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From grey to green: efficacy of eco-engineering solutions for nature-based coastal defence

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Abstract

Climate change is increasing the threat of erosion and flooding along coastlines globally. Engineering solutions (e.g. seawalls and breakwaters) in response to protecting coastal communities and associated infrastructure are increasingly becoming economically and ecologically unsustainable. This has led to recommendations to create or restore natural habitats, such as sand dunes, saltmarsh, mangroves, seagrass and kelp beds, and coral and shellfish reefs, to provide coastal protection in place of (or to complement) artificial structures. Coastal managers are frequently faced with the problem of an eroding coastline, which requires a decision on what mitigation options are most appropriate to implement. A barrier to uptake of nature-based coastal defence is stringent evaluation of the effectiveness in comparison to artificial protection structures. Here, we assess the current evidence for the efficacy of nature-based versus artificial coastal protection and discuss future research needs. Future projects should evaluate habitats created or restored for coastal defence for cost-effectiveness in comparison to an artificial structure under the same environmental conditions. Cost-benefit analyses should take into consideration all ecosystem services provided by nature-based or artificial structures in addition to coastal protection. Interdisciplinary research among scientists, coastal managers and engineers are required to facilitate the experimental trials needed to test the value of these shoreline protection schemes, in order to support their use as alternatives to artificial structures. This research needs to happen now as our rapidly changing climate requires new and innovative solutions to reduce the vulnerability of coastal communities to an increasingly uncertain future.

Introduction

Half of the world's population lives within 60 km of the ocean, and three quarters of all large cities are coastal (UNEP, 2005). Erosion and inundation are hazards that threaten humans and associated infrastructure in the coastal zone (Hinkel *et al.*, 2014, Kittinger & Ayers, 2010). The impact of these hazards has increased as the amount and value of coastal infrastructure has grown, and continues to grow. Future climate change is predicted to further increase the vulnerability of communities to coastal hazards. This is due to the influence of climate change on the drivers of these hazards, such as increases in sea level, greater wave height and more intense, and potentially more frequent, storm events (IPCC, 2014, Young *et al.*, 2011) (Fig. 1). For example, at least 70% of beaches worldwide are eroding or have a negative sediment budget, resulting in shoreline erosion and inland displacement (Bird, 1985), while up to 4.6% of the global population may experience annual flooding by 2100 (Hinkel *et al.*, 2014). Identifying effective intervention methods to protect and mitigate against such contemporary and future hazards is arguably one of the most pressing challenges facing coastal communities today.

Armouring with 'hard' engineered structures, such as seawalls and breakwaters, is the current solution for coastal defence to protect against contemporary hazards. However, financial costs of maintaining these structures under future climate change scenarios are significant (Hinkel *et al.*, 2014). In parallel, this has prompted research investigating the value of natural ecosystems, such as biogenic reefs, dunes, beaches and vegetation, to provide protection against erosion and waves, with the benefit that these systems can adapt to changes in climate and self-repair after major storm events (Gittman *et al.*, 2014). Recently, the restoration or creation of habitats through 'soft ecological engineering' techniques has been advocated as a tool for natural shoreline stabilisation, with additional ecosystem benefits, such as biodiversity provision (Temmerman *et al.*, 2013). Despite the significant limitations of hard coastal defence in a changing climate, these structures are continuing to be built, with little changes in practices or management. One barrier to the wider use of soft eco-engineering approaches for coastal defence is evidence that restored or created habitats provide equivalent protection to firstly, the intact natural habitat and secondly, hard engineered structures (Bouma *et al.*, 2014, Narayan *et al.*, 2016).

Here we present a review to determine the current evidence for the effectiveness of coastal defence using soft eco-engineering versus traditional engineering solutions. As recent studies have reviewed the role of natural habitats in coastal defence and climate change adaptation, we focus specifically on restored or created habitats and their ability to protect the coast against erosion and flooding relative to hard structures. A comparison between restored/created habitats and hard structures is more relevant to management, where a decision on what type of structure should be built to protect an eroding coastline needs to be made. Nature-based solutions through restoration or habitat creation have considerable potential for coastal defence, but have received much less attention than the additional ecosystem services (e.g. biodiversity enhancement) these habitats provide.

Natural habitats for coastal defence

Coastlines support a variety of habitats, of which sand dunes and beaches, saltmarsh, mangroves, seagrass and kelp beds, and coral and shellfish reefs have been identified as potentially important in mitigating the impacts of coastal hazards (Fig. 1). Increasing interest in the potential for these systems to function as alternatives to hard coastal defence structures has prompted research into the use of natural coastal features to support coastal resilience and risk reduction (Spalding *et al.*, 2014). Recent syntheses evaluating ‘living infrastructure’ for coastal defence have focused on the effectiveness of existing coastal habitats to provide protection against coastal hazards, some in comparison to hard infrastructure (Duarte *et al.*, 2013, Feagin *et al.*, 2015, Ferrario *et al.*, 2014, Gedan *et al.*, 2011, Hanley *et al.*, 2014, Narayan *et al.*, 2016, Ondiviela *et al.*, 2014, Shepard *et al.*, 2011). Of particular interest has been the ability of natural systems to prevent episodic coastal erosion and inundation during storms, hurricanes and tsunami, to halt or slow the chronic loss of coastal land due to persistent erosion over medium to long time periods, and minimise coastal inundation due to future sea level rise.

Natural habitats provide protection services against these coastal hazards through ecosystem processes such as increased bed friction, local shallowing of water, sediment deposition and building vertical biomass (Fig. 1). These processes elicit responses such as changes in shore profile and elevation relative to sea level and wave attenuation, which in turn mitigate the coastal hazards (Fig. 1). For instance, vegetated coastal habitats, such as seagrasses, saltmarshes and mangroves, can reduce water flow and wave height as waves pass through the dense vegetation, and similar effects are caused by the rough surfaces of reef systems (reviewed in Spalding *et al.*, 2014). In addition, subtidal habitats cause localised water shallowing, which promotes wave breaking (Ferrario *et al.*, 2014). Coastal vegetation and shellfish reefs can stabilise shorelines by promoting sediment deposition and/or reducing erosion and sediment movement (Spalding *et al.*, 2014). Further, sediment accumulation in association with coastal vegetation can increase the height of the land relative to sea-level, thus reducing the likelihood of flooding during storm events (Shepard *et al.*, 2011). Finally, the effects of natural habitats in terms of coastal protection can be additive, since two or more ecosystems may lie in close proximity (Spalding et al., 2014).

The wave height reduction of coral reefs, saltmarsh, seagrass/kelp beds and mangroves has been estimated to be 70%, 72%, 36% and 31%, respectively (Narayan *et al.*, 2016), which is comparable to that reported for low-crested detached breakwaters (30-70%, Ferrario *et al.*, 2014). Equally, a meta-analysis found a positive effect of saltmarsh on shoreline stabilisation, although these studies only compared areas with and without saltmarsh (i.e., saltmarsh was not compared with an alternative hard solution; Shepard *et al*. 2011). For saltmarsh, the vegetation characteristics and environmental setting were important for the degree of wave attenuation and shoreline stabilisation provided (Shepard *et al*. 2011). For instance, an increase in marsh width, vegetation height and density and marsh elevation had a positive effect on wave attenuation, while an increase in wave energy had a negative effect. Similarly, an increase in biomass production, percentage cover, patch size and density had a positive effect on shoreline stabilisation, but a greater tidal elevation had a negative effect (Shepard *et al*. 2011).

A reduction in the impact of extreme events (tsunami, storms and cyclones) has also been reported on coasts where sand dunes were present compared to coastlines without dunes (Bayas *et al.*, 2013, Hu *et al.*, 2016, Kathiresan & Rajendran, 2005, Wijetunge, 2010); although the degree of coastal protection depends on the shape and height of the dunes. Low dunes relative to the height of storm surge or tsunami have reduced coastal protection capacities, whereas gaps in dune barriers can cause more substantial impacts by accelerating water flows inland (Bayas *et al.*, 2013, Hart & Knight, 2009, Wijetunge, 2010). There are few direct comparisons between dunes and hard structures; however, an assessment of a low-energy tsunami in the Seychelles found that dunes were less successful than seawalls in reducing flood hazards but that dunes did reduce wave strength leading to a significant decrease in structural damage compared to seawalls (Bayas *et al.*, 2013). The coastal protection capacity of seawalls also depends on their height, and dunes have decreased inundation rates where surge levels have exceeded the height of seawalls but remained lower than the dune height (Sato, 2015).

In terms of natural shellfish reefs, there is a paucity of information on their value for coastal defence, which may be due to the widespread destruction of these habitats that has left few existing mature shellfish beds (Beck *et al.*, 2011). Recent simulations, however, suggest increased wave energy due to historical oyster bed loss in New York Harbour (Brandon *et al.*, 2016). Further, increases in the percentage cover of ribbed mussel (*Geukensia demissa*), which is found synergistically with saltmarsh in the United States, decreased saltmarsh shoreline erosion, however, the effects varied among locations and sites (Moody, 2012).

Although the protection of natural coastal features can be comparable to built infrastructure, unlike artificial defences, coastal habitats are dynamic ecosystems. From one perspective, this is an advantage as they may have the capacity to adapt with climate change. Alternatively, dynamic systems introduce uncertainty that could be a barrier to the wider use of natural habitats in coastal defence planning (see Bouma *et al.*, 2014). For instance, the aboveground biomass of coastal vegetation can vary seasonally, which may impact wave attenuation (Bouma *et al.*, 2014). Further, the persistence and effectiveness of habitats to protect the shoreline is site specific, depending on tidal inundation and foreshore width (Bouma *et al.*, 2014). Long-term persistence of coastal ecosystems needs to be predicted on similar decadal scales to engineered structures, but this is hard to assess and can change due to inherent ecosystem dynamics, or environmental factors. The latter could be the result of the many other anthropogenic impacts simultaneously affecting coastal ecosystems alongside climate change, including contamination (Browne *et al.*, 2015, Myers *et al.*, 1980, Stark, 1998, Stark *et al.*, 2004), extraction of resources (Duran & Castilla, 1989, Fanelli *et al.*, 1994, Lenihan & Peterson, 1998) and introduction and establishment of invasive species (Ruiz *et al.*, 1997).

Although there is evidence for the protective role of coastal habitats, global losses of these habitats is as high as 85% for oyster reefs (Beck *et al.*, 2011) and 50% for coral reefs (Hoegh-Guldberg, 2014) and coastal wetlands (Davidson, 2014). Often, habitat destruction is greatest around the most densely populated areas, ironically where the impact to humans is greatest during erosion and flooding. This has driven an emerging interest in restoring or creating habitats for coastal defence (Temmerman *et al.*, 2013).

Incorporating ecological engineering into coastal defence planning

Economic costs for coastal adaptation to climate change using hard infrastructure is substantial. Additional costs of US$ 4-11 billion per year are estimated for the coastal engineering protection measures required with projected climate change over the next 50 years (Parry *et al.*, 2009). Equally, it has been well documented that building infrastructure in intertidal and subtidal systems has a number of negative ecological impacts (Bulleri & Chapman, 2010). For example, artificial coastal defence structures often support less diverse communities than natural habitats (e.g. Chapman, 2003), with greater numbers of non-native species (Dafforn *et al.*, 2009). This change in assemblage composition is likely to affect ecosystem functioning in artificial systems, and consequently the services important to humans (e.g. food provision), although this remains an understudied topic (Bulleri & Chapman, 2015). To mitigate impacts of built infrastructure in the environment, there is an increasing interest in ecological engineering, which is combining ecological processes with engineering principles to develop infrastructure that benefits both humans and nature (Mitsch & Jørgensen, 2003). Coastal eco-engineering research to date has ranged from ‘hard’, to ‘hybrid’ to ‘soft’ solutions (Chapman & Underwood, 2011, Fig. 2).

Hard eco-engineering

In principle, hard eco-engineering is a solution to the ecological impacts of built infrastructure in areas where there is not an option to manage shorelines using soft engineering techniques. For instance, in coastal cities that are densely populated there may insufficient space to create or restore habitats for coastal defence (Bouma *et al.*, 2014). Equally, eco-engineered habitats can be retrofitted onto existing infrastructures (Dafforn *et al.*, 2015b, Fig. 2b). For example, much research has focussed on adding microhabitats, such as water-retaining features and crevices, to marine infrastructure to increase the overall heterogeneity of substrata and the diversity of organisms living on that structure (Chapman & Underwood, 2011). Techniques for hard eco-engineering have been extensively reviewed recently, and therefore are not addressed in this paper (Chapman & Underwood, 2011, Dafforn *et al.*, 2015b, Firth *et al.*, 2016, Firth *et al.*, 2014).

Hard eco-engineering has different objectives to soft eco-engineering as ecological principles are integrated into the design of existing or planned defence structures, with the motivation to create multi-purpose infrastructure for enhancing diversity and ecological functioning, while maintaining defence services. An exception, however, is when hard eco-engineering promotes the settlement of organisms with a calcium carbonate skeleton (e.g. barnacles), which can shelter the structure from weathering and erosion through bioprotection (Perkol-Finkel & Sella, 2015). Conversely, while soft eco-engineering is advocated as the preferred approach from an ecological perspective (Dafforn *et al.*, 2015b, Mayer-Pinto *et al.*, 2017), the created habitat foremost needs to provide sufficient coastal protection into the future if this technique is to replace (or complement) artificial defences.

Hybrid eco-engineering

An intermediate solution between hard and soft eco-engineering is a hybrid approach (Sutton-Grier *et al.*, 2015). Nature-based and built infrastructure in this case are combined to provide maximal coastal protection benefits (Sutton-Grier *et al.*, 2015). This provides an opportunity to harness the strengths of nature-based and hard infrastructure, while minimising the weaknesses of both (Sutton-Grier *et al.*, 2015). For example, a shellfish reef may be placed in front of a seawall (Fig. 2c), which could form the first line of defence, thus prolonging the life of the wall as well as contributing other functions such as water filtration and biodiversity enhancement. On the other hand, the seawall can provide protection during reef formation. New initiatives could involve removable walls after the establishment of nature-based infrastructure, or wider use of seawalls with gates that can be opened and closed in extreme events (Sutton-Grier *et al.*, 2015). Thus, hybrid engineering might provide novel alternatives to traditional infrastructure, particularly where soft engineering alone is not appropriate.

Soft eco-engineering

The diversity of terminologies in the literature that relate to actions inspired or supported by nature to solve environmental, social and economic problems may have introduced ambiguity around nature-based coastal defence (Nesshöver *et al.*, 2017). This includes 'nature-based solutions' (Nesshöver *et al.*, 2017), 'soft engineering' (Chapman & Underwood, 2011), 'nature-based features or infrastructure' (Bridges *et al.*, 2015), 'green/blue infrastructure' (Mayer-Pinto *et al.*, 2017) 'building with nature' (de Vriend *et al.*, 2014) and 'living shorelines' (Bilkovic *et al.*, 2016). In addition, restoration (defined as the re-creation of habitat that was previously in a particular area, Elliott et al. 2007) and habitat creation or enhancement, which is placing a different habitat within an area (Elliott *et al.*, 2007) have both been included under nature-based shorelines (Bilkovic *et al.*, 2016). Whichever the term used, in general, all practices have in common the promotion of nature to enhance climate change mitigation and adaptation, explicitly as an alternative to, or to complement, built infrastructure (Nesshöver *et al.*, 2017), Fig. 2d).

Coastal protection may often not be a primary motive in soft engineering projects. For example, the restoration of oysters in the United States started with the aim of enhancing fisheries, but since the framework has been used to restore other ecosystem services, including coastal defence (Beck *et al.*, 2011). Here, we evaluate the current evidence for the effectiveness of restored or created (hereafter collectively referred to as 'restored') dunes, coral and shellfish reefs, seagrass and kelp beds, mangroves, and saltmarsh as coastal defence, in comparison to hard infrastructure.

Current evidence for nature-based coastal defence

A relatively small percentage of studies reported coastal defence as a primary objective of coral reef (18%), mangrove (26%), saltmarsh (16%) and shellfish (26%) restoration projects, and none for kelp and seagrass (Supplementary methods and Table S4, Fig. 3). In contrast, over half (65%) of dune restoration studies were for coastal defence. For coral reefs and mangroves designed for coastal defence, monitoring to determine whether the created habitat had succeeded in protecting the coast was done in half, or less, of the studies (Fig. 3). A questionnaire-based study on coral reef restoration revealed a similar result, where 19.6% of respondents reported designing reefs to deliver coastal defence services, but only 10% reported measuring those benefits (Fabian *et al.*, 2014). For dunes, saltmarsh and shellfish coastal defence projects, field measurements of shoreline erosion and/or wave attenuation was greater (60-80% of projects, Fig. 3). However, all studies (except see, Gittman *et al.*, 2014) compared restored habitats to control areas without habitats, leaving a paucity of information on how nature-based defences compare to hard infrastructure (Fig. 3).

Wave attenuation

Wave attenuation is the reduction in wave height or energy that occurs as waves pass over coastal habitats. Created oyster reefs, installed to combat both natural and anthropogenic erosion, attenuated 25% of the wave height caused by boating pressures, in comparison to controls with no reefs, and was equivalent to a natural reef (23% attenuation) (Garvis, 2009). As might be expected, wave energy reduction significantly increased from immediate deployment of the oyster reef (18.7%) to one year after establishment (44.7% reduction) (Manis *et al.*, 2015). Under the same conditions, newly created and established saltmarsh reduced 6.9% and 31.4% of wave energy, respectively (Manis *et al.*, 2015). A design that incorporated both saltmarsh and oyster reef, however, was the most effective at attenuating wave energy (67.3% after one year; Manis *et al.*, 2015).

Oyster reefs reduced the power of larger wind-waves (> 0.03 m in height) by 42-44% (Taube, 2010). Restored reefs, however, dissipated less wave energy than a natural reef in the same area (61%). Under some conditions, restored saltmarsh was recorded to dissipate virtually all wave energy, over half of which was within the first few metres of the bed (Knutson *et al.*, 1982). There is likely to be an optimal water depth, however, for wave attenuation by coastal habitats, where decoupling occurs between the surface waves and structure on the seabed when depth is too great (Knutson *et al.*, 1982, Taube, 2010).

The rate of wave reduction for mangroves can be as high as 20% per 100 m of forest (Mazda *et al.*, 1997). Further, using vegetation parameters from a restored mangrove forest, a model simulation estimated a 60% wave height reduction, even under predicted sea level rise (Cuc *et al.*, 2015). Concurrently, field measurements showed that wave reduction of restored mangroves was unaffected by changes in water depth, where mangroves were sufficiently tall (Mazda *et al.*, 1997). Thus, mangroves may be more effective at shoreline protection over a larger range of depths, in comparison to subtidal habitats or low-lying coastal vegetation.

Shoreline response

Shoreline response describes the extent of lateral (i.e., a change in shoreline position) or vertical erosion/accretion to built or natural/nature-based infrastructure. The majority of studies on shoreline response came from restored dune habitats (Tables S5 and S6). Dune restoration for defence takes many forms including the direct addition of sand (i.e., nourishment) to dunes and beaches (Achab *et al.*, 2014, Matias *et al.*, 2005), the construction of sand ridges with and without hard cores (do Carmo *et al.*, 2009, Kratzmann & Hapke, 2012, Wamsley *et al.*, 2011), and the facilitation of sand accumulation using fences, vegetation and by managing pedestrian access (Anthony *et al.*, 2007, Johnston & Ellison, 2014, Lin, 1996, Miller *et al.*, 2001, Table S3). Utilising multiple techniques within a site, for example beach renourishment in combination with sand fences, to build dunes is common (Bocamazo *et al.*, 2011, Khalil & Lee, 2006). Dune restoration in conjunction with more traditional hard engineering structures has also been applied (Bezzi *et al.*, 2009, Bocamazo *et al.*, 2011, Wamsley *et al.*, 2011).

Although few dune restoration studies made meaningful comparisons with control sites, there is some evidence that created dunes can reduce shoreline loss in comparison to non-restored sites (Achab *et al.*, 2014, Dias *et al.*, 1999, Matias *et al.*, 2005). Restoration often results in an initial seaward shift in shoreline position, particularly when sand is added to the system or when the created dune was constructed seawards of the existing shoreline (Dias *et al.*, 1999, Matias *et al.*, 2005). Subsequent post-restoration beach retreat and dune erosion during storms is also frequently reported (Dias *et al.*, 1999, Kratzmann & Hapke, 2012, Matias *et al.*, 2005, Shibutani *et al.*, 2016), in extreme cases leading to the total removal of the restored dune (do Carmo *et al.*, 2010, Froede, 2010, Gares *et al.*, 2006). Restored dunes are potentially able to function in a manner akin to natural dunes and rebuild following erosive events (Nordstrom et al., 2000). Information on the post-storm recovery of restored dunes is sparse but appears limited due to the negative sediment budgets, frequent erosive events, or poor beach management practises that necessitated construction of the dunes in the first place (Bezzi *et al.*, 2009, do Carmo *et al.*, 2010, Froede, 2010, Shibutani *et al.*, 2016). Over decadal time scales shoreline stability or net progradation was only achieved through repeated dune restoration interventions (Bakker *et al.*, 2012, Bocamazo *et al.*, 2011, Gares *et al.*, 2006, Keijsers *et al.*, 2015) or the construction of hybrid eco-engineering structures (do Carmo *et al.*, 2010).

Created oyster reefs can reduce shoreline loss in comparison to control sites with no reefs, although in some cases (La Peyre *et al.*, 2014, La Peyre *et al.*, 2013b, Moody *et al.*, 2013), but not others (La Peyre *et al.*, 2013a), shorelines continued to erode, albeit less. Shoreline exposure can impact the defence value of oyster reefs, however, data that supports whether reefs are more successful in low (Piazza *et al.*, 2005) or mid- to high energy (La Peyre *et al.*, 2015) environments is unclear. Oysters are the only group of shellfish that have been restored for the goal of coastal defence and these created reefs may be able to match or exceed natural reefs in meeting this objective (Stricklin *et al.*, 2010).

Experimental saltmarsh planting in the United States represents some of the earliest examples of creating habitats for coastal defence (Knutson *et al.*, 1981). Planted areas were successful in stabilising shorelines compared to unplanted areas, with some accretion also observed (Benner *et al.*, 1982, Woodhouse *et al.*, 1976). Equally, coastal stabilisation and land reclamation have been achieved through years of ecological engineering with saltmarsh in China (Chung, 2006, Chung *et al.*, 2004). The success of saltmarsh plantings may depend on sediment grain size, length of fetch and shoreline configuration, with greater effectiveness in sheltered areas (Knutson *et al.*, 1981). Establishment of saltmarsh, however, may be achievable in more exposed areas using temporary wave breakers (Dodd & Webb, 1975) or in combination with shellfish (e.g. mussels) to attenuate wave energy (Newcombe *et al.*, 1979).

In the tropics, artificial reefs transplanted with corals were effective in promoting beach accretion following a period of significant erosion (Arnouil, 2008, Fabian *et al.*, 2014), although specific reports detailing shoreline response were unavailable, or not measured for many coral reef projects (Fabian *et al.*, 2014). Equally, although case studies were presented where mangroves were planted to provide coastal protection (IFRC, 2011), there was little data on the shoreline response to planted mangroves, despite evidence for higher sediment accretion rates at greater mangrove plantation densities (Kumara *et al.*, 2010). More commonly, a hybrid eco-engineering approach to mangrove restoration was reported (Table S3). This involved planting in combination with a breakwater to facilitate sediment accumulation and wave attenuation for mangrove establishment (Hashim *et al.*, 2010, Motamedi *et al.*, 2014, Van Cuong *et al.*, 2015). Although there are no studies on shoreline protection provided by seagrass and kelp restoration, tests of an artificial seaweed bed installed to promote build-up of a beach in the United Kingdom showed some accretion over its lifespan. However, the artificial seaweed was severely damaged by storms within a year of installation (Price *et al.*, 1968).

Flood water and storm surge attenuation

Flood water and storm surge attenuation is the ability of coastal habitats to reduce the height or duration of flood waters and protect the coast during extreme episodic events (e.g., hurricanes). There is less empirical data on the effectiveness of nature-based coastal defence for flood water and storm surge attenuation. Furthermore, even whether natural ecosystems provide effective defence against storms, in particular extreme events, such as tsunami and hurricanes is hotly debated (Kumar, 2015). Storm events were stated to have occurred in many studies that observed shoreline response over a number of years (Table S5 and S6), although the effect of the individual storm event was not necessarily quantified. Regardless, the value of nature-based coastal defence had been predicted to be negligible under storm surges where the sea level is elevated (Knutson *et al.*, 1982, Taube, 2010), although this is likely to be habitat and context dependent. For example, observations of an artificial coral reef in the Dominican Republic suggest that while the reef remained stable during two hurricanes, wave attenuation was not enough to prevent significant beach erosion (Fabian *et al.*, 2014). In contrast, remote sensing data suggested little flooding after cyclones in areas where there were natural mangroves and for coastal islands that were protected by a combination of dykes and mangrove plantings (Blasco *et al.*, 1992).

In some studies, repeated surveys of restored dunes identified the response of these systems to storm events. There were mixed results with created dunes withstanding significant storm events in some cases (Bezzi *et al.*, 2009, Dias *et al.*, 1999, Harley & Ciavola, 2013, Wamsley *et al.*, 2011), but failing in others (do Carmo *et al.*, 2010, Froede, 2010). Where measured, the surviving created dunes protected against overwash compared to adjacent non-dunal areas or areas where dunes had been destroyed (Harley & Ciavola, 2013, Wamsley *et al.*, 2011). Smaller narrower dunes are more frequently destroyed by wave action than larger ones but can also be rebuilt quickly (Nordstrom *et al.*, 2000), and in the appropriate environments can accord the desired protective function (Harley & Ciavola, 2013). Dunes constructed close to the sea were frequently eroded (do Carmo *et al.*, 2010, Froede, 2010), while those constructed further inland were able to accumulate sand even during storm events (Miller *et al.*, 2001). A wide, high beach can minimise dune erosion and serve as a source of sand for dune building (Bezzi *et al.*, 2009, Bocamazo *et al.*, 2011), although erosion of artificially elevated nourished beaches can also limit aeolian processes and dune growth (Dias *et al.*, 1999, Jackson *et al.*, 2010). The frequency and magnitude of erosive events, and the use of hybrid eco-engineering methods also influenced dune survival (Anthony *et al.*, 2007, do Carmo *et al.*, 2010, Mendelssohn *et al.*, 1991, Wamsley *et al.*, 2011).

The most compelling evidence for effective protection by nature-based coastal defence is provided by Gittman *et al.* (2014) for created saltmarshes with sills (rock or oyster shell seaward of marsh) after a hurricane in the United States. Following the hurricane, storm damage was reported for 76% of bulkheads protecting shorelines, whereas no damage was found for restored marshes with sills. From before to after the hurricane event, there was no effect on marsh surface elevation, although vegetation density was reduced. After one year, however, the vegetation had recovered to pre-hurricane levels (Gittman *et al.*, 2014). This study exemplifies the approach that should be taken in assessing soft versus traditional engineered shoreline protection schemes.

Traditional versus nature-based coastal defence

We extracted data from 15 and 23 studies for wave attenuation and shoreline response, respectively, for inclusion in our meta-analysis. In addition, we undertook a qualitative review for those studies that only presented written statements about their results (n = 76; Supplementary methods). Studies on either or both artificial and nature-based infrastructure occurred in many countries throughout the world, although a clear hotspot for this research was the United States (Fig. 4). A meta-analysis was possible for wave attenuation for saltmarsh, oyster reef and breakwaters (emergent and submerged combined, Supplementary methods, Table 1) and shoreline response for saltmarsh, oyster reef, dunes, coral reefs and breakwaters (emergent and submerged combined). Further, a qualitative review of the effect on shoreline response of mangroves, emergent and submergent breakwaters, groynes, revetments and seawalls (Table 1), as well as additional papers on coral reefs and dunes was done.

Breakwaters significantly reduced wave height by 45% (n = 7; 14 - 90%; Fig. 5a,b). There was no significant effect, however, of saltmarsh (n = 6; 4 – 74%) or oyster reefs (n = 2, 26 – 27%) on wave attenuation (Fig. 5a,b). Coral reefs and breakwaters had a significant accretionary effect on shoreline response (Fig. 6a). In addition, the proportion of studies that cited accretion in the qualitative review was significantly different among habitats (χ^2 = 77.14, d.f. = 7, P < 0.001). There was, however, no significant effect of restored saltmarsh, oyster reefs and dunes on shoreline response (Fig. 6a). For dunes, this result contrasts with the qualitative review, where a greater proportion of studies reported accretion (Fig. 6b), which likely reflects the small sample size in the meta-analysis. All studies on mangroves reported accretion following mangrove planting, which in some cases was in combination with a temporary breakwater to facilitate mangrove establishment (Fig. 6b). A greater proportion of studies on emergent breakwaters reported shoreline accretion, however erosion was more often the result of submerged breakwaters (Fig. 6b). Similarly, shoreline retreat was also reported in a greater number of studies for seawalls (Fig. 6b).

For saltmarsh, this result is in direct contrast to a recent meta-analysis, which showed a significantly positive effect of natural, intact saltmarsh on shoreline stabilisation and wave attenuation (Shepard *et al.*, 2011). The obvious point of distinction is the meta-analysis by Shepard et al. (2011) included more studies, but only two (wave attenuation) and three (shoreline change) papers included here looked at restored saltmarsh, highlighting the need for more research on the coastal defence value of restored habitats.

Currently, the evidence for the efficacy of restored habitats versus traditional infrastructure suggests that restored coral reefs, mangroves and dunes could be equivalent to artificial structures at maintaining or building the shoreline, although more quantitative evidence is needed for these habitats. The effect of saltmarsh and oyster reefs was, however, more variable and did not show a significant effect on shoreline response or wave attenuation in comparison to breakwaters. Variability in results among studies highlights the need to identify not only which habitats are effective at providing coastal defence, but also under what range of physical conditions (i.e. what locations and types of environments). Further, as with natural habitats (e.g. Shepard *et al*. 2011) the design of soft engineering projects (e.g. tidal height, length and width, density of organisms) will impact effectiveness. Thus, the design elements that contribute to the success or failure of nature-based coastal defence need to be identified. Interestingly, a greater proportion of studies on seawalls and submerged breakwaters reported erosion compared to accretion. These are structures that are commonly and increasingly used as coastal defence, but equally can result in adverse impacts in some areas (Ranasinghe & Turner, 2006).

Comparisons between traditional and soft engineering approaches, however, are difficult if they have not been tested under the same environmental conditions. Indeed, for those studies that recorded the tidal and average significant wave heights at the study area, a greater percentage of soft engineering structures were tested under smaller tidal (n = 30; micro- = 70%; meso- = 27%; macro-tidal = 3%) and wave energy conditions (n = 14; significant wave height < 1 m = 79%; < 2 m = 21%, Table S5 and S6). In comparison, studies on artificial structures included a higher percentage tested under larger tidal (n = 24; micro- = 54%; meso- = 13%; macro-tidal = 33%) and wave energy conditions (n = 14; significant wave height < 1 m = 42%; < 2 m = 25%; 2^+ m = 33%, Table S5 and S6). Further, as many studies only monitored over short-time periods (months to years) following restoration, there is limited information on the long-term effectiveness of the created habitats (Table S5 and S6). Thus, while soft engineering structures offer the potential for low-impact, effective coastal defence, until there is a greater number of studies globally to test the value of these shoreline protection schemes, their wider use in place of artificial structures is likely to remain relatively limited.

Cost-benefit of nature-based coastal defence

Nature based coastal defence needs to be effective and have an equal or greater cost-benefit when compared to traditional infrastructure. As there are few studies that make comparisons between the effectiveness of nature-based and traditional defences, it is unsurprising there is also a lack of data for site-specific cost-benefit comparisons. This is regarded as one of the significant challenges for widespread use of habitats for coastal protection (Narayan *et al.*, 2016).

A recent synthesis estimated the cost and effectiveness of nature-based coastal defences through pairing information on restored habitats for defence with nearby field data on wave attenuation at natural habitats (Narayan *et al.*, 2016). This was integrated with engineering knowledge to estimate the costs of coastal defence if the equivalent was achieved with a submerged breakwater. Saltmarsh and mangroves were the only habitats with sufficient data for comparison, with both being assessed as cost-effective alternatives to traditional infrastructure. Similarly, Ferrario *et al.* (2014) reported a comparable range of wave height reduction for coral reefs and low-crested detached breakwaters, and significantly cheaper costs for coral reef restoration in comparison to building tropical breakwaters.

Ideally, however, to produce more accurate cost-benefit analyses for the habitats reviewed, field measurements on the effectiveness of nature-based coastal defence as well as the costs associated with their creation/restoration should be reported for each project. Importantly, data for the coastal protection benefits of existing natural habitats may not necessarily translate to nature-based projects for defence because of the trade-offs that can occur when restoring or creating these systems (see below). Further, comparing the cost relative to the effectiveness of the single service of coastal protection will result in undervaluing nature-based approaches, which are expected to provide a number of additional ecosystem services.

Additional ecosystem services

One rationale for nature-based coastal defence is the assumption that they will provide other ecosystem services in addition to coastal protection (Table 2). With the global decline in natural estuarine and coastal systems, there is much interest in economically valuing the services provided by these habitats to leverage their conservation and restoration (Barbier *et al.*, 2011). To accurately evaluate the benefits of using nature-based coastal defence, cost-benefit analyses need to include all ecosystem services provided by eco-engineered and traditional coastal defence. However, created or restored habitats may not be effective at providing the same suite of services as natural ecosystems (Bilkovic & Mitchell, 2013). Thus, monitoring of restored habitats needs to include an evaluation of all ecosystem services relevant to that habitat, in addition to coastal protection.

With restoration for coastal defence, trade-offs among ecosystem services can occur due to the fact that coastal protection is predominantly needed during extreme events, which may result in different requirements for particular features of a habitat compared to biodiversity conservation (van Loon-Steensma & Vellinga, 2013). In particular, ecological trade-offs may occur with hybrid coastal protection that incorporates structural elements to facilitate restored habitats (Bilkovic & Mitchell, 2013). For instance, created saltmarsh in combination with a stabilising structure, such as a low-profile rock sill is increasingly used in the United States for shoreline protection, as well as to restore coastal habitat. Marsh sills, however, supported epifaunal suspension feeders, such as oysters, which colonised the rock sill and a lower deposit-feeding infaunal biomass than natural marshes (Bilkovic & Mitchell, 2013). As deposit feeders are important for bioturbation and nutrient cycling, incorporating marsh sills for coastal protection may result in a trade-off for this ecological service provided by saltmarsh systems. A greater number of suspension feeders, however, could increase water filtration and thus the water quality services (Bilkovic & Mitchell, 2013).

The reviewed restored coastal habitats are commonly evaluated for their effectiveness at maintaining biodiversity (Table 2). For coral reefs and kelp, other ecosystem services, such as fisheries provision and nutrient cycling have not been evaluated, which is likely due to the shorter history of restoration efforts in these habitats. There is evidence that restored mangroves, saltmarsh, seagrass and shellfish reefs can provide similar ecosystem services to natural habitats, although some gaps remain such as nutrient cycling in mangroves, fisheries provision for seagrass and provision of raw materials and food for saltmarsh (Table 2). Equally, an evaluation of additional ecosystem services potentially provided by artificial structures is largely unknown, beyond patterns of biodiversity between artificial structures and natural shorelines (Bulleri & Chapman, 2010).

Artificial structures introduce a novel substratum into the marine environment, which can be colonised by organisms. It has been well documented that human-made structures generally support less diverse assemblages than natural habitats (e.g. Chapman 2003), with greater numbers of non-indigenous species (Dafforn *et al.* 2009). Thus, artificial structures cannot be considered to provide the same biodiversity provisioning services as natural habitats. In some areas globally, however, artificial structures such as seawalls are colonised by large numbers of filter feeders (e.g. oysters, Scanes *et al.*, 2016). Whether the organisms living on coastal defence structures have the same filtration capacity as those on natural substrata, and how this contributes to water quality services is yet to be tested. Similarly, artificial structures can be associated with diverse fish assemblages (Fowler & Booth, 2013). Whether this is due to the attraction of existing biomass or new production of fish is still not well resolved, so the contribution to fisheries provisioning is difficult to quantify (Bohnsack, 1989).

Hard ecological engineering may also be used to enhance biodiversity and ecosystem functioning of coastal defence structures (Chapman & Underwood, 2011, Dafforn *et al.*, 2015a). Although it is unlikely that hardened shorelines will be able to provide the same suite of ecosystem services as softer habitats, comparisons of all ecosystem services across restored and artificial habitats are required to make reliable cost-benefit comparisons.

Conclusions

Uptake of nature-based coastal defence depends on its acceptance as an alternative to traditional engineering solutions. Support needs to come from a number of stakeholder groups including coastal managers, engineers and the public (Nesshöver *et al.*, 2017). For this, we need rigorous data that assesses the costs and effectiveness of habitats created for protection to mitigate coastal hazards. It is clear that for most of the habitats reviewed, the data is currently lacking. This is highlighted by the meta-analysis, for which we found very few studies on the coastal defence value of restored habitats to make comparisons to artificial structures. Collaborations among stakeholders, such as scientists, coastal managers and engineers, are required to facilitate the necessary research to identify which restored habitats provide effective coastal defence, where those habitats work and what is the best design to implement. Ideally, nature-based defences should be compared directly in the field to an artificial structure at a location under similar conditions, with ecosystem services of interest evaluated before and after the creation of habitat (and traditional infrastructure) at experimental sites relative to unaltered control sites (Chapman, 1999). Alternatively, the cost of an artificial structure to achieve the same coastal protection as a soft engineered shoreline can be estimated in cost-benefit analyses if the opportunity to compare nature-based and traditional infrastructure in the field is not possible (*sensu* Narayan *et al.*, 2016).

Where soft engineering approaches are established, a remaining challenge is how to estimate their persistence over similar decadal scales to engineered structures (Bouma *et al.*, 2014). At least for dunes, different restoration designs may allow for different levels of dynamism in the system (Nordstrom *et al.*, 2011). However, managing nature-based coastal defence for engineering resilience by promoting constancy and predictability may come at a cost to ecological resilience, when it is precisely this variability that allows natural ecosystems to absorb disturbances and remain stable (Holling, 1996). Adopting soft engineering practices will thus necessitate a change in the way we approach the design and evaluation of coastal defence infrastructure. This change in mindset needs to happen now as our rapidly changing climate requires new and innovative solutions to reduce the vulnerability of coastal communities to an increasingly uncertain future.

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Table 1. Artificial structures evaluated in this study, defined per Van Rijn (2013).

Structure	**Definition**
Groyne	Narrow, shore-perpendicular structure built on the shore extending into the surf zone for shoreline stabilisation
Emergent breakwater	Offshore barrier built parallel to the shore for wave attenuation and shoreline stabilisation. Crest positioned above still water height.
Submerged breakwater	Offshore barrier built parallel to the shore for wave attenuation and shoreline stabilisation. Crest positioned below still water height.
Revetment	Shore-parallel sloped structure built to reduce inundation and protect land behind from erosion.
Seawall	Shore-parallel vertical structure built to reduce inundation and protect land behind from erosion.

Table 2. Other ecosystem services provided by a) natural habitats, b) restored habitats and c) hard coastal defences. ✓ indicates ecosystem service is provided, × indicates ecosystem service is not provided, ? data are not available.

	Maintenance of wildlife	*Raw materials and food*	*Fisheries provision*	*Nutrient cycling, water purification*	*Carbon sequestration*	*Tourism, recreation, education, research*	*References*
a) Natural habitats							
Coral reef	✓	×	✓	✓	×	✓	Barbier *et al.* (2011)
Foredunes	✓	✓	×	✓	✓	✓	Everard et al. (2010), Barbier *et al.* (2011)
Kelp	✓	✓	✓	✓	×	✓	Smale *et al.* (2013)
Mangrove	✓	✓	✓	✓	✓	✓	Barbier *et al.* (2011)
Saltmarsh	✓	✓	✓	✓	✓	✓	Barbier *et al.* (2011)
Seagrass	✓	✓	✓	✓	✓	✓	Barbier *et al.* (2011)
Shellfish reef	✓	✓	✓	✓	×	✓	Beck *et al.* (2011)
b) Restored habitats							
Coral reef	✓	×	?	?	×	✓	Clark and Edwards (1999)
Foredunes	✓	?	×	?	×	✓	Nordstrom *et al.* (2000), Russell *et al.* (2009), Gallego-Fernandez *et al.* (2011)
Kelp	✓	?	?	?	×	✓	Marzinelli *et al.* (2016)

Mangrove	✓	✓	✓	?	✓	✓	Bosire *et al.* (2008), Dung *et al.* (2016)
Saltmarsh	✓	?	✓	✓	✓	✓	Davis *et al.* (2015), La Peyre *et al.* (2007), Sparks *et al.* (2015)
Seagrass	✓	✓	?	✓	✓	✓	Cole and McGlathery (2012), Greiner *et al.* (2013), McSkimming *et al.* (2016)
Shellfish reef	✓	✓	✓	✓	✗	✓	Milbrandt *et al.* (2015), Scyphers *et al.* (2011)
c) Hard defences							
Breakwater	✗	✗	?	?	✗	✓	Bulleri and Chapman (2010)
Groynes	✗	✗	?	?	✗	✓	Bulleri and Chapman (2010)
Revetment/Riprap	✗	✗	?	?	✗	✓	Bulleri and Chapman (2010)
Seawall	✗	✗	?	?	✗	✓	Bulleri and Chapman (2010)

Fig. 1. Coastal hazards and protection services provided by natural habitats.

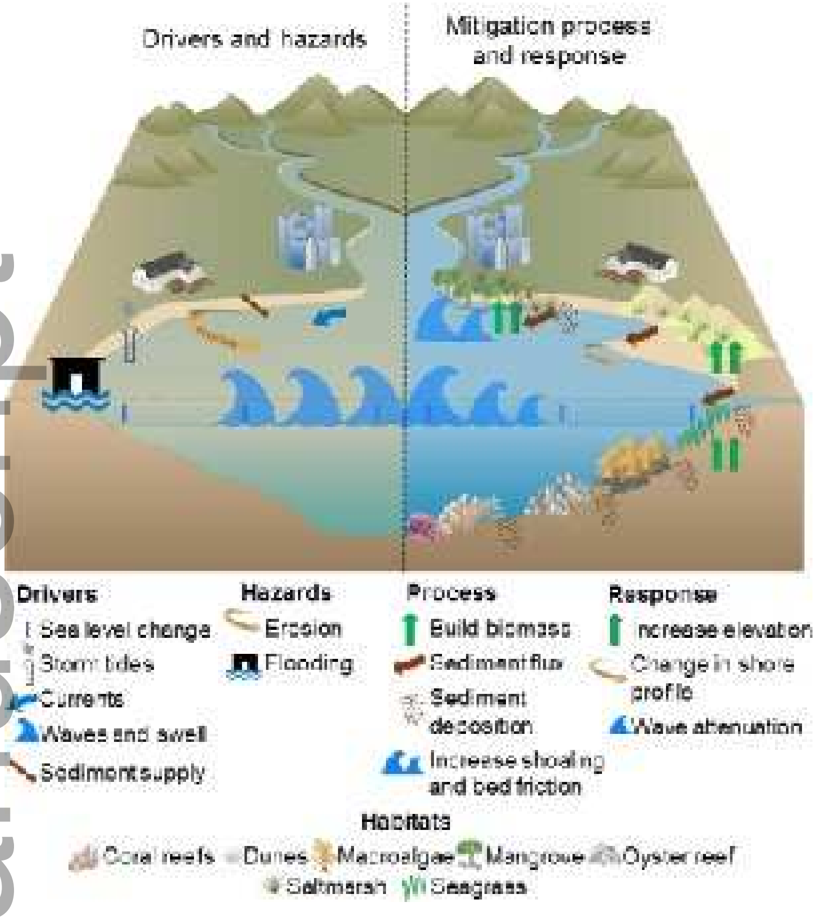
Fig. 2. Ecological engineering incorporated into coastal defence infrastructure ranges from hard to soft approaches. a) Traditional seawall, b) Seawall with water-retaining features to enhance biodiversity, c) Oyster reef in front of seawall, d) Created oyster reef with saltmarsh and e) Natural mangrove forest.

Fig. 3. Heat map of the number of restoration projects implemented for different management objectives. ‘Measured’ refers to the number of projects implemented for coastal defence that made field measurements to determine their effectiveness. ‘Vs. artificial’ refers to the number of projects that made comparisons between soft and traditional engineering shoreline protection.

Fig. 4. Map of the location and number of studies included in the review. The smallest circles represent 1-5 studies, the largest represents 45-50 studies.

Fig. 5. a) Results of the meta-analysis (log response ratios and 95% confidence intervals) testing the effects of different habitats (black = nature-based, grey = artificial) on wave attenuation. b) Graph of the percentage wave attenuation (95% confidence intervals).

Fig. 6. Results of the a) meta-analysis (Hedge’s g standard mean difference effect size and 95% confidence intervals) and b) qualitative analysis (proportion of studies citing accretion) testing the effects of different habitats (black = nature-based, grey = artificial) on sediment stabilisation.



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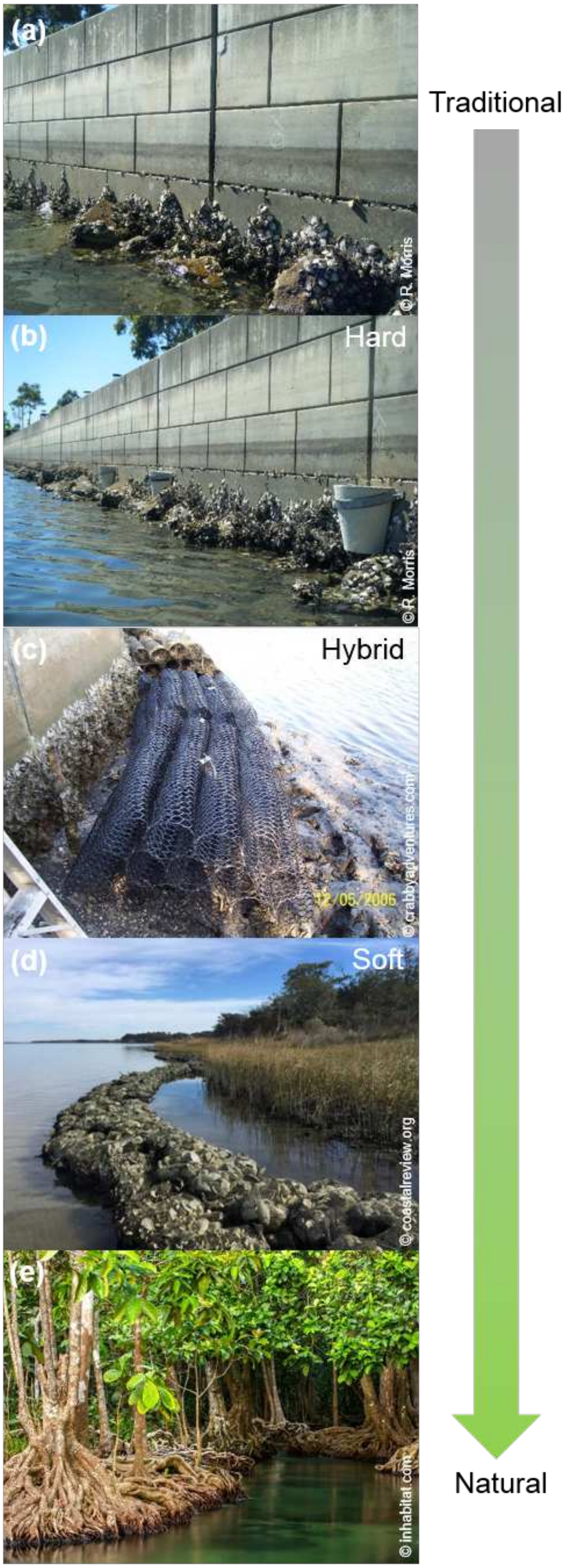

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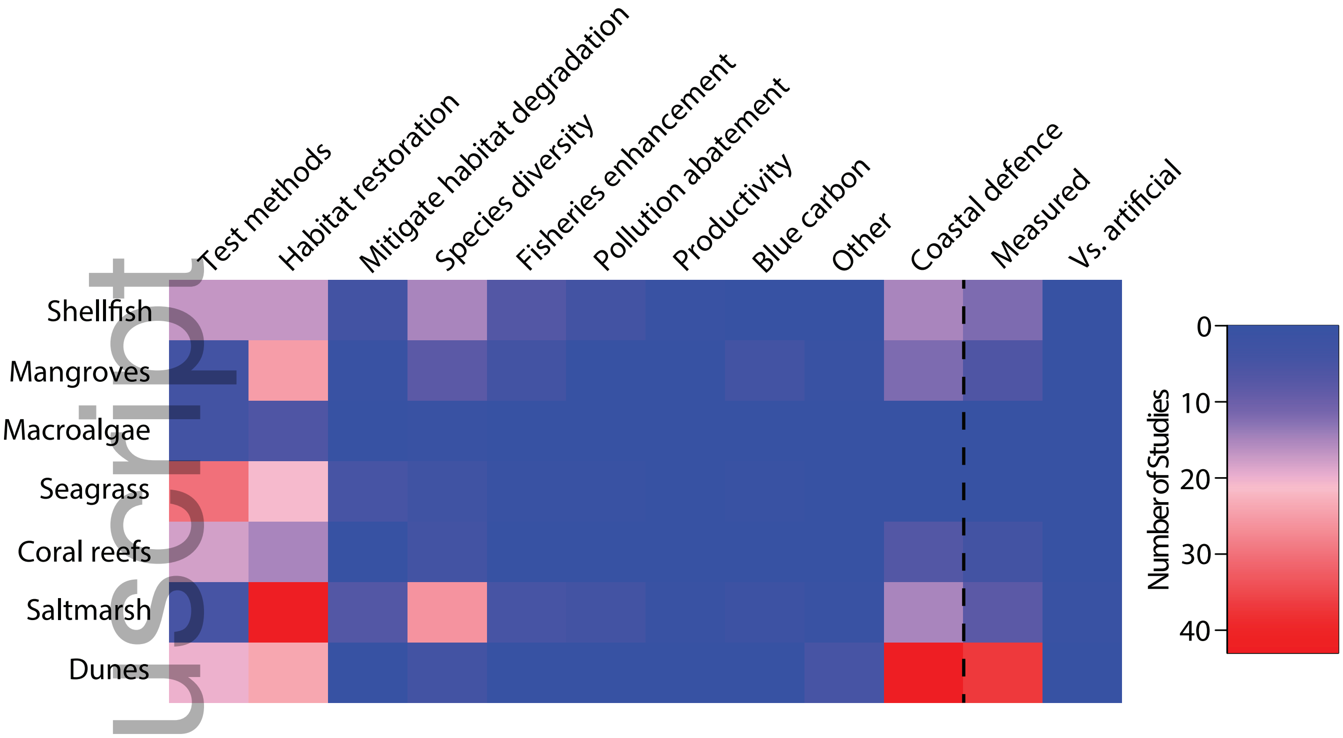

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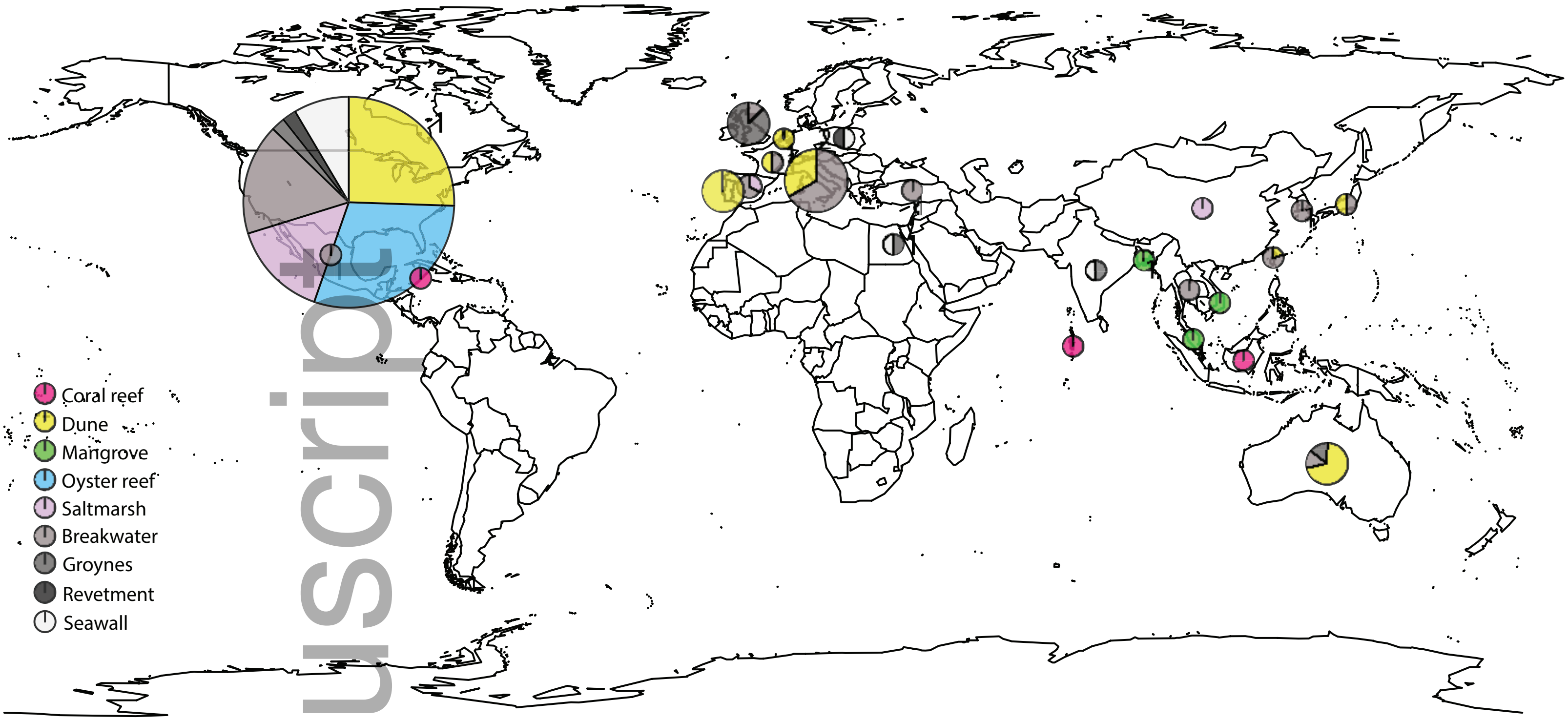

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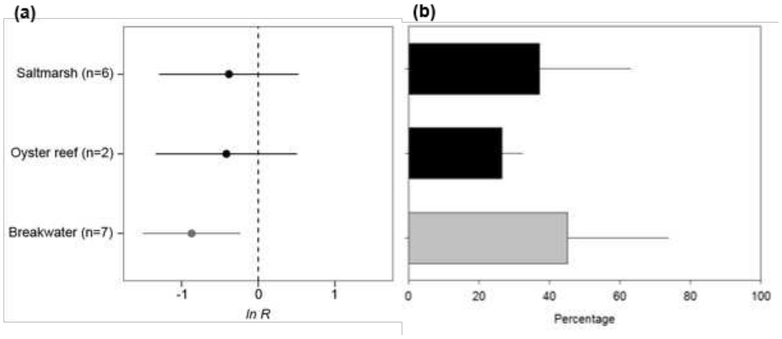

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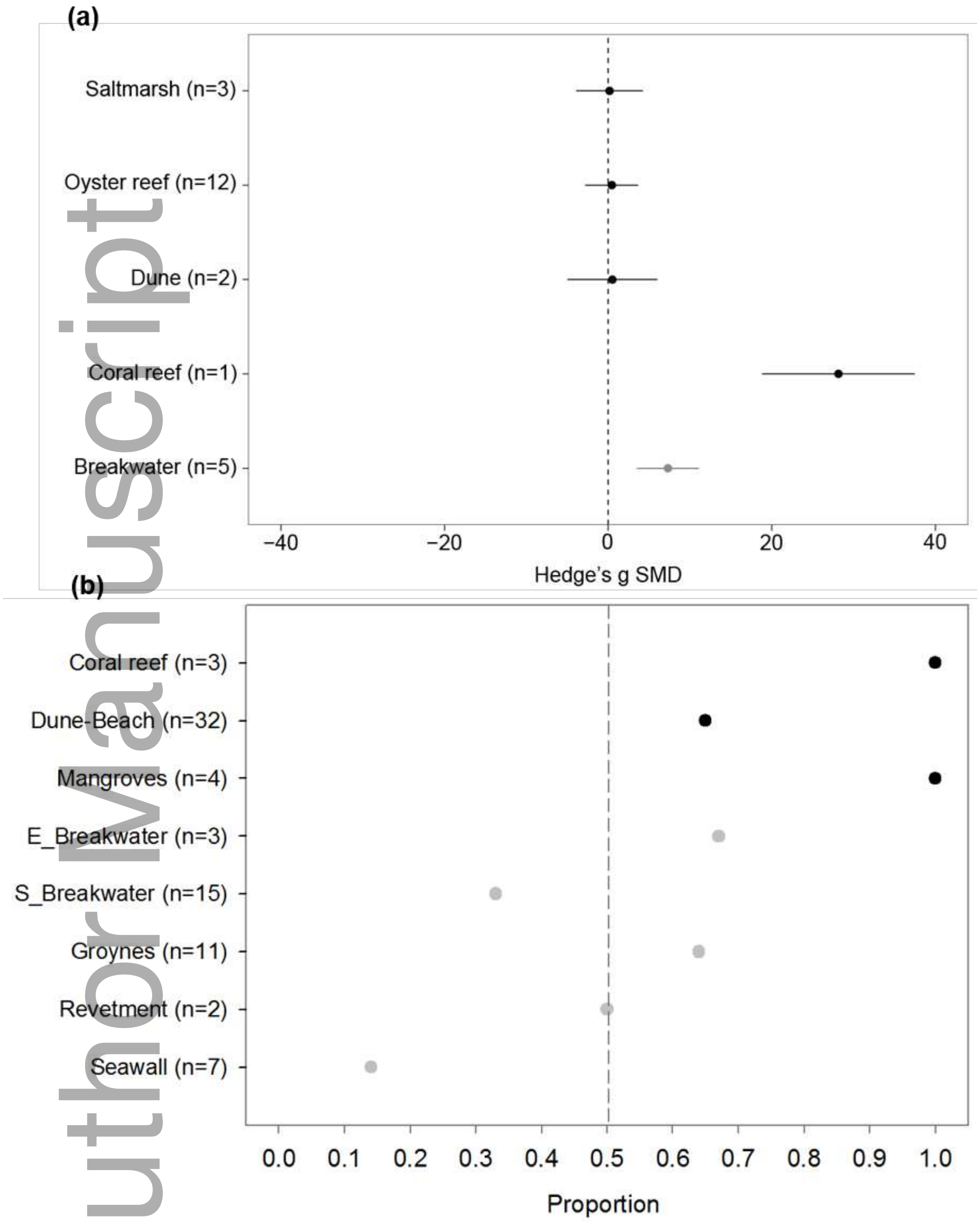

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