), and
208 in areas with fine sediment, can lead to a higher water transparency needed to sustain growth
209 (van der Heide et al. 2007; Adams et al. 2018). This means that disruption of these self-
210 reinforcing feedbacks may result in rapid losses of the seagrass-algae community (Maxwell et
211 al. 2017). That is, in beach foreshore systems without seagrasses and algae, the sediment surface
212 is freely agitated by currents and waves, yielding highly mobile sediments (Widdows et al.
213 2008; Marbà et al. 2015). Such unstable sediment conditions make it very difficult for

214 seagrasses and algae to (re-)establish (Williams 1990; Infantes et al. 2011; Balke et al. 2014;
215 Suykerbuyk et al. 2016), and can increase turbidity levels if smaller sediment particles become
216 suspended in the water column (van der Heide et al. 2007; Adams et al. 2018).

217 Human engineering through frequent beach nourishments can increase the sand supply to such
218 disturbed beach foreshore systems (Finkl & Walker 2005; Castelle et al. 2009; Stive et al. 2013).
219 However, these repeated nourishments smother establishing seagrasses and algae, and create
220 an unstable sediment surface which is more likely to erode (Fig. 3a). Thus, although engineered
221 nourishments may save the beach in the short term, it paradoxically may generate the necessity
222 for recurrent beach nourishments in the long run (Trembanis & Pilkey 1998), creating an
223 expensive and unsustainable management cycle in developing tropical regions (Silva et al.
224 2014).

225 Examples of the two alternative management regimes and one in transition, are found along the
226 coast of Mexico (see Suppl. 1). In coastal areas where seagrass and calcifying macroalgae
227 dominate the system, beach shore profiles conducted from 2008 to 2012 (methods detailed in
228 Suppl. 1) are stable (Fig. 3b). In contrast, areas devoid of these species are typified by
229 continuous erosion, which persists after engineered nourishments (Fig. 3d). A transition
230 between these contrasting management regimes is observed in a third area. Here, extensive
231 seagrass meadows of *T. testudinum* disappeared from the first 60 meters of the foreshore in
232 2015 due to a large brown tide of drifting *Sargassum* spp. (van Tussenbroek et al. 2017). As a
233 result of these losses, beach profiles taken in 2007 and 2017 show the beach foreshore
234 experienced strong vertical erosion, up to 0.4 m in some areas (Fig. 3c). However, a small area
235 of the beach foreshore where seagrass was not lost, experienced only minor erosion and
236 remained relatively stable (Fig. 3c). Overall these examples impressively illustrate the
237 effectiveness of vegetated foreshore ecosystems for maintaining stable beaches and shorelines.

238

239 **Implications & challenges for future management of tropical beaches**

240 To create stable long-term management solutions for tropical beaches, beach management
241 would benefit from shifting away from frequent engineered nourishments and hard structures,
242 towards maintenance by natural ecosystems. With current insights, anthropogenic use of
243 beaches could be designed to halt and reverse current decline of natural foreshore ecosystems.
244 Tropical seagrass and *Halimeda* spp. usually co-occur and can be found in tropical sandy
245 regions all around the world (Fig. 1d; Green and Short 2003; UNEP-WCMC and Short 2005),
246 so there is widespread potential to restore these systems (Orth et al. 2006) to create a natural,
247 self-sustaining beach management regime.

248 Conservation of areas where natural foreshore vegetation still persists will help to minimise the
249 stressors imposed on foreshore ecosystems, maximising their ability to protect beaches against
250 erosion. Where foreshore vegetation has become degraded, an effort to protect what remains
251 and to restore the ecosystem to a healthy self-reinforcing state may be necessary to implement
252 effective natural beach management regimes. Preserving and restoring foreshore vegetation that
253 still exists is especially important as climate-driven disturbance events - such as extreme wave
254 action, cyclones (Saunders & Lea 2008), and the occurrence of brown tides from *Sargassum*
255 spp. drifts (van Tussenbroek et al. 2017) - become more frequent with rising global
256 temperatures. As climate-driven factors are hard to manage at a local scale, management should
257 primarily aim at reducing local human-induced impacts (Scheffer et al. 2001). Local impacts,
258 like greater turbidity (Orth et al. 2006), nutrient enrichment and pollution (Kemp et al. 2005),
259 physical damage to seagrass meadows from trampling and boat anchoring (Eckrich &
260 Holmquist 2000), and modification of natural sediment transport and increased wave reflection
261 caused by the construction of hard structures (Defeo et al. 2009; Ruiz-Martínez et al. 2015;
262 Luijendijk et al. 2018), are all intensifying as coastlines develop further. The installation of
263 sewage treatment plants and limiting construction of hard structures along the coast are the most

264 obvious steps to help protect and restore natural foreshore vegetation. Another is to limit
265 accessibility of people to vulnerable areas, and provide boat anchoring facilities outside regions
266 of vegetation. Ensuring coral reefs remain in abundance and their sediment input to tropical
267 beaches persists, would also improve the prospects of tropical beaches to keep up with sea level
268 rise.

269 Given that the engineering management regime of a disturbed beach is self-reinforced by a
270 feedback that maintains sediment instability (Fig. 3a), it will be difficult to induce a transition
271 to the natural beach systems in areas where engineering management regimes already take place
272 and/or vegetation has been completely lost. Developing ways to stimulate natural vegetation
273 development may be necessary, such as utilising temporary structures that protect establishing
274 seagrass and calcifying macroalgae, until they grow to a point that they can self-stabilize the
275 sediment (Suykerbuyk et al. 2016; van Katwijk et al. 2016). Engineered nourishments will need
276 to either cease, or be modified to ensure that any added sediment encourages the growth of the
277 natural ecosystem rather than smothers it (Cheong et al. 2013). This may be achieved by using
278 methods that give a gradual sediment flux, like the sand engine in The Netherlands (Stive et al.
279 2013), or by using smaller doses of sediment.

280 It is imperative that we recognize the benefits of a vegetated foreshore ecosystem in preventing
281 beach erosion, and thus increase the resistance of coastal areas to storm surges and flooding.
282 Switching disturbed beach systems to natural self-sustaining ecosystems for coastal defence
283 will require financial investments (e.g. from the World Bank, in the context of climate
284 adaptation (Secretary-General 2016; World Bank 2017)), development of effective restoration
285 methods, as well as altered governance. Only a collaborative approach of many stakeholders
286 will ensure both economic and ecological benefits. This will require interdisciplinary
287 collaboration between economists focusing on tourism, ecologists focusing on ecosystem
288 functioning and natural values, engineers focusing on physical processes and design measures,

289 and sociologists focusing on governance processes and public support. With this paper, we aim
290 to provide an alternative beach management regime to traditional engineering solutions, by
291 highlighting the viable and self-sustaining capacity of vegetated beach foreshore ecosystem in
292 preventing erosion. Utilising an effective natural solution to coastal erosion will help to increase
293 the resilience of tropical coastal areas to climate change in a sustainable way.

294

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303

304 **Data availability**

305 Data associated with this study is available from 4TU.Centre for Research Data at
306 <https://doi.org/10.4121/uuid:a5f07774-9a90-4aa2-ae03-690da7d36a77>

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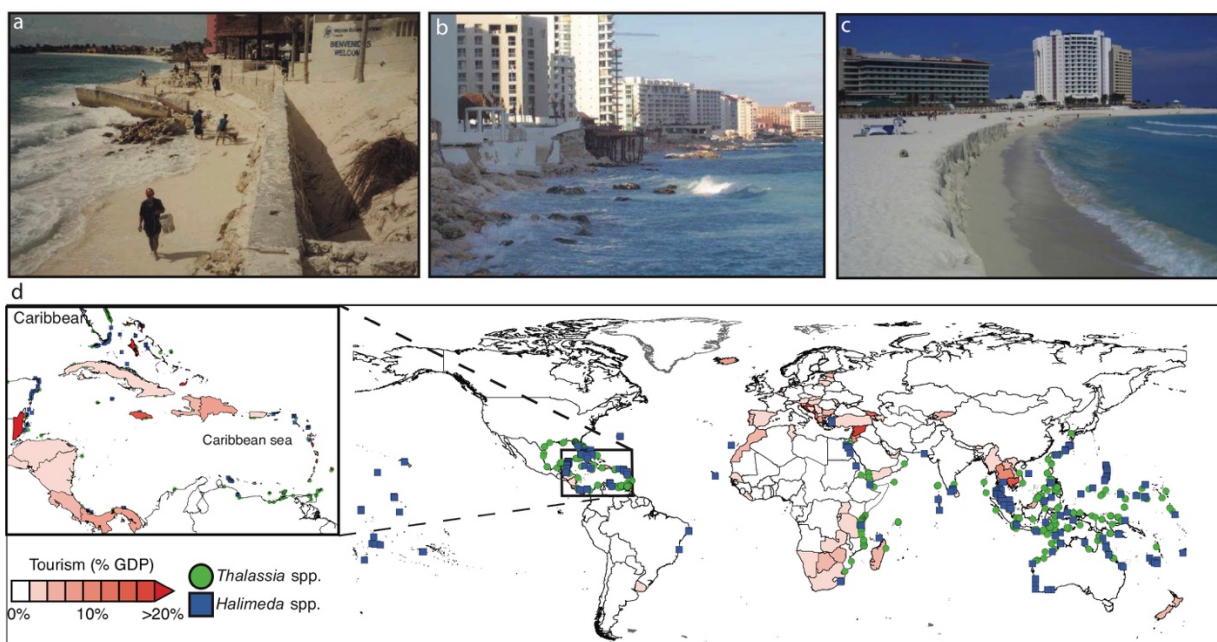
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457

458 **Figure legends**

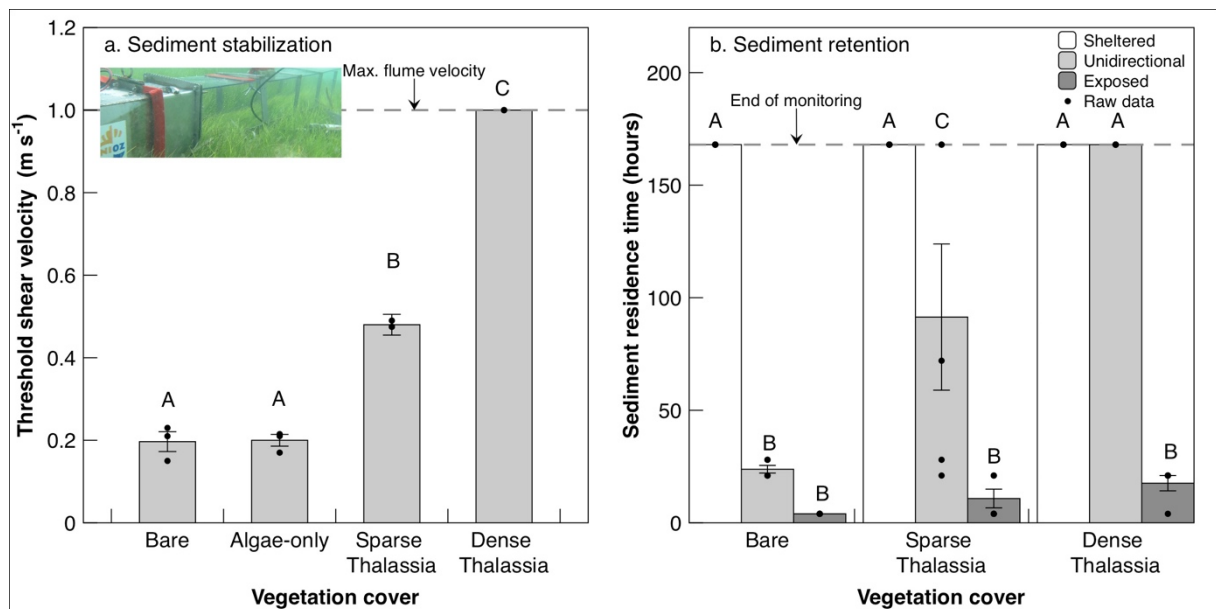


459

460 Figure 1. The building of hard structures to prevent coastal erosion, such as seawalls (a), the

461 over-development of coastlines (b), and beach nourishments (c) only serve to exacerbate coastal
 462 erosion. The global map (d) shows the proportion of GDP obtained from tourism in 2015 (data
 463 sourced from World Bank and World Tourism Organization), with the darker red shading
 464 indicating a higher proportion of the gross domestic product (GDP) is obtained from tourism
 465 for that country. The effective sediment-stabilizing seagrass *Thalassia* spp. is globally
 466 distributed (green circles, sourced from UNEP-WCMC & Short (2005)), and can be found
 467 alongside the sediment-producing calcifying macroalgae *Halimeda* spp. (blue squares,
 468 sightings reported in peer reviewed literature).

469

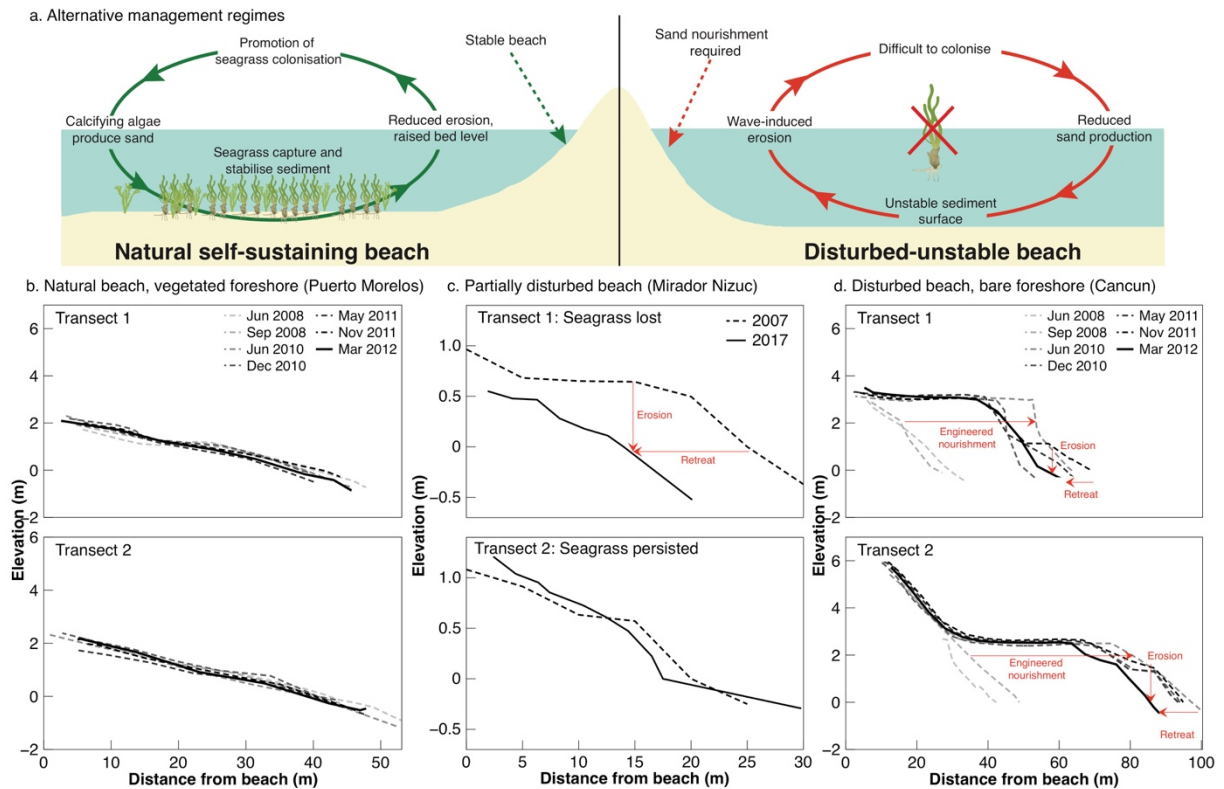


470

471 Figure 2. Carbonate sediment is stabilized by seagrass, as indicated by measuring the critical
 472 threshold for bed-load transport with a field flume in contrasting vegetation types: bare,
 473 calcifying algae only, sparse *Thalassia* (50% cover of *T. testudinum*), dense *Thalassia* (100%
 474 cover of *T. testudinum*) (a). This was corroborated by measuring the retention time of stained
 475 sediments for contrasting vegetation types in the different physical environments (b): wave
 476 sheltered (mean wave height = 0.15 m, SE = 0.004, n = 370), uni-directional (mean flow rate =
 477 0.15 m s⁻¹, SE = 0.025, n = 18), and wave exposed (mean wave height = 0.22 m, SE = 0.005,

478 $n = 429$). Bars represent means \pm SE ($n_{\text{sed.stab}} = 3$, $n_{\text{sed.ret}} = 5$) and black points indicate individual
 479 data points. Different letters above bars denote significant difference ($p < 0.05$), tested with
 480 Tukey HSD pair-wise comparisons.

481



482

483 Figure 3. Self-reinforcing feedbacks drive the contrasting beach management regimes as
 484 schematised in (a). The natural beach is driven by seagrass stabilizing the sediment, which
 485 encourages further ecosystem development. Whereas the system devoid of vegetation has
 486 increasingly mobile sediment, discouraging the growth of vegetation and leading to an unstable
 487 beach system, requiring engineering which further contributes to sediment mobility and
 488 erosion. These types of beach regimes can be seen in examples from the coastline of Mexico
 489 (map in S1). Regular beach profiles taken from two transects at the natural beach of Puerto
 490 Morelos from June 2008 (dashed lines) to May 2012 (solid line) show that this relatively
 491 undisturbed beach with extensive seagrass-calcifying algae meadows has remained stable over
 492 many years (b). While beach profiles at Mirador Nizuc in 2007 (dashed line) and June 2017

493 (solid line) show that the beach had significant erosion after a Sargassum brown tide that
494 persisted from July 2015 to May 2016 resulted in the loss of seagrass (c, upper graph), however
495 in an area of the same beach where seagrass persisted, very little erosion occurred (c, lower
496 graph). While Cancun has no natural reef or seagrass meadows and development along the sand
497 dunes has led to constant beach erosion, a sand nourishment in 2010 helped to restore the beach,
498 but this continues to erode (d). Elevations are relative to mean sea level. (Thalassia illustration
499 sourced from IAN image library (Saxby)).

500

501