The use of bioshields for coastal protection in Vietnam: current status and potential

Abstract: The coastline of Vietnam is vulnerable to a number of threats including shoreline erosion, flooding, sea level rise, typhoons and storms. Natural and anthropogenic factors have been highlighted as key driver and the physical setting of the coastline, including elevation in relation to mean sea level influence the degree of vulnerability. In this review paper, we investigated the possibilities, advantages and limitations to using coastal vegetation as a bioshield for coastal protection in Vietnam. Special attention has been given to mangrove forests, seagrass meadows, nearshore-coral reefs and marshes. Hard structures such as seawalls and breakwaters can be used for immediate relief from coastal vulnerabilities whereas ecosystem-based adaptation using bioshield is highly effective for long-term coastal protection. However, the applicability of bioshields depends on a number of factors, such as coastal geomorphology, degree of vulnerability and biodiversity. Northeastern and southern coast of Vietnam are highly suitable for mangrove vegetation and can be used as a bioshield in these areas. Central and northern Vietnamese coasts are rich in seagrasses and coral reefs and in these areas, this vegetation can be a suitable coastal bioshield.

Keywords: Coastal vegetation; shoreline protection; bioshield; sea level changes; coastal livelihood; Vietnamese coastline

Introduction

Coastal areas around the globe are highly dynamic in nature and provide a range of ecosystems service and this is particularly striking in Southeast Asia (Veettil et al. 2020a). The population density in many coastal regions of the world is higher than inland areas (Small and Nicholls 2003).

Since the economy of these regions is highly dependent on natural coastal resources, they are vulnerable to direct anthropogenic degradation (Friess et al. 2016; Veettil et al. 2020a). In addition to direct anthropogenic threats (e.g. aquaculture, deforestation, urbanization), phenomena, such as sea level rise, shoreline erosion, floods, storms and typhoons compound the impacts of these negative anthropogenic stressors (Veettil et al. 2020a).

One of the key natural resources in coastal and nearshore regions is the biogenic coverage, including mangroves, seagrasses, and coral reefs. The rapid loss of ecosystems within estuarine and coastal zones has raised concerns over the role of such ecosystems, particularly coastal vegetation, in protecting coastal communities from storms, floods, tsunamis and other natural calamities (Barbier 2020). Many coastal ecosystems (e.g. mangrove forests, seagrass meadows, near-shore coral reefs, marshes, etc.) provide a measure of protection from storms, tsunamis and sea level rise (Shepard et al. 2011; Paul et al. 2012; Zhang et al. 2012; Christianen et al. 2013; Ferrario et al. 2014; Ondiviela et al. 2014; Rupprecht et al. 2017; Reguero et al. 2018; Dasgupta et al. 2019; Montgomery et al. 2019). In other words, coastal vegetation and biogenic reefs can be used as a bioshield for coastal protection (Tanaka et al. 2009). For example, mangrove forests in Southeast Asia were shown to be effective in reducing the negative impacts of the 2004 Indian Ocean Tsunami (Veettil et al. 2018).

It has been reported that, compared to other parts of the world, coastal regions within Asia in general, and Southeast Asia in particular, experience a higher number of hydro-meteorological disasters (Zou and Wei 2010). In fact, more than 50% of all people killed and more than 90% of all people affected by natural disasters between 1993 and 2006 were in Asia (Zou and Wei 2010).

In addition to natural disasters, inappropriate development activities, including industrial development, aquaculture ponds, and tourism, increase coastal vulnerability in Southeast Asia (Veettil et al. 2020a). The Vietnamese coastline, from the northeast to the south, is an example of a region, where natural and anthropogenic stressors result in a number of threats to coastal communities, such as sea level rise, shoreline erosion, floods, and pollution.

In this review paper, we investigated the possibilities, advantages and limitations of using coastal vegetation as a bioshield for coastal protection in Vietnam. Application of above-ground, below-ground and submerged vegetation biomass for coastal protection in Vietnam has been considered in this review. A vegetation bioshield in combination with soft and hard coastal defence measures (sand dunes and rock walls) is also considered. Special attention is given to mangrove forests, seagrass meadows, nearshore-coral reefs and tidal marshes, and the possibility of using other plant species, such as *Casuarina equisetifolia* and *Pandanus odoratissimus*, in mitigating coastal hazards in Vietnam.

Coastal hazard vulnerability in Vietnam

The coast of Vietnam can be broadly divided into northern (from Ngoc Cape to Lach River Mouth), central (from Lach River Mouth to Vung Tau Cape) and southern (coast of Southern Vietnam) zones (**Figure 1**). The Red River Delta belongs to the northern zone and the Mekong Delta belongs to the southern zone. Based on the distribution of mangrove vegetation, some researchers (e.g. Hong and San 1993; Veettil et al. 2019a) divided the Vietnamese coastline into four, where the northern zone has been subdivided into northeast (from Ngoc Cape to Do Son Cape) and north (from Do Son Cape to Lach River Mouth). Two major river deltas, known as the Red River Delta and the Mekong Delta in the north and the south, respectively, have been facing threats, such as shoreline erosion and saline intrusion in recent decades (Bangalore et al. 2019). Central Vietnam, particularly the coast of Quang Nam Province, has been facing high rates of shoreline erosion (in some areas up to 300 +/- 43m) in recent years (Veettil et al. 2020a). According to Nguyen and Shaw (2010), the Vietnamese coastline is one of the most populated regions in Southeast Asia and a large proportion of the gross national income originates from coastal economic activities, such as fisheries, aquaculture, tourism and marine transport.

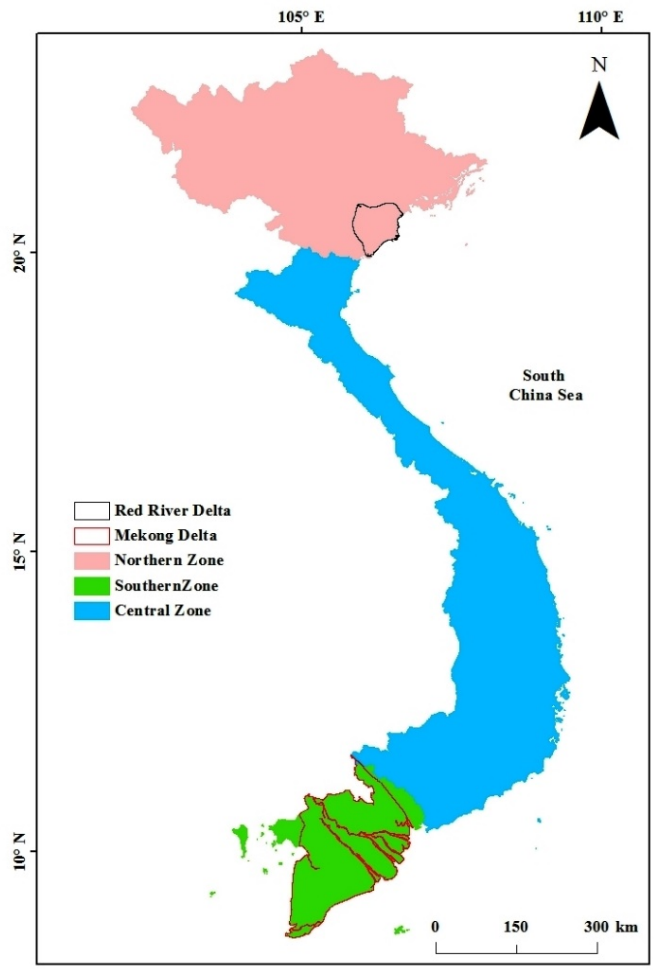

Figure 1: Different zones in Vietnam based on geographical features

The Vietnamese coastline, has a length of 3260 km, and is susceptible to storms, tropical cyclones and sea level changes (Neumann et al. 2015), predominantly affecting coastal and island communities. On average, ten tropical typhoons strike the coast of Vietnam every year (Neheren et al. 2017). Low-lying areas, such as the Red River and Mekong Deltas, are the most vulnerable areas in the country from the combined effects of coastal disasters and climate change. The Vietnamese coastline is being affected progressively by coastal hazards and climate change rather than by sudden catastrophic events (Veettil et al. 2020a).

Coastal erosion has been reported from the northern (Quang Ninh, Haiphong, Nam Dinh), central (Quang Binh, Quang Nam, Phan Thiet-Binh Thuan) and southern (Tien Giang, Ca Mau) coastal zones in Vietnam. In some areas, such as the beach of Cua Dai in Quang Nam Province in Central Vietnam, coastal erosion is serious, and20% of the beach is forecasted to disappear in a few years (Hens et al. 2018). Some of the key reasons for increased shoreline erosion in Vietnam is the high rate of sand mining, reduction in sediment transport through river channels due to the construction of hydroelectric and irrigation dams and irrigation canals, and the construction of coastal hard structures (e.g. sea dykes) influencing downstream coastal cells (Takagi et al. 2015).

Typhoons are one of the biggest threats to coastal communities in Vietnam, particularly in the northern zone surrounding the Red River Delta. Compared to northern and central zones, typhoons are not very common in the southern zone, even though the chance of typhoons making landfall cannot be considered as negligible (Anh et al. 2017). On the contrary, according to a latest study by Nguyen et al. (2019), both the Red River Delta and the Lower Mekong Delta are vulnerable to typhoon-driven flood threats in Vietnam. Together with sea level rise, this could be alarming in these low-lying areas of the country.

Even though Vietnam has taken a number of measures to protect their coastlines, such as creation of sea dykes, river channel enhancement, implementation of flood early warning and forecasting systems, the country still experiences significant damage from flooding (Boateng 2012). Coastal flooding is one of the main natural hazards in Vietnam (Bangalore et al. 2019). Since low lying areas of the country (Red River Delta and Mekong Delta) are important in terms of food security and socio-economic development for the country, exposure to floods in these regions will have serious negative impacts on livelihoods (Balica et al. 2014). Floods are experienced from the north to the south of Vietnam, depending on seasonal variations in precipitation. The probability flood occurrences are principally dependent on geomorphological and geoenvironmental factors (Khosravi et al. 2016).

Sea level rise and saline intrusion during the dry season is a serious threat affecting low lying coastal zones (the Red River Delta in the north and the Mekong Delta in the south) and agriculture in Vietnam. Low lying regions in Vietnam are some of the most threatened by sea level rise in the world. Hens et al. (2018) estimated that a 1m rise in sea level could result in inundation of about 16.8% of the Red River Delta and 38% of the Mekong Delta, whereas this value is only 1.47% in the central provinces of Vietnam due to the lower lying nature of the former areas. Despite the fact that the low lying Mekong delta is under serious threat of sea level rise, Minderhoud et al. (2019) reported that the level of assessments of the impacts of sea level rise in the region is still poor and suffer data scarcity. The same study (Minderhoud et al. 2019) also estimated that the mean elevation of the Mekong Delta is about 0.8 m a.s.l., which contrasts with the earlier assumed value of 2.6 m, highlighting the severe vulnerability of this region towards rising sea level.

In Vietnam, coastal vegetation in general and mangrove forests in particular are on key for protecting coastlines from the dual impacts of storms and sea level rise (Veettil et al. 2019a). Natural resource management, including mangroves, has been recognized as a potential agent in mitigating climate change impacts in Vietnam since the 1990s (e.g. Tri et al. 1998). However, other biogenic coastal ecosystems, including seagrasses and nearshore-corals have not attracted the attention of environmentalists as coastal protection agents in the country. Large communities of seagrass meadows and coral reefs are found along the coastline, including islands, which in Vietnam could play a key role in mitigating the impacts of coastal hazards. Even though still incomplete, advances in remote sensing applications have helped the scientific community in mapping and creating databases of coastal vegetation, such as mangrove forests, seagrass meadows and coral reefs in the country.

Methods for mitigating coastal hazards in Vietnam

Various mitigation strategies adapted for coastal protection include hard and soft structures, natural barriers and a combination of these (known as hybrid barriers). Hard structures or grey infrastructures, such as seawalls, dykes and breakwaters, have been used for coastal protection from sea level rise throughout the world (Schoonees et al. 2019). It has been reported that the number of hard structures for coastal protection will continue to increase as a result of climate change and continuing sea level rise (Firth et al. 2013). In Vietnam, many coastal areas are protected using hard structures, such as rocky barriers (revetments) and concrete walls and sea dykes (**Figure 2a, 2b**), particularly in central Vietnam, where shoreline erosion is an ongoing issue in recent decades. In Quang Nam Province, where large scale shoreline erosion (>300m) has been observed, nearly 1.3 km of concrete sea dykes were built and a large area is protected with geotube sandbags and approximately 70,000 m^3 of sand and sludge fillings to protect the coastline. Hard foreshore structures (e.g. breakwaters, jetties, groynes) have structural integrity under extreme weather conditions not exceeding their design conditions (Schoonees et al. 2019). However, a number of failure modes need to be considered in the design of hard foreshore structures, which include geotechnical stability, movement of the structure (e.g. due to illegal sand mining), and long-term erosion effects (if implemented in unsuitable conditions). At sites, where illegal sand mining operations are extensive, hard structures need to be complemented by applying soft engineering approaches such as sediment nourishment techniques (Schoonees et al. 2019). One of the drawbacks of hard foreshore structures is that they are not very effective against storm surges and flooding and they need to be complemented by hard shoreline structures (e.g. seawalls, sea dykes) (Schoonees et al. 2019). For rapid mitigation of coastal hazards, such as in Central Vietnam, where more than 100 meters of shoreline has been eroded recently, a combination of hard foreshore and nearshore structures can be effective.

Figure 2: hard rock wall (revetments) and sea dykes (**a** and **b**, respectively) and soft measures (**c** and **d**) for shoreline protection in Vietnam (Quang Nam Province, central Vietnam). Photographs: Dr. Bijeesh K Veettil.

Environmental issues, including ecosystem alteration, as a result of the construction of hard structures has resulted in the development of eco-friendly hard structures. Ecological enhancement of hard coastal structures is an emerging technique used for long-term coastal protection. For example, the installation of artificial reefs and tidal marshes with mudflats in front of hard structures is a kind of ecological enhancement of hard structures. For this purpose, the choice of species is either aquatic (e.g. seagrass meadows, coral reefs) or semi-terrestrial (e.g. marshes, mangroves), depending on the environmental conditions and the type of protection needed. Understanding the interactions between the substrate (hard structures) and the colonizing organisms is important in their application for ecological enhancement (Coombes 2011). A few plant species, such as Pandanus (found abundant along the southern coastal zone in Vietnam), can thrive on hard rock structures and possibly enhance its sediment retaining capacity.

Soft measures used for shoreline protection against sea level rise and erosion in Vietnam (**Figure 3**) include beach nourishment, sand bags, geotextile reinforced sand bags, and breakwaters using sandbags. Beach fills or beach nourishment (the addition of sand into the beach) for protecting the beaches from erosion serves to maintain the value of coastal investments and beach amenity to tourism and recreation (Masria et al. 2015). The advantage of beach nourishment includes flexibility in coastal management and reversibility. However, this method is not a permanent solution for preventing shoreline erosion and the addition of sediments may cause alterations in natural biodiversity of the beach, including the burial of animals and organisms living on the beach (Masria et al. 2015). Dune stabilization and restoration, can be undertaken using structural controls and native vegetation, such as Beachgrass, providing another soft measure that can be applied for shoreline erosion prevention in combination with beach nourishment. This method is possible along the Vietnamese coast, as native vegetation (e.g. *Ammophila arenaria*) suitable for this method is found in the region (**Figure 4**). Native dune vegetation is important in stabilizing the surface against wind erosion in coastal areas, as well as wave action and tidal inundation. Geotubes are used throughout Vietnam from the north to the south coast for shoreline erosion prevention. In addition to breakwaters made from geotube sandbags, breakwaters made from bamboo and wooden piles have found to be effective when used in the eroded coasts of the Mekong Delta, particularly for improving sedimentation (Schmitt and Albers 2014). A total of 7,100 m of permeable bamboo fences installed on the east coast of the Lower Mekong Delta have provided a low-cost solution for areas where wave heights are lower than 0.9m (Ngyyet-Minh et al. 2020). Furthermore, fences using Nypa palm (*Nypa fruticans*) leaves are used in some areas (e.g. Ben Tre, southern Vietnam) for temporary protection, which is cost-effective and easily replaced every three months (Phong 2015). Double bush fences (two lines of dried *Rhizophora* *apiculata*) reinforced with sandbags have been effectively employed for coastal protection in Ben Tre province (Phong 2015).

Figure 3: Soft measures using Geotubes in Ba Ria-Vung Tau, southern Vietnam

Figure 4: Native plant species found in the coastal areas of southern Vietnam (Ba Ria-Vung Tau), which has the potential in dune stabilization.

Coastal bioshields or green structures have been used worldwide for long-term coastal protection (Feagin et al. 2015). In Vietnam, ecosystem-based measures for coastal hazard risk reduction have attracted the attention of science, policy and planning agencies (Nehren et al. 2017). Maintaining and restoring mangrove forests can be a cost-effective alternative to hard structures to mitigate coastal hazards as one of several important ecosystems services. Coastal dune stabilization by afforestation is also an application of vegetation as a bioshield, although not widely applied in Vietnam. Coastal dunes in Vietnam provide protection against saltwater intrusion, particularly in the central and south-central region (e.g. Thua Thien-Hue). Cost effectiveness, which is regionally variable, is a key factor in choosing hard structures or bioshield for coastal protection. For example, breakwater construction costs are broadly similar in Europe and the United States whereas these are 10 times lower in Vietnam (Nayayan et al. 2016).

Key vegetation bioshield species in Vietnam are native mangrove and Casuarina trees (**Figure 5**). A number of non-mangrove plant species, such as Screw Pine (*Pandanus fascicularis*) and Casuarina (*Casuarina equisetifolia*) have potential as bio-fences or green belts along the coastal areas (Jose et al. 2016). Casuarina is already used in some regions (e.g. Ba Ria-Vung Tau coast) in Vietnam for this purpose. Submerged vegetation at large scale, such as seagrasses (e.g. *Cymodocea rotundata, Cymodocea serrulata, Enhalus acoroides, Halodule pinifolia, Halodule uninervis, Halophila beccarii, Halophila decipiens, Halophila minor, Halophila ovalis, Ruppia maritima, Syringodium isoetifolium, Thalassia hemprichii, Thalassodendron ciliatum and Zostera japonica*) that are found in Vietnamese waters, can reduce current velocities and dampen waves, which in turn can trap sediments (Borsje et al. 2011).

Figure 5: Mangroves (Ben Tre Province) and Casuarina (Ba Ria-Vung Tau) as bioshield for coastal hazard reduction in southern Vietnam. Photographs: Dr. Bijeesh K Veettil.

Ecological benefits offered by bioshields in coastal areas

A large number of ecological benefits are provided by coastal vegetation, including protection from shoreline erosion, sediment trapping, reducing the effects of flash floods, tsunamis and typhoons as well as post-tsunami regeneration of the coastal environment, providing livelihood (fisheries), reducing the effects of sea level rise, trapping floating debris, and functioning as feeding grounds and hatchery for fishes and other marine animal species. After the 2004 Indian Ocean Tsunami, Hurricane Katrina and Cyclone Nargis, coastal vegetation has been widely promoted as a bioshield against extreme events (Feagin et al. 2010).

Shoreline erosion protection and stabilization offered by coastal wetlands such as mangroves, have additional ecological and economic benefits. Mangrove vegetation can modify shorelines in many ways, including sediment accumulation. However, it has to be noted that, even though mangrove vegetation has been shown to be effective as shoreline buffer, they cannot protect the coastal areas from large-scale regional erosion, river meandering, and large tsunami waves and storm surges beyond the attenuation influence of the vegetation and there exists a lack of knowledge about the mechanistic and context-dependent aspects of shoreline protection (Gedan et al. 2011).

As a result of rising sea level, storminess and subsidence, coastal communities in Southeast Asia are facing an increased flood risks (Möller et al. 2014). In addition to protection from shoreline erosion, coastal vegetation also offers natural protection against flooding (Hanley et al. 2020) and reducing the threats of rising sea levels (Möller et al. 2014). Coastal wetland vegetation can buffer excess flood water during the rainy season, which in turn reduce the impacts of floods. Coastal plant communities, such as mangroves, can considerably increase wave attenuation during storm events, and up to 60% higher wave attenuation has been recorded compared with non-vegetated areas (Möller et al. 2014). In addition to mangrove species mangrove associates, such as *Nypa fruticans*, are also helpful in stabilizing soils in the coastal zone, thereby protecting against erosion and reducing effects of floods.

Coastal vegetation, such as mangrove forests, is helpful in reducing the effects of small-scale tsunamis and post-tsunami regeneration of the environment. Based on tsunami hydrodynamic models, a few studies (e.g. Hiraishi and Harada 2003; Teo et al. 2009) mention that current velocities and wave heights are reduced when the tsunami waves traverse mangrove vegetation (*Rhizophora* spp., *Avicennia* spp.) in comparison to non-vegetated coastal areas. Mangroves (*Rhizophora* in particular) and a few other coastal tree species (*Pandanus odoratissimus*, *Casuarina equisetifolia*, *Cocos nucifera*, and *Anacardium occidentale*) were observed to slow the water flow and reduce wave heights during the 2004 Indian Ocean Tsunami (Gedan et al. 2011).

Coastal vegetation is one of the key livelihood providers in Vietnam and the broader SE Asian region. In some provinces in Vietnam, mangrove forests influence socioeconomic conditions and the livelihood of local communities (Veettil et al. 2019a). Both direct and indirect services are provided by coastal vegetation to the community in and around the coastal areas in Vietnam. Vietnamese mangrove forests, coral reefs and seagrass meadows are a habitat for a number of economically valuable species (e.g. shrimp, crab, fish, etc.), supporting the livelihood of coastal rural communities (Nordlund et al. 2018; Veettil et al. 2019a). Mangroves of Vietnam also provide fuel wood (charcoal), industrial raw materials (timber), salt production, trapping floating debris, carbon sequestration, and biodiversity conservation (Orchard et al. 2015; Veettil et al. 2019a). Whilst not a sustainable practice, mangrove areas in Vietnam have been widely used for aquaculture, particularly shrimp farming (Thu et al. 2012). In addition, coastal vegetation (mangrove forests and seagrass beds) provide feeding and nursery grounds for various ecologically and economically important species.

From the perspective of climate change, mangroves, saltmarshes and seagrasses are likely to have some similar responses to the range of factors impacting them. These include increases in temperature, which can have either a positive or negative impact on plant productivity and potentially alter range distribution (Ward et al. 2016a; Lima et al. 2020; Ward 2020a). Climate change is also likely to influence the frequency and intensity of storm events (IPCC 2013), with potential for increasing sediment accretion or erosion rates depending on track, associated wind and wave strength, local geomorphology, species present and diversity of species, aspect of the site and level of degradation (Ward et al. 2016a; Lima et al. in submission). Likewise, sea level rise could result in greater sediment accretion or potentially drowning/loss of plant communities (particularly relevant for mangroves and saltmarshes), this will be dependent on rates of sea level rise, available sediment, ability of plants to trap sediments (species and condition dependent) and local rates of subsidence/uplift (Ward et al. 2014; Ward et al 2016a; b; Ward 2020b). Alteration of precipitation regimes will also impact resilience/vulnerability of seagrasses, mangroves, and saltmarshes although in different ways. Seagrasses are unlikely to thrive in areas with very high freshwater input, mainly as a result of increased competition from aquatic plants or potentially increases in turbidity linked to freshwater runoff and associated decreases in light availability (Stipek et al. 2020). Increases in drought conditions have been found to have a negative impact of vegetation condition (Mafi Gholami et al. 2018) particularly where liked with aquaculture (Lacerda et al. 2021). Drought conditions can also be linked to increases in salinity, which can result in switches between mangrove dominated to saltmarsh dominated communities (Duke et al. 2019).

Distribution of coastal vegetation in Vietnam

Four key ecosystems providing a bioshield in Vietnam are: mangroves, seagrasses, coral reefs and salt marshes (**Figure 6**). Other vegetation species that are valuable as bioshield, such as Casuarina and Beachgrass, are also discussed. Many studies (e.g. Guannel et al. 2016) consider the three coastal vegetation (mangroves, seagrasses and coral reefs) as the key protectors and resilience enhancers of the coastal regions. The spatial distribution patterns of various coastal vegetation in Vietnam varies from the north to the south, depending on environmental, geomorphological and meteorological conditions. For example, mangrove forests are denser in the northeast and southern zones (Veettil et al. 2019a) whereas seagrass beds are more diverse in the central zone (Tin et al. 2020a).

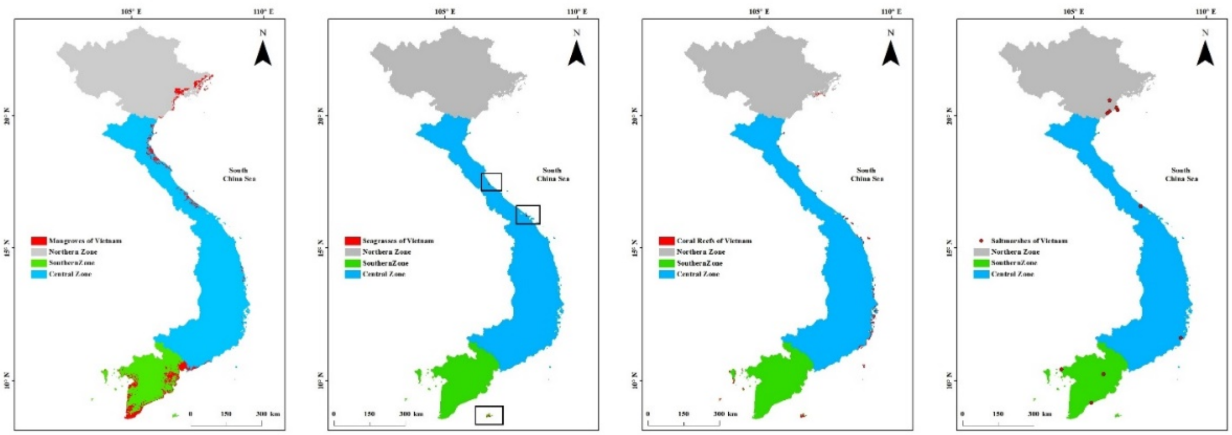

Figure 6: Distribution of various coastal vegetation in Vietnam. (a) Mangrove forests (Spalding et al. 2010; Giri et al. 2011; Veettil et al. 2020a), (b) Seagrass meadows (UNEP-WCMC 2020), (c) Coral reefs (UNEP-WCMC 2018), (d) Salt marshes (Mcowen et al. 2017).

Mangrove forests are found throughout the coastline of Vietnam from northeast to the south (**Figure 6a**). Those in the central region are not as extensive or diverse as those in the south and north of the country due to non-planarity of the coast, less fertile soils, and influence from strong winds, water currents and frequent storms (Veettil et al. 2019a). In fact, environmental conditions in Vietnam vary from the north to the south and the extent of mangroves depend on these conditions as well as coastal geomorphology. Two globally important deltas (the Red River Delta and Mekong Delta) in Vietnam have extensive mangrove coverage. The southern zone has the most favourable conditions for mangrove ecosystems, including low lying topography, nutrient abundance in the soil, and fewer storms and weaker water currents (Loon et al. 2007). The most commonly occurring mangrove genera in Vietnam are *Rhizophora* and *Avicennia* (Marchand

2008; Veettil et al. 2019a). Reforestation and afforestation of mangroves is currently being carried out in a number of coastal areas (e.g. Ben Tre, Southern Vietnam and Quang Nam, central Vietnam) in Vietnam. Most of the mangrove forest database in Vietnam has been mapped using remotely sensed data (e.g. Giri et al. 2011). A few recent studies have estimated areas that were not included in these databases with mangrove coverage from Central Vietnam (e.g. Tin et al. 2020a; Veettil et al. 2020a). In some provinces (e.g. Ben Tre, southern Vietnam), the saline intrusion has been high in recent years and planting mangroves can be effective in lowering the salinity of groundwater (Ridd and Sam 1996).

Seagrass meadows are fragile ecosystems that can be degraded or lost as a result of natural disasters and anthropogenic activities. There is nearly 37,000 km^2 seagrass-covered areas in southeast Asia, which is probably an underestimation due to the lack of information (Fortes et al. 2018) and there is a lack of information on seagrass meadows in Vietnam (Vo et al. 2020). Seagrass meadows in Vietnam (**Figure 6b**) are found throughout the coastline of Vietnam (UNEP-WCMC 2020), with extensive meadows near Nha Trang in the central zone (Vo et al. 2020). In some areas in Vietnam (e.g. the biggest seagrass bed in Vietnam in Van Phong Bay, Nha Trang), more than 35% of the original seagrass beds were lost since the late 1980s and key drivers have been suggested as industrialization and rapid urbanization in the coastal areas (Vo et al. 2020; Tin et al. 2021). Even though the number of studies on seagrasses in Vietnam is limited compared to mangroves in Vietnam, a few recent studies utilized remotely sensed data for mapping seagrass meadows in central Vietnam (e.g. Chen et al. 2016; Vo et al. 2020; Tin et al. 2020b, 2021). Remote sensing data, including imagery from spaceborne and airborne platforms, can be used as an alternative and cost-effective way compared to expensive field data collection methods to conduct seagrass studies in Vietnam (Veettil et al. 2020b).

Coral Reefs in Vietnam are found throughout the coastal zone and surrounding islands (about 3000) of the country (**Figure 6c**). The total area of coral reefs in Vietnam has been estimated as 11000 km^2 with more than 400 species identified (Burke et al. 2002). The highest coral diversity in Vietnam is found in the south-central region (more than 300 species belonging to 65 genera). In fact, the coastal waters of Khanh Hoa province have the most diverse coral reefs in the western South China Sea (Vo et al. 2019). Primary production of coral ecosystems along the Vietnamese coast and adjacent marine waters is high and the GPP of coral reef systems has been estimated as 7.85 to 17.10 $gCm^{-2}day^{-1}$ and this plays an important role in biogeochemical nutrient cycles in waters around the reefs (Tac-An et al. 2013). In addition to coastal protection and primary production, coral reefs in Vietnam attract a large number of tourists every year (Tkachenko et al. 2016). Main threats to coral reefs in Vietnam are dredging, landfilling, mining, coastal infrastructure development, overfishing, and sewage discharges and pollution in addition to natural factors (Tkachenko et al. 2016). In some areas (e.g. Co To Archipelago, Quang Ninh, northern Vietnam), serious degradation (80-90%) of coral reefs occurred (Ngai et al. 2013). One of the reasons for this high degradation was found to be associated with the use of cyanide residues used by local fishermen for fishing on reefs (Ngai et al. 2013). Hedberg et al. (2018) reported that the use of antibiotics by farmers in fish and lobster sea farms in Vietnam cause negative effects on the coral-symbiont relationship. A few studies (e.g. Svensson et al. 2009) reported that privately managed coral reef reserves in Vietnam could play a vital role in coral conservation.

Saltmarshes, dominated by herbaceous and small shrubby vegetation compared to trees in mangrove swamps, are also found in Vietnam (**Figure 6d**). However, compared to the surface area distribution of mangroves, seagrasses and coral reefs, the areal coverage of saltmarshes in Vietnam is not extensive. Saltmarshes in Vietnam are found in Tam Giang Lagoon in Hue and Ninh Thuan (central Vietnam), Ben Tre, Bac Lieu and Kien Giang (southern Vietnam), and Thai Binh and Nam Dinh (northern Vietnam) (Mcowen et al. 2017). In fact, Tam Giang-Cau Hai lagoon, where the area is highly suitable for the development of saltmarshes, is the largest saltmarsh in Southeast Asia. However, sea level rise and coastal development activities have reduced the extent of this ecosystem and increased vulnerability (Tuan 2012).

Other coastal vegetation in Vietnam, including the planted Casuarina trees, also play an important role in coastal protection. For example, *Pandanus tectorius* is found in the north and northeast of Vietnam whereas *Pandanus tonkinensis* is found in Central Vietnam (Veettil et al. 2019a). *Spinifex sericeus* and *Pandanus* are generally found dominating the foredune (Nehren et al. 2016). A number of plant species were noted by Tang et al. (2020) to reduce coastal erosion in Vietnam, predominantly from the families *Asteraceae*, *Chenopodiaceae*, *Convovulaceae*, *Fabaceae*, *Malvaceae*, *Verbenaceae*, *Flagellariaceae*, *Amaryllidaceae*, *Cyperaceae*, *Hydrocharitaceae*, *Poaceae*, *Pandanaceae*, *Oleadraceae* and *Schizeaceae*. The spatial distribution of non-mangrove tree species depends on meteorological and soil salinity conditions of the coastal areas. Mangrove forests in muddy soil and other trees, such as coconut, palm, casuarina and other sand-binding vegetation, in sandy soil can be suitable for shoreline protection (Kathiresan and Rajendran 2005) in Vietnam. *Casuarina equisetifolia*, which is abundant in the southern coastal zone in Vietnam, can be planted to stabilize coastal dunes (Nehren et al. 2016).

Vegetation biomass types and coastal protection

For convenience in understanding the dynamics of bioshield against coastal hazards, here we consider three types of biomass – above-ground, below-ground and submerged. A number of studies have investigated the differences in the changes in erosion and wave attenuation due to the presence or absence of coastal wetland vegetation. The dynamics of biogenic coastlines with regards to coastal hazards highly depends on the types of biomass and the intensity of the hazard.

Above-ground coastal wetland biomass (including stem and leaves of mangroves, saltmarsh plants, intertidal seagrasses, pandanus, casuarina, beachgrass, etc.) are in direct contact with seawater and sediments transported by water thereby reduce water flow velocity and turbulence and increase sediment deposition (Gedan et al. 2011; Ward et al. 2016; Lima et al. 2020; Ward 2020). Above-ground biomass (stem and leaves) exerts a drag force in the opposite direction of the water flow and slowing down water velocity (Gedan et al. 2011; Ward et al. 2014). A reduction in turbulence and increase in sediment deposition can be caused by stems and leaves of coastal vegetation (Ward et al. 2014).

Below-ground biomass, which includes roots, rhizomes and shoots of plants, is helpful in slowing erosion by stabilizing the soil substrate. Micheli and Kirchner (2002) reported the increase in the shear strength of wetland soils due to the enhancement in cohesion and tensile strength of the soil substrate due to the presence of below-ground vegetation biomass. In addition, the roots of coastal vegetation are helpful in stabilizing tidal creeks by providing a physical barrier between water and soil (Wolanski et al. 2009) and also provides a physical protection against coastal erosion

(Gedan et al. 2011). The protection against erosion offered by the roots is limited to the root depth (typically ≤1m) and thus more effective in micro-tidal and meso-tidal estuaries, were erosion typically occurs above the root levels (Gedan et al. 2011). Saltmarsh plants have been found to prevent lateral wave-induced erosion along wetland edges as they bind the soil with their live roots (Leonardi et al. 2016). Below-ground biomass, once decayed, is also helpful in coastal soil protection because erosion in organic-rich soils is slower than normal soil (Feagin et al. 2009).

Submerged biomass, such as seagrasses, macro-algae and coral, plays an important role in preventing coastal erosion in coastal areas. Large submerged vegetation can be persistent and slow growing (e.g. some seagrass species) and those species that reach maximum biomass under high hydrodynamic forcing can provide strong protection against coastal hazards (Ondiviela et al. 2014). However, Christiansen et al. (2013) mentioned that low-canopy seagrass beds also provide important coastal protection services, including enhancing sedimentation and preventing erosion. Coastal defence provided by submerged biomass is highly dependent on its capacity in attenuating flooding and erosion (Borsje et al. 2011). For example, current flows and wave action are modified by submerged seagrasses (Ondiviela et al. 2014). However, wave attenuation characteristics of seagrass may depend on blade stiffness, shoot density, and leaf length (Paul et al. 2012). In addition to protection from coastal hazards, submerged aquatic vegetation is highly valuable for organic carbon storage (Hillmann et al. 2020). In a recent study, Reguero et al. (2018) observed that coral reefs control the positioning of shoreline on a long-term basis and severe coastal erosion can occur in areas with coral degradation. Macro-algal beds are also considered as a means for coastal protection. For example, in shallow waters of temperate reefs, *Ecklonia radiata* was observed to have a high capacity for attenuating wave activity (Morris et al. 2020).

Advantages and limitations of using bioshield for coastal protection in Vietnam

There are a number of advantages, including cost-effectiveness and long-term service, when using bioshield as a strategy for coastal protection. One of the most important advantages of coastal protection using bioshield is the maintenance of a natural shoreline habitat with its original biodiversity and ecosystem as well as natural transport of sediments across coastal areas. Compared to hard structures, such as seawalls and dykes, a bioshield is a good absorber of water during coastal floods. Hard structures are not effective in nutrient cycling whereas natural bioshields are effective for water nutrient cycle and pollutant filtering. Bioshields do not cause a serious reduction in the aesthetic appearance of shorelines and, hence, the recreational value is not reduced considerably. In fact, vegetated coastal environments are good at stabilising sediments and coastal forests are effective at reducing wind speed during (low/medium) cyclones (Parvathy 2012). Hard structures have no role in carbon sequestration whereas bioshield ecosystems, particularly mangroves, seagrasses and saltmarshes, are great carbon sinks and hence provide a key role in climate change mitigation. Furthermore, bioshield ecosystems, produce very little energy reflection and wave attenuation by friction, the opposite of hard structures (i.e. hard structures causes wave attenuation by breaking and friction, which is responsible for substrate loss) (Garcia et al. 2018). In addition, a more resilient foreshore defence can be provided by using a group of complimentary ecosystems (mangroves, salt marshes, seagrasses, coral reefs or oyster reefs) rather than using a single ecosystem (Schonees et al. 2019).

Mangroves are considered as excellent bioshields against coastal hazards due to the advantages of using them. They are well adapted to grow in saline environments with reduced soil oxygen and long hydroperiods. Mangrove forests are effective at reducing harmful UV radiation and thereby protecting animal life underneath the canopy (Moorthy and Kathiresan 1997). Mangroves are the key protective vegetation against coastal floods caused by storm surges and heavy rainfall. The root systems of mangrove vegetation are more effective than any other coastal vegetation for flood control and sediment accumulation (Alongi et al. 2004; Veettil et al. 2019a). Coastal erosion due to wave action can be reduced effectively with increases in mangrove vegetation density. The cost effectiveness of mangrove bioshields compared to concreate seawalls and other structures is higher and longer lasting, particularly considering its ability to self-repair following storm damage (Harada et al. 2002).

Seagrasses have substantial advantages as a bioshield for coastal protection, due to their high recovery potential (Alagna et al. 2019), sediment stabilization, and soil retention in its roots (Barbier et al. 2011). Seagrass meadows have been found to have highly significant positive changes on coastal sediment surface elevation in England, Scotland, Kenya, Saudi Arabia and Tanzania (Potouroglou et al. 2017; Lima et al 2020). When the canopy heights are more than 15% of the water column height, seagrass ecosystems are effective in altering bottom roughness and the vertical flow profile (Dayton et al. 2005; Garcia et al. 2018). Garcia et al. (2018) reported that waves are between 10 and 30% smaller in seagrass (*Posidonia ostemfeldii*) dominated areas than non-vegetated coastal areas in Albany in Western Australia.

Coral reefs provide similar wave attenuation characteristics to hard structures such as breakwaters and more than 100 million people around the world benefit from coastal protection offered by coral reefs (Ferrario et al. 2014). In fact, all the bioshield ecosystems suggested in this article have a high potential for reducing wave heights (in the order: coral reefs > salt-marshes ~ mangroves > seagrass/macroalgal beds) in coastal environments (Nayayan et al. 2016). Considering cost-effectiveness, the construction of tropical breakwaters is substantially more expensive than coral reef restoration projects, where the latter are present (Ferrario et al. 2014). Furthermore, coral reefs have a higher rigidity and hence can be efficient breakwaters compared to flexible vegetation such as seagrasses (Bauma et al. 2014). In addition to coastal protection, additional advantages of coral conservation are from additional associated ecosystem service provision, including income from tourism (Diedrich 2007) and conservation of a large number of fish species (Galbraith et al. 2021).

Salt marshes and mangroves are considered as highly cost-effective (2 to 5 times) and cheaper than submerged breakwaters for reducing wave heights (Nayayan et al. 2016). Similar to coral reefs, saltmarshes also have a significant potential in wave height reduction and shoreline protection. In fact, salt marshes and mangroves provide a high number of benefits (erosion control, coastal protection, tourism and recreation, food and raw materials, nursery habitat for fish, pollution storage, water purification and carbon sequestration and education) (Barbier et al. 2011; Celis Hernandez et al. 2020a, b; Pinheiro et al. 2021). Saltmarshes are located at high elevation intertidal zones and hence can be more effective in wave attenuation compared to seagrass meadows or coral reefs, which are found in lower intertidal/subtidal areas (Bouma et al. 2014). Despite the fact that saltmarsh biomass is not as massive as mangrove vegetation, they are still effective for coastal protection against small tsunami waves, storm surges and erosion (Gedan et al. 2011).

Some of the key disadvantages of using bioshields for coastal protection include their inability to be used in high energy environments and the success of their restoration/creation depends on a number of external factors (meteorological, hydrological and geomorphological conditions). The long-term stability of coastal bioshields is still understudied and may hamper the implementation of such systems (Schoonees et al. 2019). Furthermore, it is difficult to estimate the effectiveness of bioshields for different types of shorelines with varying energy regimes and storm conditions. It can be argued that coastal bioshields using non-native plant species may damage native ecosystems and need to be careful before introducing such alien species. For example, *Casuarina equisetifolia* tend to invade mangrove forests in low saline environments (Lugo 1998). Changes made on the soil conditions for planting bioshields may negatively affect associated fauna.

Mangroves are not distributed equally along the coastline of Vietnam and hence cannot be used as a method for coastal protection throughout the country. The protection offered by mangrove vegetation against tsunamis is limited to low - medium strength and cannot be used against severe ones (Dahdouh-Guebas et al. 2006), particularly when the forest width is less than 100 m (Alongi 2008). Moreover, the magnitude of energy absorption by mangrove vegetation depends on a number of bio-geological factors such as tree density, diameter of stem and roots, geomorphology of the coast, and bathymetry (Alongi 2008).

One of the key limitations of seagrass meadows is their high sensitivity to natural and anthropogenic environmental disturbances. The wave attenuation benefits provided by seagrasses are variably effective dependent on the periods of the tidal cycle (Koch et al. 2009) and is influenced by seasonal changes in shoot density (Bouma et al. 2014). Moreover, the wave attenuation capacity of seagrass leaves, especially when the biomass is low, is inferior to salt marshes due to their mobility (Bouma et al. 2010). Nutrient enrichment alters the morphological and biomechanical properties (e.g. increases the brittleness of seagrass plants), which can result in breakage during high wave activity (La Nafie et al. 2012). However, the effectiveness of seagrass beds in coastal protection has not been fully assessed.

Wave reduction by coral reefs is influenced by a number of factors, such as reef width, reef depth relative to wave height, reed width relative to the average wavelength and slope of the reef (Nayayan et al. 2016). Despite the fact that coral reefs are excellent for coastal protection, the majority of restoration projects are targeted on habitat restoration rather than coastal protection (Nayayan et al. 2016) particularly when compared with other coastal ecosystems, such as mangrove forests. Moreover, restoration costs are higher for coral reefs than mangroves and salt marshes (Nayayan et al. 2016). Despite the fact that anthropogenic activities on both land and the sea threaten coral reefs, most reef conservation initiatives focus on threat removal in the sea and neglect threats from land (Klein et al. 2012). Coral bleaching and ocean acidification, which threaten coral reefs worldwide, is a widespread threat and cannot be compensated completely with restoration practices. Furthermore, reefs are mostly found below sea level and can be less effective in protecting coastal structures from waves (Bauma et al. 2014).

Saltmarshes are also sensitive to coastal eutrophication and other anthropogenic stresses (Deegan et al. 2012). Similar to other coastal vegetation, wave attenuation characteristics of saltmarsh vegetation are also dependent on vegetation density. As with mangroves, saltmarsh vegetation cannot survive if inundation depths exceed species specific tolerances resulting in potential impacts from sea level rise where sediment accretion is insufficient to maintain a positive elevation capital (Saintilan et al. 2013).

Conclusions and the way forward

Coastal bioshields, typically mangroves, coastal forests, saltmarshes, dune vegetation, seagrasses or coral reefs, are useful in protecting coastal areas from various hazards, such as shoreline erosion, flooding, tsunamis and storms. Coastal bioshields offer an ecologically sound and environmentally beneficial protection against coastal hazards on a long-term basis in a cost-effective way, providing a range of additional ecosystem services (biodiversity, fisheries support, carbon sequestration and storage, estuarine filtration/improved water quality amongst others). Even though hard structures offer immediate mitigation of coastal hazards, they have a number of key limitations, including reduction in aesthetic appearance, horizontal and vertical access restrictions, changes in natural sediment transport, loss of natural coastal biodiversity and ecosystems service provision, and erosion can be similar to other areas of the same coastline. In general, a number of parameters, such as water depth and vegetation height/reef depth affect wave attenuation properties and cost.

An integrated strategy for coastal protection with different models depending on the geomorphological and meteorological conditions can be suitable in Vietnam. A combination of coastal vegetation, natural or semi-natural sand dunes and submerged vegetation can offer sustainable development of coastal zones in Vietnam. A number of bioshields can be applied in Vietnam, which include mangroves, seagrasses, coral reefs and salt marsh plants, depending on the availability of native species and climate conditions along the coast.

The ecoengineering concept (combined hard structures and natural ecosystems) could provide multiple opportunities in Vietnam from the perspective of coastal protection, tourism development as well as economic stability. Combining multiple ecosystems together with hard structures can play a key role in the shoreline protection by promoting accretion, thereby stabilizing the foreshore areas. In addition to hard structures, planting mangroves or seagrasses as complementary can facilitate sediment deposition, thereby ensuring the continued protection of shoreline for a larger timescale. Seagrass meadows and coral reefs can also attract tourists for snorkelling/diving to see marine associate species, particularly charismatic megafauna. Salt marshes are important feeding grounds for migratory birds and can attract tourists interested in bird watching.

Last but not least, coastal protection using bioshields can be better managed with the aid of remote sensing and GIS applications. Mapping and time-series monitoring utilising novel tools (Google Earth Engine, CoastSat, CASSIE) for coastal systems can be important for timely and cost-effective management of bioshield systems and should play a key role in coastal planning and management.

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