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

Running head: Maintaining beaches with seagrass and algae

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Abstract

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

Introduction:

Beaches are key ecosystems in coastal zones, making up 31% of the world’s shoreline in ice-free regions of the world (Luijendijk et al. 2018). They have a vital role in flood defence, provide a source of income as a tourist attraction, and are essential habitats for various tropical “flag-ship” species, such as sea turtles and sea birds (Defeo et al. 2009). Beach erosion, however, has become a major global problem, with a recent analysis showing that 24% of the world’s sandy beaches experience chronic erosion (Luijendijk et al. 2018). The development of human infrastructure along the coast and waterways (Fig. 1a-c) has led to the rapid loss of natural systems that accumulate and stabilize sediment - such as coastal dunes, seagrass meadows and mangroves - disrupting the regular pathways of sediment transport (Feagin et al. 2015; Luijendijk et al. 2018). Moreover, the combination of sea level rise with increasing storm occurrence and intensity will exacerbate beach erosion in the future (Defeo et al. 2009; Nicholls & Cazenave 2010). This is of great concern for many tropical areas, which typically have a high dependency on beaches for flood safety, and also economically for local tourism (red shading in Fig. 1d). For example, Caribbean islands together received over 23 million tourist visitors in 2015, creating a revenue of 26.5 billion USD (UNWTO 2016). On average, 23% of the gross domestic product (GDP) of countries within the Caribbean is obtained from tourism (Fig. 1d), with most tourists being attracted by the sandy beaches. Cost effective solutions to prevent or mitigate beach erosion are thus urgently needed for the long-term economic sustainability in these countries (Secretary-General 2016; Morris et al. 2018).

Many tropical countries lack the infrastructure and finances to undertake engineering solutions for beach protection. Hence, beaches continue to disappear into the sea, increasing the vulnerability of coastal areas to flooding, and threatening coastal structures and beach tourism (Fig. 1b). Where there are sufficient resources, two schemes of coastal engineering strategies are used to counter beach erosion: hard and soft (Finkl & Walker 2005; Castelle et al. 2009; Stive et al. 2013; Silva et al. 2016), both incurring a high capital cost. Hard coastal defence schemes are employed to mitigate wave attack and reduce local erosion (Fig. 1a; Ranasinghe and Turner 2006; Ruiz-Martínez et al. 2015; Walker, Dong and Anastasiou 1991). Such physical barriers typically inhibit the natural sand transport pathways, thereby depleting sand from neighbouring areas (Ranasinghe & Turner 2006; Ruiz-Martínez et al. 2015; Luijendijk et al. 2018). Soft defence schemes, such as beach or foreshore nourishments, have recently become more popular (Fig. 1c; Bishop et al. 2006; Castelle et al. 2009; Ruiz-Martínez et al. 2015; Stive et al. 2013). Although effective, soft engineering requires continuous maintenance, resulting in repeated smothering and disturbance of the natural beach communities (Bishop et al. 2006; Defeo et al. 2009) and neighbouring ecosystems (e.g. coral reefs). In the long-term, nourishments can alter beach grain characteristics (Hanson et al. 2002), which can potentially cause permanent changes to the benthic community (Bishop et al. 2006).

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

Natural foreshore nourishment by vegetation: sediment stabilization and production

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

With a newly developed portable flume, designed to be used in the field, the ability of different vegetation types (bare, vegetated with only calcifying macroalgae, sparse seagrass: 50% cover of *T. testudinum*, and dense seagrass: 100% cover of *T. testudinum*) to stabilize sediment was measured directly within Galion Bay, St Martin (Caribbean). Regulating the speed of two motor-driven propellers allowed the flow velocity within the flume tunnel to be modified (see photo in Fig. 2a, and further methods in Suppl. 1). The point at which the surface sediment began to move was recorded as the threshold shear velocity. We found that in bare areas and areas with only calcifying macroalgae, the coarse carbonate sediments (median grain size: 337 µm, SE = 33) that are present in these areas start eroding already at flow speeds caused by moderate breezes (i.e. a wind of 10 m s^{-1} can cause flow speeds of 0.2 m s^{-1} within shallow areas (Hughes 1956)). However, where a sparse cover of seagrass is present, the sediment is finer (median grain size: 297 µm, SE = 17) as the protected seagrass canopy promotes fine grains to settle (De Boer 2007), but the flow required to erode the carbonate sediment doubles. And when *T. testudinum* seagrass cover is dense, the sediment is finer again (median grain size: 129 µm, SE = 7), but remains stable at flows stronger than 1.0 m s^{-1} (Fig. 2a); the maximum flow velocity of the flume. These flume results were confirmed by the seven times longer retention time of stained sediment that was placed in dense seagrass beds as compared to bare areas, in a high uni-directional flow environment within Galion Bay, and the four times higher retention time in a wave-exposed area (Fig. 2b).

Although relatively few studies have directly measured the sediment stabilizing effect of seagrass (Scoffin 1970; Widdows et al. 2008), the available literature widely supports our findings. For example, Christianen et al. (2013) found that even low density, heavily grazed seagrass meadows significantly reduce sediment erosion in Indonesia. A global review by Potouroglou et al., (2017) shows an average accretion rate of 5.33 mm $year^{-1}$ occurring within seagrass meadows compared to adjacent unvegetated areas that experience an average erosion rate of 21.3 mm $year^{-1}$. Seagrasses reduce erosion and cause sediment accretion by stabilizing the sediment with their root-rhizome mat (Potouroglou et al. 2017), and by attenuating water flow and waves. Hansen & Reidenbach (2012) reported that dense seagrass canopies of *Zostera marina* can attenuate flow velocity by 70-90%, whereas Fonseca & Cahalan (1992) showed a wave energy reduction of 34-44% for four varying species of seagrass, including *T. testudinum*. Flow and wave attenuation cause sediment particles to settle and reduces their resuspension, while additionally, seagrass leaves can bend over the sediment surface, further stabilizing the sediments. For a beach to remain stable over the long-term, however, a continuous supply of sediment is required to offset any erosion that occurs during storm events or from seaward currents that may transport unprotected sediment out of the beach system.

The breakdown and erosion of nearby coral reefs can provide a large contribution of sediment when the reefs are present (Chave et al. 1972; Hallock 1981). Another sediment contributor is calcifying macroalgae from the Halimedaceae family, which are composed of 70-90% $CaCO_3$ (van Tussenbroek & Van Dijk 2007). Because they grow directly within and adjacent to seagrass meadows on tropical beach foreshores, the sediment they produce is deposited where it is most valuable for providing a natural foreshore nourishment. This sediment production does vary significantly depending on the season, species and their abundance, however, the fast growth and rapid turn-over rates mean that the average sediment production reported for *Halimeda* spp. growing within seagrass meadows in the Pacific region is 337 g_{dwt} $CaCO_3$ m^{-2} $year^{-1}$ (SE = 70, n = 10) (Suppl. 2; Garrigue 1991; Merten 1971; Payri 1988), and in Caribbean region, 166 g_{dwt} $CaCO_3$ m^{-2} $year^{-1}$ (SE = 93, n = 8) (Suppl. 2; Armstrong and Miller 1988; Freile 2004; Multer 1988; Neumann and Land 1975; van Tussenbroek and Van Dijk 2007; Wefer 1980). Although this average rate contributes less than 0.28 (Pacific) and 0.15 mm (Caribbean) of sediment to the bed level per year (assuming a dry bulk density of 1.08 g per cm^3), the deposition of this $CaCO_3$ occurs directly within the foreshore where seagrass is present. The algae-produced sediment is therefore immediately captured and retained within the beach foreshore ecosystem by the seagrass, thereby supplying a continuous and natural nourishment.

Engineering and natural nourishment as contrasting management regimes

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

The combined sediment-stabilization by seagrass and sediment-production by calcifying algae yields a biologically-driven landscape with self-maintaining feedbacks. Specifically, by attenuating waves, preventing excessive erosion, and replenishing lost sediments, seagrass meadows and calcifying algae together create a self-reinforcing loop (Maxwell et al. 2017). Stable sediment has been shown to be a main requirement for the long-term persistence of seagrass meadows (Reise & Kohlus 2008; Christianen et al. 2014; Suykerbuyk et al. 2016), and in areas with fine sediment, can lead to a higher water transparency needed to sustain growth (van der Heide et al. 2007; Adams et al. 2018). This means that disruption of these self-reinforcing feedbacks may result in rapid losses of the seagrass-algae community (Maxwell et al. 2017). That is, in beach foreshore systems without seagrasses and algae, the sediment surface is freely agitated by currents and waves, yielding highly mobile sediments (Widdows et al. 2008; Marbà et al. 2015). Such unstable sediment conditions make it very difficult for seagrasses and algae to (re-)establish (Williams 1990; Infantes et al. 2011; Balke et al. 2014; Suykerbuyk et al. 2016), and can increase turbidity levels if smaller sediment particles become suspended in the water column (van der Heide et al. 2007; Adams et al. 2018).

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

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

Implications & challenges for future management of tropical beaches

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

Conservation of areas where natural foreshore vegetation still persists will help to minimise the stressors imposed on foreshore ecosystems, maximising their ability to protect beaches against erosion. Where foreshore vegetation has become degraded, an effort to protect what remains and to restore the ecosystem to a healthy self-reinforcing state may be necessary to implement effective natural beach management regimes. Preserving and restoring foreshore vegetation that still exists is especially important as climate-driven disturbance events - such as extreme wave action, cyclones (Saunders & Lea 2008), and the occurrence of brown tides from *Sargassum* spp. drifts (van Tussenbroek et al. 2017) - become more frequent with rising global temperatures. As climate-driven factors are hard to manage at a local scale, management should primarily aim at reducing local human-induced impacts (Scheffer et al. 2001). Local impacts, like greater turbidity (Orth et al. 2006), nutrient enrichment and pollution (Kemp et al. 2005), physical damage to seagrass meadows from trampling and boat anchoring (Eckrich & Holmquist 2000), and modification of natural sediment transport and increased wave reflection caused by the construction of hard structures (Defeo et al. 2009; Ruiz-Martínez et al. 2015; Luijendijk et al. 2018), are all intensifying as coastlines develop further. The installation of sewage treatment plants and limiting construction of hard structures along the coast are the most obvious steps to help protect and restore natural foreshore vegetation. Another is to limit accessibility of people to vulnerable areas, and provide boat anchoring facilities outside regions of vegetation. Ensuring coral reefs remain in abundance and their sediment input to tropical beaches persists, would also improve the prospects of tropical beaches to keep up with sea level rise.

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

It is imperative that we recognize the benefits of a vegetated foreshore ecosystem in preventing beach erosion, and thus increase the resistance of coastal areas to storm surges and flooding. Switching disturbed beach systems to natural self-sustaining ecosystems for coastal defence will require financial investments (e.g. from the World Bank, in the context of climate adaptation (Secretary-General 2016; World Bank 2017)), development of effective restoration methods, as well as altered governance. Only a collaborative approach of many stakeholders will ensure both economic and ecological benefits. This will require interdisciplinary collaboration between economists focusing on tourism, ecologists focusing on ecosystem functioning and natural values, engineers focusing on physical processes and design measures, and sociologists focusing on governance processes and public support. With this paper, we aim to provide an alternative beach management regime to traditional engineering solutions, by highlighting the viable and self-sustaining capacity of vegetated beach foreshore ecosystem in preventing erosion. Utilising an effective natural solution to coastal erosion will help to increase the resilience of tropical coastal areas to climate change in a sustainable way.

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Data availability

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

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Figure legends

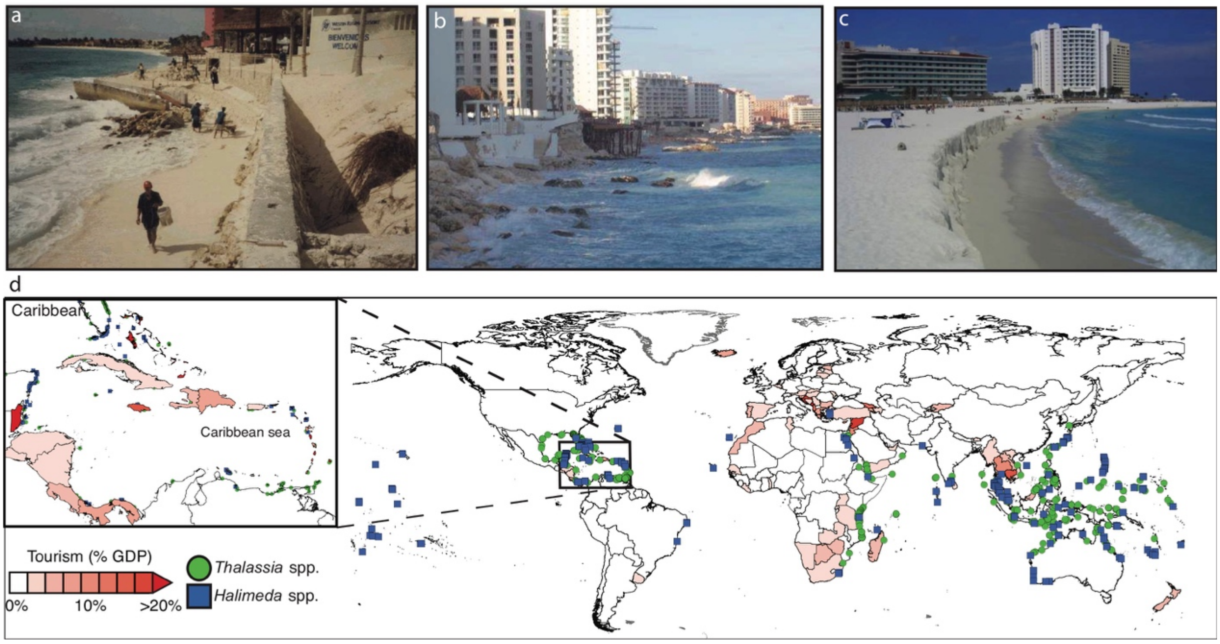

Figure 1. The building of hard structures to prevent coastal erosion, such as seawalls (a), the

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

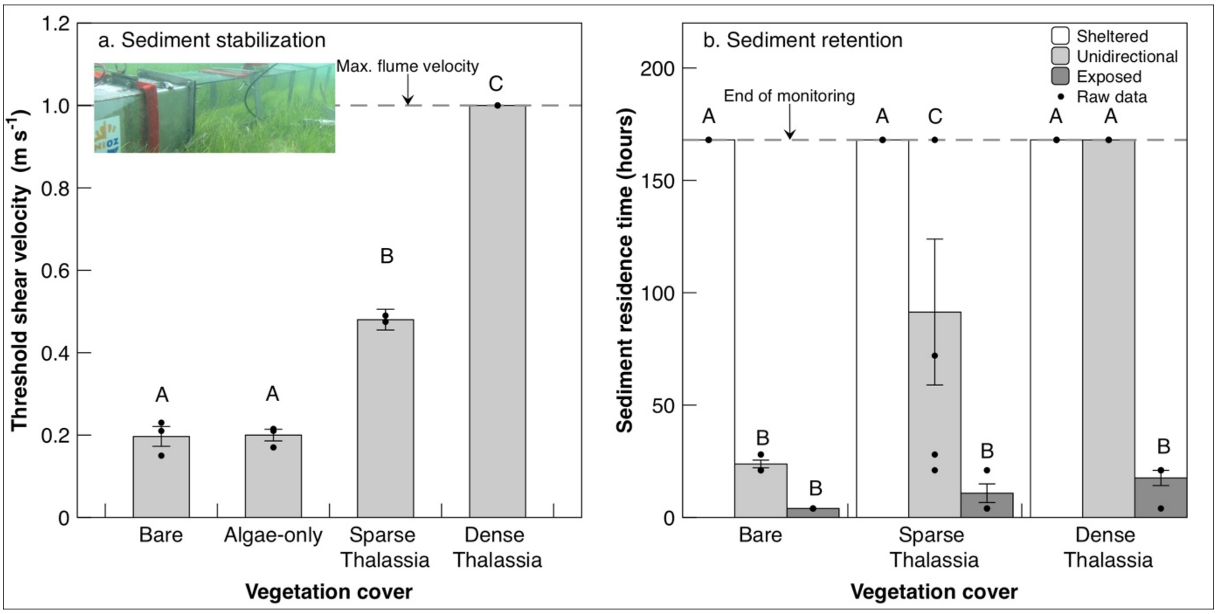

Figure 2. Carbonate sediment is stabilized by seagrass, as indicated by measuring the critical threshold for bed-load transport with a field flume in contrasting vegetation types: bare, calcifying algae only, sparse Thalassia (50% cover of *T. testudinum*), dense Thalassia (100% cover of *T. testudinum*)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

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

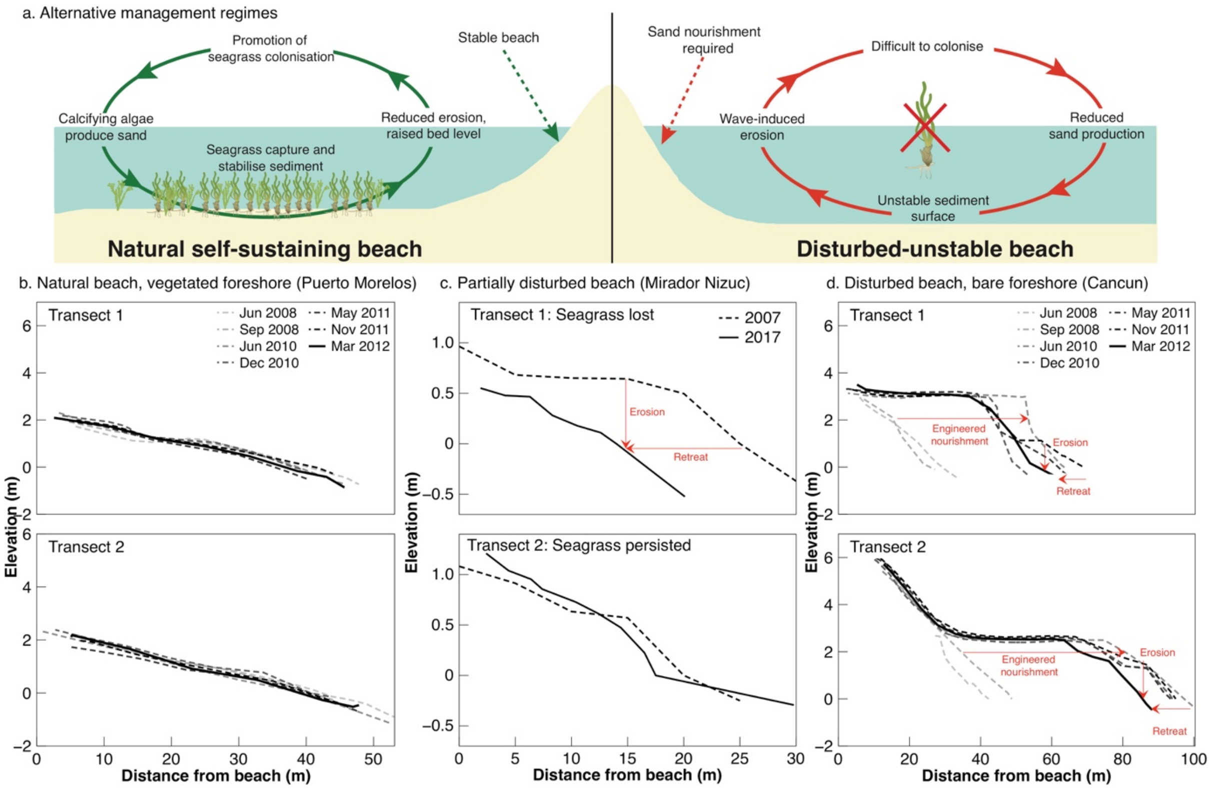

Figure 3. Self-reinforcing feedbacks drive the contrasting beach management regimes as schematised in (a). The natural beach is driven by seagrass stabilizing the sediment, which encourages further ecosystem development. Whereas the system devoid of vegetation has increasingly mobile sediment, discouraging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

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