Coastal Risk Mitigation by Green Infrastructure in Latin America

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Abstract

This paper aims to highlight the prevailing experiences of Latin America and to clarify what 'green infrastructure' entails in addition to describing seven case studies from a range of coastal ecosystems (wetlands, coastal dunes, beaches and coral reefs) at scales varying from local to regional. The case studies are categorised according to their degree of naturalness (nature-based, engineered ecosystems, soft engineering, ecologically enhanced hard infrastructure and de-engineering). Generally, the implementation of green infrastructure projects aims to increase resilience, enhance the provision of ecosystem services, recover biodiversity, reduce the negative effects of hard infrastructure and implement corrective measures. The greatest benefits of these projects relate to the creation of multi-functional spaces, which often combine the above advantages with improved opportunities for recreation and/or economic activities. It is hoped that this paper will disseminate the experience in green infrastructure among academics and practitioners and stimulate wider adoption of green infrastructure projects and good practices.

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1. Introduction

Coastal areas in developing countries are of particular concern because of high population growth, unplanned development and other activities which may be in conflict with the rich and vulnerable ecosystems present. However, a growing understanding of the links between natural capital and human wellbeing is changing the traditional view of nature conservation and development being irreconcilable activities (Romero et al., 2012) into complementary and interacting options.

In this context, green infrastructure is widely seen as a solution that responds to economic, social and developmental demands while ensuring ecosystem functioning (Andersson et al., 2014; Snäll et al., 2016). Although the concept of green infrastructure is very broad, it may be understood as natural, seminatural or artificial constructions that contribute to the conservation or restoration of biological diversity and the enhancement of ecosystem services (Maes et al., 2012; Wickham et al., 2010). These concepts are underpinned by established links between human and ecosystem health, which form a framework for conservation, restoration and development that benefit both nature and people in the long term (Lovell and Taylor, 2013; Wickham et al., 2010).

Latin America is an extremely biodiverse region with many opportunities for green infrastructure. The 33 countries of Latin America and the Caribbean vary in size and level of economic development, with human development indices ranging from 0.45 in Haiti to 0.82 Chile, but are all considered "developing countries" (Silva et al., 2014). Overall, the region is rich in natural resources and includes six of the ten most biodiverse countries in the world (Mittermeier et al., 1998). Although these resources are not evenly distributed, the overall richness and economic importance of Latin American ecosystems and natural capital are undeniable (UNEP, 2012).

This paper presents a regional perspective of green infrastructure projects in coastal Latin America. The projects are grouped into five categories, based on the level of naturalness (nature-based, engineered ecosystems, soft engineering, ecologically enhanced hard infrastructure and de-engineering), across a range of coastal habitats and four countries. The paper is structured in five sections. First, the environmental and socioeconomic realities of Latin America are described. Then, coastal infrastructure developments in Latin America are analysed historically. In the third section, the five categories of green infrastructure projects are described using case studies, which show how green infrastructure projects succeed in solving coastal problems common to the region. The next section summarises current experiences in Latin America and discusses the challenges for wider implementation of green infrastructure in the region. Finally, main conclusions are provided.

2. A historical overview of coastal infrastructure in Latin America

Prior to 1492, the population of the Americas was approximately 54 million and was mostly located in the areas currently occupied by Mexico (37%), the Andes (20%) and Amazonia (15%) (Denevan, 1992). The activities of the indigenous peoples did not significantly modify coastal ecosystems, as the main centres of population were established inland (Willey, 1962).

During the first stages of colonialism (1492 to 17th century), the indigenous population fell from 53.9 million in 1492 to 5.6 million in 1650 due to diseases previously unknown in the Americas (Denevan, 1992). In the 17th century, the coastal population of Latin America began to grow slowly in response to the establishment of strategic ports, which were built in naturally sheltered areas with sparse population.

By the 19th century the population had increased from 10 to 68 million. Natural harbours had evolved into port cities. In addition, forts were constructed for protection from pirates, and areas of wetlands and riverbeds were cleared for agriculture or urbanization.

In the 20th century, the population soared to 514 million and development shifted from rural to urban and industrial sites. Urban growth was often disordered and infrastructure plans generally placed social, economic or political concerns above environmental issues. The development of coastal tourist destinations gained pace in sheltered areas close to existing port infrastructure. However, with the popularisation of "sun and beach" holidays, planned tourist complexes, for example Cancun (Mexico) and Puerto Plata (Dominican Republic) were built in areas of dunes and wetlands, with little or no concern for environmental impact.

The countries in the region share a number of common challenges, including population growth and degradation of coastal ecosystems. In 2010, 32.6 million people were living in low elevation coastal areas (<10 meters above sea level), and the coastal population in these areas is predicted to grow to over 96 million by 2100 (Silva et al., 2014). Other common problems include the occupation of high risk areas (flooding, erosion, landslides), lack of coastal urban planning and widespread corruption. As a consequence of coastal land-use changes, critical ecosystem services have been degraded (e.g. flood regulation and erosion control). Some of the detrimental effects of the extensive, inappropriate use of coastal areas are due to the implementation of remedial coastal schemes that are expensive to maintain (e.g. beach nourishment, and reconstruction; Silva et al., 2016). More recently, stakeholders have tried to incorporate ecological aspects in coastal management plans with mixed results, as decision-makers, investors and authorities often lack sufficient knowledge of the processes that occur on the coast.

3. Classification of green infrastructure: degree of naturalness

Based on the scheme of van der Nat et al. (2016), we use the following five categories for the classification of green infrastructure: 1) nature-based design, 2) engineered ecosystem, 3) soft engineering, 4) ecologically enhanced hard infrastructure and 5) de-engineering (Table 1).

Seven case studies in four countries (Figure 1) are described from a multi-functionality perspective with focus on different approaches to deal with erosion and flood-risk mitigation, which involve ecosystem recovery, provision of ecosystem services, biodiversity conservation and human wellbeing. The case studies are further contextualised to identify lessons learned and to highlight challenges and opportunities for their implementation elsewhere.

Table 1. Infrastructure classification and case studies from Latin America

Type of green infrastructure	Definition	Case study (Country)
Nature-based	Habitat conservation and restoration are viable and may be accompanied by other measures to increase the ecological resilience of ecosystems that provide ecosystem services of interest	Case study 1 – wetland restoration (Mexico) Case study 2 – dune rehabilitation (Brazil)
Engineered ecosystems	Rehabilitates ecosystems and has a similar level of natural complexity. Natural features (e.g. vegetation) are allowed to modify ecosystems to a certain degree, as a means of intervention to return systems to a more natural form	Case study 3 – artificial coral reef (Mexico)
Soft engineering	Traditional hard engineering measures are modified to change physical processes, and certain benefits may be indirectly obtained from natural processes that are maintained (e.g. dune formation after sand nourishment). Soft engineering is only partly dependent on ecological processes to be successful	Case study 4 – artificial dune (Mexico) Case study 5 – coconut timber as a coastal structure (Brazil)
Ecologically enhanced hard infrastructure	Extensive traditional civil infrastructure is involved, although its design includes adaptations to imitate natural ecosystem functioning	Case study 6 – post-tsunami measures (Chile)
De-engineering	Hard and/or soft coastal structures are removed in order to recover the system and move towards more natural functioning	Case study 7 – beach rehabilitation through corrective actions (Dominican Republic)

3.1. Nature-based design

3.1.1. *Case Study 1- Wetland restoration: Recovering wetland biodiversity and hydrological services*

Tecolutla, in the state of Veracruz, has a coastal wetland belt of 75 km^2 located behind a dune field that extends 2 km inland. Half of this area has already been developed, and considerable tourist infrastructure, hotels and beach houses, are present. Severe flooding frequently occurs during and after tropical storms due to the combined effect of storm surge and river flooding resulting from torrential rainfall in the upper watershed. Flood events often damage infrastructure and lead to loss of lives. Dams are the traditional engineering solution to prevent flooding, but they cause serious ecological impacts on riverine environments. Other solutions in this area have relied on the construction of infrastructure on the coastal plain, at a high cost; including straightening parts of the river and covering the river banks with concrete to protect agricultural fields. These solutions do not work during strong rainstorms or hurricanes because the embankments are overtopped in these extreme events. In addition, by reducing the friction and increasing water velocity, revetments and channel straightening causes floods and erosion in areas downstream of the lining point.

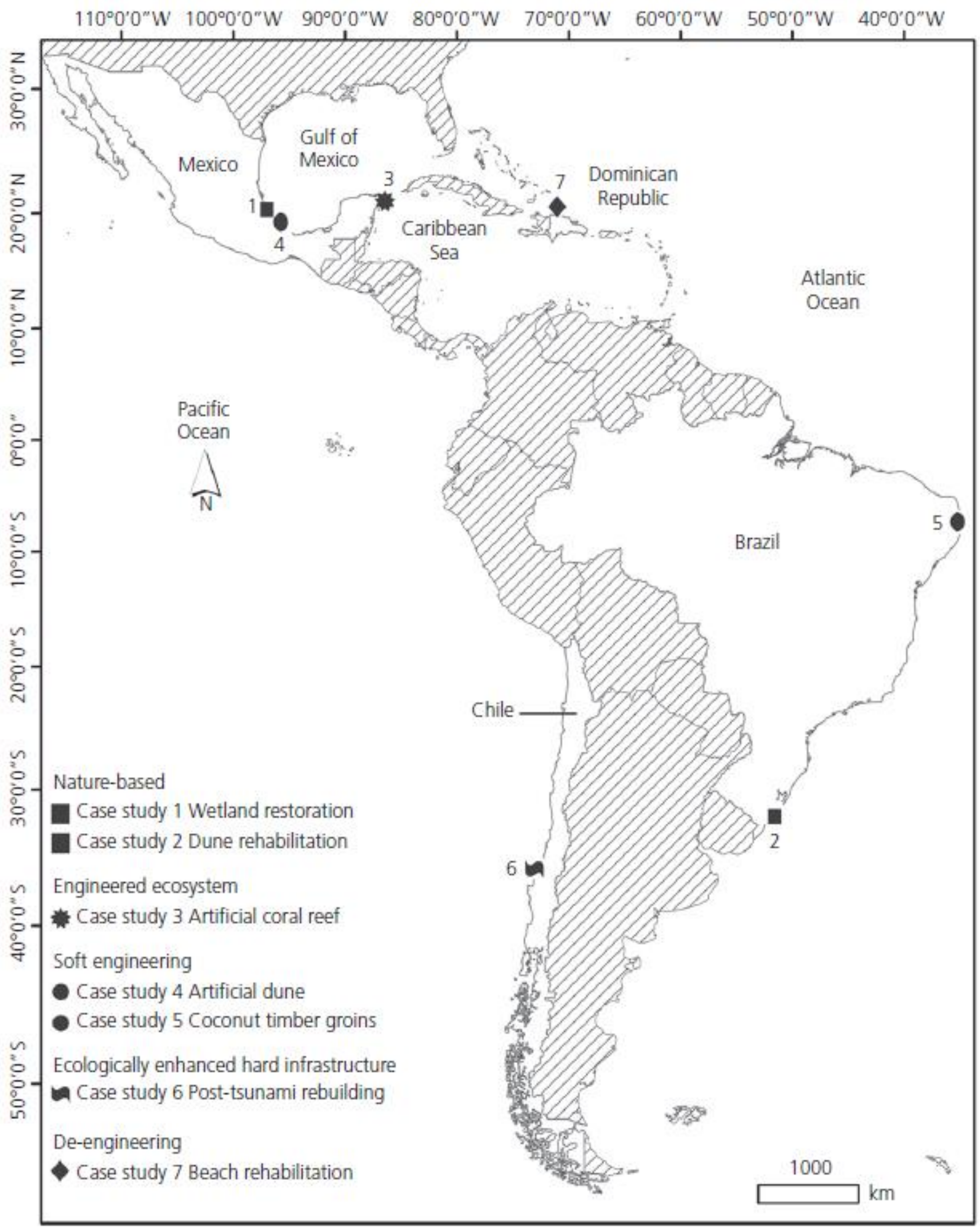

Figure 1. Location of the case studies

Restoration of wetlands is a green alternative that can help mitigate flood risk. Wetlands reduce the danger of flooding by reducing the peak flood stages in rivers, which are the main cause of damage. Wetlands slow down and temporarily store runoff by regulating the discharge of water over a longer period of time. The thickness of the soil organic layer is closely related to the water storage capacity. For example, in Tecolutla the wetland soil has a water holding capacity ranging from 556 to 834 L m^{-2}, which is seven or eight times its own weight (Campos-Cascaredo et al., 2011). Also, wetlands help to sustain fisheries and cattle ranching, two of the main primary activities in Tecolutla municipality.

The most extensive freshwater flooded forest is located in the Natural Protected Area 'Cienaga del Fuerte'; its vegetation structure and composition as well as its soil structure have been extensively modified by cattle ranching and by hurricanes that have uprooted trees. The loss of tree cover due to both cattle ranching and hurricanes has resulted in large areas of exposed and highly compacted soil with low amounts of organic matter (Moreno-Casasola et al., 2012). This has exacerbated runoff and fluvial floods.

In 2015, a project was designed to restore the original tree cover of the flooded forest by planting *Pachira aquatica* (Figure 2). The main aim of the restoration was to recover the flood mitigation benefits of the wetland by improving vegetation and soil characteristics, such as organic matter and porosity. Thirty hectares were planted with a survival rate of over 70% of the trees. The project has been financed by the National Forestry Commission with an investment of 150,000 US dollars**.**

Figure 2. (a) View of a swamp dominated by *Pachira aquatica*, (b) an area within the swamp covered with grasses, including *Leersia spp*., favoured by cattle and (c) the same area planted with young *P. aquatica* trees, during the dry season

Funding is still needed for monitoring over time. However, decreases in flood peaks and damage to touristic infrastructure are expected as a result of the recovery of the soil´s water storage capacity; field data are needed to confirm the influence of restoration through flood hydrographs. Furthermore, wetlands provide key ecosystem services, such as coastal protection, flood mitigation and water purification, for the inhabitants of Tecolutla. The recovery and maintenance of these services is important from both a social and economic perspective. Wetlands provide important provision services (de Groot et al., 2002) to local communities who use or commercialise their natural resources, thereby contributing to family economies. In addition, regulation services decrease economic losses during catastrophic events.

Latin America has many freshwater wetlands that provide ecosystem services; these areas should be protected through legislation and management programs. In many of these cases, restoration is feasible. If performed with local communities, restoration also constitutes a source of financial income for the participants and serves as an opportunity to provide environmental education to the local inhabitants.

3.1.2. *Case study 2- Dune rehabilitation: Restoring flood resilience and biodiversity through dune reconstruction and management*

Cassino Beach is located in southern Brazil, at the north of one of the longest sandy beaches in the world, extending ~220 km south from the mouth of Patos Lagoon to Chuí Creek on the Brazil-Uruguay border. This case study is unique for the following reasons. There has been accretion on this beach since the 1910s due to longshore drift obstruction, caused by the presence of jetties, over 4 km long, built to stabilise the Patos Lagoon inlet. While beach erosion is not an issue here, the site is prone to floods due to a combination of physical conditions (the area is very low-lying, flat and formed by porous sandy terrain) and exposure to extra-tropical storms with storm surges that reach > 0.5 m. Finally, the beach is a transport route and is used for vehicular access to the beach in summer (Figure 3a).

In Brazil and elsewhere, the environmental and socioeconomic values of dunes were not appreciated by the local population or decision-makers. At Cassino Beach, the dunes were perceived as a hindrance, obstructing the view and access to the beach, as well as causing problems of wind-blown sand for nearby roads and properties. By the 1980s, the dunes fronting the urban stretch of Cassino Beach had been totally removed (Figure 3b) as a result of the intensive use of the dunes for grazing, illegal sand mining and to facilitate vehicular beach access. Consequences of the dune removal included: increased flood risk to low-lying roads and properties, biodiversity loss and saltwater contamination into aquifers.

A local NGO, Núcleo de Educação e Monitoramento Ambiental (NEMA), recognised that dune reconstruction could reverse the problems caused by the removal of local dunes and bring multiple benefits, such as natural coastal protection, restoration of habitats and biodiversity and control of aquifer contamination. Funded by the local government, NEMA started the Dunas Costeiras project in 1988, aiming to restore the dunes (Figure 3c) along a 12-km stretch of coastline and to prevent human activities that were detrimental to the dunes through the development of a dune management plan. Therefore, one of the objectives of NEMA was to enable the enforcement of national legislation protecting native vegetation (Law 4771, passed in 1965) and declare vegetated coastal dunes to be statutory areas for permanent protection.

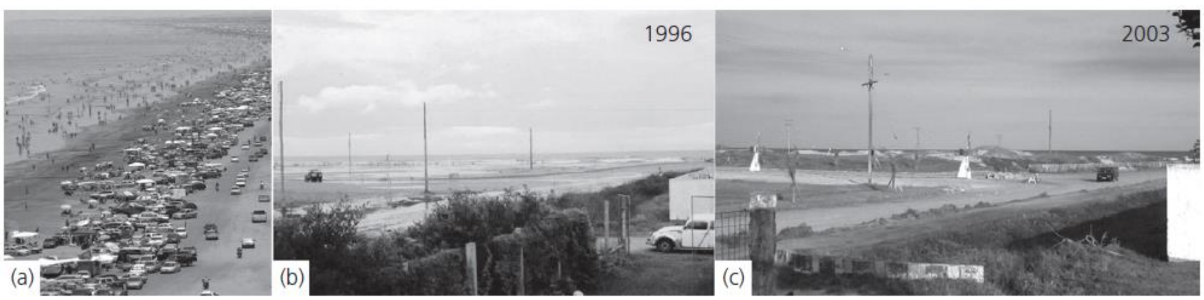

Figure 3. (a) A typical summer day at Cassino Beach; the same location before and after dune restoration (b and c, respectively). Images b and c were courtesy of NEMA

The project focused on the enhancement of natural processes, using locally available material. First, dead tree branches were used to retain wind-blown sand. Then, a layer of organic matter was added to provide a nutrient-rich substratum. Dune fixation was then achieved by planting native species (*Senecio crassiflorus, Spartina ciliata, Panicum racemosum and Hidrocotyle bonariensis*) grown in the local NEMA nursery. The project continues to date and NEMA has extended its dune restoration and conservation activities to other locations in the state of Rio Grande do Sul (Carvalho et al., 2008). Over its 28 years of operation, the project has achieved the following: dune regeneration; development, monitoring and enforcement of the local dune management plan; construction of a 160-m long cross-dune boardwalk for pedestrian access to the beach; public engagement and environmental education.

The importance of dunes as natural coastal protection is now widely recognized by the local population. However, a compromise had to be made in permitting the local tradition of vehicle access to the beach to continue. Anecdotal evidence suggests that flooding risk has been reduced but is still an issue in areas adjacent to the few remaining beach access roads.

3.2. Ecosystem engineering design

3.2.1. Case study 3- Artificial coral reef

Puerto Morelos is 30 km south of Cancun, on the Yucatan Peninsula, Mexico, and is only 350–1,600 m from the Mesoamerican Reef (Figure 4). The economy of this location largely depends on tourism, and in the last 20 years the local population has grown rapidly. The lack of coastal development regulations has spawned the proliferation of poorly planned tourism infrastructure resulting in environmental degradation and the loss of ecosystem services, such as coastal protection and leisure services.

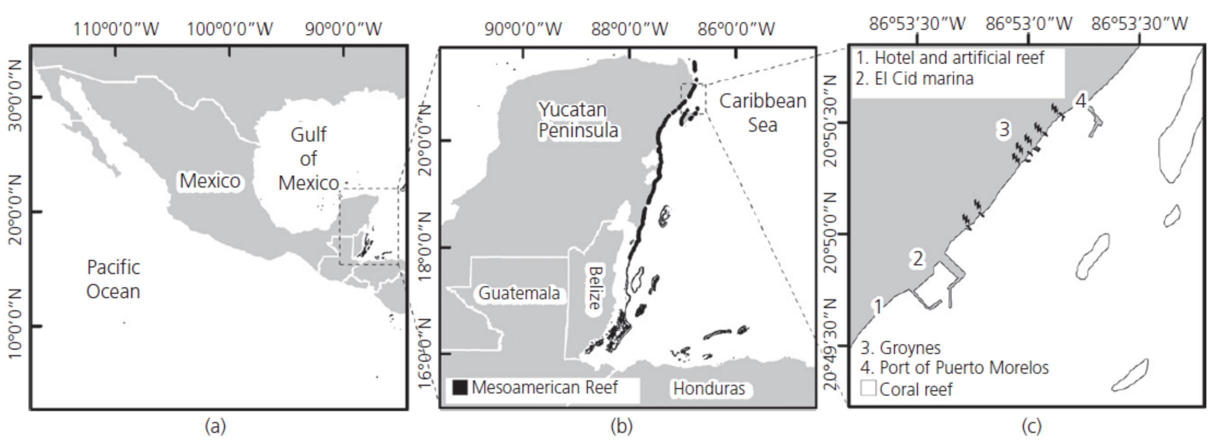

Figure 4. From left to right: (a) general location, (b) Mesoamerican Reef and (c) artificial reef structure

One of the more common problems is beach erosion, which has commonly been solved through artificial nourishment or the construction of hard and semi-hard infrastructure (e.g. seawalls, groynes, breakwaters and other shoreline stabilization structures). However, the first method may produce ecological and economic problems in areas where the sand is "borrowed" from offshore sand banks and is only feasible if they can naturally recover (Silva et al., 2016b). Problems related to hard or semi-hard structures include their unattractive design and the fact that they may increase the rate of erosion on the beach or transfer the problem to neighbouring beaches. The natural dynamics of sediment transport in Puerto Morelos have been altered and partially conditioned by a series of structures built along the coast, principally the El Cid marina. Consequently, greener alternatives were considered to deal with beach erosion.

Prior to 2007, the beach of Puerto Morelos had a pattern of accretion in summer and retreat during winter, yet there is generally always sufficient sand for tourist activities. In 2007, the Puerto Morelos coast was hit by Hurricane Dean, and the most energetic waves caused considerable sand to travel from south to north. However, longitudinal currents were interrupted by a breakwater adjacent to the hotel (Figure 5a) inducing chronic erosion south of the marina. The beach response has been monitored since then, and in 2010 it was decided that further works to improve the resilience of the beach were necessary. At that time, the beach remained narrow and was composed of sand and gravel, with erosion continuing.

Sand bypass and different hard structures were considered as options to alleviate the erosion problem, but site specific conditions required that any structure be not only effective but also aesthetic, affordable and ecologically friendly. An artificial reef was selected given that: a) reefs are dissipative wave energy structures; b) the dynamics of sediment transport had already been altered by other hard structures; c) the closeness of the Mesoamerican Reef enabled low-cost species colonization and; d) an artificial reef would contribute to the touristic and conservation value of the area.

The reef was constructed 120 m offshore (Figure 5b) and made of prefabricated concrete elements, known as Wave Attenuation Devices (WAD©), approved by the Environmental Protection Agency (EPA). The spatial design was established, based on small scale laboratory tests (Burcharth, et al., 2015) at the Coastal Engineering Laboratory of the National Autonomous University of Mexico (UNAM for its initials in Spanish). Five years later, the structure had contributed to the recovery of a wider beach, with a natural cycle of growth and retreat, and a large number of fish and coral species from the Mesoamerican Reef had colonised the structure (Figure 5-d). The reef colonisation experienced a temporary decline in 2015 due to a substantial regional increase in *Sargassum*. A variety of brown seaweeds normally float freely in the ocean and occur naturally in small quantities, representing an important element of beach stability and providing habitat to several species. However, in 2015, some *Sargassum* species consolidated on large, island-like, floating mats which changed the physicochemical properties of the sea water (PH, water transparency etc.), washed ashore and affected tourism. Since then the reef system has been recovering its biological richness without any human intervention.

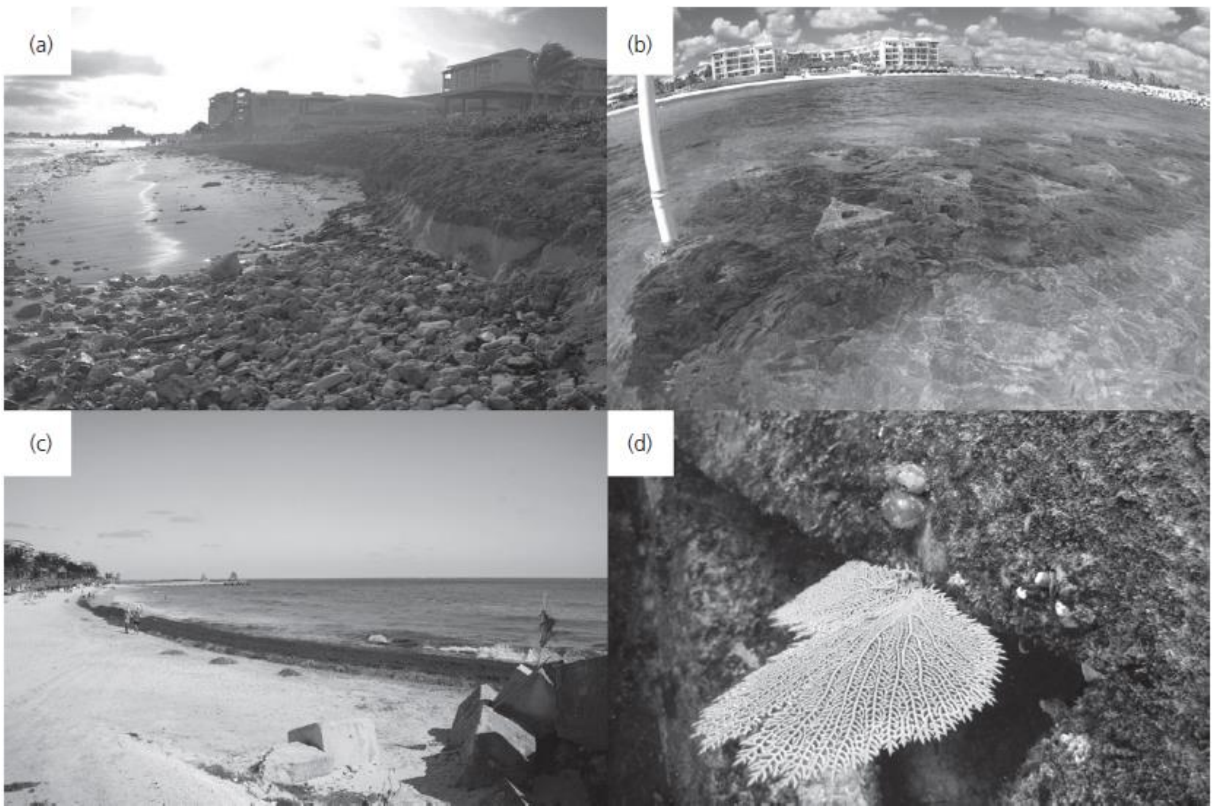

Figure 5. An artificial reef improves coastal protection. (a) Erosion in hotel grounds, (b) prefabricated concrete structure, (c) seagrass crisis and (d) coral colonies established on the structure after 5 years

3.3. Soft engineering

3.3.1. *Case study 4: Artificial dune: Building sand dunes for protection from sand blast*

On the coast of the Gulf of Mexico, the port of Veracruz and adjacent Boca del Río make up a flourishing seaside city of approximately 600,000 people. For nearly five centuries, this has been Mexico's main port on the Gulf Coast. The urban area has expanded over and around wetlands and dunes. In the 19th century, in order to prevent sand blowing into the city, a wooden palisade was built behind the beach to create an artificial dune that would detain sand long enough for trees and grasses to be introduced. Australian sea-pines (*Casuarina equisetifolia*) were planted since these are adapted to extreme conditions, including those of the beach-dune environment. The artificial Casuarina forest became known as “the pinera” and was very much appreciated by the local inhabitants. However, urbanization and the expansion of port infrastructure encroached on the Casuarina forest, and the dunes to the north of the city were destroyed. As windblown sand began to accumulate in the city once again, the community demanded an urgent solution.

Bulldozers were used to pile up sand and create a 10 m high, 2 km long dune, parallel to the shoreline. The artificial dune was later covered with vegetation and two approaches were considered: a) using native plants and accelerating the natural successional process and b) recovering plant cover as fast as possible. There were no other alternatives to deal with the windblown sand, due to limited time and budget.

The first option was considered as the initial alternative because restoration with native plants should be promoted, as it helps recover natural biodiversity and also provides additional ecosystem services, such as water purification, pollination, and habitat for other species. Information needed for the first option was already available, since the successional sequence on the dunes of Veracruz had previously been observed (Álvarez-Molina et al. 2012; Martínez et al., 1997). Furthermore, earlier studies had shown that dune plants (such as *Ipomoea pes-caprae*) are able to tolerate burial by increasing their biomass and are thus effective dune builders (Martínez and Moreno-Casasola, 1996; Martínez et al., 1997). In addition to their dune-building ability, *psammophilous* plants (those tolerant to burial by sand) have been shown to have a protective role in dunes (Silva et al., 2016b). In addition, plants do not need to be replaced, as would be the case with sand fences. In the specific case of Veracruz, using *Ipomoea pes-caprae* adds to the scenic beauty of the beach and also provides habitat to other dune builder species.

Although the first alternative was considered as the best option in terms of ecological benefits, there were logistic problems that made it difficult to implement: lack of propagules at the time and the urgent need to recover plant cover and stop the shifting sand as quickly as possible to prevent it from being blown into the city by the oncoming northerly winds the following winter. The natural successional sequence takes longer than the local inhabitants and authorities were willing to wait for. Thus, the second method was applied. Three types of vegetation cover were used: a) a mixture of the native cactus (*Opuntia stricta*) with an exotic but naturalised grass very abundant in dunes due to its importance for cattle ranching (Panicum maximum), b) only *Panicum maximum*, which forms a tall, dense cover and c) short grasses dominated by *Paspalum* spp., which were obtained as sod from a nearby cattle pasture (Figure 6). Sand stabilisation occurred fastest at the locations with both grass types, while plant diversity was highest at the native cactus locations (Moreno-Casasola et al., 2008). After five years, 29 to 37 % of the original dune species had returned and windblown sand was under control. Remnant patches of native vegetation (thickets and tropical dry forests) from neighbouring areas played an important role in species turnover and in colonization by native species. The recreated ecosystems have been self-sustaining for more than ten years, preventing the sand from moving into the city.

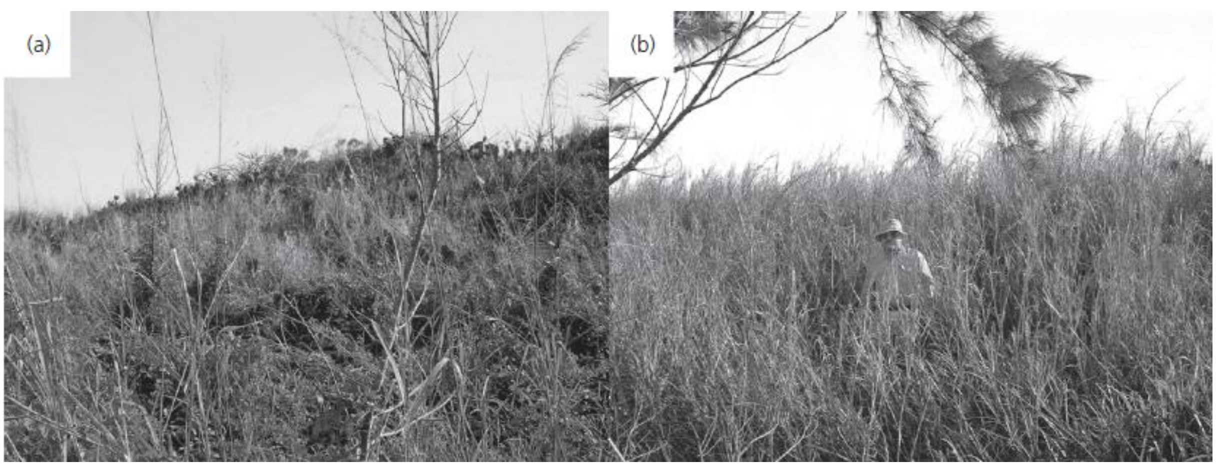

Figure 6. Dune vegetation cover formed by: (a) a mixture of the native cactus Opuntia stricta with Panicum maximum, a naturalised tall grass and (b) P. maximum, forming a tall cover

When considering dune restoration at other sites, native dune builder plants should be the first option. Dune builders can be recognized from the literature (see for example Maun 1998; 2009), or, in case of necessity and lack of information, from field observations: dune builder species will normally grow on mobile dunes and their stems are likely to be partially buried by sand. Typical dune builders are: *Ammophila arenaria* (Europe); *Ammophila breviligulata* (North America); different species of *Spinifex* in Asia and Australia; and *Ipomoea pes-caprae* in the Tropics.

3.3.2. Case study 5: Coconut timber as a coastal structure

The main cause of the erosion along Carne de Vaca beach, 66 km north of Recife, the capital of Pernambuco state, Brazil, is unknown. Some hypotheses suggest that the coastline has experienced higher waves for longer periods in recent years because the reefs, a natural defence that works like a submerged breakwater, are being overtopped for longer periods of time. The increase in the submergence time of the reefs has led to lower wave energy dissipation and increased alongshore sediment transport. The increased overtopping period could be related to the combined effect of higher storm surges and sea level rise. Additionally, decreasing river discharges may contribute to changes in the morphodynamics of the beaches, while increasing coastal runoff causes higher nutrient influx, turbidity and salinity of seawater. All of these phenomena are stress factors for most coral species. Local monitoring is necessary to determine which factors are definitively influencing erosion.

In an attempt to reduce beach erosion and control longshore drift cheaply, local people built groynes made of coconut timber piles (Figure 7). The material selected was chosen as there are numerous coconut plantations in the area and so the timber is not costly. The method appeared to be efficient for building groynes and seawalls and construction was based on local knowledge and the experience of living close to the sea, without the advice of experts. The use of low cost local materials and labour brought benefits to the owners of the coconut plantations and to the local community which provided the labour. Although most groynes in the state are made from rock, coconut timber has a lower cost in the case study area since it is readily available.

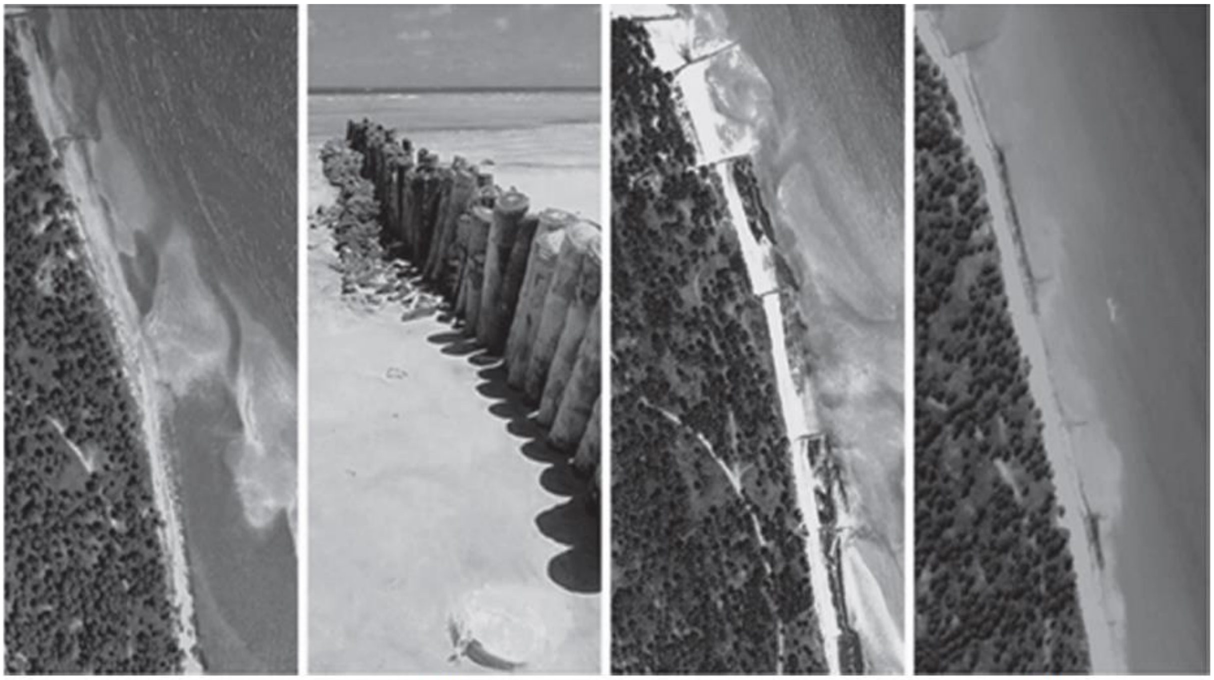

Figure 7. Shoreline configuration at Carne de Vaca: (a) absence of groynes (February, 2004); (b) a coconut timber pile groyne at low tide; (c) reduction of the indented pattern (November, 2010); (d) stabilised beach (October, 2015). Image source (a, c and d): modified from Google Earth

The groynes were first built in December 2006 and rapidly produced an indented coastline once sand was trapped on the updrift side of each structure. Through time this pattern gradually changed as the groynes deteriorated and became more permeable (Figure 7). The cheap, readily available and environmentally friendly timber has been replaced, in order to continue controlling the longshore drift. This case study highlights that locally devised green infrastructure can be a suitable alternative to rock groynes for beach protection.

3.4. Ecologically enhanced hard engineered structures

3.4.1. *Case study 6- Post-tsunami measures: Green infrastructure design based on hard lessons and science*

The Chilean earthquake of 2010 had a magnitude of 8.8 Mm (Mercalli intensity scale) triggering a tsunami that devastated several coastal towns in south-central Chile and the Maule region, including

Pelluhue county and its urban centres (Pelluhue, Curanipe and Mariscadero). The earthquake and waves that followed this event caused 531 deaths, considerable beach erosion and damage to 370,000 houses, resulting in an estimated 30 billion US dollars loss, the equivalent of 15 % of Chile's Gross Domestic Product (GOB, 2010).

The Chilean government, in collaboration with a multidisciplinary team of experts (academics and professionals), began to rebuild the most damaged communities less than six months after the catastrophe. However, in 2012, a zoning plan was implemented in Pelluhue County in order to restrict construction in some areas and to promote the adoption of green infrastructure policies, in an effort to make coastal structures more resilient in the face of flood risk.

This case study describes changes in building practices in the county over a 5-year period, as a consequence of the zoning plan that incorporates tsunami hazard in the definition of land uses. The key measures of the plan were to define a green buffer zone where building is restricted (ZAV) and a low-density touristic zone (ZTBC) between the coastal dunes and the urban area (ZU) to prevent the reestablishment of residential infrastructure in areas of extremely high flood risk. Figure 8 depicts the zone differentiation, the buildings that were destroyed by the 2010 tsunami and those rebuilt outside the buffer zone.

Since the tsunami, three field surveys have been carried out (Igualt et al. submitted): the 2010 campaign was a standard post-tsunami field survey (Dominey-Howes et al., 2014), where water depths, run-up and impacts of damaged infrastructure were recorded. The 2013 and 2015 surveys aimed to record the impact of the zoning plan on the new houses being built. Interviews were also conducted to evaluate community awareness of flooding and tsunami risks.

The application of the zoning plan has been partially successful in reducing the vulnerability of the coastal population to floods: No new buildings have been constructed in the buffer zone (with the exception of three illegal houses), and a new building type, which is able to indirectly withstand tsunami loads, has been introduced in compliance with the low-density requirements of the touristic zone. This new building prototype has slender structural elements on the first floor (Figure 8, bottom). The costs of implementing these new guidelines were absorbed by the property owners.

The application of the zoning plan has not been homogeneous in all the affected areas. Additional measures such as i) increasing visitors' awareness of the evacuation plans and ii) assessing the structural integrity of new buildings to other loads (e.g., earthquakes) are still needed.

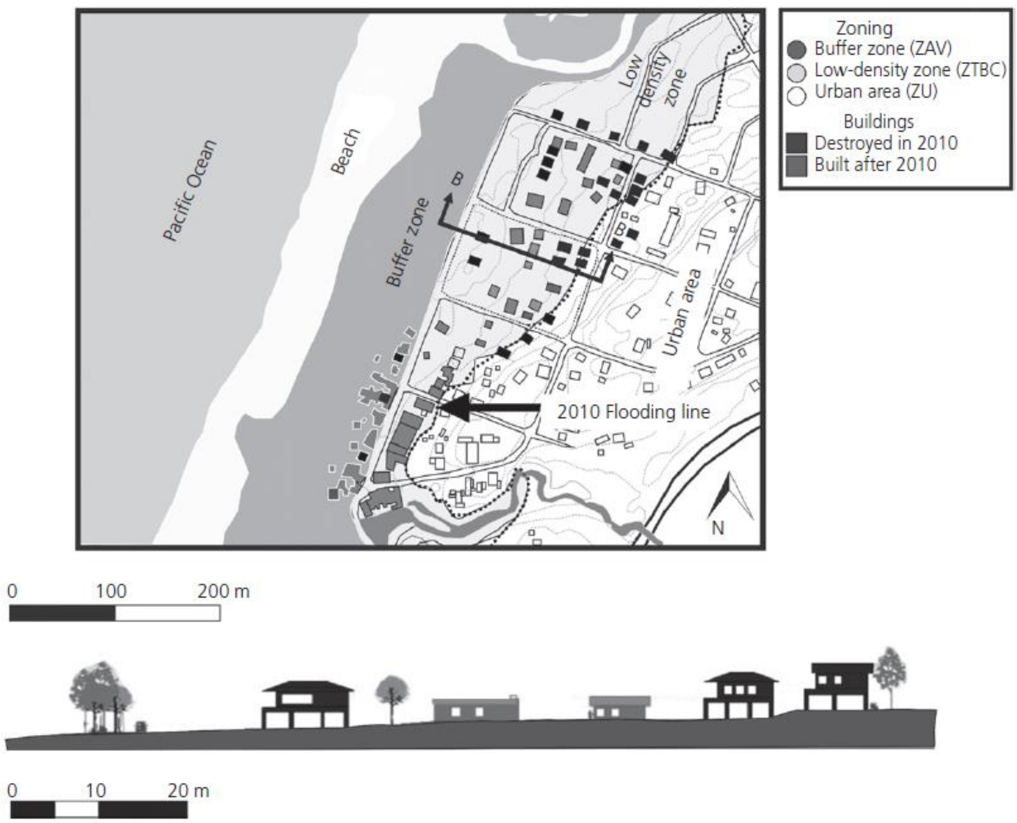

Figure 8. Upper panel: zoning plan in Mariscadero, as in 2015, depicting the buffer zone (ZAV) and the low-density touristic zone between the coastal dunes and the urban area (UZ). Lower panel depicts the cross-section BB, where the houses destroyed by the 2010 tsunami (in grey) were replaced by a new building type with slender structural elements on the first floor (in black). Adapted from Igualt et al. (2016)

3.5. De-engineering

3.5.1. Case study 7: Beach rehabilitation through corrective actions: structure removal

Playa Dorada is located east of the city of Puerto Plata, on the northern coast of the Dominican Republic. This beach is an important tourist destination, but in the last 30 years erosion has greatly increased, progressively degrading its aesthetic value and functional characteristics. Local measures aimed to address this problem through the construction of seawalls, breakwaters and coastal revetments (Figure 9a), actually produced the contrary, and erosion accelerated in several areas.

Originally, the sediments in the coastal ecosystem of Playa Dorada were approximately 90% mineralogical and 10% biogenic. Mineralogical material was derived from terrigenous sources and delivered by the Camú, Boca Nueva and Muñoz rivers. To a lesser extent, calcareous biogenic sediments are produced by marine organisms of the submarine platform. Both types of sediments are transported by wave action and longshore drift both parallel and perpendicular to the coast.

A reduction in the amount of sand, caused by the damming of nearby rivers and mining of sand and gravel, meant that sediment transport was limited to the existing sand reserves of the beach. Calculation of potential solid transport capacity showed a movement of 1,400,000 m^3 of sand $year^{-1}$ to the west, and 800,000 m^3 of sand $year^{-1}$ to the east, resulting in a potential net transport of 600,000 m^3 $year^{-1}$ east to west. These rates of potential transport demonstrate significant sand mobility along the coastline.

Breakwaters and revetments (Figure 9b) placed in the central part of the beach modified the longitudinal sediment transport, favouring the canalization of sediment away from the system and worsening the erosive processes.

To mitigate the erosion, beach nourishment was prioritised, with the goal of meeting the deficit in natural sediment supply. The nourishment project deposited 135,000 m^3 of sand with an average placement density of 90 m^3m^{-1} to increase the width of the beach by 30 m. Sand was taken from the northeast bank of the San Juan river in Espaillat province, on the northern coast of the Dominican Republic. But first, coastal zoning and management practices were implemented, including the removal of some facilities built on the beach and the reconstruction of dunes in 2006. The demolition of three breakwaters which had been constructed in front of the Paradise Hotel was carried out to allow the free circulation of sediments along the length of the beach. The results of these actions are shown in Figure 9c, where the considerable improvement in the aesthetic values and functional characteristics of the beach may be observed.

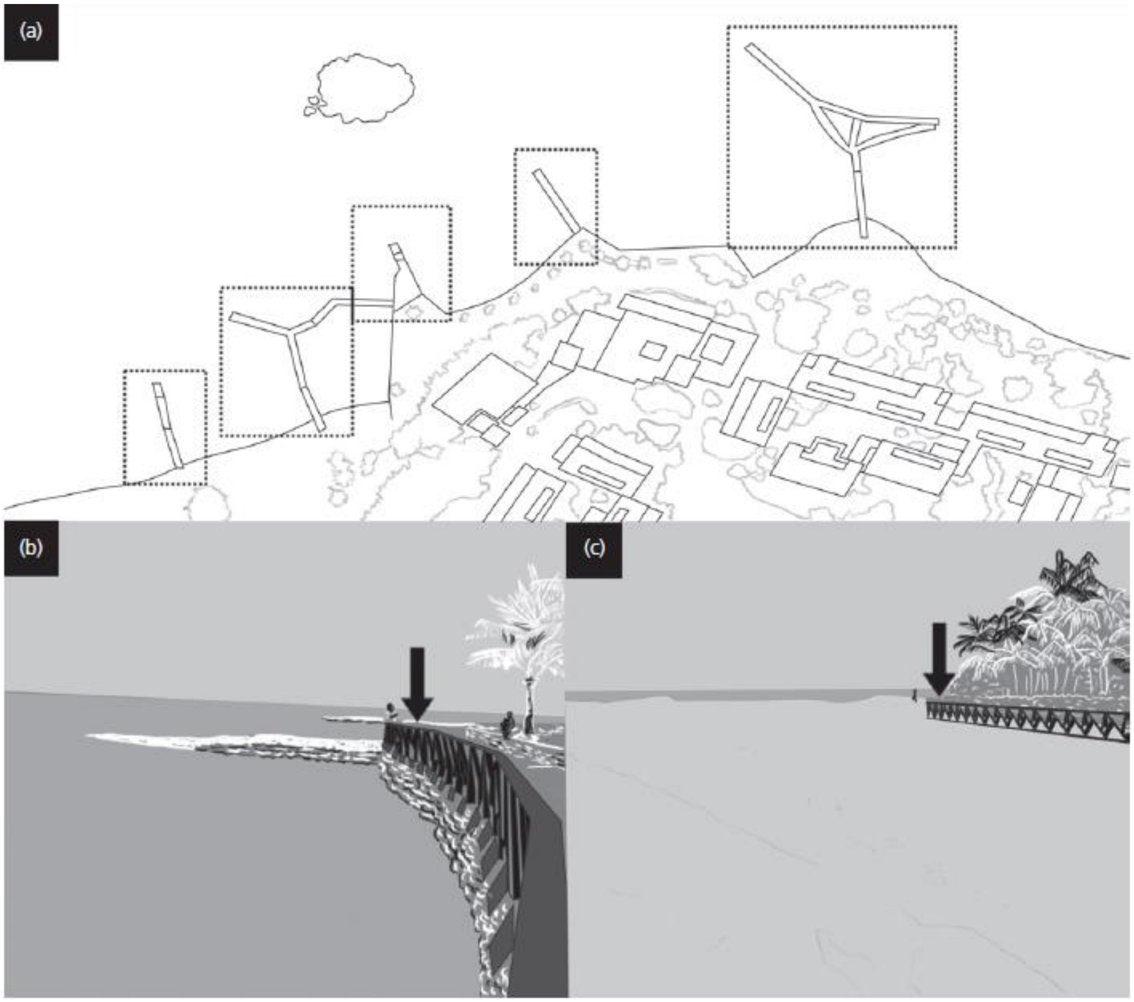

Figure 9. (a) Aerial view of breakwaters and revetments prior to the project in 2005; (b) breakwaters and revetments in front of Paradise Hotel and (c) view of the beach after beach nourishment and the removal of breakwaters and revetments in 2007

4. Discussion

The socioeconomic and ecological challenges faced across Latin American countries are maximized in coastal areas, where poor populations are much more reliant on ecosystem services and therefore more vulnerable to environmental degradation (UNEP, 2012). Green infrastructure is likely to bring benefits as it creates multi-functional spaces or structures that are able to address environmental and socioeconomic needs in an integrated way (Breed et al., 2015; Esteves and Williams 2017). All the case studies described have either accomplished, or are on their way to achieving, their main goal (flood risk reduction and/or erosion control), but in addition have promoted ecosystem services and human wellbeing.

The multi-functionality of green infrastructure means that several benefits can be provided in the same spatial area (Table 2; Pakzad and Osmond, 2016). These functions can be environmental, such as protecting/recovering ecosystems integrity and biodiversity (e.g. case study 1 – wetland restoration project); social, such as providing recreation opportunities (e.g. case study 2 – dune rehabilitation); and economic, such as supplying jobs (case study 5 – coconut timber as coastal structure).

From an ecological point of view, some case studies have functioned by protecting/recovering the integrity and biodiversity of ecosystems (wetland restoration, artificial coral reef, coastal dune rehabilitation, dune reconstruction, artificial dune, zoning plan including a green belt for protection against tsunamis, and even removing hard infrastructure to prevent erosion). In turn, all the cases had a positive impact in societal wellbeing.

Beach and dune rehabilitation projects (Case studies 2, 3, 4, 5 and 7) have been shown to enhance the wellbeing of communities by protecting property values and providing local employment. The economies of Casino beach, Puerto Morelos and Puerto Plata depend on sun-and-beach tourism, so green infrastructure projects ensure the provision and protection of recreation opportunities. In contrast, Case study 5 (Coconut timber structure) was implemented in an area where the recovery of the beach was vital to protect the main local source of income: coconut plantations. Case study 6 (post-tsunami zoning plan) included changes in building strategies, such as the inclusion of a green belt between dunes and the urban area, allowing the recovery of native dune vegetation and protecting coastal infrastructure.

Due to the multi-functionality of green infrastructure, it is difficult to assign a single category of benefits; besides their original objectives, additional services are expected from all projects (Snäll et al., 2016). It is worth mentioning that ecosystem functioning and resilience were improved in the case studies that were nature-based, engineered ecosystems and soft engineering projects. Also, almost all the projects increased ecological connectivity and were built in areas of particular importance for biodiversity.

Table 2. Green infrastructure: benefits and challenges

Main benefits an challenges		1. Wetland restoration	2. Dune rehabilitation	3. Artificial coral reef	4. Artificial dune	5. Coconut timber structure	6. Post-tsunami measures	7. Beach rehabilitation
Socioeconomic	Protect property values	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Flood risk mitigation	Yes	Yes	Yes	No	Yes	Yes	Yes
	Erosion or shifting sand control	No	Yes	No	Yes	No	Yes	No
	Water quality improvement	Yes	Yes	No	Yes	No	Yes	No
	Recreation and tourism	Yes	Yes	Yes	No	No	Yes	Yes
	Green job opportunities	Yes	Yes	Yes	Yes	Yes	No	No
Ecological	Habitat recovery	Yes	Yes	No	Yes	No	Yes	Yes
	Biological corridor	Yes	Yes	Yes	Yes	No	No	No
	Protection of endangered and threatened species	Yes	Yes	Yes	No	No	No	No
Socio-ecological challenges	Long-term, quantitative monitoring programme	No	Yes	No	No	No	No	No
	Community involvement	Yes	Yes	No	No	Yes	No	No
	Communication of results To academia	Yes	Yes	Yes	Yes	No	No	No
	Communication of results to all interested parties	Yes	Yes	No	No	No	No	No
	Funding source: governmer or private (including local residents)	Gov.	Gov.	Private	Gov.	Both	Both	Gov.
	Long-term funding	Yes	Yes	No	No	No	No	No
	Cost–benefit valuation	No	No	No	No	No	No	No

The provision of services such as food (Case studies 1, 3 and 7), medicinal plants (Case studies 1, 2, 4) and raw materials (Case studies 1, 5); regulating services such as carbon sequestration and storage (Case studies 1, 2, 4), control of wind-blown sand (Case studies 2, 4 and 6), waste-water treatment (Case studies 1,2, 4); cultural services such as recreation (all case studies) are additional, perhaps unexpected or underestimated, benefits of the projects described.

Furthermore, while the economic costs and benefits of green infrastructure are often not seen clearly (Cobbinah et al., 2015), if green projects (nature-based, ecosystem engineering designs) or even hybrid projects (soft engineering, ecologically enhanced hard engineering designs) are well managed, they can achieve project objectives and recover their cost through the additional ecosystem services they supply (Breed et al., 2015). Although full cost–benefit appraisals have not been carried out for the green infrastructure projects described in this paper, there are data on the value of some of the additional ecosystem services provided. For example, case study 3 (artificial coral reef) described earlier is one example: the total cost of the project was around US$100 000, yet the benefits were calculated at US$80 500/(ha/year) (Mendoza-González et al., 2012). This amount considers only two of the ecosystem services fostered by the rehabilitated beach: coastal protection and recreation, and is therefore only illustrative and underestimated. Moreover, while grey infrastructure is static and does not respond to changing conditions, the ‘hybrid grey–green’ artificial reef employed in this case has shown a degree of resilience to perturbations and succeeded in recovering after the *Sargassum* crisis (Silva et al., 2016a).

Promoting communication between scientists, decision makers and policy makers is the only way to develop integrative policies and to advance science-based green infrastructure projects, transcending the traditional compartmentalised and sectorial approach (Esteves, 2014). The collaboration between hydrologists and civil engineers in case study 1 (wetland restoration) is such an example. Similarly, that between natural resource managers, biologists and engineers in both coastal dune rehabilitations, between sociologists, geographers and engineers in the design of post-tsunami measures (case study 6) and the collaboration between the tourism sector, ecologists, geomorphologists and engineers in the beach rehabilitation cases in Brazil, Dominican Republic and Mexico demonstrate the benefits of interdisciplinary efforts.

Further examples of collaboration between biologists, ecologists and engineers are seen in the use of numerical modelling to improve the understanding of hydrosedimentary dynamics and its application for beach restoration, or in the design of ecologically enhanced infrastructures. The use of numerical modelling for beach restoration has been carried out for a natural reef at El Rosario archipelago (Colombia) to quantify wave reduction over natural coral cover of Elkhorn Coral- *A. palmata* (Osorio-Cano, et al., 2015).

5. Conclusion

Increasing pressures on the coastal areas of Latin America should not be an excuse to prevent improvements in the use and management of coastal areas. The examples described in this paper show different green infrastructure alternatives that can help restore coastal habitats as well as mitigate shoreline erosion and flood risks.

Green infrastructure programs are as different as the problems they address, as well as the regions and landscapes in which they occur. Yet almost all successful efforts share some common planning approaches: they bring together stakeholders; are grounded in scientific knowledge and good practice; create mechanisms for making decisions; establish strong governance mechanisms; develop a clear vision and mission; include political will and support and engage the public throughout the process. When a community chooses to begin planning for green infrastructure, these steps can help to ensure success in the development and preservation of natural ecosystems.

The multi-functionality of the projects described in this article and their transdisciplinary approach illustrate the technical capability of the region, which is encouraging for future projects. Indeed, strength- and experience- based practice and collaboration, as well as cross-disciplinary cooperation, is needed to complete projects successfully. Equally, publicising results and raising public and professional awareness is important in influencing management policies, even failures offer the opportunity to learn from experience and improve projects with similar characteristics.

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