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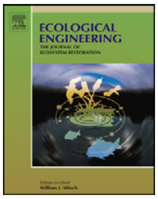

Review

How ecological engineering can serve in coastal protection

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ABSTRACT

Traditionally, protection of the coastal area from flooding is approached from an engineering perspective. This approach has often resulted in negative or unforeseen impacts on local ecology and is even known to impact surrounding ecosystems on larger scales. In this paper, the utilization of ecosystem engineering species for achieving civil-engineering objectives or the facilitation of multiple use of limited space in coastal protection is focused upon, either by using ecosystem engineering species that trap sediment and damp waves (oyster beds, mussel beds, willow floodplains and marram grass), or by adjusting hard substrates to enhance ecological functioning. Translating desired coastal protection functionality into designs that make use of the capability of appropriate ecosystem engineering species is, however, hampered by lack of a generic framework to decide which ecosystem engineering species or what type of hard-substrate adaptations may be used where and when. In this paper we review successful implementation of ecosystem engineering species in coastal protection for a sandy shore and propose a framework to select the appropriate measures based on the spatial and temporal scale of coastal protection, resulting in a dynamic interaction between engineering and ecology. Modeling and monitoring the bio-physical interactions is needed, as it allows to upscale successful implementations and predict otherwise unforeseen impacts.

1. Introduction

Incorporation of ecology and ecosystem services into coastal protection is a development that has gained strong interest over the last decade (e.g. King and Lester, 1995; Capobianco and Stive, 2000; Lamberti and Zanuttigh, 2005; Nordstrom, 2005; Swann, 2008). Two main reasons for this incorporation can be indicated. First, there is a strong need for innovative, sustainable and cost-effective coastal protection solutions that deal with threats related to climate change, such as accelerating sea level rise. Second, there is need for measures that minimize anthropogenic impacts of coastal protection structures on ecosystems and that might perhaps even offer possibilities to enhance ecosystem functioning (Day et al., 2000). These objectives are reflected in two approaches by which ecology is integrated into coastal protection systems: (1) methods that use selected ecosystem engineering species that modify their environment to enhance safety and/or save costs on coastal protection and (2) methods in which classical coastal constructions like dams and dikes are adapted to enhance local biodiversity and ecosystem functioning.

Coastal protection systems can profit from ecosystem engineering species that have the ability to modify the local physical environment by their structures or activities, like mussel beds, oyster beds and vegetation (Jones et al., 1994, 1997). The ability of these various species that are common to intertidal areas to trap and stabilize sediment, so that soil elevation increases, and subsequently attenuate waves, make them suitable to execute functions similar to dams. Moreover, by increasing soil elevation vegetation possesses the ability to keep up with sea level rise (Allen and Duffy, 1998; Van der Wal and Pye, 2004; Temmerman et al., 2004; Van Proosdij et al., 2006), implying that they might offer sustainable and cost-effective coastal protection solutions. Finally, in extreme physical environments, ecosystem engineer-

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ing species that ameliorate physical stresses, like mussel beds, oyster beds and vegetation, are essential for ecosystem functioning, while these ecosystem engineering species create hospitable habitats for organisms that would otherwise be unable to tolerate extreme physical conditions (Crain and Bertness, 2006). Within this approach, the species that are able to attenuate waves and trap sediment are either used to fully replace man-made coastal protection systems consisting of dikes and dams, or are used as foreland protection to minimize forces on the dikes and dams. An example of the first can be found in sandy coasts where marram grass (*Ammophila arenaria*) is used to trap sand, thereby building protective sand dunes that make dikes superfluous. Examples of the latter are dikes and dams accompanied by wetlands, reef-forming shellfish species, coral reefs or mangrove forests in their foreshore, so that they require less maintenance, less reinforcement and thus less financial investments.

Several recent studies quantified effects of ecosystem engineering species, such as shellfish and vegetation, on wave dampening and sediment trapping (see Murray et al., 2002; Koch et al., 2009 for a review). A major step forward in the awareness of opportunities for using these ecosystem engineering species was made by translating their ecosystem services into economical benefits (Barbier et al., 2008; Koch et al., 2009). Nevertheless, despite the growing body of literature showing the value and potential use of organisms and landscapes in coastal protection, actual applications of these concepts remain scarce (Mitsch and Jørgensen, 2003; Gedan et al., 2010). This may be due to a lack of proper framework and pilot projects on how to incorporate ecosystem engineering species in designs for coastal protection.

Engineering design criteria and local morphological or hydrodynamical conditions may make it impossible to use ecosystem engineering species for coastal protection purposes. In that case, ecology may be incorporated into coastal protection to enhance the ecological value (i.e. local biodiversity and local biomass) of man-made hard substrate coastal protection systems. This may be done by making simple adjustments to the traditional engineering design, by including modified structures that enhance habitat complexity. This approach does not necessarily reduce costs, but is valuable in that it may mitigate the ecological impact of the construction, and thereby facilitate the required permitting process and community acceptance.

In this paper we review successful implementations of ecosystem engineering species in coastal protection. Furthermore, several pilot projects from the field, where ecosystem engineering species are specifically introduced to provide their desired services, are briefly presented. The aim of this paper is (1) to propose a framework to include ecological engineering tools in coastal protection and (2) to apply this framework in different pilot projects which make use of ecosystem engineer services. We will achieve these objectives by reviewing the spatial and temporal scales involved in coastal protection both from an engineering perspective and an ecological perspective (Section 2). We subsequently focus on examples to apply this framework in coastal protection or enhance ecological values in coastal protection (Section 3). Next, the main findings of this paper are discussed (Section 4), leading to several general conclusions (Section 5).

2. Framework: dynamic interactions on different scales

The framework used in this paper is inspired from insights on coastal evolution and ecosystem functioning. Concerning coastal evolution, De Vriend (1991) suggests that dynamic interactions between driving forces in coastal evolution are only possible if processes act on the same temporal and spatial scale. Influences from higher scales are described as boundary conditions, whereas influences from lower scales are considered to be noise. Noise does not mean that these processes are irrelevant, but that only the net effects of these processes are important. For example, a single wave can be seen as noise in coastal evolution. However, the net effect of waves is assumed to trigger the entrainment of sediment and reacts in a dynamic interaction in coastal evolution. On the other hand, sea level rise can be seen as a boundary condition in coastal evolution. Later, Day et al. (1995) introduced the pulsing concept. In this concept, the functioning of coastal ecosystems is assumed to be affected by energetic forcings which serve to enhance productivity, increase material fluxes and affect the morphology and evolution of the system on different spatial and temporal scales (Day et al., 1997). From an ecological perspective, Odum (1996) stressed the importance of linkage of scales, stating that information is fed forward from lower scales and fed back from higher scales to the scale of interest. De Vriend et al. (1991), Day et al. (1995), Odum (1996) and Mitsch and Day (2004) all argued that increasingly detailed process knowledge and modeling capabilities on a small scale will not inevitably lead to the correct prediction of processes on a larger scale and vice versa. Therefore, we first focus on dynamic interactions for different temporal and spatial scales in coastal protection and ecosystem engineering individually. By combining the different temporal and spatial scales, we will be able to integrate ecosystem engineering species and coastal protection in a framework.

2.1. *Coastal protection*

Coastal protection aims to protect the hinterland against flooding and preventing erosion of the shoreline. The threat of flooding generally acts on large spatial and temporal scales, as the whole coastline needs to be safe during occasionally occurring short storm events. In contrast, threats related to erosion of the shoreline are site specific, and can therefore act on both limited spatial and temporal scales affecting small stretches of the coastline or impact entire coastlines on large spatial and temporal scales (Wolters et al., 2005). Several traditional coastal protection measures are available for coastal engineers (i.e. groins, revetments, breakwaters or dams) to mitigate the threats of flooding and erosion, with each of them typically set to resolve a problem at a specific scale. Groins (both permeable and impermeable) or revetments are generally implemented to mitigate small scale (both spatial and temporal) erosion threats. Dams, such as the Deltaworks in the Netherlands, are generally applied to provide protection on large spatial and temporal scales against the threat of flooding.

2.2. *Ecosystem engineering species*

Ecosystem engineering species are organisms that change biotic or abiotic materials, thereby controlling availability of resources to other organisms (Jones et al., 1994, 1997). However, practically any organism in any system can function as an ecosystem engineer (Reichman and Seabloom, 2002). Therefore, we focus in this paper on organisms for which the temporal and spatial scale of their engineering capacity is much larger than their own spatial and temporal scale (Bergen et al., 2001; Hastings et al., 2007). Moreover, we focus on the combined biotic and abiotic effect the selected ecosystem engineering species have on their environment (Odum and Odum, 2003; Byers et al., 2006; Wright and Jones, 2006).

On larger scales plant cover, such as eelgrass (*Zostera marina*) or English cordgrass (*Spartina anglica*), is able to reduce current velocities and dampen waves and thereby trap sediment and clarify the water (e.g. Bos et al., 2007; Van der Heide et al., 2007; Van Wesenbeeck et al., 2007; Bouma et al., 2009a,b, 2010). Consequently, other species are facilitated through habitat modification (e.g. Bruno, 2000; Van Hulzen et al., 2007). Mussel beds and oyster beds have similar effects on currents and sediment trapping on a smaller scale (Folkard and Gascoigne, 2009; Van Leeuwen et al., 2010). Moreover, mussel beds and oyster beds can influence water quality by filtering the water (Dolmer, 2000; Newell, 2004) and provide a habitat for a large, biodiverse community (e.g. Commito et al., 2005; Coen and Luckenbach, 2000). On the scale of ecosystems, salt marshes are known to increase soil elevation by building a platform that can significantly decrease wave impact on hinterlands and dikes (Möller et al., 1999). On landscape-scales marram grass (*A. arenaria*) is used along sandy coasts to realize a protective stretches with sand dunes (e.g. Avis, 1989; Anthony et al., 2007). Moreover, cordgrass is used to protect the hinterland on a landscape scale in e.g. China (Zhang et al., 2004; Chung, 2006).

2.3. Ecosystem engineering species in coastal protection

By integrating ecosystem engineering species in coastal protection, different temporal and spatial scales need to be distinguished. On the smallest scale, breakwaters protect the hinterland against flooding and erosion. On this small scale, hydrodynamical forces may make it impossible to introduce ecosystem engineering species. However, by making small adaptations of both texture and structure of these breakwaters better settlement and grow conditions could be created, without decreasing the safety level.

On a larger scale, groins and revetments are used to lower the wave impact on dikes and at the same time prevent erosion of the shoreline. Mussel beds and oyster beds are also known to damp waves and stabilize the bed. However, for mussel beds, a habitat suitability analysis in the Dutch Wadden Sea showed that the distribution of mussel beds is related to wave action, sediment grain size at the bed and emersion time (Brinkman et al., 2002). Moreover, food competition in mussel beds causes that mussel beds will only have a maximum coverage of 5–10% on an intertidal flat system (Hertweck and Liebezeit, 2002). Therefore, mussel beds and oyster beds could take over the role of groins or revetments, but only on a limited scale, given habitat suitability and food competition of these ecosystem engineering species.

On a floodplain scale, dikes are used to protect the hinterland against flooding. These dikes have to withstand wave impact during high water levels. High dikes will result in resistance of the inhabitants living near the dike. By constructing willow floodplains in front of these dikes, the dike height could be lowered due to the wave damping by the vegetation. Compared to mussel beds and oyster beds, the willow floodplain is less sensitive to physical conditions, which make it possible to introduce these ecosystem engineering species on a larger scale.

On a landscape scale, it is possible to strengthen or partly replace engineering constructions for coastal protection by ecological elements, such as dunes and wetlands. However, dune and wetland growths are known to be dynamic, and a period of growth may be followed by a period of lateral erosion (Nordstrom and Gares, 1990; Arens, 1997; Van de Koppel et al., 2005). Consequently, introducing dunes and wetlands in coastal protection requires good monitoring and understanding of the dynamic character of these ecological elements (Day et al., 2000).

How the linking between different scales can result in successful dynamic interaction between ecology and engineering is demonstrated in this paper by presenting several pilot projects on the different scales, based on field, flume and model experiments (Fig. 1). Moreover, a review on successful implementations of ecosystem engineering solutions in coastal protection is given to support the results of the pilot projects. Impacts of boundary conditions, such as sea level rise, and noise, such as seasonal variation in biomass of ecosystem engineering species, needs to be monitored and modeled in order to fulfill desired safety levels in future. Further, these combined solutions will require a form of adaptive management, which is dealt with in more detail in Section 4 of this paper.

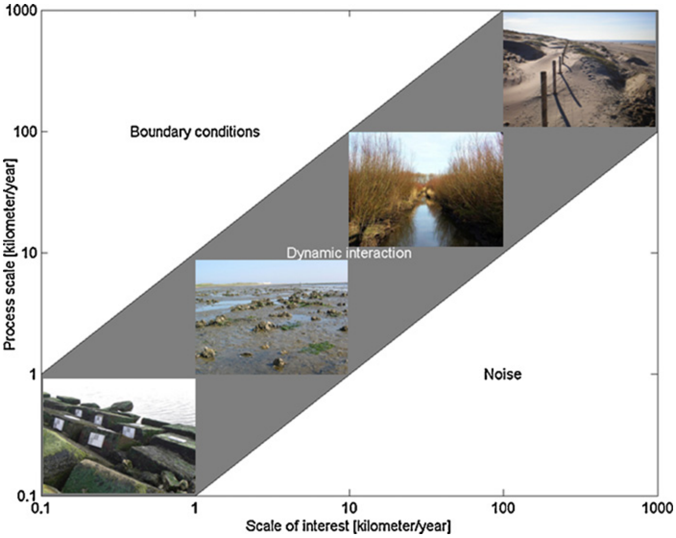

Fig. 1. Framework to classify the different pilot projects in the 'scale concept'. Dynamic interaction occurs when the spatial and temporal scale of interests are comparable to the process scale. When the process scale is larger than the scale of interest, the process is identified as boundary conditions. The process is identified as noise when the process scale is smaller than the scale of interest (after Van Ledden, 2003).

3. Applications: ecosystem engineering species in coastal protection

3.1. Micro-scale: optimizing texture and structure of concrete in the intertidal zone

The breakwaters of the entrance of the North Sea Channel at IJmuiden (The Netherlands) protect the hinterland against waves. On one of these breakwaters ('Het Zuiderhavenhoofd'), which consists of concrete blocks of 22 and 30 metric ton embedded in asphalt, several slabs were mounted. These slabs measured 75 cm × 50 cm and the top surface was divided into six sections (25 cm × 25 cm), different in texture or geometric structure, that were tested for algal and macrofaunal colonization. Two locations were selected; a 'low dynamic' (south east exposed) and 'high dynamic' one (south west exposed) in terms of wave attacks (south west is the dominant wind direction in the Netherlands). In the high, middle and low part of the intertidal zone different types of slabs were mounted on the blocks from April 2008 till September 2009 (Fig. 2).

Analysis of the photographs taken of the sections on the slabs showed that the sections on the slabs with a fine or coarse surface were colonized more rapidly by small green algae (*Ulothrix flacca* and *Urospora penicilliformis*) than those with a smoother surface. The geometric structures, cup and holes, which retained water longer during low tide favored the initial colonization by larger green algae (*Ulva intestinalis*). As succession proceeded the differences in algal density between the sections on the slabs became less obvious. All sections of the slabs in the mid and low tidal zone of both locations were rapidly overgrown by barnacles (*Elminius modestus*). Mussels (*Mytilus edulis*) were only found in the sections with grooves, holes and cup, and developed best within the grooves (Fig. 3). Both grooves and holes were used by periwinkles (*Littorina littorea*) for shelter at low tide. In general, slabs which were

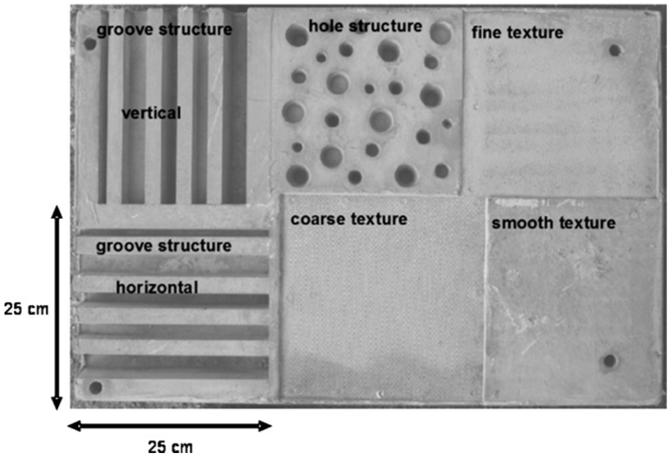

Fig. 2. An example of a slab, composed of different structures and textures, that was mounted on the blocks of the breakwater.

mounted low in the intertidal area showed a more rapid and diverse colonization, compared to the slabs which were mounted higher in the intertidal area. Moreover, 3 out of 10 slabs in the high dynamic environment broke down, and showed the importance to protect the slabs against extreme conditions.

These results were in line with studies carried out in the Azores (Martins et al., 2010), where pits with varying densities and sizes were drilled in a seawall, resulting in higher number of algae and macrobenthos within those pits.

In conclusion, small adaptations of both texture and structure of concrete constructions within the intertidal zone of the marine environment lead to better settlement and growth conditions for algae and macrobenthos. Thus primary and secondary productions are enhanced, without decreasing the safety level of the hinterland. Given the ‘scale-concept’, these small scale adaptations can provide benefits for groins and revetments as sources of enhanced productivity and habitat diversity on the meso-scale.

3.2. Meso-scale: mussel beds and oyster beds for protecting intertidal flats from erosion

Reef building species, such as mussels and oysters are clear examples of ecosystem engineering species in that they modify their local hydrodynamic and sedimentary surrounding (e.g., Folkard and Gascoigne, 2009; Van Leeuwen et al., 2010). Whereas most studies have concentrated on the effect of current velocities, a recent flume experiments showed that there is also a clear effect on wave attenuation. Two reef building bivalve species were focused upon in this flume study: the native mussel (*M. edulis*) and the invasive Pacific oyster (*Crassostrea gigas*). Mussel beds and oyster beds were placed in a wave flume with a total length of 13.5 m and a width of 0.5 m. The section with bivalve beds was placed 7.90 m from the wave generator. The length of the section with bivalve beds was 3.1 m. The water depth was kept constant at 25 cm and waves with a significant wave height of 3.34 cm were generated by the wave generator. Mussel beds were composed with a density of 1400 mussels m^{-2} and an average height of 7 cm. Oyster bed consists of 148 oysters m^{-2} with an average height of 7.1 cm. Both mussel and oyster densities reflect field conditions (Gregalis et al., 2008; Van Leeuwen et al., 2010). For the same physical forcing, natural oyster beds are more effective in wave attenuation compared to natural mussel beds (Fig. 4).

Fig. 3. Photograph of the slab (Fig. 2) after 17 months at a low dynamic position low in the intertidal area. High densities of mussels (*Mytilus edulis*) were found at the groove structures and low density of mussels were found at the hole structure, whereas mussels where absent at the other sections of the slab.

The habitat modifications of both reef building species can contribute to stabilizing the bed of intertidal flats in front of dikes. Additionally, mussel beds or oyster beds enhance biodiversity by providing shelter and nesting area for fish and crustacean species (e.g. crabs and lobsters). Further, mussels and oysters are filter feeders, filtering algae from the water column for food. By doing this they clarify the water by removing not only algae, but also silt and organic particles from the water column (Coen et al., 2007). These particles are glued together and excreted as pseudofaeces (Foster-Smith, 1975). These pseudofaeces accumulate in the vicinity of mussel and oyster beds. From an engineering perspective mussels and oysters might be helpful in protecting intertidal flats against erosion and by increasing sediment input on these flats. On the other hand, optimal habitat requirements for filter feeders include long periods of submersion to assure food availability, which limits their occurrence to lower elevations in the tidal prism, which conflicts with engineering goals to stabilize higher areas in the intertidal (Wildish and Miyares, 1990; Widdows and Brinsley, 2002; Herlyn, 2005).

Stabilization by reef builders is valuable for coastal protection, as large intertidal flats can significantly reduce wave energy reaching the dikes. A pilot project aiming to construct oyster reefs on intertidal flats, has demonstrated that although the concept seems straightforward, putting it into practice asks for a complete understanding of habitat requirements for oyster settlement. For example, attenuation of hydrodynamic energy via the interaction between shells and hydrodynamics makes these reef-building species relevant for coastal protection, but hydrodynamics also limit locations where these species occur. At the most wave exposed sites, where stabilization of intertidal flats would be most useful from a coastal protection perspective, it has proven to be most difficult to create such a reef (De Vries et al., 2007).

Summarizing, in this pilot project we learned that creation of mussel beds and oyster beds to stabilize intertidal flats in front of dikes is very promising, as these reefs clearly attenuate hydrodynamic energy and accumulate muddy sediment (De Vries et al., 2007). These results were in line with results found in Northern America (Meyer et al., 1997; Meyer and Townsend, 2000; Piazza et al., 2005), where oysters are used to stabilize the sediment. The challenge we currently face is to define good methods to create viable reefs at the most wave exposed areas. Placed in the ‘scale-concept’, oyster beds take over the role of groins or revetments and will impact the design of coastal levees on the macro scale. Oyster beds will influence ecology on the micro scale by providing shelter, lee and increased silt deposition in and around the oyster beds (Piazza et al., 2005).

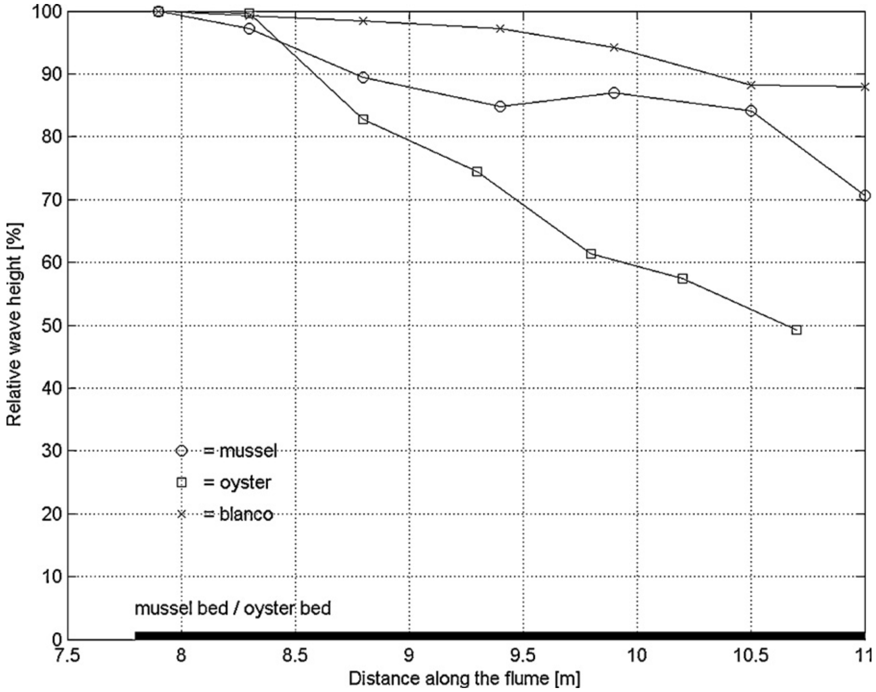

Fig. 4. Wave attenuation over a 3.10 m long mussel bed (circles) and oyster bed (squares), compared to wave attenuation without mussel bed or oyster bed in the flume (crosses).

3.3. *Macro-scale: building willow floodplains to reduce wave overtopping of dikes*

Recently, the Dutch government initiated the program 'Room for the River' to cope with the expected increase in river discharge as a result of climate change (Van Vuren et al., 2005). The main goal of this program is to reduce extreme water levels in rivers by creating more space for the river to accommodate extreme discharges and at the same time enhance biodiversity (Havinga et al., 2010). Part of the plan is to give the polder Noordwaard (around 2000 ha; Fig. 5), situated in the west of the Netherlands, back to the river by lowering the surrounding dikes to 2 m above sea level. This would result in flooding of the polder during extreme discharges, which occur several times a year. This measure will lower water levels in the river by 0.3–0.5 m at specific upstream locations which are prone to flooding.

As a result of this plan a village located within the Noordwaard, including a historical fortress, needs to be protected against flooding by means of a new dike. The extreme height of the new dike design compared to traditional design standards resulted in resis-

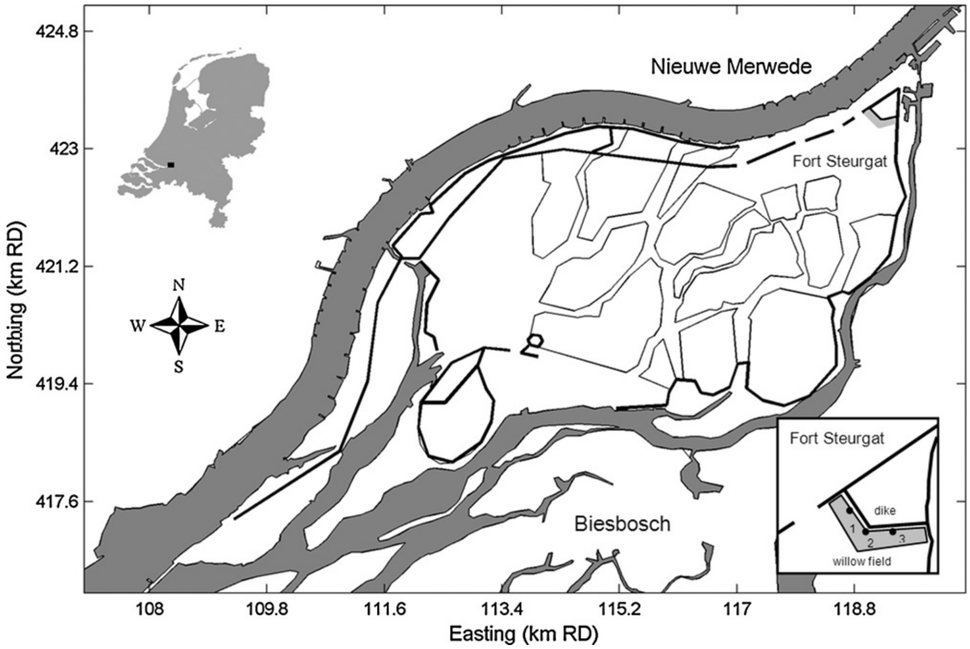

Fig. 5. Overview of the Noordwaard, located in the south-west of the Netherlands, enclosed by the river Nieuwe Merwede and the park Biesbosch.

tance of the inhabitants. Therefore, it was decided to re-design the dike with the use of eco-engineering concepts. The new design consisted of a bank in front of the old dike with a width varying between 60 m near the edges and 100 m near the bend, a length of 600 m and a height of 0.8 m (Fig. 5; gray shaded area). On top of this bank, willow trees (*Salix alba*) are planted. This bank is required to make sure that the willows are not continuously situated in the saturated soil. The willow tree *S. alba* is chosen because it can cope with long inundation periods, resists extreme storms and grows in clay soil. It consists of a stub from which the branches grow after cutting. Consequently, the willow is schematized by two layers. The first layer is the stub with a height of 0.3 m, a width of 0.2 m and a density of 4.3 stubs m^{-2}. On average every stub has 60 branches, with a width of 0.015 m and a height exceeding the maximum water level during storm conditions. The willows reduce wave impacts on the dike and therefore allow for a considerably lower dike height while maintaining required safety levels of 1 in 2000 storm frequency. The willow-bush will be maintained for many decades in order to provide the required safety level.

The new design was evaluated with the wave model SWAN (Booij et al., 1999) in which the effect of vegetation on waves was included by implementation of the equations of Mendez and Losada (2004). It was found that a reduction of 60–80% in wave heights can be achieved with the willow forest, leading to a reduction of the required dike height by about 0.8 m (see Fig. 6 for a typical modeling result). The interested reader is referred to De Oude et al. (2010) for the calibration and validation of the model with flume data and background in the theoretical approach.

The new design incorporates an innovative dike that creates conservation value, results in a lower height of the dike thus reducing the construction costs, limiting maintenance time and costs, increasing landscape attractiveness and complying with the historical landscape in this area. Linking to the 'scale-concept', the willow floodplain is a design implemented on an ecosystem scale. On smaller scales, the design increases habitat diversity. Moreover, given the willow floodplain the need of implementing small scale hard structures such as revetments to stabilize the foreshore is reduced.

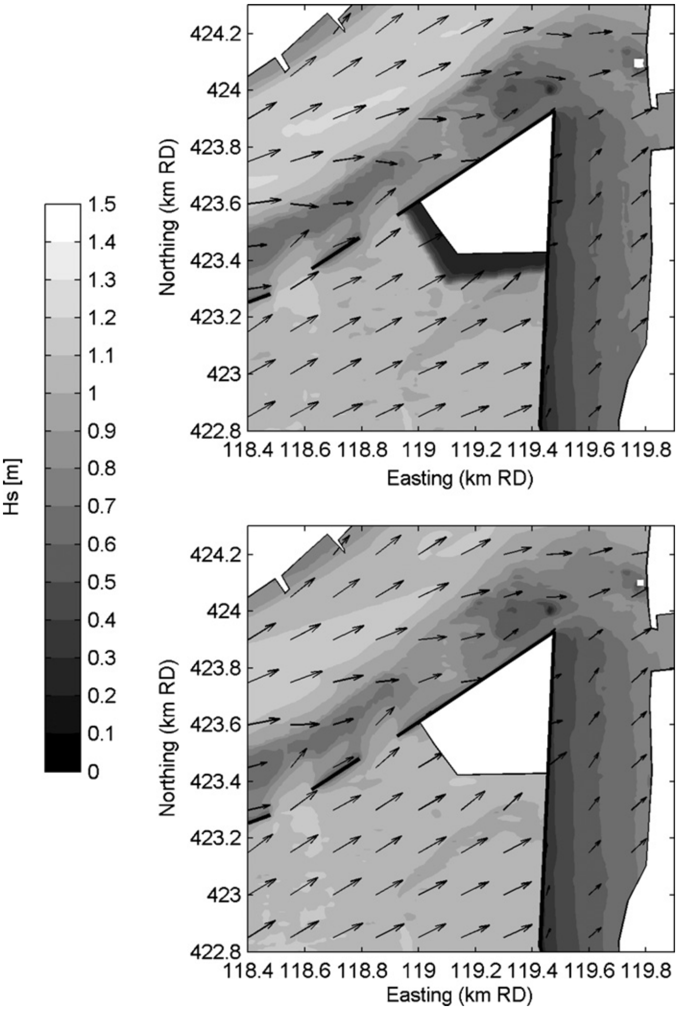

Fig. 6. Model outcome for the significant wave height, for the situation where vegetation is included in front of the dike (top) and with the no inclusion of willow vegetation (under). The significant wave height is reduced up to 80% in front of the dike.

3.4. *Mega-scale: using sand dunes and wetlands for coastline protection*

The Dutch coastline mainly consists of sandy beaches with dunes (around 260 km), which act as a buffer between the sea and the densely inhabited hinterland that generally is situated well below sea level. To prevent the coastline from eroding backwards it needs to be nourished regularly (Hanson et al., 2002). Entrapment and fixation of the sand are mostly accounted for by sand couch (*Elytrigia juncea*) and marram grass (*A. arenaria*) constituting the base of dune formation (Doing, 1985). On these coasts marram grass builds extensive dune areas that serve as a protective barrier between the sea and populated areas. Sand is transported from the coast towards the sea during storms and slowly transported back to the coasts by daily wave transport. Traditionally, the management of the sandy Dutch coastline used to be event driven, meaning that sand nourishments would follow after a major erosion event. However, in 1990 the Dutch government changed this philosophy by defining a basic coastline (De Ronde et al., 2003), and allowing a well-defined small percentage of the coastline to temporarily recede behind this basic coastline. This implies that small storms do not acquire immediate nourishment, thereby enabling a longer term management of the Dutch coastline. Nowadays, sand nourishments last for approximately 5 years (De Ronde et al., 2003). The nourished sand will be transported to the dunes, which result in an increase in concavity of the dune face as well as an increase in elevation of the dune top (Bochev-van der Burg et al., 2009). However, between the nourishment and the impact on the dune dimensions, a time lag of a couple of years is present. Consequently, the management of this type of coastal protection needs to be adaptive as discussed in detail in Section 4.

Sand dunes are used world-wide as coastal protection on a landscape scale (see Wiliams et al., 2001 for a review). In addition, large wetlands areas like salt marshes that occur along the coastline can also serve as landscape scale coastal protection. To create marshlands appropriate techniques are available. For example, salt marshes are created by making use of sedimentation fields, in which groins create conditions of low hydrodynamic energy levels that encourage the precipitation of sediment (Bakker et al., 2002). A man-made creek system speeds up drainage and thereby enhances marsh formation (e.g. Kentula, 2000; Teal and Weishar, 2005; Hinkle and Mitsch, 2005). To protect natural marshes, sediment fences are used to dissipate wave energy and thereby protect marshes from erosion (Boumans et al., 1997; Scarton et al., 2000). In general, the perspective that large wetland areas are indispensable as a buffer against flooding of hinter-lying lands is gaining ground. In this perspective, marsh restoration and conservation is required to protect coastal cities, such as New Orleans (Costanza et al., 2006).

The examples above show that even on a landscape-scale it is possible to strengthen or partly replace dikes, dams and levees for coastal protection by ecological elements, such as dunes and wetlands that are native to the area. On these scales ecological benefits are enormous. Many species profit from restoration and sustainable management of these landscapes for coastal protection. On a landscape level biodiversity and productivity are enhanced and these effects will echo through the foodchain (Mitsch and Gosselink, 2007). For example, marshes and shellfish reefs are so-called nursing grounds and many marine species spend a part of their life in the marsh or reef. Many of these species, such as shrimp and crabs are a source of food for other animals, such as birds, and are of economic importance to humans (Barbier, 2007). Also, marshes and reefs have high nutrient and particle filtering capacities, improving water quality. Besides serving as coastal protection dunes and marshes also have a large recreational value. Finally, marshes have the potential to sequestrate carbon (Brevik and Homburg, 2004; Rhee and Iamchaturapatr, 2009), showing their service on a global level.

4. Discussion

This paper presents examples of three pilot projects and reviews successful projects that aim to enhance coastal safety by making use of ecological engineering species. A framework is proposed to include ecosystem engineering species in coastal protection, by focusing on the integration of spatial and temporal scales between ecology and engineering. The examples illustrate that, for a given spatial and temporal scale of a specific protection strategy, various ecosystem engineering species can be used to dynamically interact in coastal protection. The most suitable ecosystem engineering species depend on the specific characteristics of each separate location, such as wave action, tidal height, sediment availability and salinity. Thereby, not all locations will be suitable for this approach, depending on available space for example. This illustrates important fundamental differences between the traditional engineering approach and the ecological engineering approach (Thom, 1997).

Traditional engineering solutions are generally over-dimensioned and static in that they do not respond to changing boundary conditions. Integration of ecosystem engineering species into coastal protection allows a dynamic interaction between organisms and the natural evolution of the coastal system. In case of uncertain scenarios related to sea-level rise, ecological engineering solutions may be used to postpone destructive and irreversible engineering measures for coastal protection. Thereby, organisms that trap sediment to keep up with long-term trends in boundary conditions like sea level rise (e.g. accreting dunes and salt marshes) may provide a long-term sustainable protection and might, at least locally, reverse ongoing trends of subsidence. Moreover, given the adaptive abilities of ecosystem engineering species, solutions could be less over-dimensioned compared to traditional engineering solutions, which reduces costs (Fig. 7). Thorough knowledge of ecosystem functioning and ecosystem-based management is needed to make these approaches successful (Granek et al., 2010).

Monitoring of ecological components in their function as coastal protection structure is important while variation in the exact outcome is an inherent property of biological elements (Airoldi et al., 2005; Martin et al., 2005; Frihy et al., 2006). This characteristic of ecological components is also referred to as 'self-design' (Mitsch and Wilson, 1996; Odum and Odum, 2003; Mitsch and Day, 2004). Next to this, threshold dynamics of ecosystems will complicate accurate predictions of ecosystem conditions and response (Scheffer et al., 2001; Suding et al., 2004). Extreme events, such as storm surges, might be able to harm ecological systems to such an extent that returning to the state valuable for coastal protection can prove troublesome. Information on resilience of specific engineering functions of species is lacking (Groffman et al., 2006), meaning that use of engineering species for coastal protection will require systematic and continuous monitoring (Möller, 2006). Moreover,

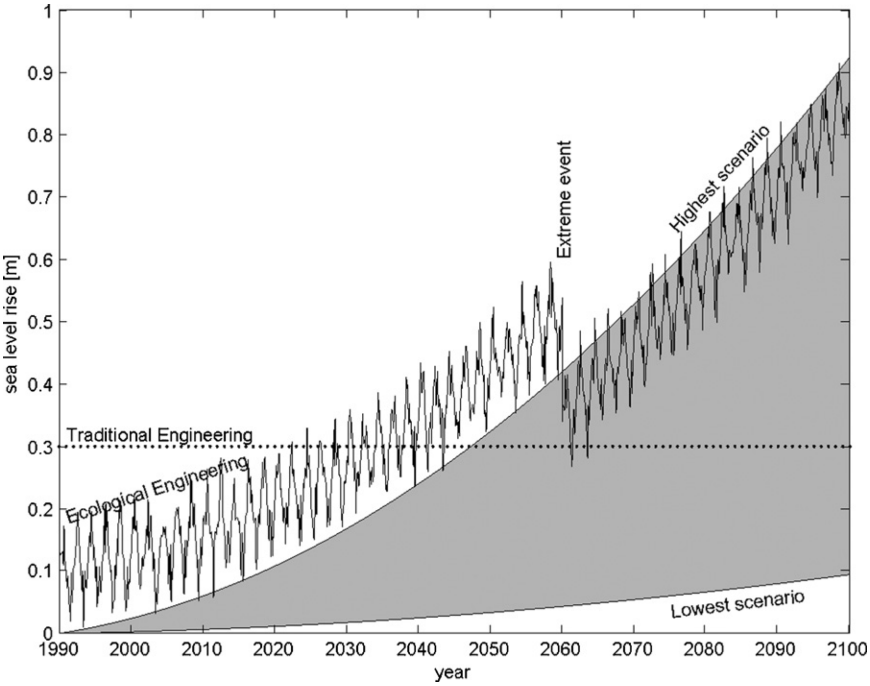

Fig. 7. Conceptual framework to demonstrate the difference between traditional engineering (dotted line) and ecological engineering (thick line) concerning sea level rise and coastal protection (gray area enclosed by a lowest and highest scenario). Traditional engineering (e.g. a dam designed to block a water level set-up of 0.3 m) solutions are over-dimensioned in the first years after construction and do not respond to changing boundary conditions, whereas ecological engineering solutions are dynamic and less over-dimensioned (e.g. accreting salt marshes which are 0.1 m above mean sea level at 1990). After an extreme event (e.g. 2060) the accreting salt marshes might recover.

the effects of ecosystems on coastal protection are ambiguous. For salt marshes there is an ongoing debate about their effectiveness in attenuating waves (Barbier et al., 2008; Feagins et al., 2009; Gedan et al., 2010). In general there is a need for more specific field measurements that quantify claimed services of ecosystems on landscape scales.

Providing standard protocols for monitoring effectiveness of ecological coastal protection structures will be one of the major challenges. Simulation models are currently available to effectively predict safety and sustainability of traditional engineering solutions. Similar modeling expertise is only starting to emerge for ecological engineering approaches. However, to predict the impact of events on ecosystem engineering species and, thus, on coastal evolution use of mathematical models is essential. For example, Kirwan et al. (2010) assessed the model outcome of five numerical models in which the adaptability of coastal marsh with respect to rising sea level was investigated. In all models, eco-geomorphic feedback were included to account for the coupled effect between vegetation growth and changes in bed level. They found, that the adaptability of a coastal marsh depends on the combination between the rate of sea level rise, tidal range and suspended sediment concentration in the channels adjacent to the marsh platform. For example, given a low suspended sediment concentration (~1–10 mg/L), coastal marshes could survive when the maximum rate of sea level rise is only a few millimeters per year. However, coastal marshes with high sediment concentrations (30–100 mg/L) could adapt to sea level rise rates of several centimeters per year.

This illustrated the importance for the development of predictive modeling tools in which two-way coupling between biotic and physical processes is addressed (Borsje et al., 2009; Reinhardt et al., 2010). This requires further development of state of the art model tools and validation data sets by collaboration between engineers and ecologist (Frihy et al., 2006; Chapman and Blockley, 2009). The envisioned models should allow for prediction of long-term large-scale effects of ecosystem engineering species within coastal protection, as there is a strong need for quantitative insights on these larger scales to support policy and decision making.

5. Conclusions

Given the temporal and spatial scale of the protection against flooding and preventing erosion of the shoreline, the review and three pilot projects show how ecosystem engineering species can serve in coastal protection. Meanwhile, also the limitations based on morphological, hydrodynamical and water quality conditions, to realize a combination between traditional engineering and ecological engineering is revealed. Nevertheless, inclusion of ecological engineering in coastal protection is shown to be a promising approach to integrate multiple functions in areas where demands for space are becoming more urgent every day. Thereby, several positive side effects are noted in that these approaches might realize a reduction of costs and can also have a large recreational value. A transition to a more adaptive management might be essential in ecological engineering, while the outcome of the dynamic interactions between ecological engineering and traditional engineering is not known. Monitoring and modeling these interactions is recommended as it allows to predict and to upscale the outcome of this dynamic interaction.

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