Combining grey and green infrastructure to improve coastal resilience: lessons learnt from hybrid flood defences

Authors: Paweł Waryszak[1]†, Alice Gavoille[1]†, Ashley A. Whitt[1], Jaya Kelvin[1], Peter I. Macreadie[1*]

[1] *School of Life and Environmental Sciences, Centre for Integrative Ecology, Deakin University, Victoria 3216 Australia.*

**Corresponding author: p.macreadie@deakin.edu.au*

† Authors contributed equally to this manuscript

ORCiDs and Twitter handles		
Name	***ORCiD***	***Twitter***
Paweł Waryszak	0000-0002-4245-3150	@PWaryszak
Alice Gavoille		
Ashley Whitt	0000-0002-4130-8031	@CoastalWhitt
Jaya Kelvin		@jayakelvin
Peter I. Macreadie	0000-0001-7362-0882	@PeterMacreadie

Combining grey and green infrastructure to improve coastal resilience: lessons learnt from hybrid flood defences

Shoreline erosion and storm tide inundation increasingly threaten coastal populations, infrastructures and economies. Hard infrastructure, known as grey infrastructure (*e.g.,* concrete seawalls), has commonly been used to protect coastal communities but is expensive to build, maintain and deteriorates coastal vegetation. Green infrastructure (*e.g.*, restored or conserved mangrove and marsh ecosystems) delivers nature-based coastal protection but in comparatively lower-density coastal areas. Nowadays a more popularized approach to coastal protection is hybrid eco-engineering. In this study, we discuss lessons-learnt on how the hybridization of engineered structures and wetland restoration practices compare with traditional grey and green approaches. We contrast hybrid applications in mangrove and tidal marsh areas in the UK and south-east Asia. The majority (70%) of successful hybrid infrastructure cases were underpinned by understanding of ecological and hydrological changes in response to infrastructure and involved a wide range of stakeholders. In terms of construction and maintenance cost, limited data suggested that hybrid infrastructure may be more cost effective than grey infrastructure, but more expensive than green; however, data was very limited and therefore we suggest need for further cost-benefit analyses to inform a robust comparison. Development of new technologies should see growing efficacy of future hybrid infrastructure in mitigating coastal flood risks.

Keywords: hybrid infrastructure, grey infrastructure, green infrastructure, eco-engineering, climate change, coastal flood defence, flood risk reduction, coastal ecosystem, restoration, nature-based solution, wave attenuation, land accretion rate, erosion control.

Introduction

Coastal protection is an important issue for human well-being, recognized as far back as the 13th and 14th centuries (Charlier, Chaineux, and Morcos 2005). In a changing climate, with potentially more frequent or severe storms (Young and Ribal 2019; Babcock et al. 2019; Różyński, Hung, and Ostrowski 2009) and coupled with sea level rise, it is becoming imperative to find sustainable coastal protection solutions. Nicholls et al. (2007) reported at least 40 million people and USD 3,000 billion of assets are highly exposed to coastal flooding, projected to rise to 150 million people and USD 35,000 billion of assets by 2070. Moreover, the risk of coastal flooding is projected to rise (Rahmstorf 2017) due to the increasing trend of extreme wind speed and wave height (Hemer et al. 2013; Young and Ribal 2019; Hinkel et al. 2014), sea level rise and intensification of tropical cyclones (Woodruff, Irish, and Camargo 2013).

Land managers seek the most efficient ways to reduce coastal flood risks and traditionally have used grey or green infrastructure. Grey infrastructure represents conventional engineering – *i.e.*, hard constructions such concrete seawall, breakwaters, groins or dikes. Green infrastructure on the other hand, relies on restoring or conserving coastal wetlands to produce natural buffer from storms (Borsje et al. 2011; Temmerman et al. 2013), such as wetlands, barrier islands and reefs (Tibbetts 2006; Chowdhury et al. 2019). However, over the past few decades there was growing interest in hybrid infrastructure combining grey and green approaches to flood defence where restoration and/or conservation of coastal wetlands is supported by "soft" engineered structures (C. S. Smith et al. 2020):

- **Grey infrastructure**. Traditionally, grey infrastructure – such as breakwaters and seawalls – is built to protect populations and infrastructure against coastal erosion, high wave energy and storm impacts. Structures parallel or perpendicular to the shoreline, of varied design and materials make them suitable for many kinds of situations especially when space is a limiting factor. As a result of relatively low spatial requirements, grey infrastructure may be readily in densely populated urbanized areas where space is a limiting factor (Bulleri and Chapman 2010). This hard engineering practice has been studied for hundreds of years and carries sense of certainty in relation to their protection capacity, infrastructure's design and durability but their failure is inevitable (Vallero and Letcher 2012; Galili et al. 2019). Unreliability and negative impacts of grey infrastructure on the environment stimulated growth of studies on eco-engineering solutions to coastal flood risks, such as hybrid infrastructure, in the last decade (Gittman et al. 2016; O'Shaughnessy et al. 2020).

Green infrastructure refers to using or restoring coastal ecosystems such as wetlands, dunes or reefs to enhance coastal resilience and mitigate shoreline erosion. Coastal vegetation mitigates shoreline erosion by attenuating wave energy, increasing soil accumulation and binding soils together which strengthen soil cohesion and consequently decreases vulnerability to erosion (Dasgupta et al. 2019; Krauss et al. 2014; Lo et al. 2017). As waves flow through a wetland, the complex vegetation structures increase friction which dissipates wave energy and promotes energy reflection in the offshore direction (Duarte et al. 2013; Yoshihiro Mazda et al. 2006; Y. Mazda et al. 1990). In addition, sediment deposition increases as wave energy dissipates and particulates settle out of the water column (Kathiresan 2003; Vermaat and Thampanya 2006). Sedimentation processes in coastal vegetation increase soil organic matter which is suggested to be less vulnerable to erosion than mineral soils (Feagin et al. 2009) and help mitigating climate change through sequestration of atmospheric carbon dioxide (Taillardat et al. 2020; Gulliver et al. 2020). Green infrastructure may provide prolonged coastal protection with minimum maintenance within suitable coastal areas (Arkema et al. 2013). However, green approach requires larger space compared to grey infrastructure. For example, provision of coastal protection by 20 m wide mangrove swathe, located on mudflats, is comparable to 5 m seawall (Anthony and Gratiot 2012). Similarly, a 100 m wide saltmarsh swathe can fully attenuate high tide waves (Yang et al. 2012). More, green infrastructure presents an ability to self-sustain under changing coastal conditions driven by hydrodynamic processes, anthropogenic activities, and vegetation expansion (Ruckelshaus et al. 2016).

- **Hybrid infrastructure**. In this paper we focus on hybrid approaches to coastal defence infrastructure which incorporate elements of green and grey engineering. Hybrid approaches seek to improve coastal protection as well as promote benefits from wetland ecosystem service, for example, enhanced fisheries, support biodiversity, and sequester carbon (Sutton-Grier, Wowk, and Bamford 2015; Macreadie et al. 2017). While there are many hybrid approaches, here we focus primarily on those where permeable walls are constructed to attenuate wave energy to provide favourable conditions for coastal vegetation (Van Cuong et al. 2015), or seawalls are breached to reintroduce tidal regimes that allow dispersion and establishment of marsh vegetation (Wolters et al. 2005). These hybrid approaches facilitate restoration of new coastal vegetation and act as a cost-effective buffer that protects inland settlements and secures provision of numerous ecosystem service (Boorman and Hazelden 2017; Tovey, Pontee, and Harvey 2009; Winterwerp et al. 2020). Overall, hybrid approaches aim at combining the advantages of grey and green infrastructures and minimising the disadvantages, such as by limiting negative environmental impacts while providing low-cost protection to withstand low-frequent extreme events.

In this study, we compare the effectiveness and benefits of hybrid versus grey or green approaches for coastal flood defence. We approached this study in two phrases. In the first phase we broadly screened literature for studies that reported on the application of hybrid infrastructure to reduce coastal flood risk. This first search (described in detail below) revealed an enormous quantity of literature (5,806 hits, Fig. S1) – a volume that was too great for detailed investigation. It did, however, provide valuable insight into the scale of search being done in this field, historical trends, and justification for projects. Therefore, we sought to narrow down the scope, which was done through a second phase that involved progressive screening against a list of criteria (described in our methods), which ultimately led to a details comparison of application of hybrid infrastructure in coastal mangroves across south-east Asia and tidal marshes in the United Kingdom. The reason we focussed on these two regions is because: 1) they vary tremendously in terms of economies, environment, and sentiments towards wetlands; and 2) they contained highly detailed information (both grey and scientific literature) that allowed for useful comparison against a set of specific criteria of interest.

Through our qualitative comparison of grey, green and hybrid approaches for coastal protection, we sought to understand the following:

(1) How efficient hybrid approaches can be in comparison to grey and green infrastructure in mitigating coastal flood risks?
(2) What future research is needed to improve the success of hybrid approaches for coastal flood defence?

Method

We conducted a literature search for well-described hybrid infrastructure case studies that were aimed at reducing coastal flood risk. We focused on hybrid infrastructure projects that involved mangrove or tidal marshes to fulfil the 'green infrastructure' component. We searched both the scientific and grey literature via Google Scholar and Web of Science (accessed 2 November 2017, Fig. S1, Table S1) using the following search terms: "wetlands restoration" and "coastal erosion", "coastal green infrastructure*", "coastal hybrid infrastructure*", "coastal protection strateg*", "tidal marsh restoration project*", "mangrove restoration project*", "building with nature project*", "managing coastal erosion with ecosystems", "mangrove coastal protection", "tidal marsh and coastal protection", "soft engineering", "living shoreline*". The search hits were progressively reviewed and eight hybrid infrastructure case studies from each of two ecosystems, within two distinct regions, were then selected (mangroves and tidal marshes). We selected case studies that satisfied the following criteria: 1) detailed information available on the project such as project implementation, location, project duration until completed, project monitoring time, cost, outcome; 2) represent widest possible diversity of hybrid approaches to reduce coastal flood risks involving mangroves or tidal marshes within one region for ease of comparisons; and 3) conduct a monitoring program for at least a year to investigate the long-term dynamics of natural landform adjustment and ecosystem.

In addition, we screened the literature on three flood defence types (grey, green and hybrid) for the cost data to be able to compare their implementation in financial terms. To compare price of multiple flood defence types we implemented methods by Narayan (2016) where the cost of projects was expressed per length (m) of seaward defence line. Where data on seawall length were unavailable these were obtained from Google Earth based on the project location. Additionally, we extended the cost data acquired from reviewed case studies to studies available worldwide. All reported costs were standardised to 2019 USD equivalents using adequate exchange rates and Consumer Price Index (CPI) inflator indices (FXTOP 2019) and reported in main text as means ± standard error (SE).

Results

We progressively reviewed 235 of 5,806 entries of which 15 entries met our criteria (Fig. 1, Table 1, Table 2) and clustered within two regions: south-east Asia (n=7) and the United Kingdom (n=8). Of 15 entries, ten case studies reported here were published in grey literature (reports).

Mangrove hybrid projects

Implementation

Mangrove-based hybrid flood infrastructure projects are characterized by broad participation of stakeholders from the public and private sectors, starting from consultation and planning stage through to the construction of permeable walls [A1, C1, D1, Fig. 2]. The case studies that did not report ecological and socio-economic indicators here (40%) underscore the importance of such indicators prior to the implementation of hybrid flood defences. Failure to recognize indicators such as soil/water conditions, sediments movement and hydrology but also local farming needs, may significantly reduce the success of coastal restoration projects (Kodikara et al. 2017).

All hybrid infrastructure projects reviewed here aimed at rehabilitating mangroves by constructing a permeable wall in front of the shoreline. These permeable walls were designed to control hydrodynamic conditions to improve conditions for mangrove growth, mainly through attenuating high wave energy and increasing sediment accretion rates. Such conditions help decrease shoreline erosion and increase mangrove seedling establishment

(Hashim et al. 2010). Permeable wall structures were constructed from either local raw material such as *Melaleuca* sp. or bamboo [A1, C1], artificial oyster reefs [D1, B1], breakwaters made of concrete or gabion baskets [E1, F1].

In most (80%) case studies, mangrove seedlings were actively planted (from 10 to 25 thousands seedlings ha^{-1}) while the remainder of case studies allowed for their natural dispersals into restoration areas. In one case [A1], natural dispersal of propagules was estimated as too low and natural recruitment was enforced with enrichment planting. The most common planting method was to transplant nursery-raised ~50cm seedlings into the restoration zones where sufficient amount of sediment has accumulated. Additional protective measures such as plastic bag [C1] or coir logs of coconut fibre [E1] were used to protect freshly transplanted seedlings from wave action.

Outcome

We analysed the selected case studies (Table 1) with focus on performance of hybrid infrastructure in relation to their coastal flood defence functions *i.e.*, land accretion, wave attenuation, survival of planted vegetation, and also their ecosystems service co-benefits. All hybrid flood defence projects incorporated monitoring schemes to assess their success. Monitoring time following project completion ranged from one [E1, F1] to 22 years [G1]. Hybrid infrastructures showed measurable advantages over green infrastructure [B1]. For example, coastal vegetation expanded seaward behind the artificial reef structure and retreated landward in no-reef control site [B1].

Mean land accretion rates ranged from 290 mm yr^{-1} [B1] to estimated 500 mm yr^{-1} [A1] following the construction of permeable wall structures. These permeable structures stabilized the substrate and allowed mangroves to recruit and establish. The re-established mangroves protected by permeable walls accreted sediments at various rates depending most likely on number of geomorphic and socio-economic settings they grew in. For example, high sediment transportation reported in Demak case study [A1] was caused by expansive deltaic shoreline topography but also it was a legacy of intensive aquaculture practices in the past that led to ongoing shoreline erosion. The case study from Bangladesh [B1] further demonstrated an additive effect of permeable walls on local sedimentation rate; land accretion within hybrid flood defences (290 ±12 mm yr^{-1}) was higher when compared to green coastal defences only (125 ±45 mm yr^{-1}). Land accretion rates reported for mangroves (green infrastructure) in south-east Asia, ranged from -2 to 20.8 mm yr^{-1} and were relatively low (Chaudhuri, Chaudhuri, and Ghosh 2019) when compared to hybrid infrastructure. Grey infrastructure is known for having largely negative effect on land accretion (Morris et al. 2018). Grey infrastructure generally weakens with wave and storm impacts, leading to exacerbation of erosion in adjacent areas and ecosystem fragmentation (Bulleri and Chapman 2010).

Survival of planted seedlings in reviewed case studies ranged from 0.15% [G1] to 75% [F1] three years after planting and was strongly affected by selection of species. For example, *Avicennia alba* recorded higher survival within silt trap barrier (44%) compared with *Rhizophora apiculata* (14%) in the Mekong Delta within the Gulf of Thailand [C1]. Planting technique resulted in 2-fold differences in survival as reported in Carey Island study [F1], with clumping technique being more successful (75%) compared to uniform planting (30%). For planting activities to be successful, local geomorphological conditions, such as sedimentation rate, tidal activity, salinity should be accounted for beforehand. Importantly, coordination between construction of hard structure and planting activities is critical to the success of mangrove-based flood defences as well. Low survival of mangroves reported in the case study from West Kalimantan [G1] was due to allocating little time for sediments to accrete and stabilize after erecting hard flood-defence structures. When compared to survival of seedlings reported for natural mangroves in south-east Asia, ranged from 73–87%

(Rafdinal et al. 2020), or 5–50% within mangrove restoration projects (Lee et al. 2019), hybrid approaches shown capability to reach near-natural efficiency. Often, sedimentation processes need to be more carefully studied to increase survival of seedlings within hybrid structures. Active sedimentation following the construction of harder structure may suffocate the roots and salinity above 25 PPT may further decrease plant survival [F1].

Successful restoration of mangroves as part of hybrid flood defence structures benefited local economies comparable with ecosystem services provided by green infrastructure only, for example by sustaining aquaculture and raw material production [A1, C1]. The profitability of aquaculture is directly linked to the capability of mangrove ecosystems to provide water purification and nursery services for local fish and shrimp species. Other branches of coastal economies can profit from sustainable harvesting of raw materials such as leaves, bark and wood that can be used as fuel, fodder or construction materials. More, hybrid infrastructure in mangrove ecosystem settings can provide long-term vehicle to sequester and store atmospheric carbon that can be traded against major carbon polluters if included in the market-based climate mitigation policies (Ullman, Bilbao-Bastida, and Grimsditch 2013).

Tidal marshes hybrid projects

Implementation

Implementation of hybrid infrastructure in tidal marsh habitats (via managed realignment, Table 2) is due to the ageing grey coastal defences no longer protecting the coast from risks such as sea level rise or have been damaged by extreme events. For example, it has been reported that over the past 100 years, coastal profiles have steepened in nearly 50% of England's shoreline due to increased erosion, particularly on coasts protected by grey infrastructures (MCCIP 2008).

Managed realignment projects require acquisition of new (mostly landward) areas adjacent to existing seawall that would be subsequently converted into tidal marsh. The acquisition of mostly agricultural land, as explicitly mentioned in two cases [C2, E2], is described as complex because it competes with other land uses [B2, E2] (Esteves 2014). Managed realignment projects are perceived as giving valuable land back to the sea and met with low social acceptance [see cases: A2, C2, D2, E2, G2]. Therefore, success with these projects involves substantial consultancy with numerous stakeholders. Local authorities, businesses, residents, farmers are consulted in most cases and take part in the decision-making process. These social processes are highlighted in four cases [A2, B2, C2, E2, H2]. For example, the Freiston case [C2] emphasized the difficulty in finding public support due to lack of confidence in the outcomes of the project. Once approved, the managed realignment projects progressed through a series of stages to breach the seawall causing adjacent land to become a tidal marsh.

The next step following social acceptance is site suitability assessment, focussing on site sediment dynamics and hydrology, and environmental impact assessment of potential managed realignment. Subsequently, design of the realignment scheme is determined according to the suitability assessment and supported by modelling activities [see cases: A2, B2, E2, F2]. Models assist in estimating the optimal position, size of the breach, the location and depth of creeks and channels in relation to projected flooding events. Engineering works are commonly necessary in order to prepare the site to be exposed to a tidal regime and to promote tidal marsh vegetation establishment - key factor to successful defence against floods. For examples [see cases: A2, B2, E2, F2], earthworks include excavation of channels and creeks to divert and drain water, and levelling operations to enable the vegetation to colonize the flooded areas. Vegetation can only occur when the substrate is elevated to the level and above the mean high water neap tides (1.71 m in the North Norfolk, UK), hence quality levelling works are critical to successful colonization by marsh plants (Davy et al. 2011). The import of suitable sedimentary material is often required to achieve levelling operations, this material should be carefully selected on its properties and provenance to avoid contaminations by heavy metals and herbicides that could disrupt the natural colonization of the marsh (Boorman and Hazelden 2017). More, the sediment properties used for levelling properties, such as compaction (Wolf, Rejmánková, and Cooper 2019) and resistance to erosion (Feher, Willis, and Hester 2018) could greatly affect plant colonization.

In all cases, the construction landward of a new sea-defence line is also undertaken *i.e.*, an additional flood bank or an embankment are erected to protect infrastructures. In one case [G2], a sluice in the existing sea-defence line is, prior to the breach, introduced to divert a stream in the future rehabilitated site. Sluice enables a control of tidal movements and rate of sedimentation (Boorman and Hazelden 2017).

The last step in managed realignment projects consists of breaching the existing sea-defence (Fig. 2). In all of our case studies, existing seawalls were breached in one or several places - carefully predetermined in the design scheme (the option of complete removal of the defence structure was not undertaken in any selected case studies). Sediment transport patterns and amount of water entering and leaving the site is determined by the size of the breaching and are key parameters affecting the creation of the marsh (Boorman and Hazelden 2017). In one case [G2] the creation of marsh was experimentally supported by additional seed sowing and planting, but with lower than expected results; the planted species showed a low rate of successful establishment due to tidal inundation and natural colonization by local plant species. It is recommended that managed realignment sites to be left to regenerate naturally.

Outcomes

Managed realignments increased levels of coastal protection by means of levelling works, supporting colonization of intertidal areas by wetland vegetation and inducing sediment accretion. Monitoring of vegetation recovery and respective sediment accretion rate were undertaken in half of the case studies we have presented. These monitoring periods varied in length from one to ten years after completion of realignment works [A2, B2, C2, D2].

Vegetation recovery was reported in three cases: annual pioneer species colonized first, like *Salicornia europaea* and *Suaeda maritima* and were gradually replaced by perennial species, the distribution depending on the elevation of the marsh [A2, C2, G2]. After four years, coverage rates reaching 86% were observed in Freiston [C2]. However, though all common species were found the vegetation community composition at restored sites was comparatively different from reference sites. Depending on cases, the reference plant species composition and per cent coverage are estimated to be reached between five [A2] and twelve [G2] years after the seawall breaching. Moreover, minimal vegetation covers and even bare soils were remaining where sediments were compacted by engineering works [B2]. By contrast, sites with longer hydroperiods and remnants crop stumps promoted vegetation establishment by trapping seeds and propagules [B2]. In comparison, habitats for tidal marshes (green infrastructure) in the UK are eroding due to high presence of artificial embankments within their natural range (Wolters et al. 2005). When embankments are removed the reclaimed lands tend to be colonized relatively quickly by tidal marsh plants (Garbutt and Wolters 2008). On the other hand, these embankments (grey infrastructure) are protecting local communities from coastal floods but due to degrading coastal wetlands, tidal realignments are being considered more and more often (Hughes, Fletcher, and Hardy 2009).

Land accretion rates were reported in two studies: in Medmerry, results are available for the first year of monitoring after the breach completion [B2]. They highlight the sediment redistribution occurring due to the man-made shaping of the site and the global accretion trend on flat areas. Otherwise, accretion rates varied depending on the location of the evaluated site in the rehabilitated area. In Freiston [C2], accretion rates varied between 5 and 55 mm yr^{-1} over four years of monitoring, values of mean global accretion rates inside the managed realignment site comprised between 5.4 and 7.9 mm yr^{-1}. Boorman & Hazelden (2017) mentioned those accretion rates were critical in the success of the managed realignment because they drove plant colonization and the creation of new habitats for benthic and bird communities. In comparison, restored tidal marshes in Eastern England are capable to accrete 1.5 mm yr^{-1} as recorded in the long-term study by Pye (1995). These land accretion rates are variable though and negatively affected by increased wave frequencies and distance to tidal creeks (Reed et al. 1999).

Restored coastal ecosystems function as flood defence structures by forming flood control areas and reducing the risk of floods by preventing overflow. Two case studies estimated that rehabilitated areas provided coastal protection from 1-in-100 [F2] to 1-in-1000 years' floods [B2] depending on the case. Additionally, these restored ecosystems protect inland flood defence infrastructure that in turn requires less maintenance (Boorman and Hazelden 2017). Tidal marsh realignments are estimated to be sustainable over 25 to 50 years [E2, H2]. The Environment Agency, who was involved in most of managed realignment cases in the UK, estimated that a 80 m wide tidal marsh could provide protection that could reduce the sea-defence height from 12 to 3 meters (Greene 2006). As well as providing flood protection, marsh realignment sites provided suitable habitats for numerous species of birds, crustaceans and fishes which can boost local agriculture and tourism economies [A2, B2, C2, D2].

Cost

Cost data were difficult to obtain and are economically and geographically diverse. Hence the cost values gathered in this study represent guidance values and not true cost estimates. Mean construction cost of green flood defence infrastructure located in tidal marshes was USD 4384 ±1380 m^{-1} (±SE, all located in the UK) and was slightly lower when compared with overall mean cost of grey infrastructure (concrete breakwaters, USD 5237 ±1597 m^{-1}). Similarly, mean cost of hybrid infrastructure mangroves (USD 597.3 ±1095 m^{-1}) was on average 8.7 times lower (Fig. 3, Table S2). The cost of pre-assessment activities, prior and post monitoring and related ecosystem services are not included.

Discussion and looking ahead

This review provides a synthesis of the most current state of knowledge (both grey and scientific literature) on how hybrid approaches to coastal flood defences compare with their two traditional alternatives: grey and green flood defences. Hybrid coastal defences are an alternative to green and grey infrastructure in that they provide coastal protection through incorporating restoration of mangroves and tidal marshes with eco-engineered structures. Hybrid infrastructure are recently attracting a growing interest worldwide, and are being developed under many banners, for example, ‘Building with Nature’ in the Netherlands (Slobbe et al. 2013) ‘Living Shoreline’ (Scyphers et al. 2011; C. S. Smith et al. 2020) or ‘Engineering with Nature’ within the US Army Corps of Engineer in the USA (D. Smith et al. 2017). The case studies selected here highlight knowledge gaps in the use and design of hybrid infrastructure within regional marsh and mangrove ecosystems but also offer an overview of emerging recommendations for practitioners, land managers and decision-makers can be drawn upon globally (see Table 3).

Comparing costs of construction and maintenance (grey, green and hybrid)

Globally, projected losses in the absence of flood protection due to erosion alone are estimated at USD 1 trillion per year (Hallegatte et al. 2013). For example, half of the Asian case studies reviewed here implemented mangrove restoration in response to coastal vulnerability associated with aquaculture development. Across south-east Asia, an estimated 30,000 ha of mangroves were cleared for aquaculture over 2000-2012 (Richards and Friess 2016), following extensive clearances over the previous century (Valiela, Bowen, and York 2001). This deforestation has increased coastal vulnerability to erosion, *e.g.,* accumulation of lithogenic material in the sea shelf amounted to 37 mm yr^{-1} in Vietnam (Szczuciński, Stattegger, and Scholten 2009) and caused direct financial losses to local economies. High cost of inaction motivates local land managers (both private and public sector) to invest in coastal flood defences. The choice of flood defences is driven principally by finance and their cost-effectiveness. Cost data compiled for this study indicates that the lowest construction and maintenance cost is associated with green (natural) flood defences, followed by hybrid and grey. However, additional risks in relation to storms and population densities need to be accounted for. In areas of high densities, for example Mekong River in Vietnam, coastal flood defences can be inefficient due to reduced sediment supply caused by ongoing anthropogenic pressures such as, dams, sand mines or groundwater pumping (Besset et al. 2019).

Green infrastructure presents the lowest construction cost (no cost if coastal ecosystems were intact), but green approaches are often viewed as more susceptible to extreme events (hurricanes, tsunamis), especially when immature, and require adequate large land area (Khazai, Ingram, and Saah 2007; Dharanirajan et al. 2007). When land area is sufficiently expansive, risks to near coastal livelihoods are reportedly lower compared to areas with less or no vegetation cover (Hochard, Hamilton, and Barbier 2019). In the absence of vast coastal vegetation, land managers are often faced with a choice between grey and hybrid flood defences. However, the ongoing maintenance cost of grey infrastructure, valued at 105 million USD km^{-1} 50 $years^{-1}$ years for seawalls is higher compared to maintenance of permeable walls in hybrid infrastructures - valued at 82.5 million USD km^{-1} 50 $years^{-1}$ (Table 1 in: Cunniff and Schwartz, 2015). Hybrid structures present lower construction and maintenance cost when compared to grey infrastructure, largely due to implementation of the nature-based solutions through enhanced conservation or restoration of coastal ecosystems (Gittman et al. 2014). Established ecosystems show self-regulating ability to withstand sea level rise by means of accreting above and belowground biomass (Stagg et al. 2018; Baustian, Mendelssohn, and Hester 2012). The accreted biomass, in the form of belowground root and aboveground canopy, provide low maintenance protection against flooding events, provided that hydrodynamics parameters such as, wave energy, critical shear stress, settling velocity, critical plant inundation height and tidal variations are accounted for at the design stage (Bao 2011; Best et al. 2018).

Comparing co-benefits (grey, green and hybrid)

Both green and hybrid infrastructures contribute to coastal economies such as fisheries, timber production, blue carbon credits and tourism through provision of ecosystem and cultural services that are still difficult to be valued monetarily (Himes-Cornell, Grose, and Pendleton 2018; Wylie, Sutton-Grier, and Moore 2016). Hybrid infrastructure may comprise of up to 440 ha [D2] of natural or restored areas immediately adjacent to first line of flood defences (permeable walls made of bamboo [C1], gabion baskets [E1], riprap [E1] or floodbanks [A2-H2]) and provide ecosystems services such as shoreline and sediment stabilization, water supply, nutrient cycle, water purification, raw materials, food, genetic, medical and ornamental resources and carbon sequestration (Moberg and Rönnbäck 2003; Atwood et al. 2017; Russi et al. 2013; Yando et al. 2019; McAlinden 2015b; Hughes, Fletcher, and Hardy 2009; Rogers et al. 2019). These ecosystem services are valued at 1995 to 215,349 USD ha^{-1} year^{-1} for mangrove and tidal marshes (Table 2.2 in: Russi et al. 2013). In comparison, linear structure of grey flood defences, *e.g.*, seawall and groin, present are devoid of additional ecosystems services associated with green and hybrid flood defences. Grey infrastructure often causes undesirable effects on adjacent coastal ecosystems (Cheong et al. 2013; Griggs and Gary Griggs 2005; Spalding et al. 2014; Temmerman et al. 2013; Slobbe et al. 2013; C. S. Smith et al. 2017). For example, majority of the studies on sedimentation near seawalls and breakwaters reported erosion (Morris et al. 2018). The erosion induced by hard infrastructure and associated shoreline recession is distinctively concerning for the small islands communities (Nunn, Klöck, and Duvat 2021). Moreover, perpendicular structures such as groins can disrupt along-shore currents and may limit water flow, thus also preventing the dispersal and stranding of propagules of macrophytes (Nordstrom 2014). The multiplicative impacts of grey structures to adjacent ecosystems are likely to be context-dependent and difficult to predict though (Nordstrom 2014).

Comparing wave attenuation and land accretion capacities

All case studies emphasize the importance of hybrid flood defences in reducing wave energy, yet wave attenuation was measured only in the Kien Giang project [C1]. The wave barrier fence tested therein demonstrated capacity to reduce wave energy (63%) similar to healthy mangrove fringe (67%). Mangroves exposed to high energy waves though showed a decrease in their wave damping capacity following reduction in basal area, pneumatophore density, canopy diameter and forest width (Horstman et al. 2014; Bao 2011; Hoque, Husrin, and Oumeraci 2018). By comparison, ability to attenuate waves energy by green infrastructure varies considerably depending on coastal vegetation type (Koch et al. 2009; Bouma et al. 2014), density and biomass productivity (Shepard, Crain, and Beck 2011; Koch et al. 2009). There is also a non-linear relationship between the width of vegetated area in front of a shoreline and the amount of wave attenuation (Barbier et al. 2011). Dissipation effects are stronger as waves enter into coastal wetlands and decreases with water depth (McIvor et al. 2013). Experimental data on tidal marshes located in low energy environments revealed wave heights attenuated by 40% through the first 80 m, wave energy decreased by 92% through 20-30 m, and cross-shore current velocities reduced by 50% in 15 m (Carus, Paul, and Schröder 2016; Möller et al. 1999). Whereas, evidence suggests a typical rate of wave height attenuation of 13–66% per 100 m of mangroves (McIvor et al. 2013). Though to reduce large storm surges, kilometres of mangroves would be needed to have significant attenuations (Spalding et al. 2014). In comparison, grey infrastructure is capable to deflect but not to attenuate wave energy. As a result the fixed hard structures modify sediment and hydrologic dynamics (*e.g.*, fixing new high water mark) that “squeeze” coastal ecosystems out of their coastal habitat (Mills et al. 2016). Similarly, hard grey structures parallel to the coastline, prevent migration and establishment of coastal ecosystems (*e.g.*, mangroves and tidal marshes), causing a phenomenon known as ‘coastal squeeze’ (Mills et al. 2016; Gilman et al. 2008).

All studies on hybrid and green infrastructure that we reviewed were found to support land accretion and sediment stabilization; in contrast, grey infrastructure did not support accretion and caused erosion (Figure 4), but see Jan et al (2015). The relatively higher sedimentation rate reported for hybrid infrastructure (up to 500 mm year^{-1}) are mostly due to their location in the lowest areas of coastline and within the highest tidal exchange frame. Consequently, the sediment suspended and brought in with tidal waters infill the lower tidal frame, as induced by hybrid infrastructure, and support establishment of coastal vegetation. Subsequently, as hybrid infrastructure is getting old, the rates of land accretion slow down (over 150-300 years, see French 1993) to levels reported for natural green infrastructure (up to ~2 mm yr^{-1} for marshes and ~20 mm yr^{-1} in mangroves).

Looking ahead

One of major disadvantage that prevents the implementation of green and hybrid flood defence strategies at a wider scale is their relatively high spatial footprint. Hybrid infrastructures need sufficient space and time for the ecosystem to develop and are susceptible to high wave energy environments during establishment stage (Balke et al. 2011). By comparison, grey infrastructure has small spatial requirements when compared to green and hybrid infrastructures. For examples, seawalls built along low wave energy shoreline occupy up to 0.0004 ha per meter of shoreline (Nicholls et al. 1995) while restoration of coastal mangroves in green and hybrid approaches can range from 0.015 to 0.8 ha (Muhari 2018). Grey structures provide coastal protection as soon as they are built, in contrast to green and hybrid infrastructure, which take time to establish following local restoration action (Yando et al. 2019). Permits for grey infrastructure installation can also be easier to obtain than for wetland restoration (Nordstrom 2014). Success of green infrastructure can be undermined when restoration efforts do not adequately consider site or species selection nor fully understand hydro- and morpho-dynamics, thus resulting in a failure to ensuring the long-term survival of coastal vegetation (Lee et al. 2014). Green approaches to coastal flood risk are also much less feasible along urbanized areas of the coastlines (Kabisch et al. 2017). To ensure the long-term success and benefits from coastal ecosystems, hybrid infrastructure approaches should be considered in sites with unfavourable environmental conditions which could undermine traditional green infrastructure approaches.

New technologies are emerging that could aid hybrid approaches in restoring coastal vegetation in unfavourable environmental conditions such as biodegradable materials. For example, different companies are offering solutions consisting of mats made of wood or coconut fibre in which coastal plants are grown (von Häfen 2015). Those mats could then be rolled-out to be settled on banks in intertidal zones. Plants anchored on the mats are less vulnerable to uprooting by waves and currents and could accelerate the growth and establishment of coastal plants that are critical for providing services related to coastal protection. A pilot project that was undertaken in 2012 in the Netherlands (EcoShape 2012) used this technology and reported means to improve establishment of coastal vegetation. These new technologies might increase survival rate of the newly planted coastal plants by enhancing their growth conditions, for example, by reducing wave energy and stabilizing the sediments. More, recently tested biodegradable mimicry structures allow sediments to form suitable substrate and encourage the spontaneous recruitment of coastal pioneer plants in the following growing season (Fivash et al. 2018). Further trials could eventually lead to the development of local solutions to enhance restoration of coastal ecosystems.

A frequently occurring obstacle to undertake this review was lack of long-term monitoring data (typical duration of monitoring time in case studies analysed here was five years). Although hybrid infrastructures are site-specific and require a particular design and implementation in each case, lessons learnt by monitoring these structures could greatly serve future practitioners. Repeated quantification of vegetation cover, wave height and energy reduction, current's velocity reduction and rates of accretion could eventually provide a good evaluation of the ecosystem's performances. Providing such data could progress the development and guide successful implementation of hybrid infrastructures by practitioners. Moreover, technological tools such as remote sensing offer great possibilities for monitoring (Chapple and Dronova 2017). Remote sensing might be used to monitor the progress of mangrove restoration programs over time (Alexandris et al. 2013; Long, Giri, and Trivedi 2016). For example, high or medium resolution satellite imageries from Landsat or WorldView could assist in tracing the change of canopy cover in mangroves.

Conclusion

Here we reviewed case studies of implementing hybrid approaches to mitigate coastal flood risks in the UK and Asia-Pacific. While grey and green approaches are well-established in land management practices, an alternative hybrid approach provides competitive level of coastal protection through combination of soft engineering and the restoration of coastal ecosystems like mangroves and tidal marshes. These coastal hybrid infrastructures provide not only cost-effective approaches to flood and storm risks but also deliver multiple co-benefits emerging from restoration of mangrove and tidal marsh ecosystems. The economic value of ecosystem co-benefits, such as sediment stabilization, atmospheric carbon sequestration (blue carbon); fisheries enhancement; water purification, nutrient recycle and source of raw materials, are often difficult to estimate and yet could further promote the implementation of hybrid infrastructures. Revisiting, repeating and expanding the experiments on hybrid infrastructure is highly recommended either in a fail or successful project over broader spatio-temporal scales to improve the evidence base and can reduce the uncertainty that may lead to an increasing acceptability from stakeholders, policymakers, and public towards this hybrid coastal defence approach. Moreover, a global and robust cost-benefit analysis of implementing hybrid infrastructure in coastal flood defence practices is required to reduce the uncertainty in the decision-making processes.

Furthermore, as highlighted in the case study on managed realignment in Freiston [C2], there is a risk of misperception of hybrid infrastructure projects due to lack of communication between scientists, practitioners and populations (Myatt, Scrimshaw, and Lester 2003). Making science and knowledge of hybrid infrastructure approaches accessible to every stakeholder and public should be a key element to improve public understanding and broaden managerial toolkit to tackle coastal flood risks.

Acknowledgments

We thank Clare Duncan for contributing ideas and comments on an earlier version of this manuscript.

Funding

Not applicable.

Disclosure statement

No conflict of interest was reported by the authors.

References

Akbar, AA, J Sartohadi, and TS Djohan. 2017. "The Role of Breakwaters on the Rehabilitation of Coastal and Mangrove Forests in West Kalimantan, Indonesia." *Ocean & Coastal Management* 138: 50–59. https://doi.org/https://doi.org/10.1016/j.ocecoaman.2017.01.004.

Alexandris, N., B. Chatenoux, L. Harriman, L. Lopez Torres, and Pascal Peduzzi. 2013. *Monitoring Mangroves Restoration from Space*. UNEP/GRID-Geneva.

Anthony, Edward J, and Nicolas Gratiot. 2012. "Coastal Engineering and Large-Scale Mangrove Destruction in Guyana, South America: Averting an Environmental Catastrophe in the Making." *Ecological Engineering* 47: 268–73. https://doi.org/https://doi.org/10.1016/j.ecoleng.2012.07.005.

Arkema, Katie K., Greg Guannel, Gregory Verutes, Spencer A. Wood, Anne Guerry, Mary Ruckelshaus, Peter Kareiva, Martin Lacayo, and Jessica M. Silver. 2013. "Coastal Habitats Shield People and Property from Sea-Level Rise and Storms." *Nature Climate Change* 3 (10): 913–18. https://doi.org/10.1038/nclimate1944.

Atwood, TB, RM Connolly, H Almahasheer, PE Carnell, CM Duarte, CJ Lewis, X Irigoien, et al. 2017. "Global Patterns in Mangrove Soil Carbon Stocks and Losses." *Nature Climate Change* 7 (7): 523.

Babcock, Russell C, Rodrigo H Bustamante, Elizabeth A Fulton, Derek J Fulton, Michael D E Haywood, Alistair James Hobday, Robert Kenyon, et al. 2019. "Severe Continental-Scale Impacts of Climate Change Are Happening Now: Extreme Climate Events Impact Marine Habitat Forming Communities Along 45% of Australia's Coast." *Frontiers in Marine Science* 6: 411. https://doi.org/10.3389/fmars.2019.00411.

Bakrin Sofawi, Ahmad, Mohamad Zakaria Rozainah, Osman Normaniza, and Hashim Roslan. 2017. "Mangrove Rehabilitation on Carey Island, Malaysia: An Evaluation of Replanting Techniques and Sediment Properties." *Marine Biology Research* 13 (4): 390–401. https://doi.org/10.1080/17451000.2016.1267365.

Balke, Thorsten, Tjeerd J. Bouma, Erik M. Horstman, Edward L. Webb, Paul L.A. Erftemeijer, and Peter M.J. Herman. 2011. "Windows of Opportunity: Thresholds to Mangrove Seedling Establishment on Tidal Flats." *Marine Ecology Progress Series*. https://doi.org/10.3354/meps09364.

Bao, Tran Quang. 2011. “Effect of Mangrove Forest Structures on Wave Attenuation in Coastal Vietnam.” *Oceanologia* 53 (3): 807–18. https://doi.org/https://doi.org/10.5697/oc.53-3.807.
Barbier, Edward B, Sally D Hacker, Chris Kennedy, Evamaria W Koch, Adrian C Stier, and Brian R Silliman. 2011. “The Value of Estuarine and Coastal Ecosystem Services.” *Ecological Monographs* 81 (2): 169–93. https://doi.org/10.1890/10-1510.1.
Baustian, Joseph J, Irving A Mendelssohn, and Mark W Hester. 2012. “Vegetation’s Importance in Regulating Surface Elevation in a Coastal Salt Marsh Facing Elevated Rates of Sea Level Rise.” *Global Change Biology* 18 (11): 3377–82. https://doi.org/10.1111/j.1365-2486.2012.02792.x.
Besset, Manon, Nicolas Gratiot, Edward J Anthony, Frédéric Bouchette, Marc Goichot, and Patrick Marchesiello. 2019. “Mangroves and Shoreline Erosion in the Mekong River Delta, Viet Nam.” *Estuarine, Coastal and Shelf Science* 226: 106263. https://doi.org/https://doi.org/10.1016/j.ecss.2019.106263.
Best, S.N., M. Van der Wegen, J. Dijkstra, P. W.J.M. Willemsen, B. W. Borsje, and Dano J.A. Roelvink. 2018. “Do Salt Marshes Survive Sea Level Rise? Modelling Wave Action, Morphodynamics and Vegetation Dynamics.” *Environmental Modelling and Software*. https://doi.org/10.1016/j.envsoft.2018.08.004.
Blankespoor, Brian, Susmita Dasgupta, and Glenn-Marie Lange. 2017. “Mangroves as a Protection from Storm Surges in a Changing Climate.” *Ambio* 46 (4): 478–91. https://doi.org/10.1007/s13280-016-0838-x.
Boorman, Laurence A., and John Hazelden. 2017. “Managed Re-Alignment; a Salt Marsh Dilemma?” *Wetlands Ecology and Management* 25 (4): 387–403. https://doi.org/10.1007/s11273-017-9556-9.
Borsje, Bas W., Bregje K. van Wesenbeeck, Frank Dekker, Peter Paalvast, Tjeerd J. Bouma, Marieke M. van Katwijk, and Mindert B. de Vries. 2011. “How Ecological Engineering Can Serve in Coastal Protection.” *Ecological Engineering*. https://doi.org/10.1016/j.ecoleng.2010.11.027.
Bouma, TJ, J Van Belzen, T Balke, Z Zhu, L Airoldi, AJ Blight, AJ Davies, et al. 2014. “Identifying Knowledge Gaps Hampering Application of Intertidal Habitats in Coastal Protection: Opportunities and Steps to Take.” *Coastal Engineering*, no. 87: 147–57.
Brown, SL, A Pinder, L Scott, J Bass, E Rispin, and S Brown. 2007. “Wash Banks Flood Defence Scheme. Freiston Environmental Monitoring 2002-2006.”
Bulleri, Fabio, and Maura G. Chapman. 2010. “The Introduction of Coastal Infrastructure as a Driver of Change in Marine Environments.” *Journal of Applied Ecology* 47 (1): 26–35. https://doi.org/10.1111/j.1365-2664.2009.01751.x.
Burgess, K, N Pontee, T Wilson, S C Lee, and R Cox. 2013. “Steart Coastal Management Project: Engineering Challenges in a Hyper-Tidal Environment. Coasts, Marine Structures and Breakwaters.” https://www.researchgate.net/profile/Nigel_Pontee/publication/259533695_Steart_Coastal_Management_Project_engineering_challenges_in_a_hyper-tidal_environment/links/56cb43ec08ae5488f0daee4e/Steart-Coastal-Management-Project-engineering-challenges-in-a-hype.
Carus, Jana, Maike Paul, and Boris Schröder. 2016. “Vegetation as Self-Adaptive Coastal Protection: Reduction of Current Velocity and Morphologic Plasticity of a Brackish Marsh Pioneer.” *Ecology and Evolution* 6 (6): 1579–89. https://doi.org/10.1002/ece3.1904.
Chapple, Dylan, and Iryna Dronova. 2017. “Vegetation Development in a Tidal Marsh Restoration Project during a Historic Drought: A Remote Sensing Approach.” *Frontiers in Marine Science* 4: 243. https://doi.org/10.3389/fmars.2017.00243.

Charlier, Roger H., Marie Claire P. Chaineux, and Selim Morcos. 2005. "Panorama of the History of Coastal Protection." *Journal of Coastal Research* 211 (January): 79–111. https://doi.org/10.2112/03561.1.

Chaudhuri, Punarbasu, Subhamita Chaudhuri, and Raktima Ghosh. 2019. "The Role of Mangroves in Coastal and Estuarine Sedimentary Accretion in Southeast Asia." In *Sedimentation Engineering [Working Title]*. https://doi.org/10.5772/intechopen.85591.

Cheong, So-Min, Brian Silliman, Poh Poh Wong, Bregje van Wesenbeeck, Choong-Ki Kim, and Greg Guannel. 2013. "Coastal Adaptation with Ecological Engineering." *Nature Climate Change* 3 (9): 787–91. https://doi.org/10.1038/nclimate1854.

Chowdhury, Mohammed Shah Nawaz, Brenda Walles, S M Sharifuzzaman, M Shahadat Hossain, Tom Ysebaert, and Aad C Smaal. 2019. "Oyster Breakwater Reefs Promote Adjacent Mudflat Stability and Salt Marsh Growth in a Monsoon Dominated Subtropical Coast." *Scientific Reports* 9 (1): 8549. https://doi.org/10.1038/s41598-019-44925-6.

Cunniff, Shannon, and Aaron Schwartz. 2015. "Performance of Natural Infrastructure and Nature-Based Measures as Coastal Risk Reduction Features."

Cuong, Chu Van, Sharon Brown, Huynh Huu To, and Marc Hockings. 2015. "Using Melaleuca Fences as Soft Coastal Engineering for Mangrove Restoration in Kien Giang, Vietnam." *Ecological Engineering* 81 (August): 256–65. https://doi.org/10.1016/j.ecoleng.2015.04.031.

Dasgupta, Susmita, Md Saiful Islam, Mainul Huq, Zahirul Huque Khan, and Md Raqubul Hasib. 2019. "Quantifying the Protective Capacity of Mangroves from Storm Surges in Coastal Bangladesh." *PLoS ONE* 14 (3). https://doi.org/10.1371/journal.pone.0214079.

Davy, Anthony J., Michael J. H. Brown, Hannah L. Mossman, and Alastair Grant. 2011. "Colonization of a Newly Developing Salt Marsh: Disentangling Independent Effects of Elevation and Redox Potential on Halophytes." *Journal of Ecology* 99 (6): 1350–57. https://doi.org/10.1111/j.1365-2745.2011.01870.x.

Dharanirajan, K., P. Kasinatha Pandian, B. Gurugnanam, R. M. Narayanan, and S. Ramachandran. 2007. "An Integrated Study for the Assessment of Tsunami Impacts: A Case Study of South Andaman Island, India Using Remote Sensing and GIS." *Coastal Engineering Journal*. https://doi.org/10.1142/S0578563407001617.

Duarte, Carlos M., Iñigo J. Losada, Iris E. Hendriks, Inés Mazarrasa, and Núria Marbà. 2013. "The Role of Coastal Plant Communities for Climate Change Mitigation and Adaptation." *Nature Climate Change* 3 (11): 961.

EcoShape. 2012. "Pioneer Salt Marsh Restoration for Coastal Protection - Eastern Scheldt, NL." 2012. https://www.ecoshape.org/en/.

Esteves, Luciana S. 2014. "What Is Managed Realignment?" In , 19–31. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-9029-1_2.

Feagin, R. A., S. M. Lozada-Bernard, T. M. Ravens, I. Möller, K. M. Yeager, and A. H. Baird. 2009. "Does Vegetation Prevent Wave Erosion of Salt Marsh Edges?" *Proceedings of the National Academy of Sciences* 106 (25): 10109–13.

Feher, Laura C., Jonathan M. Willis, and Mark W. Hester. 2018. "Importance of Site History and Environmental Setting on Soil Properties in Restored Louisiana Back-Barrier Island Salt Marshes." *Journal of Coastal Research* 341 (January): 58–66. https://doi.org/10.2112/JCOASTRES-D-16-00149.1.

Fivash, Greg S., Ralph Temmink, Wouter Lengkeek, Karin Didderen, Tjisse van der Heide, and Bouma Tjeerd. 2018. "Enabling Restoration of Coastal Vegetation by Creating Windows of Opportunity for Establishment through Mimicry." In *Ecological Society of America Annual Meeting*, OOS 21. New Orleans. https://eco.confex.com/eco/2018/meetingapp.cgi/Paper/70053.

French, Jonathan R. 1993. "Numerical Simulation of Vertical Marsh Growth and Adjustment

to Accelerated Sea-level Rise, North Norfolk, UK.” *Earth Surface Processes and Landforms* 18 (1): 63–81.
Friess, Daniel, and Iris Möller. 2008. “Managed Realignment and the Reestablishment of Saltmarsh Habitat, Freiston Shore, Lincolnshire, United Kingdom.”
FXTOP. 2019. “Inflation Calculator and Change of Price between 2 Dates.” 2019. https://fxtop.com/en/inflation-calculator.php.
Galili, Ehud, Jonathan Benjamin, Vered Eshed, Baruch Rosen, John McCarthy, and Liora Kolska Horwitz. 2019. “A Submerged 7000-Year-Old Village and Seawall Demonstrate Earliest Known Coastal Defence against Sea-Level Rise.” *PLOS ONE* 14 (12): e0222560. https://doi.org/10.1371/journal.pone.0222560.
Garbutt, Angus, and Mineke Wolters. 2008. “The Natural Regeneration of Salt Marsh on Formerly Reclaimed Land.” *Applied Vegetation Science*. https://doi.org/10.3170/2008-7-18451.
Giang, GIZ Kien. 2012. “Coastal Rehabilitation and Mangrove Restoration Using Melaleuca Fences: Practical Experience from Kien Giang Province.” *Deutsche Gesellschaft Fur Internationale Zusammenarbeit (GIZ) GmbH*.
Gilman, Eric L., Joanna Ellison, Norman C. Duke, and Colin Field. 2008. “Threats to Mangroves from Climate Change and Adaptation Options: A Review.” *Aquatic Botany* 89 (2): 237–50. https://doi.org/https://doi.org/10.1016/j.aquabot.2007.12.009.
Gittman, Rachel K., Alyssa M. Popowich, John F. Bruno, and Charles H. Peterson. 2014. “Marshes with and without Sills Protect Estuarine Shorelines from Erosion Better than Bulkheads during a Category 1 Hurricane.” *Ocean and Coastal Management*. https://doi.org/10.1016/j.ocecoaman.2014.09.016.
Gittman, Rachel K., Steven B. Scyphers, Carter S. Smith, Isabelle P. Neylan, and Jonathan H. Grabowski. 2016. “Ecological Consequences of Shoreline Hardening: A Meta-Analysis.” *BioScience*. https://doi.org/10.1093/biosci/biw091.
Greene, H. 2006. “Taking Managed Realignment Forward as a Policy Option for Coastal Management in England and Wales.”
Griggs, Gary, and By B Gary Griggs. 2005. “The Impacts of Coastal Armoring” 73 (1): 13–13.
Gulliver, Anne, Paul E. Carnell, Stacey M. Trevathan-Tackett, Micheli Duarte de Paula Costa, Pere Masqué, and Peter I. Macreadie. 2020. “Estimating the Potential Blue Carbon Gains From Tidal Marsh Rehabilitation: A Case Study From South Eastern Australia.” *Frontiers in Marine Science*. https://doi.org/10.3389/fmars.2020.00403.
Häfen, H von. 2015. “Coco-Mesh Mattresses as Alternative Protection Layer against Erosion at Balinese Coasts.” Leibniz Universität Hannover. https://seafile.cloud.uni-hannover.de/d/3097188b03904f848b2a/.
Hallegatte, Stephane, Colin Green, Robert J. Nicholls, and Jan Corfee-Morlot. 2013. “Future Flood Losses in Major Coastal Cities.” *Nature Climate Change* 3 (9): 802–6. https://doi.org/10.1038/nclimate1979.
Hashim, Roslan, Babak Kamali, Noraini Mohd Tamin, and Rozainah Zakaria. 2010. “An Integrated Approach to Coastal Rehabilitation: Mangrove Restoration in Sungai Haji Dorani, Malaysia.” *Estuarine, Coastal and Shelf Science* 86 (1): 118–24. https://doi.org/10.1016/J.ECSS.2009.10.021.
Hemer, Mark A., Yalin Fan, Nobuhito Mori, Alvaro Semedo, and Xiaolan L. Wang. 2013. “Projected Changes in Wave Climate from a Multi-Model Ensemble.” *Nature Climate Change* 3 (5): 471–76. https://doi.org/10.1038/nclimate1791.
Himes-Cornell, Amber, Susan O Grose, and Linwood Pendleton. 2018. “Mangrove Ecosystem Service Values and Methodological Approaches to Valuation: Where Do We Stand?” *Frontiers in Marine Science* 5: 376. https://doi.org/10.3389/fmars.2018.00376.

Hinkel, Jochen, Daniel Lincke, Athanasios T. Vafeidis, Mahé Perrette, Robert James Nicholls, Richard S.J. Tol, Ben Marzeion, Xavier Fettweis, Cezar Ionescu, and Anders Levermann. 2014. "Coastal Flood Damage and Adaptation Costs under 21st Century Sea-Level Rise." *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.1222469111.

Hochard, Jacob P, Stuart Hamilton, and Edward B Barbier. 2019. "Mangroves Shelter Coastal Economic Activity from Cyclones." *Proceedings of the National Academy of Sciences of the United States of America* 116 (25): 12232–37. https://doi.org/10.1073/pnas.1820067116.

Hoque, Ashabul, Semeidi Husrin, and Hocine Oumeraci. 2018. "Laboratory Studies of Wave Attenuation by Coastal Forest under Storm Surge." *Coastal Engineering Journal*. https://doi.org/10.1080/21664250.2018.1486268.

Horstman, E. M., C. M. Dohmen-Janssen, P. M.F. Narra, N. J.F. van den Berg, M. Siemerink, and S. J.M.H. Hulscher. 2014. "Wave Attenuation in Mangroves: A Quantitative Approach to Field Observations." *Coastal Engineering*. https://doi.org/10.1016/j.coastaleng.2014.08.005.

Hughes, R. G., P. W. Fletcher, and M. J. Hardy. 2009. "Successional Development of Saltmarsh in Two Managed Realignment Areas in Se England, and Prospects for Saltmarsh Restoration." *Marine Ecology Progress Series*. https://doi.org/10.3354/meps08027.

Jan, Chyan-Deng, Ta-Hsiung Peng, Shih-Jen Huang, and Hung-Chu Hsu. 2015. "An Experimental Field Study Using A Flexible High-Strengh Net Breakwater for Shore Protection." *Journal of Marine Science and Technology* 23 (1): 117–26.

Kabisch, Nadja, Horst Korn, Jutta Stadler, and Aletta Bonn. 2017. "Nature-Based Solutions to Climate Change Adaptation in Urban Areas—Linkages Between Science, Policy and Practice." In . https://doi.org/10.1007/978-3-319-56091-5_1.

Kathiresan, K. 2003. *How Do Mangrove Forests Induce Sedimentation? Revista de Biologia Tropical*. Vol. 51. Universidad de Costa Rica.

Khazai, Bijan, Jane C Ingram, and David S Saah. 2007. *The Protective Role of Natural and Engineered Defence Systems in Coastal Hazards*. Spatial Informatics Groups.

Koch, Evamaria W, Edward B Barbier, Brian R Silliman, Denise J Reed, Gerardo ME Perillo, Sally D Hacker, Elise F Granek, et al. 2009. "Non-Linearity in Ecosystem Services: Temporal and Spatial Variability in Coastal Protection." *Frontiers in Ecology and the Environment* 7 (1): 29–37. https://doi.org/10.1890/080126.

Kodikara, Kodikara Arachchilage Sunanda, Nibedita Mukherjee, Loku Pullukuttige Jayatissa, Farid Dahdouh-Guebas, and Nico Koedam. 2017. "Have Mangrove Restoration Projects Worked? An in-Depth Study in Sri Lanka." *Restoration Ecology* 25 (5): 705–16. https://doi.org/10.1111/rec.12492.

Krauss, Ken W., Karen L. Mckee, Catherine E. Lovelock, Donald R. Cahoon, Neil Saintilan, Ruth Reef, and Luzhen Chen. 2014. *How Mangrove Forests Adjust to Rising Sea Level. New Phytologist*. Vol. 202. https://doi.org/10.1111/nph.12605.

Lee, Shing Yip, Stu Hamilton, Edward B. Barbier, Jurgenne Primavera, and Roy R. Lewis. 2019. "Better Restoration Policies Are Needed to Conserve Mangrove Ecosystems." *Nature Ecology and Evolution*. https://doi.org/10.1038/s41559-019-0861-y.

Lee, Shing Yip, Jurgene H. Primavera, Farid Dahdouh-Guebas, Karen Mckee, Jared O. Bosire, Stefano Cannicci, Karen Diele, et al. 2014. "Ecological Role and Services of Tropical Mangrove Ecosystems: A Reassessment." *Global Ecology and Biogeography*. https://doi.org/10.1111/geb.12155.

Lo, V.B., T.J. Bouma, J. Van Belzen, C. Van Colen, and L. Airoldi. 2017. "Interactive Effects of Vegetation and Sediment Properties on Erosion of Salt Marshes in the Northern

Adriatic Sea." *Marine Environmental Research* 131: 32–42.
Long, Jordan, Chandra Giri, and Mandar Trivedi. 2016. "Damage and Recovery Assessment of the Philippines' Mangroves Following Super Typhoon Haiyan." *Marine Pollution Bulletin* 109 (2): 734–43. https://doi.org/10.1016/J.MARPOLBUL.2016.06.080.
Lovelock, Catherine E., Donald R. Cahoon, Daniel A. Friess, Glenn R. Guntenspergen, Ken W. Krauss, Ruth Reef, Kerrylee Rogers, et al. 2015. "The Vulnerability of Indo-Pacific Mangrove Forests to Sea-Level Rise." *Nature* 526: 559–63. https://doi.org/10.1038/nature15538.
Lucking, Rob. 2015. "Coastal Protection by Managed Realignment, Titchwell Marsh." North Norfolk, Lincolnshire and The Brecks. https://climate-adapt.eea.europa.eu/metadata/case-studies/coastal-protection-by-managed-realignment-titchwell-marsh.
Macreadie, Peter I., Daniel A. Nielsen, Jeffrey J. Kelleway, Trisha B. Atwood, Justin R. Seymour, Katherina Petrou, Rod M. Connolly, Alexandra C.G. Thomson, Stacey M. Trevathan-Tackett, and Peter J. Ralph. 2017. "Can We Manage Coastal Ecosystems to Sequester More Blue Carbon?" *Frontiers in Ecology and the Environment* 15 (4): 206–13. https://doi.org/10.1002/fee.1484.
Mazda, Y., Y. Sato, S. Sawamoto, H. Yokochi, and E. Wolanski. 1990. "Links between Physical, Chemical and Biological Processes in Bashita-Minato, a Mangrove Swamp in Japan." *Estuarine Coastal and Shelf Science* 31 (6): 817–33.
Mazda, Yoshihiro, Michimasa Magi, Yoshichika Ikeda, Tadayuki Kurokawa, and Tetsumi Asano. 2006. "Wave Reduction in a Mangrove Forest Dominated by Sonneratia Sp." *Wetlands Ecology and Management* 14 (4): 365–78. https://doi.org/10.1007/s11273-005-5388-0.
McAlinden, Ben. 2015a. "Managed Realignment at Abbotts Hall, Essex." Institute of Civil Engineers. 2015.
———. 2015b. "Managed Realignment at Alkborough Flats, Lincolnshire." https://www.ice.org.uk/knowledge-and-resources/case-studies/managed-realignment-at-alkborough-flats-lincoln.
———. 2015c. "Managed Realignment at Medmerry, Sussex." https://www.ice.org.uk/knowledge-and-resources/case-studies/managed-realignment-at-medmerry-sussex.
———. 2015d. "Managed Realignment at Steart, Somerset." https://www.ice.org.uk/knowledge-and-resources/case-studies/managed-realignmentat-steart-somerset.
MCCIP. 2008. "Marine Climate Change Impacts: Annual Report Card 2007-2008." http://www.mccip.org.uk/media/1371/arc2007.pdf.
McIvor, AL, I Möller, T Spencer, and M Spalding. 2013. "Mangroves as a Sustainable Coastal Defence." *7th International Conference on Asian Pacific Coasts (APAC)*. Bali, Indonesia.
Mills, Morena, Javier X. Leon, Megan I. Saunders, Justine Bell, Yan Liu, Julian O'Mara, Catherine E. Lovelock, et al. 2016. "Reconciling Development and Conservation under Coastal Squeeze from Rising Sea Level." *Conservation Letters* 9 (5): 361–68. https://doi.org/10.1111/conl.12213.
Moberg, Fredrik, and Patrik Rönnbäck. 2003. "Ecosystem Services of the Tropical Seascape: Interactions, Substitutions and Restoration." *Ocean & Coastal Management* 46 (1–2): 27–46. https://doi.org/10.1016/S0964-5691(02)00119-9.
Möller, I, T Spencer, JR French, DJ Leggett, and M Dixon. 1999. "Wave Transformation over Salt Marshes: A Field and Numerical Modelling Study from North Norfolk, England." *Estuarine, Coastal and Shelf Science* 49 (3): 411–26.

Morris, Rebecca L., Teresa M. Konlechner, Marco Ghisalberti, and Stephen E Swearer. 2018. "From Grey to Green: Efficacy of Eco-Engineering Solutions for Nature-Based Coastal Defence." *Global Change Biology*. https://doi.org/10.1111/gcb.14063.
Muhari, Abdul. 2018. "EcoShape 2018 Conference." In *Institutional Arrangement in Mainstreaming BwN (Hybrid Engineering): Strategic Planning, Policies and Implementations*. Utrecht, The Netherlands.
Myatt, L.B., M.D. Scrimshaw, and J.N. Lester. 2003. "Public Perceptions and Attitudes towards a Forthcoming Managed Realignment Scheme: Freiston Shore, Lincolnshire, UK." *Ocean & Coastal Management* 46 (6–7): 565–82. https://doi.org/10.1016/S0964-5691(03)00035-8.
Narayan, S., M.W. Beck, B.G. Reguero, I.J. Losada, B. Van Wesenbeeck, N. Pontee, J.N. Sanchirico, J.C. Ingram, G.M. Lange, and K.A. Burks-Copes. 2016. "The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences." *PLoS ONE* 11 (5).
Nicholls, R.J., S. Hanson, C. Herweijer, N. Patmore, S. Hallegatte, J. Corfee-Morlot, J Chateau, and R. Muir-Wood. 2007. "Ranking of the World's Cities Most Exposed to Coastal Flooding Today and in the Future."
Nicholls, R.J., S.P. Leatherman, K.C. Dennis, and C.R. Volonté. 1995. "Impacts and Responses to Sea-Level Rise: Qualitative and Quantitative Assessments." *Journal of Coastal Research*. Coastal Education & Research Foundation, Inc. https://doi.org/10.2307/25735699.
Nordstrom, Karl F. 2014. "Living with Shore Protection Structures: A Review." *Estuarine, Coastal and Shelf Science*. https://doi.org/10.1016/j.ecss.2013.11.003.
Nunn, Patrick D, Carola Klöck, and Virginie Duvat. 2021. "Seawalls as Maladaptations along Island Coasts." *Ocean & Coastal Management* 205: 105554. https://doi.org/https://doi.org/10.1016/j.ocecoaman.2021.105554.
O'Shaughnessy, Kathryn A., Stephen J. Hawkins, Ally J. Evans, Mick E. Hanley, Paul Lunt, Richard C. Thompson, Robert A. Francis, et al. 2020. "Design Catalogue for Eco-Engineering of Coastal Artificial Structures: A Multifunctional Approach for Stakeholders and End-Users." *Urban Ecosystems*. https://doi.org/10.1007/s11252-019-00924-z.
Pye, K. 1995. "Controls on Long-Term Saltmarsh Accretion and Erosion in the Wash, Eastern England." *Journal of Coastal Research*.
Rafdinal, Rizalinda, Adityo Raynaldo, and Sukal Minsas. 2020. "Growth and Survival Rate Analysis of Avicennia Lanata Seedlings in Mempawah Mangrove Areas, West Kalimantan, Indonesia." *AACL Bioflux*.
Rahmstorf, Stefan. 2017. "Rising Hazard of Storm-Surge Flooding." *Proceedings of the National Academy of Sciences of the United States of America*. National Academy of Sciences. https://doi.org/10.1073/pnas.1715895114.
Reading, C. J., A. Garbutt, C. W. Watts, P. Rothery, A. Turk, M. Yates, C. Boffey, J. Saunders, and M. Wolters. 2008. "Managed Realignment at Tollesbury."
Reed, Denise J., Thomas Spencer, Anne L. Murray, Jonathan R. French, and Lynn Leonard. 1999. "Marsh Surface Sediment Deposition and the Role of Tidal Creeks: Implications for Created and Managed Coastal Marshes." *Journal of Coastal Conservation*. https://doi.org/10.1007/BF02802742.
Richards, Daniel R., and Daniel A. Friess. 2016. "Rates and Drivers of Mangrove Deforestation in Southeast Asia, 2000-2012." *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.1510272113.
Rogers, K., P. I. Macreadie, J. J. Kelleway, and N. Saintilan. 2019. "Blue Carbon in Coastal Landscapes: A Spatial Framework for Assessment of Stocks and Additionality."

Sustainability Science. https://doi.org/10.1007/s11625-018-0575-0.
Różyński, Grzegorz, Nguyen Manh Hung, and Rafal Ostrowski. 2009. "Climate Change Related Rise of Extreme Typhoon Power and Duration over South-East Asia Seas." *Coastal Engineering Journal*. https://doi.org/10.1142/S0578563409002028.
Ruckelshaus, Mary H., Gregory Guannel, Katherine Arkema, Gregory Verutes, Robert Griffin, Anne Guerry, Jess Silver, Joe Faries, Jorge Brenner, and Amy Rosenthal. 2016. "Evaluating the Benefits of Green Infrastructure for Coastal Areas: Location, Location, Location." *Coastal Management*. https://doi.org/10.1080/08920753.2016.1208882.
Russi, D, P ten Brink, Andrew Farmer, T Badure, David Coates, C B D Secretariat, Johannes Förster, Ritesh Kumar, and N Davidson. 2013. "The Economics of Ecosystems and Biodiversity for Water and Wetlands." http://img.teebweb.org/wp-content/uploads/2013/04/TEEB_WaterWetlands_ExecSum_2013.pdf.
Scyphers, Steven B., Sean P. Powers, Kenneth L. Heck, and Dorothy Byron. 2011. "Oyster Reefs as Natural Breakwaters Mitigate Shoreline Loss and Facilitate Fisheries." Edited by Howard Browman. *PLoS ONE* 6 (8): e22396. https://doi.org/10.1371/journal.pone.0022396.
Shepard, Christine C., Caitlin M. Crain, and Michael W. Beck. 2011. *The Protective Role of Coastal Marshes: A Systematic Review and Meta-Analysis*. Edited by Julian Clifton. *PLoS ONE*. Vol. 6. Public Library of Science. https://doi.org/10.1371/journal.pone.0027374.
Slobbe, E., H. J. Vriend, S. Aarninkhof, K. Lulofs, M. Vries, and P. Dircke. 2013. "Building with Nature: In Search of Resilient Storm Surge Protection Strategies." *Natural Hazards* 65 (1): 947–66. https://doi.org/10.1007/s11069-012-0342-y.
Smith, Carter S., Rachel K. Gittman, Isabelle P. Neylan, Steven B. Scyphers, Joseph P. Morton, F. Joel Fodrie, Jonathan H. Grabowski, and Charles H. Peterson. 2017. "Hurricane Damage along Natural and Hardened Estuarine Shorelines: Using Homeowner Experiences to Promote Nature-Based Coastal Protection." *Marine Policy*. https://doi.org/10.1016/j.marpol.2017.04.013.
Smith, Carter S., Morgan E. Rudd, Rachel K. Gittman, Emily C. Melvin, Virginia S. Patterson, Julianna J. Renzi, Emory H. Wellman, and Brian R. Silliman. 2020. "Coming to Terms With Living Shorelines: A Scoping Review of Novel Restoration Strategies for Shoreline Protection." *Frontiers in Marine Science*. https://doi.org/10.3389/fmars.2020.00434.
Smith, David, Scott Miner, Charles Theiling, Randall Behm, and John Nestler. 2017. "Levee Setbacks : An Innovative, Cost-Effective, and Sustainable Solution for Improved Flood Risk Management," no. June. https://doi.org/10.21079/11681/22736.
Spalding, Mark D., Susan Ruffo, Carmen Lacambra, Imèn Meliane, Lynne Zeitlin Hale, Christine C. Shepard, and Michael W. Beck. 2014. "The Role of Ecosystems in Coastal Protection: Adapting to Climate Change and Coastal Hazards." *Ocean & Coastal Management* 90 (March): 50–57. https://doi.org/10.1016/J.OCECOAMAN.2013.09.007.
Spencer, T, D A Friess, I Möller, S L Brown, R A Garbutt, and J R French. 2012. "Surface Elevation Change in Natural and Re-Created Intertidal Habitats, Eastern England, UK, with Particular Reference to Freiston Shore." *Wetlands Ecology and Management* 20 (1): 9–33.
Stagg, Camille L., Melissa M. Baustian, Carey L. Perry, Tim J.B. Carruthers, and Courtney T. Hall. 2018. "Direct and Indirect Controls on Organic Matter Decomposition in Four Coastal Wetland Communities along a Landscape Salinity Gradient." *Journal of Ecology*. https://doi.org/10.1111/1365-2745.12901.
Sutton-Grier, Ariana E., Kateryna Wowk, and Holly Bamford. 2015. "Future of Our Coasts: The Potential for Natural and Hybrid Infrastructure to Enhance the Resilience of Our

Coastal Communities, Economies and Ecosystems.” *Environmental Science and Policy*. https://doi.org/10.1016/j.envsci.2015.04.006.
Szczuciński, Witold, Karl Stattegger, and Jan Scholten. 2009. “Modern Sediments and Sediment Accumulation Rates on the Narrow Shelf off Central Vietnam, South China Sea.” *Geo-Marine Letters* 29 (1): 47–59. https://doi.org/10.1007/s00367-008-0122-6.
Taillardat, Pierre, Benjamin S Thompson, Michelle Garneau, Karelle Trottier, and Daniel A Friess. 2020. “Climate Change Mitigation Potential of Wetlands and the Cost-Effectiveness of Their Restoration.” *Interface Focus* 10 (5): 20190129. https://doi.org/10.1098/rsfs.2019.0129.
Tangelder, M., T. Ysebaert, Shah Chowdhury, A.J. Reinhard, F. Doorn, M. Hossain, and A.C. Smaal. 2015. “Eco-Engineered Coastal Defense Integrated with Sustainable Aquatic Food Production in Bangladesh (ECOBAS).”
Temmerman, Stijn, Patrick Meire, Tjeerd J. Bouma, Peter M. J. Herman, Tom Ysebaert, and Huib J. De Vriend. 2013. “Ecosystem-Based Coastal Defence in the Face of Global Change.” *Nature* 504 (7478): 79–83. https://doi.org/10.1038/nature12859.
Tibbetts, John. 2006. “Louisiana’s Wetlands: A Lesson in Nature Appreciation.” *Environmental Health Perspectives* 114 (1): A40-3. https://doi.org/10.1289/ehp.114-a40.
Tonneijck, F.H., H. Winterwerp, Bregje van Weesenbeeck, R.H. Bosma, A.O. Debrot, Yus Rusila Noor, and T. Wilms. 2015. “Building with Nature Indonesia: Securing Eroding Delta Coastlines : Design and Engineering Plan.”
Tovey, E. L., N. I. Pontee, and R. Harvey. 2009. “Managed Realignment at Hesketh Out Marsh West.” *Proceedings of the Institution of Civil Engineers - Engineering Sustainability* 162 (4): 223–28. https://doi.org/10.1680/ensu.2009.162.4.223.
Ullman, Roger, Vasco Bilbao-Bastida, and Gabriel Grimsditch. 2013. “Including Blue Carbon in Climate Market Mechanisms.” *Ocean and Coastal Management* 83 (October): 15–18. https://doi.org/10.1016/j.ocecoaman.2012.02.009.
Valiela, Ivan, Jennifer L Bowen, and Joanna K York. 2001. “Mangrove Forests: One of the World’s Threatened Major Tropical Environments: At Least 35% of the Area of Mangrove Forests Has Been Lost in the Past Two Decades, Losses That Exceed Those for Tropical Rain Forests and Coral Reefs, Two Other Well-Known Threa.” *BioScience* 51 (10): 807–15. https://doi.org/10.1641/0006-3568(2001)051[0807:MFOOTW]2.0.CO;2.
Vallero, Daniel A., and Trevor M. Letcher. 2012. “Engineering Risks and Failures: Lessons Learned from Environmental Disasters.” *Leadership and Management in Engineering* 12 (4): 199–209. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000199.
Vermaat, Jan E., and Udomluck Thampanya. 2006. “Mangroves Mitigate Tsunami Damage: A Further Response.” *Estuarine, Coastal and Shelf Science* 69 (1–2): 1–3. https://doi.org/10.1016/J.ECSS.2006.04.019.
Winterwerp, Johan C, Thorsten Albers, Edward J Anthony, Daniel A Friess, Alejandra Gijón Mancheño, Kene Moseley, Abdul Muhari, et al. 2020. “Managing Erosion of Mangrove-Mud Coasts with Permeable Dams – Lessons Learned.” *Ecological Engineering* 158: 106078. https://doi.org/https://doi.org/10.1016/j.ecoleng.2020.106078.
Wolf, Evan C., Eliška Rejmánková, and David J. Cooper. 2019. “Wood Chip Soil Amendments in Restored Wetlands Affect Plant Growth by Reducing Compaction and Increasing Dissolved Phenolics.” *Restoration Ecology*, April. https://doi.org/10.1111/rec.12942.
Wolters, Mineke, Jan P. Bakker, Mark D. Bertness, Robert L. Jefferies, and Iris Möller. 2005. “Saltmarsh Erosion and Restoration in South-East England: Squeezing the Evidence Requires Realignment.” *Journal of Applied Ecology*. https://doi.org/10.1111/j.1365-2664.2005.01080.x.

Woodruff, Jonathan D., Jennifer L. Irish, and Suzana J. Camargo. 2013. "Coastal Flooding by Tropical Cyclones and Sea-Level Rise." *Nature*. https://doi.org/10.1038/nature12855.
Wylie, Lindsay, Ariana E. Sutton-Grier, and Amber Moore. 2016. "Keys to Successful Blue Carbon Projects: Lessons Learned from Global Case Studies." *Marine Policy*. https://doi.org/10.1016/j.marpol.2015.12.020.
Yando, Erik S., Michael J. Osland, Scott F. Jones, and Mark W. Hester. 2019. "Jump-Starting Coastal Wetland Restoration: A Comparison of Marsh and Mangrove Foundation Species." *Restoration Ecology*. https://doi.org/10.1111/rec.12963.
Yang, S L, B W Shi, T J Bouma, T Ysebaert, and X X Luo. 2012. "Wave Attenuation at a Salt Marsh Margin: A Case Study of an Exposed Coast on the Yangtze Estuary." *Estuaries and Coasts* 35 (1): 169–82. https://doi.org/10.1007/s12237-011-9424-4.
Young, Ian R., and Agustinus Ribal. 2019. "Multiplatform Evaluation of Global Trends in Wind Speed and Wave Height." *Science* 364 (6440): 548–52. https://doi.org/10.1126/science.aav9527.

Tables

Table 1. A summary of published case studies on use of hybrid infrastructure in mangrove ecosystem settings. The hybrid infrastructure measures described here are visualized in Figure 2 (see the approach part).

Project	Location	Duration	Implementation	Outcomes	Reference
A1	Demak, Indonesia	2015- present	Permeable walls are made of bamboo poles and brushwood. New lines of dams to be created once mangrove established on the first ones.	In 1.5 years: 45 cm of mud accreted and *Avicennia* mangrove juveniles of 50 cm. Enrichment planting in under-vegetated areas.	(Tonneijck et al. 2015) www.indonesia.buildingwithnature.nl
B1	Kutubdia island, Bangladesh	2015-2016	Precast concrete rings: 0.8 m in diameter, 0.8 m high, and 0.05 thick placed along 20m transect.	Seaward marsh vegetation expansion of 1.37 ± 0.13 m per year. 95–100% wave attenuation vertical relief at water levels <0.5–0.6 m. Up to 29 ± 1 cm land accretion recorded.	(Chowdhury et al., 2019)
C1	Kien Giang Province, Vietnam	2009 - 2013	2 treatments: 1. Wave barrier consisting made of *Melaleuca*, branch tree, bamboo matting and fishing net. Barrier located 60 metres offshore. 2. Wave barrier + silt trap fence made of *Melaleuca*, bamboo matting and fishing net located 20-25 metres offshore Control site: nothing.	Wave attenuation rates increased. Planting of 40 cm tall seedlings prepared in plastic bag in nursery. 25 000 seedlings ha^{-1}. About 40 cm of mud accumulated in the protected areas. Survival rate after 3 years: 62% for *Avicennia*, 35% for *Rhizopora* (in treatment 2). Natural recruitment of Avicennia after 18 months with a maximal survival rate of 63%.	(Giang 2012; Van Cuong et al. 2015)
D1	Kutubdia Island, Bangladesh	2012-2014	Implementation of 69 artificial oyster reefs with rings made of concrete, covering a length of 45 metres.	Visible accretion, behind the reef. Wave damping and protection of the earthen embankment. Positive influence of the reefs on mangrove saplings' survival.	(Tangelder et al. 2015)
E1	Sungai Haji Dorani, Malaysia	2008 - 2009	Breakwater structures form a semi-circular arc. Made of stone placed in gabions basket and let on foundations made of bamboo stems.	In a 4-month period: accretion on the leeward side of the breakwater only. Planting of 30 cm tall pre-grown seedlings in coir logs at 10000 seedlings ha^{-1}. Mangrove survival rate: 30% estimated eight months after initial restoration.	(Hashim et al. 2010)
F1	Carey Island, Malaysia	2009-2012	Breakwater structures are made of concrete forming together a half circular arc. Restoration site compared with one controlled site non-protected.	No survival in the first phase of planting. 2nd phase: no survival and no natural recruitment in the non-rehabilitated site. Survival rate of 25% for the clumped pattern, no survival otherwise after 1 year. 11 natural recruitments in the rehabilitated site with survival rates of 60% after one year.	(Bakrin Sofawi et al. 2017)

G1	West Kalimantan, Indonesia	1992-2014	Construction of 22 km of breakwater structures, no more detail.	Very low rates of development of the seeds into trees. Planting of *Rhizopora* seeds at a density of 8778 ha^{-1}. Colonization by *Avicennia* in some bays. Erosion reduction up to 70% in some areas, but erosion exacerbation in other places.	(Akbar, Sartohadi, and Djohan 2017)

Table 2. A summary of published case studies on hybrid infrastructure in tidal marsh settings. The hybrid infrastructure measures described here are visualized in Figure 2 (see the approach part).

Project	Location	Duration	Implementation	Outcomes	Reference
A2	Abbotts Hall Essex, UK	2000-2002	Land realignment and cut in the sea wall to support succession of saltmarsh vegetation. Sea-defence moved inland. Creation of feeder creeks. Five breaching spots within the seawall.	No embankment as land slopes upwards, 80 ha of arable land restored in intertidal ecosystems including tidal marshes, mudflat and coastal grassland.	(McAlinden 2015a; Hughes, Fletcher, and Hardy 2009)
B2	Medmerry, Sussex, UK	Completed in 2013	Construction of a new 7 km long floodbanks located 2 km inland. Excavation of diversion channel, creation of drainage system. Completion of a 110 m wide breach within the existing sea-defence.	Creation of 183 ha of intertidal habitat. Global trend of accretion on flat land. Protection of 348 properties to a standard of 1 in 100 years.	(McAlinden 2015c)
C2	Freiston shore, UK	1990's-2002	Strengthening of the landward sea-defence and breaching of the seaward bank in three places.	Restoration site of 68 ha. Mean annual accretion rates: 6 to 10 mm yr^{-1} 2005: 70% of the area covered by plants. Protection of 80,000 ha with a 1 in 200 year standard of defence.	(Brown et al. 2007; Friess and Möller 2008)
D2	Alkborough Flats, Lincolnshire, UK	1999-2006	Construction of a new 1500 m long lowered embankment and completion of a 20 m breach within the existing floodbanks of Humber River.	Site of 440 ha, including 170 ha of mudflats and tidal marshes	(McAlinden 2015b)
E2	Hesketh Out Marsh West in the Ribble Estuary	2005-2008	Creeks and lagoons excavation, construction of a new bank inland, completion of four breaches within the sea-defence.	Restoration site of 168 ha.	(Tovey, Pontee, and Harvey 2009)
F2	Steart Peninsula, North Somerset, UK	2012-2014	New set back defences, creeks excavation, one large single breach.	Creation of 400 ha of new habitats	(McAlinden 2015d; Burgess et al. 2013)

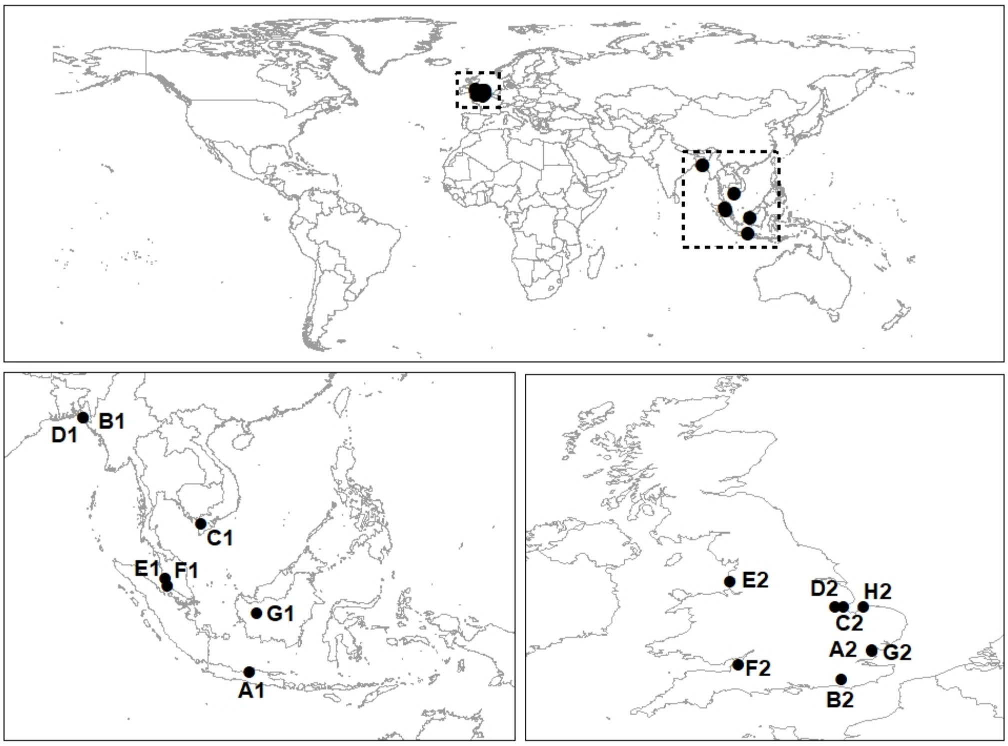
G2	Tollesbury, UK	Completed in 1995	Sluice within the existing seawall allowing the development of a stream in the site. Construction of low embankments behind the existing seawall. Breaching of the seawall and sealing of the sluice.	Restoration site of 21 ha. 2007: half of the site covered by vegetation included 21 plant species. Mean accretion rate: 10 $mm.yr^{-1}$	(Reading et al. 2008)
H2	Titchwell Marsh, UK	2009-2011	Strengthening of a seawall, construction of a new one and breach of a last one to connect brackish marsh with tidal marshes. Sluice enabling the control of the water level inside the marsh.	Restoration site of 11 ha. Flood defence standard of 1 in 30 years.	(Lucking 2015)

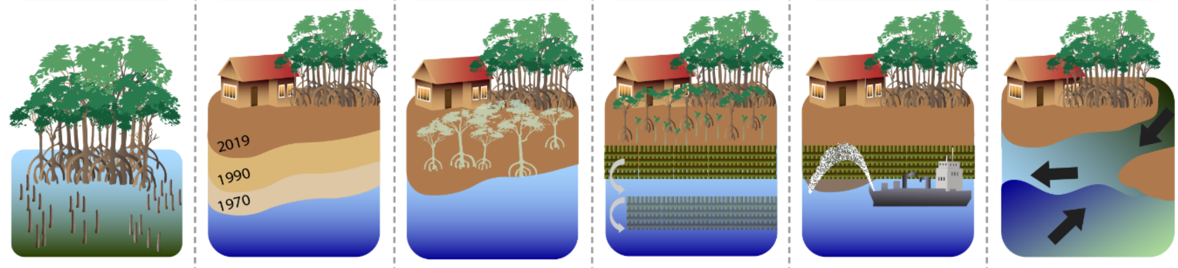
Table 3. Comparison between grey, green and hybrid infrastructure on major criteria concerning projects managers and decision-makers (Blankespoor, Dasgupta, and Lange 2017; Bouma et al. 2014; Cunniff and Schwartz 2015; Esteves 2014; Sutton-Grier, Wowk, and Bamford 2015).

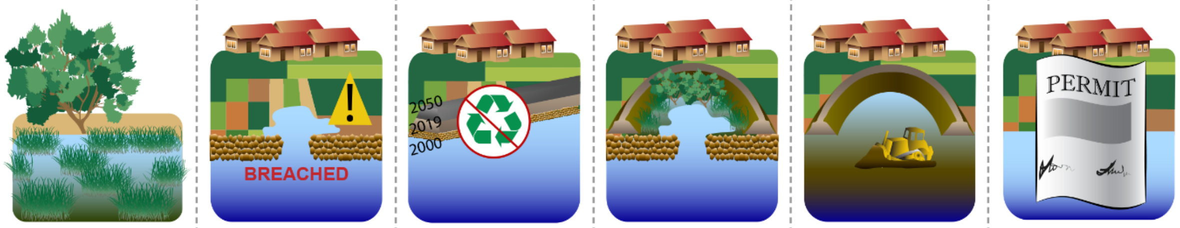
Criteria	Grey infrastructures	Green Infrastructures	Hybrid infrastructures
Design of the structure	General engineering expertise needed.	Expertise in ecology and restoration ecology needed.	Site-specific, cross-disciplinary expertise needed in both ecology and engineering.
Implementation	Designable for every shoreline type.	Preferably shallow shelf waters with low wave energy environment.	Low to moderate wave energy environments. Unsuitable for rocky shores.
Time to benefit realisation	Immediate.	Immediate if based on conservation of existing coastal vegetation. If based on restoration works difficult to quantify.	The time required by the ecosystem to rehabilitate. Difficult to quantify, and context-dependent.
Wave attenuation	Wave energy is reflected and exacerbate the erosion of coastal substrate	On average, coastal habitats reduce wave heights between 35% and 71%.	Steady wave energy dissipation.

Land accretion	Frequent reports of land abrasion instead.	Capable of land accretion above sea level rise rate.	Rapid land accretion in mangroves from 290 to 500 mm $year^{-1}$ and 5–10 mm $year^{-1}$ in tidal marshes.
Spatial Footprint	Small.	Large.	Small to large.
Stakeholder involvement	A reduced number of stakeholders. Long-term stakeholders involvement in monitoring and maintenance.	Land owners and local authorities.	Strong involvement of multiple stakeholders requiring coordination.
Maintenance cost	High. Can be damaged/destroyed by coastal hazards (stochastic). High vulnerability to sea level rise.	Low.	Low. Can recover from coastal hazards (stochastic). Potential for low vulnerability to sea level rise.
Ecosystem services	No added benefits, but conversely possible undesirable effects on the ecosystems and on adjacent areas.	Numerous ecosystem services (carbon sequestration; fisheries enhancement; water purification) provided.	Numerous ecosystem services (carbon sequestration; fisheries enhancement; water purification) provided.
Ecological impact	Potential reduced coastal ecosystem functioning. No increase in habitat provision. Potential to reduce ecosystem connectivity.	Improved coastal ecosystem functioning.	Improved coastal ecosystem functioning. Habitat provision for faunal communities. Potential to enhance ecosystem connectivity.

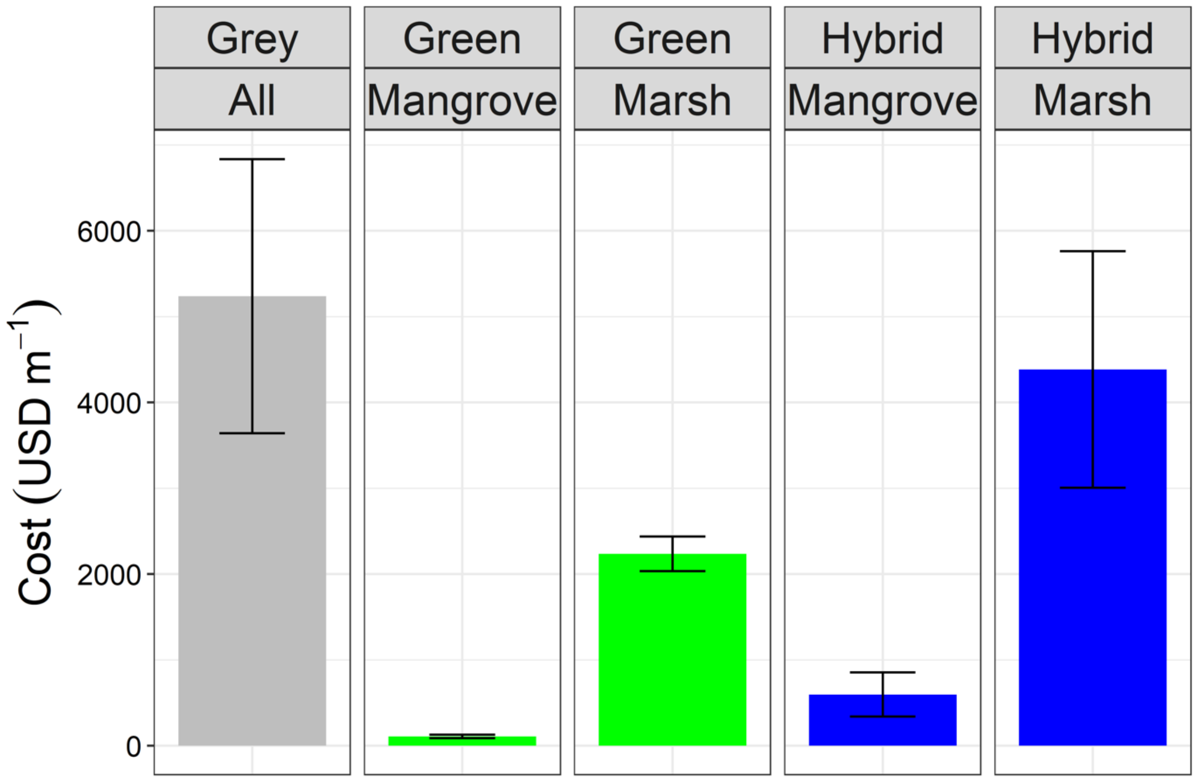
Figures







Hybrid Ecosystems	Prior Condition	Objective	Approach	Additional Work	Main Challenge
Mangrove	Initial mangrove condition is degraded from anthropogenic impacts resulting in erosion and flooding.	Reclaim the land and regain long-term shoreline protection by planting or natural recruitment of mangroves through sustainable and effective efforts.	Create a suitable environment for mangrove seedling growth, such as utilizing a permeable wall (made of bamboo and brushwood) to buffer wave energy.	When necessary, use engineering techniques like sediment nourishment to restore sediment balance.	Understanding complex hydrodynamic processes that shape sediment transport in order to maximize ideal conditions for mangrove seedling survival and growth.
Saltmarsh	Aged, weakened seawall breaches during extreme events or no longer protects against the rising sea levels; resulting in continuous flooding events.	Realign the unsustainable, high-maintenance, costly seawall by integrating a saltmarsh to provide long-term protection and a higher chance to naturally cope against climate change.	Create a suitable environment for saltmarsh growth by adjusting hydrological flow and sediment transport. A flood bank is required to control inundation level.	In addition to flood bank construction, this often requires other engineering work, such as ground leveling to control the hydrological connection.	Acquiring permits from landowners and policy makers for a hybrid approach is challenging due to the spread across different land tenures and polices.


Grey
All
Green
Mangrove
Green
Marsh
Hybrid
Mangrove
Hybrid
Marsh
Cost (USD m⁻¹)
6000
4000
2000
0

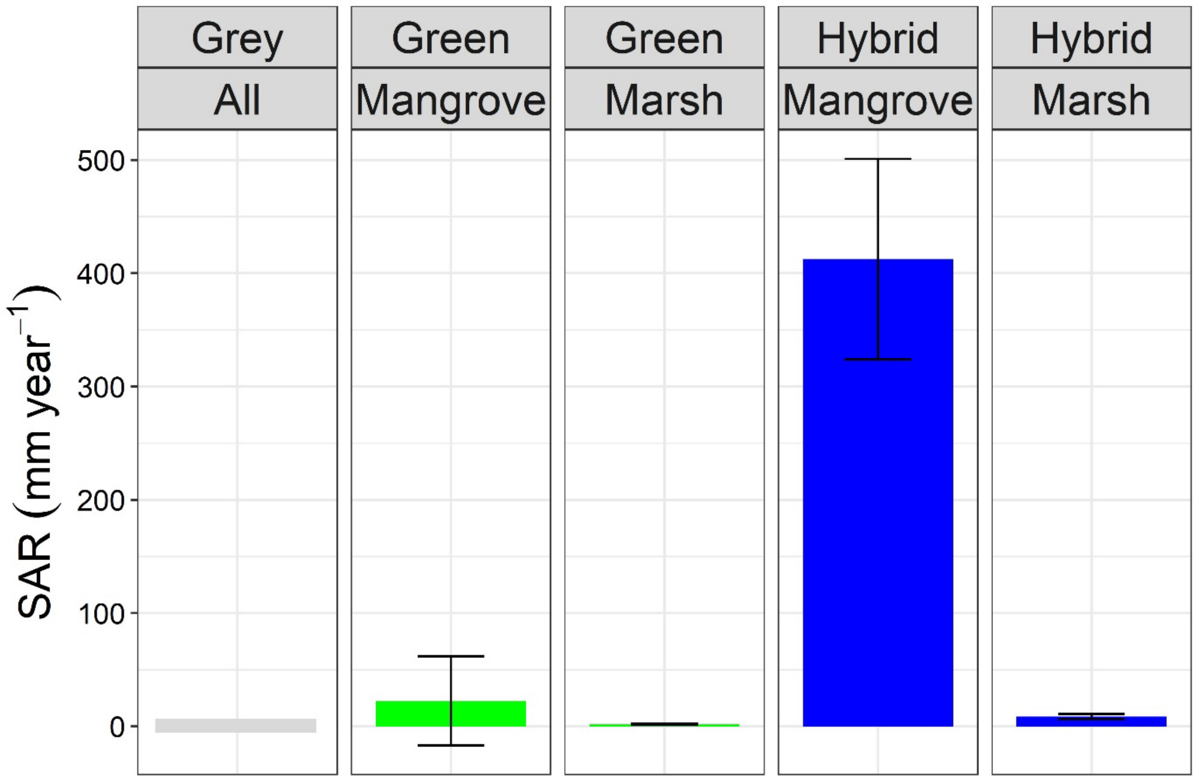

Grey
All
Green
Mangrove
Green
Marsh
Hybrid
Mangrove
Hybrid
Marsh
SAR (mm year⁻¹)
500
400
300
200
100
0

Figure captions

- Figure 1. Location of fifteen case studies on hybrid infrastructure approaches around mangrove (1) and saltmarsh (2) ecosystems reported in this review (See Table 1 and Table 2 for detailed descriptions of case studies).

- Figure 2. Overview of differences in implementation of coastal hybrid infrastructures within mangrove and tidal marsh (saltmarsh) ecosystems.

- Figure 3 Mean cost (USD per meter, ±SE) of grey (n=), green (n = 4) and hybrid infrastructure (n = 18 for mangrove, n=8 for marsh). See Table S2 for data source details.

- Figure 4 Mean sediment accretion rate (SAR, ±SD) as reported for grey (see figure 6b in: Morris et al. 2018). green (see marsh control in table 2 in: Spencer et al. 2012; see suppl. data from: Lovelock et al. 2015) and hybrid infrastructure case studies from this study. As grey infrastructure, such as seawalls, reported erosion in greater proportion the grey bar depicts a conservative value of zero accretion.