Oyster reefs and coastal protection

A literature review

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Abstract

Coastal ecosystems and their related services are under pressure worldwide because of human development. In the future sea level rise will pose an extra risk to these fragile and important ecosystems. One of the disadvantages of traditional methods of coastal protection with hard structures is that they do not provide the same amount of ecosystem services as soft solutions. Building with nature looks for solutions that protect the coasts and enhance natural values at the same time. The features of oysters make it a promising candidate for such a soft solution. Oysters are considered ecosystem engineers because of their ability to form a reef that can dampen the impact of waves, that offers a habitat for valuable fish and crustacean species and that increases benthic pelagic coupling by its filtering capacity. Oysters capture carbon from the atmosphere, accumulate it in their shells and thus help to mitigate climate change. Oyster populations have been severely depleted all over the world. Restoration projects have been carried out, especially in the USA and they offer many criteria for successful restoration programs. In the Netherlands however, the pacific oyster *Crassostrea gigas* has shown a rapid expansion of its distribution since the 1990s, but this expansion has slowed in recent years. For the Eastern Scheldt small scale experiments have been carried out to see if oyster reefs could prevent the erosion of the shoals, however, creating artificial oyster reefs in a high dynamic environment is very difficult. Habitat analysis revealed that proliferation of the Pacific oyster in the intertidal area of the Eastern Scheldt is mainly limited by exposure time.

Introduction

This paper reviews some of the literature on the ecology of oyster reefs, their use for coastal protection and their protection and restoration. Oyster reefs can play a role in coastal defense due to the their possibility to attenuate waves. Furthermore oyster reefs are living structures and therefore have possibilities to adapt to changing conditions. By forming a hard substrate in a soft sediment environment, oyster reefs increase the biodiversity of the intertidal zone. These aspects are in accordance with the basic assumption of the 'Building with Nature' approach of combining coastal protection with increasing natural values and ecosystem services.

Threats to coastal systems

Coastal ecosystems, like mangroves, coral reefs, coastal wetlands and estuaries are one of the most productive and at the same time most threatened ecosystems worldwide. Human populations put considerable, and increasing pressure on these systems. Losses of mangroves, sea grass meadows and salt marshes are estimated to be 25-50% in the last 50 years (Duarte et al., 2013). Today an estimated 40% of humans live within 100 km of the coast and of these, 71% live within 50 km of estuaries. Human pressure on the coastal ecosystem is depleting crucial ecosystem services and has resulted in decreased stocks of finfish, shellfish and crustaceans globally. The development of ports, , resorts, aquaculture, urbanization and industrialization have caused massive and irreversible destruction of coastal ecosystems and their related services. (Hassan et al. 2005)

Climate change poses a possible threat to coastal ecosystems due to the sea level rise.

Atmospheric concentration of carbon dioxide, methane and nitrous oxide have increased significantly since the beginning of the industrial era (± 1750) and are now far above pre-industrial levels as measured in ice-core samples. The net anthropogenic radiative forcing (RF)[1] of both warming and cooling elements is most probably one of warming (see figure 1). The effect of this is seen in increased global air and

[1] Radiative forcing (RF) is expressed in Wm^{-2} and is a measure to express the capacity of a factor to change the balance of in incoming and outgoing energy in the atmospheric system. A positive RF has a warming effect and a negative a cooling effect.

ocean temperatures, increased water vapor content in the atmosphere, large-scale melting of snow and ice and the sea level rise. Additionally, changes in ocean salinity, precipitation patterns, increased arctic temperatures and aspects of extreme weather like droughts and storms have been observed. For this century an increase in average global temperature is estimated at 0.2 ^{0}C per decade, resulting in an increase of 1.8 to 4.0 ^{0}C in 2100, compared to 1990 and depending on the development scenario. The changes in sea level ranges from 0.18 m to 0.59 m. These effects on weather, temperature and ice are expected to increase. (Tropical) storms are likely to occur more frequently and to be more severe (IPCC, 2007).

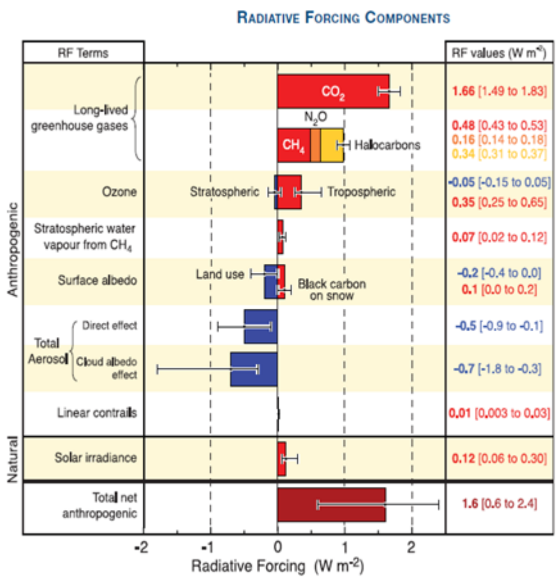


Figure 1: Radiative forcing of the main components of the global climatic system. Positive RF leads to warming and negative to cooling of the global climate. (IPCC, 2007)

Since sea level rise will put major pressure on coastal ecosystems, a closer look at the complexities and uncertainties in the predictions is needed. Estimating future sea level rise is very complex due to the combination of several processes that act on different time scales, like the thermal expansion of the ocean water, the input of water from glaciers and the changing storage of water on land. Rahmstorf (2007) states that a semi-empirical approach will perform better in predicting sea level rise. The result of his approach is an expected rise in sea level of 0.5 to 1.4 m in 2100, compared to 1990. A reconstruction of global mean sea level from 1870 to 2004 has revealed not only a rise of 0.195 m, but also a significant acceleration of the sea level rise in the 20th century. When remained constant this acceleration will lead to a rise of 0.28 – 0.34 m in 2100, compared to 1990. (Church & White, 2006)

Coastal protection

Coastal protection and adaptation is needed to secure coastal ecosystems and protect current and future populations and avoid large scale economic damage. Coastal defense systems that are based on ecosystems offer a more sustainable and cost-effective solution than conventional engineering techniques (see table 1) (Temmerman et al., 2013).

Using case studies from the Netherlands, the UK and Japan, Klein et al. (1999) propose a four step approach in coastal adaptation to climate change with a prominent role for raising public awareness and planning of spatial and temporal adaptive measures.

Because of the multitude of functions and the stakeholders involved, an integrated approach is needed for a sustainable long-term management of the coastal zone. Building with Nature aims to integrate land and water in the coastal zone, making use of materials and forces of nature, while taking the values of the natural environment into account (Waterman et al., 1998). Slobbe et al. (2013) present a conceptual framework for Building with Nature that makes use of three elements of socio-ecological systems: resilience, social learning and ecological services.

Traditional ways of shore protection like beach nourishment are under discussion because of their negative impacts on the ecosystem. Speybroeck et al. (2006) give an overview of these impacts in a review article and list some recommendations to alleviate the effects on the beach ecosystem.

The experimental Delftland sand engine that finished construction in the summer of 2011, might offer an alternative to beach nourishment. Proper monitoring and evaluation over a period of 20 years is needed to see if this multidisciplinary approach will mitigate some of the negative impacts of small scale nourishments and will offer additional wildlife habitats, ecological services like increased fresh water content under the dunes and economic and recreational possibilities. (Slobbe et al., 2013)

In the Eastern Scheldt a specific situation occurs that is caused by the construction of the open storm surge barrier in combination with the building of secondary dams in the eastern part of the basin. The result of the Eastern Scheldt Project was a reduction of the tidal volume by 22%, the water exchange with the North Sea by 28% and the freshwater load by 68% (Smaal & Nienhuis, 1992). This has changed the

Table 1: A comparison between conventional and ecosystem-based coastal defence, showing the possibilities and the limitations (Temmerman et al., 2013) .

Affected variable	Conventional coastal engineering	Ecosystem-based coastal defence
Natural habitat	Degradation or destruction	Conservation or restoration
Sediment accumulation (after sea-level rise)	Disturbed or stopped by embankments, groynes, dams, and so on.	Sustained (if enough sediment is available)
Land subsidence	Exacerbated by wetland reclamation, soil drainage, groundwater and gas extraction	Counterbalanced by sediment trapping, but continues behind ecosystems
Storm surge propagation through an estuary or delta	Wetland reclamation reduces water storage and friction, enhancing inland storm surges	Wetland restoration enlarges water storage and friction, lowering inland storm surges
Long-term sustainability	Low: regular maintenance is needed at high cost	High: ecosystems are self-maintaining (if enough sediment is available)
Cost–benefit appraisal	Moderate to high	Mostly high due to added benefits
Water quality of estuary, delta and coastal sea	May degrade by organic matter accumulation and toxic algal growth in closed-off estuaries	Improved and sustained by nutrient and contaminant cycling in restored wetlands
Climate mitigation through carbon sequestration	None	Mangroves and marshes are important carbon sinks
Fisheries and aquaculture production	Reduced: less habitat for young fish, shellfish and crustaceans due to wetland reclamation	Improved: more habitat for young fish, shellfish and crustaceans due to wetland and reef restoration
Human recreation potential	Negative perception of artificial landscape	Positive perception of natural landscape
Required space	Moderate	High, therefore, not applicable for cities on the coast
Difficulty of creating the defence structure	Moderate	Relatively high due to natural dynamics and variability
Existing implementation and experience	Substantial, but many failures in the past	Limited so far. More research is urgently needed
Social and political acceptance	Widely accepted	So far, only accepted in certain areas (Europe and United States)
Health hazards (other than flooding)	None	Wetlands with stagnant water may facilitate breeding of mosquitoes that could spread disease

properties of the basin from an eroding estuary with expanding channels and growing sandy shoals into a tidal bay with channels that are being filled with sediments and the degrading shoals (Mulder & Louters, 1994). If no measures are taken the shoals and mudflats area will be halved by 2050, the area will shrink from 11,000 hectares in 1984, to 5,000 in 2045 and finally 1500 in 2100. Salt marshes will only be found in sheltered areas. The consequences for the intertidal ecology are large. The carrying capacity for oyster catchers (*Haematopus otralegus)* will reduce by 80% in 2045 . For other waders that find their food on the mudflats and shoals similar future trends are expected (Zanten & Adriaanse, 2008).

Ecosystem engineers

Ecosystems engineers are organisms that "directly or indirectly modulate the availability of resources (other than themselves) to other species by causing physical state changes in biotic and abiotic materials" and thus create, maintain or modify habitats (Jones et al., 1994). *Autogenic engineers* have impact on their environment by their own physical structures, like for example trees and coral reefs. *Allogenic engineers* transform living or abiotic material and thereby modify the environment. The difference between these two forms of engineering can simply be illustrated by the example of a little pool of water in a tree. If the pool is the result of rotting by a fungus, it is a form of allogenic engineering, but when the pool is formed at the connection between a branch and the trunk, it is the result of an autogenic engineering process. Although not much research has been done on the qualitative and quantative impacts of ecosystem engineers, it seems that there are no habitats on earth to be found without some form of engineering by one or two species.

Engineering species can have both negative and positive influences on the abundance and number of other species, but the net effects will probably be positive at larger space and time scales. Although trophic relations are not part of the concept of ecosystem engineering, a combination of the two is called *coupled engineering* and *trophic cascade*. An example is found in sandy shorelines where diatom species stabilize the sand by binding it with carbohydrate exudates. Diatoms are grazed on by amphipods, which in their turn are preyed on by sandpipers. The effect of a large population of sandpipers is that the sediment is more stable. The effect of the sandpiper is a cascading trophic relation, with the diatom as an engineering species (Jones et al., 1997).

Ecosystem services

Where the concept of ecosystem engineer is defined on species level and refers to the effect on other species, the term ecosystem services refers to entire ecosystems and their relationship to human life.

Daily (1997) defines ecosystem services as 'the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life'.

Ecosystem services are distinguished into five categories:

1. Production of goods or provisioning services (food, pharmaceuticals, energy, durable materials and genetic resources)
2. Regeneration processes or regulating services (purification of air and water, decomposition of wastes, pollination)
3. Stabilization processes or supporting services (coastal and river stabilization, mitigation of droughts and floods of control of pests)
4. Life fulfilling functions or cultural services (beauty, spiritual inspiration, scientific discovery)
5. Preservation of options or preserving services (preserving for future use or discovery) (Daily, 1997; Geertsema, W & Steingröver, E, 2008)

An interesting way to have an idea of the multitude of species humans need to support life is imagining that the moon has a suitable atmosphere and climate to support life, but is without species. The question is how many species one would have to take to the moon to start a livable human colony there. The answer to that question is very hard to give, especially if one would include the species that support the species that are directly used by humans. No one knows the exact amount of species needed to support human life (Daily, 1997).

Meanwhile most ecosystems are being seriously altered, depleted or destroyed all over the world, leading to a major environmental crisis in the 21st century if no proper measures are taken. Dialy (2000) proposes a management framework for the protection of ecosystem services. The framework consists of four elements: identification, characterization, safeguarding and monitoring of the services. Characterization of ecosystem services is an important step and is not only dealing with the relationship between the ecosystem and the services it provides, like the size of a forest and the amount of fresh water, but also the value in economic terms.

Assessing the economic value of (coastal) ecosystems is a useful, but very complex task which might help to take the proper decisions in managing these ecosystems. Wilson et al. (2005) use the concept of total economic value (TEV) to estimate the total value of goods and services of the entire system. And although they give an overview of a great number of studies that calculate the economic value of specific coastal systems, one of the main conclusions is that in most cases the value of potential goods and services are missing. Adding these missing values will be a challenging task for scientists and decision makers.

Coastal protection and climate adaptation with engineering species.

Methods of coastal protection that use engineering species instead of traditional engineering techniques are receiving attention from policymakers, scientists and engineers. Cheong et al. (2013) discuss three examples in which engineering species play a major role in coastal protection: marshes, mangroves and oyster reefs. The use of engineering species in coastal protection results in a system that is adaptive to for example climate change, and that will have synergetic effects in the form of increased biodiversity, more stable ecosystems and social and economic benefits. Although the latter needs more research to quantify the exact amount.

Occupying only 0,2% of the surface of the oceans coastal plant communities like mangroves, sea grass meadows and salt marshes, contribute almost 50% of the total oceanic burial of carbon. The burial rates are 30-50 times higher than in terrestrial forests. Since sequestered carbon is preserved over millennia, protecting and restoring these communities offer an effective tool to mitigate climate change (Duarte et al., 2013).

In a review paper, Borsje et al. (2011) discuss the possibilities of different ecosystem engineering species that act on several spatial and temporal scales. At a micro-scale optimizing the texture and structure of concrete in the intertidal zone can stimulate growth of algae and macrobenthos thereby enhancing primary and secondary production. At a meso-scale the capacity of mussel and oyster reefs to dampen waves and trap sediments were evaluated. Willow floodplains act on a macro-scale to reduce wave impact on dikes and on a mega-scale sand dunes and wetlands function in protecting the shoreline. In the latter case the sand couch (*Elytrigia juncea*) and marram grass (*A. arenaria*) are the primary engineering species.

Macrophytes can function as ecosystem engineers by reducing flow speed and increasing sediment accretion (Duarte et al., 2013). In an experiment to measure sedimentation annual eelgrass (*Zostera marina L.)* was transplanted to an unvegetated tidal flat. Sedimentation increased together with the silt content in the experimental plots. However, during winter the extra sediments disappeared again and extra erosion even took place (Bos et al., 2007).

The influence of common cord grass (*Spartina anglica*) tussocks on the morphology of the intertidal area is diverse and depends on the local sedimentation-erosion processes and the hydrodynamic characteristics (Balke, 2009). The spatial sedimentation and erosion processes that play a role in this have been studied by placing artificial structures (tussocks made out of bamboo canes) in the field for two years and combine this with detailed hydrodynamic flume studies. With the flume experiments the underlying erosion and sedimentation processes that play a role in the observed erosion and sedimentation patterns could be revealed (Bouma et al., 2007).

The establishment of the Pacific oyster in NW Europe

The Pacific oyster *Crassostrea gigas* was introduced in the Eastern Scheldt in 1964 to serve as an alternative for the commercial culture of the European flat oyster *Ostrea edulis* whose numbers were reduced by more than 95% during the severe winter of 1962-'63 (Kater, 2003).

Table 2: A selection of characteristics that make invaders successful. All traits are valid for the Pacific oyster (from Troost, 2010)

Stage	Trait
Colonization	*r*-selected life history strategy:
	• Rapid growth
	• Rapid sexual maturation
	• High fecundity
	Generalists:
	• Ability to colonize wide range of habitat types
	• Broad diet
	• Tolerance to wide range of environmental conditions
	Gregarious behavior
	Genetic variability and phenotypic plasticity
	Ability to recolonize after population crash
Establishment	Lack of natural enemies
	Ecosystem engineering
	Association with humans
	Repeated introductions
	Genetic variability and phenotypic plasticity
	Competitiveness
Natural range expansion	Traits of successful colonists (see above)
	Dispersability

The Pacific oyster was believed to not be able to disperse in the Eastern Scheldt, because of the cold temperatures. However in the summer of 1975 the first spatfalls were recorded, followed by other larval outbursts in 1982 and 1989 (Drinkwaard, 1998). Since then the Pacific oyster has spread out successfully in the Eastern Scheldt and the Dutch Wadden Sea as well in the neighboring countries of Belgium and Germany after being introduced for mariculture in those regions. Oyster beds can be found in both intertidal and subtidal areas. On hard subtidal substrates on dikes up to 90% coverage has been observed during diving surveys (Smaal and Kater, 2012).The specific traits that explain the successful settlement of bivalve invaders, and thus *C. gigas*, are shown in table 2. The most important characteristics that explain the rapid expansion of the Pacific oyster in the estuaries of NW Europe are the relative lack of enemies and the ecosystem engineering (reef building) capacities of *C. gigas*. The Pacific oyster modifies its own habitat because of its gregarious behavior that leads to the formation of reefs and results in facilitating settlement, enhancing food intake and offering shelter (Troost, 2010).

Table 3: Ecological effects of *C. gigas* on the Dutch coastal ecosystem. From Troost (2010) and Troost (2009)

Ecological effect	Details
Habitat modification	Reef formation starts on hard substrate or on shell debris in Eastern Scheldt; in Wadden Sea on mussel beds.
	Pacific oyster stabilizes sediment more firmly than mussel beds.
Species richness	Is enhanced by oyster reefs because of habitat heterogeneity. Several studies show higher species richness in oyster reefs than in mussel beds.
Competition for space	Most native bivalves (cockle *C. edule*, clam *M. arenaria* and *Macoma balthica*) occupy different habitats in the intertidal zone, except for the mussel. Evidence for large scale displacement however of mussels by the oysters is not found.
Competition for food	Oysters probably have a higher intake for zooplankton than mussels and cockles.
	Oysters filter the same size in particles as native bivalves and therefor compete for the same resources and if they do not compete directly they interfere by reducing food availability for other species.
	Compared to mussels the ingestion rate of oysters is higher, but the absorption rate is lower.
	When mussels are placed near an oyster reef the growth rate decreases, the other way around no effect is seen.
	In the Eastern Scheldt the carrying capacity for bivalves is reached; in the Wadden Sea the limit is not yet reached. Note here that determining the carrying capacity is difficult.
	Mortality of both mussel and oyster larvae is high because of filtration by filter feeders. Mussel larvae seem to be more affected by this. In laboratorial conditions mussel larvae escape predation by swimming faster and display vertical displacement.
Effects on higher trophic levels	Oysters lower phytoplankton levels and this will have effect on higher trophic levels, like fish, seals and birds, although it is unclear what the effects exactly will be.

Troost (2010) provides an extensive overview of the effects of *Crassostrea gigas* on the ecosystem of the Eastern Scheldt and the Wadden Sea. Table 3 summarizes the main conclusions of this review.

Table 3 shows that the rapid expansion of the Pacific oyster has considerably altered the Dutch coastal ecosystem. However, the competition for space has not led to the disappearance of native bivalves, in fact, the presence of oyster reefs has even led to the expansion of mussels in the Eastern Scheldt. However, the competition for food in combination with larviphagy can lead eventually to the vanishing of mussels (*Mytilus edulis*), but the cockle (*Cerastoderma edule*) seems to be better resistant to low food conditions. A study of the effect of the Pacific oyster on the native ecosystem in the German Wadden Sea comparing an intertidal *M. edulis* mussle bed with a recently established *Crassostrea gigas* oyster reef revealed that biodiversity on the oyster reef was higher and that even *M. edulis* persisted on the site that was invaded by the oysters. The oysters seem to replace all ecological functions of *M. edulis* (Markert et al., 2009).

A lack of resources will slow down the expansion of all shellfish numbers, including those of the Pacific oyster (Troost, 2009).

Ecosystem services of oyster (reefs)

Native oyster reefs were once dominant ecological structures in estuaries all over the world and have provided food to coastal human populations and income for fishermen for thousands of years. Estimations of the effects of pristine oyster population before colonial times (<1600) in the Chesapeake Bay (USA) indicate that the oysters were able to filter the entire water column in minutes to a couple of hours (Mann et al., 2009). In Europe and North America exploitation of oysters began locally by providing food to the fishermen's families and gradually grew to the commercial industry which still exists nowadays (MacKenzie Jr et al., 1997).

Large scale exploitation of natural oyster reefs combined with coastal degradation and shipping activities have led to a severe degradation of oyster reefs worldwide. (Grizzle et al., 2002; Coen et al., 2007).

Beck et al. (2011) estimate that 85% of natural oyster reefs have been lost globally. In many bays and estuaries losses of more than 99% have been recorded, making them functionally extinct. The situation is most serious in North America, Europe and Australia. Specific data from ecoregions like China, South Africa and the Koreas are not available, but anecdotal evidence suggests that the situation resembles an overall picture of decline.

As a keystone species and an ecosystem engineer, oysters perform a crucial role in the estuarine ecosystem. The ecosystem services of oysters have been acknowledged in many publications (Beck et al., 2011; Coen et al., 2007; Grabowski and Peterson, 2007). Table 4 gives an overview of the main ecosystem services of oyster reefs.

The ecosystem services of oysters can be accounted for by two crucial properties of oysters: the formation of reefs and the filtration capacity. Extensive oyster reefs accumulate carbon in the calcium carbonate of their shells that reduces the concentration of greenhouse gases. Oysters create a solid underground in a soft substrate environment. Dense assemblages of oysters provide habitat for many species of invertebrates and fish. Subtidal breakwater reefs made from dead oyster shells supported higher abundances of mobile invertebrates and demersal fishes (Scyphers et al., 2011). Peterson et al., (2003) estimate that restoration of oyster reefs on a sedimentary bottom would generate 2.6 kg yr^{-1} of fish and large crustaceans for each 10 m^2 of restored reef.

Reefs also attenuate wave energy and thereby protect valuable shoreline habitats like salt marshes (Peterson and Lipcius, 2003). Meyer et al. (1997) showed that adding oyster cultch to the shoreline of a *Spartina* marsh reduced the erosion rates significantly and increased the accretion of sediment in the marsh. Artificial fringing oyster reefs made from oyster cultch were able to reduce shoreline retreat in low-energy environments, while in environments with high wave energy no effect on shoreline retreat was observed. Recruitment rate and growth of the oyster spat indicated that a reef would be able to maintain itself over time (Piazza et al., 2005).

Oyster reefs can have a physical impact on the sedimentation in an adjacent sandflat area. Fine sediment and organic matter are higher in the presence of a reef, even when the reefs are small (10 m^2) (Molesky, 2003).

Table 4: Ecosystem services and their benefits or values related to oyster reefs (Grabowski and Peterson, 2007)

Ecosystem services	Benefit/value
Production of oysters	↑market and recreational value
Water filtration & concentration of pseudofeces	↓suspended solids, turbidity, phytoplankton biomass, & microbial production. ↑denitrification, submerged aquatic vegetation & recreational use
Provision of habitat	↑biodiversity & productivity
Carbon sequestration	↓greenhouse gas concentration
Augmented fish production	↑market & recreational value
Stabilization of adjacent habitats and shoreline	↑ submerged aquatic vegetation & salt marsh habitat ↓effects of sea-level rise
Diversification of landscape and ecosystem	↑ synergies among habitats

The filtering capacity of oysters promotes denitrification by concentrating feces and pseudofeces and lowers phytoplankton biomass. This transfer of energy and material from the pelagic zone to the benthic zone is generally referred to as benthic pelagic coupling (Coen et al., 2007). Benthic pelagic coupling results into a shift to benthic primary production and will lower the anoxic conditions caused by the microbial decomposition of algae that dominate many eutrophic estuarine communities. Instead of entering into microbial loops, primary production flows in the consumer food chain starting at pelagic fauna and bottom feeding fishes up to predators like dolphins. The decreased turbidity of the water stimulates the growth of submerged vegetation like sea grass beds (Grabowski and Peterson, 2007).

La Peyre et al. (2014) monitored the development of three key ecological services in restored oyster reefs with a total surface of 260 m^2 during three years: increasing water quality because of filtration, stabilizing the shoreline and augmented habitat for fish and invertebrates. Filtration rates increased during the monitoring period and were related to the development of the reef and the amount of living and thus filtering oysters. Both shoreline stabilization and habitat provision developed rapidly, because they are linked to the development of a hard substrate in a soft bottom environment, but this didn't change over time.

The economic value of the services by oyster reefs is estimated to be $ 5500-99,000 (2011 US dollar) per hectare per year, excluding oyster harvesting. Coastal defense by shoreline stabilization is considered to be the most valuable service and varies greatly, depending on the location. The estimation is conservative since services like recreational fishing, carbon burial and augmented biodiversity are not included. The break-even point between the cost of restoration and the value of the provided services is estimated at 2-14 years (Grabowski et al., 2012).

Restoration of oyster reefs

Shellfish restoration in general and oyster restoration in particular used to be executed only to enhance commercial and recreational production of shellfish. In the last decade however, restoration projects have acknowledged the ecosystem services of oysters and propagate the rebuilding of the natural capital that is capable of sustaining both fisheries and healthy coastal ecosystems (Brumbaugh et al., 2006). It is as-

Table 5: Sources of stress and their causes that limit oyster restoration and the strategies to overcome these limitations (Brumbaugh et al., 2006, Lenihan and Peterson, 2004, Powers et al., 2009, Coen and Luckenbach, 2000).

Sources of stress	Causes	Strategies for restoration
Fisheries mortality	excessive take and destructive fishing practices	No-take areas or sanctuaries: also reduces impact of fishing for other benthic species (Powers et al., 2009) Reducing or redirecting fisheries: allow fishing for a non-native oyster, while protecting native oysters or use less destructive fishing techniques (tonging or diving instead of dredging (Lenihan and Peterson, 2004))
Habitat limitation	modification, degradation and loss of oyster habitats	Construction of 3-dimensional reefs made from oyster shells or limestone marl rock Broad scale placement of shells or shell fragments on the bottom
Recruitment limitation	overabundance of predators, excessive fishing pressure, degraded water quality, diseases or parasites like caused by *Perkinsus marinus* and *Haplosporidium nelsoni*	Add extra adult oysters to the population to enhance spawning • Take genetic diversity into account • Reduce the impact of predation Locate the restoration site in salinities that is below or above the optimum of the organism that causes the disease. No harvesting areas seem to allow disease tolerant strains of oysters to develop (Coen and Luckenbach, 2000)

sumed, for example, that the production of reef-associated fish and crustaceans is limited by the presence of oyster reefs in the southeast United States (Peterson et al., 2003).

Coen and Luckenbach, (2000) summarize six requirements for a successful oyster restoration project: (1) sufficient three dimensional material that offers a substrate for the oysters, (2) in sites that have sufficient recruitment rates, (3) good water quality, (4) restrictions on harvesting methods that damage the habitat (5) restrictions on harvesting methods that over exploit the population, and (6) have sufficient old oysters to develop disease resistant strains (see also table 5).

Brumbaugh et al. (2006) propose a three step method for shellfish restoration. The first step is to identify the sources of stress that affect shellfish population. Once the sources of stress are known, the strategies to abate the stress (step 2) can be formulated.

Table 5 provides an overview of the sources of stress, their causes and the strategies to restore the health of the shellfish population. Effective methods of protecting natural and restored oyster reefs include the establishment of no-harvest sanctuaries (Powers et al., 2009) or changing the method of harvesting from dredging to tonging or diving (Lenihan and Peterson, 2004). The third and final step is to formulate success measures to determine if the restoration project has reached its goals.

Several papers describe the development of oyster restoration projects. In a long-term project in South Carolina, with the objective to formulate success criteria, the development of an experimental oyster reef was compared with a natural reef nearby. Three years after the construction of the experimental reefs abundance and size frequencies of the oysters differed considerably, while the species richness between the experimental and the natural oyster reefs was similar (Coen and Luckenbach, 2000).

The height of the reef above the bottom of the water system seems to be an important parameter for a successful restoration project. An experiment that compared high relief (>1.0 m vertical relief) oyster reefs and low relief (0.1-0.2 m) reefs in Mobile Bay, Alabama (USA) revealed that oyster recruitment was higher in high relief reefs. This could be an important design parameter in cases where oyster mortality is high or when the larvae supply is low (Gregalis et al., 2008).

In a restoration project in the Chesapeake Bay Schulte et al. (2009) found that the oyster density in high relief reefs was fourfold greater on high relief reefs (0,25 – 0.40 m) than on low relief reefs (0.08 – 0.12 m). The high relief of the reefs largely explained the success of this restoration, together with the protection of the reef against harvesting by fishery.

If a salt marsh restoration were paired in proximity to a restored oyster reef, interactions between the two habitats would be likely to provide additional ecosystem benefits that derive from landscape-level synergism between the habitats and that would not normally be included in the two independent scaling exercises. (Grabowski and Peterson, 2007)

Monitoring a restoration project gives possibilities to carry out a mid-course correction in order to reach the goals of the project and helps to improve future projects. Success measures of a restoration project are closely related to the ecosystem services of oysters. These measures can be divided into four categories (Brumbaugh et al., 2006):

1. Recruitment and growth of the oyster population.
2. Provision of habitats for other organisms.
3. Effects on the water quality.
4. Effect on the protection of the shoreline.

Brumbaugh et al. (2006) give an overview of the monitoring methods that are available to effectively measure the effect of restoration. They also point out the importance of monitoring the situation before the restoration project has started.

In order to compare the effect of different restoration projects a standardized monitoring system and a list of indicators for success should be developed (Black, 2011).

Coen and Luckenbach, (2000) suggest that futher testing is required to measure the effect of (restored) oyster reefs on the water quality and on the value of the oyster reefs as a habitat for other species. This testing would require many manipulative field studies, monitoring programs and mesocosm experiments. Also modelling is a tool to study the relation between oyster reefs and other species and it has been used to show the effect of oyster reefs on the possibilities for sea grass growth (Smith et al., 2009).

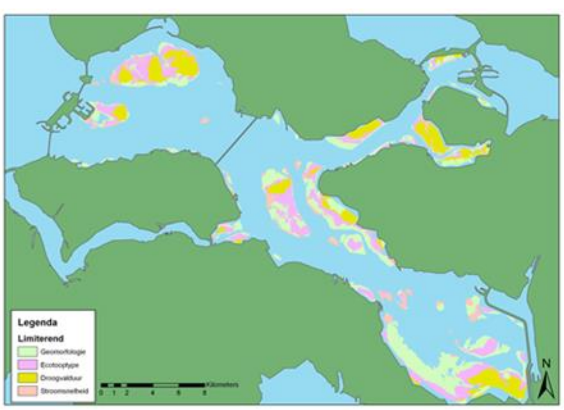
Peterson and and Licius (2003) discussed new ways of determining the scaling of the restoration project in order to compensate for the losses of ecosystem services. Instead of assuming that size follows function, the amount of secondary production could serve as a goal for a restoration project.

Possibilities for the use of oyster reefs in the Eastern Scheldt

Restoring, enhancing or creating oyster reefs seem to be a promising adaptive measure for coastal protection that does not have large negative impacts on the environment. The use of a living oyster reef for wave attenuation, stimulating natural sedimentation processes and coastal protection is in line with the Building with Nature approach. Van Zanten and Adriaanse (2008) see building of oyster reefs as an interesting possibility to slow down erosion of the shoals and mudflats.

To investigate these possibilities a pilot project was carried out in 2006 and 2007 that included flume experiments, model studies and small scale field experiments (Vries et al., 2007). The flume experiments confirm the wave attenuation and current reduction capacities of shellfish reefs. Both model studies and field experiments showed that reefs have the capacity to accumulate sediment in the reef itself, but not directly by the reef. The only possibility to accumulate the sediment that is captured by the reef is through the presence of sea grass beds or salt marshes in the vicinity of the reef. Field experiments confirmed the difficulty of constructing an oyster reef in a high dynamic situation. The artificial reef made out of oyster shells was washed away by winter storms and the hard substrate (tiles and cobbles) needed for the attachment of oyster spat became buried in the sediment.

Wijsman et al. (2008) combined the ecological requirements of *Crassostrea gigas*, concerning salinity, temperature, period of dryness, current speed etc., with the geomorphology of the Eastern Scheldt. This resulted in a map of the area that indicates the habitat suitability for the Pacific oyster (see figure 2). This map should be viewed in combination with figure 3 that shows the factors that limit the growth of *C. gigas*. By combining the information in the two maps, Wijsman et al. (2008) concluded that the length of the period of dryness is the most important factor that limits the growth and expansion of *C. gigas* in the Eastern Scheldt.



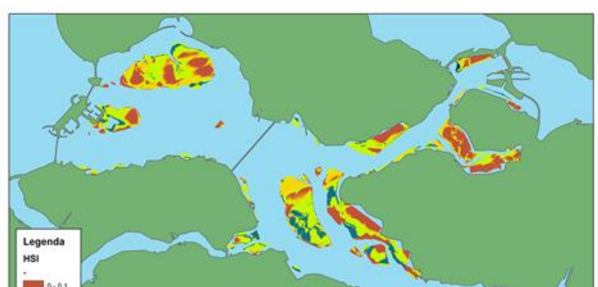


Figure 3: Factors that limit growth of *C. gigas* in the Oosterschelde. Green indicates geomorphology, purple the type of ecotope (depth and substrate), yellow the period of dryness and pink the current velocity (Wijsman et al., 2008).

sterschelde for *C.*
means more suit-

Discussion

Simulation models for evaluation or prediction of the effectiveness of the ecological engineering of safety structures are needed in the same way as they are available for testing traditional engineering structures (Borsje et al., 2011).

To monitor the impact of oyster reef construction or the success of oyster restoration a carefully designed monitoring program is essential. Measuring the situation before restoration should be a part of this monitoring program (Brumbaugh et al., 2006).

The commercial value of oyster reef restoration probably exceeds by far the increased harvest of oysters because of the wide range of ecosystem services connected to the presence of oysters. And although quantative data are lacking, the increased landing of commercial fish, increased recreational use, the augmented motivation to eat seafood and the reduced need to build water purification systems are a few examples that can be distinguished (Grabowski and Peterson, 2007).

In contrast with the past, where the human influence was almost absent, the human pressure nowadays makes that oyster populations are not capable of building biogenic reefs through accretion and therefore not able of adapting to the rising of the sea level (Mann et al., 2009).

References

Balke, T., 2009. Biogeomorphology of Spartina anglica tussocks GIS based comparison of contrasting sites at the Westerschelde and Blackwater estuary (Thesis). Institut für Physische Geographie und Landschaftsökologie der Leibniz Universität Hannover, Hannover and Yerseke.

Beck, M.W., Brumbaugh, R.D., Airoldi, L., Carranza, A., Coen, L.D., Crawford, C., Defeo, O., Edgar, G.J., Hancock, B., Kay, M.C., Lenihan, H.S., Luckenbach, M.W., Toropova, C.L., Zhang, G., Guo, X., 2011. Oyster Reefs at Risk and Recommendations for Conservation, Restoration, and Management. BioScience 61, 107–116.

Black, J.A., 2011. Oyster Reef Restoration in North Carolina: Recommendations for Improvements in Techniques and Monitoring. Duke University.

Borsje, B.W., van Wesenbeeck, B.K., Dekker, F., Paalvast, P., Bouma, T.J., van Katwijk, M.M., de Vries, M.B., 2011. How ecological engineering can serve in coastal protection. Ecological Engineering 37, 113–122.

Bos, A.R., Bouma, T.J., de Kort, G.L.J., van Katwijk, M.M., 2007. Ecosystem engineering by annual intertidal seagrass beds: Sediment accretion and modification. Estuarine, Coastal and Shelf Science 74, 344–348.

Bouma, T.J., van Duren, L.A., Temmerman, S., Claverie, T., Blanco-Garcia, A., Ysebaert, T., Herman, P.M.J., 2007. Spatial flow and sedimentation patterns within patches of epibenthic structures: Combining field, flume and modelling experiments. Continental Shelf Research 27, 1020–1045.

Brown, C., 2006. Marine and coastal ecosystems and human well-being: A synthesis report based on the findings of the Millennium Ecosystem Assessment. UNEP.

Brumbaugh, R.D., Beck, M.W., Coen, L., 2006. A practitioners guide to the design and monitoring of shellfish restoration projects.

Cheong, S.-M., Silliman, B., Wong, P.P., van Wesenbeeck, B., Kim, C.-K., Guannel, G., 2013. Coastal adaptation with ecological engineering. Nature Clim. Change 3, 787–791.

Church, J.A., White, N.J., 2006. A 20th century acceleration in global sea-level rise. Geophysical Research Letters 33, n/a–n/a.

Coen, L.D., Brumbaugh, R.D., Bushek, D., Grizzle, R., Luckenbach, M.W., Posey, M.H., Powers, S.P., Tolley, S.G., 2007. Ecosystem services related to oyster restoration. Mar Ecol Prog Ser 341, 303–307.

Coen, L.D., Grizzle, R.E., Lowery, J.L., Paynter, K.T., Thomas, J., Nygard, J., 2007. The Importance of Habitat Created by Molluscan Shellfish to Managed Species Along the Atlantic Coast of the United States. Atlantic States Marine Fisheries Commission.

Coen, L.D., Luckenbach, M.W., 2000. Developing success criteria and goals for evaluating oyster reef restoration: Ecological function or resource exploitation? Ecological Engineering 15, 323–343.

Daily, G.C., 1997. Nature’s Services: Societal Dependence on Natural Ecosystems. Island Press.

Daily, G.C., 2000. Management objectives for the protection of ecosystem services. Environmental Science & Policy 3, 333–339.

Drinkwaard, A.C., 1998. Introductions and developments of oysters in the North Sea area: a review. Helgolander Meeresunters 52, 301–308.

Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I., Marbà, N., 2013. The role of coastal plant communities for climate change mitigation and adaptation. Nature Clim. Change 3, 961–968.

Geertsema, W, Steingröver, E, 2008. Ecosystem services of green-blue networks in participative landscape planning. Centrum Landschap, Alterra Wageningen UR.

Grabowski, J.H., Brumbaugh, R.D., Conrad, R.F., Keeler, A.G., Opaluch, J.J., Peterson, C.H., Piehler, M.F., Powers, S.P., Smyth, A.R., 2012. Economic Valuation of Ecosystem Services Provided by Oyster Reefs. BioScience 62, 900–909.

Grabowski, J.H., Peterson, C.H., 2007. Restoring oyster reefs to recover ecosystem services, in: Kim Cuddington, J.E.B. (Ed.), Theoretical Ecology Series. Academic Press, pp. 281–298.

Gregalis, K.C., Powers, S.P., Heck, K.L., 2008. Restoration of Oyster Reefs along a Bio-physical Gradient in Mobile Bay, Alabama. Journal of Shellfish Research 27, 1163–1169.

Grizzle, R.E., Adams, J.R., Walters, L.J., 2002. Historical changes in intertidal oyster (Crassostrea virginica) reefs in a Florida lagoon potentially related to boating activities. Journal of Shellfish Research 21, 749–756.

Hassan, R.M., Scholes, R., Ash, N., 2005. Ecosystems and Human Well-Being: Current State and Trends: Findings of the Condition and Trends Working Group. Island Press.

IPCC, 2007. Summary for Policymakers., in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jones, C.G., Lawton, J.H., Shachak, M., 1994. Organisms as Ecosystem Engineers. Oikos 69, 373.

Jones, C.G., Lawton, J.H., Shachak, M., 1997. POSITIVE AND NEGATIVE EFFECTS OF ORGANISMS AS PHYSICAL ECOSYSTEM ENGINEERS. Ecology 78, 1946–1957.

Kater, B.J., 2003. Ecologisch profiel van de Japanse oester. Nederlands Instituut voor Visserijonderzoek (RIVO).

Klein, R.J.T., Nicholls, R.J., Mimura, N., 1999. Coastal Adaptation to Climate Change: Can the IPCC Technical Guidelines be applied? Mitigation and Adaptation Strategies for Global Change 4, 239–252.

La Peyre, M.K., Humphries, A.T., Casas, S.M., La Peyre, J.F., 2014. Temporal variation in development of ecosystem services from oyster reef restoration. Ecological Engineering 63, 34–44.

Lenihan, H.S., Peterson, C.H., 2004. Conserving oyster reef habitat by switching from dredging and tonging to diver-harvesting. Fishery Bulletin 102, 298–305.

MacKenzie Jr, C.L., Burrell Jr, V.G., Rosenfield, A., Hobart, W.L., 1997. The History, Present Condition, and Future of the Molluscan Fisheries of North and Central American and Europe: Volume 1, Atlantic and Gulf Coasts.

Mann, R., Harding, J.M., Southworth, M.J., 2009. Reconstructing pre-colonial oyster demographics in the Chesapeake Bay, USA. Estuarine, Coastal and Shelf Science 85, 217–222.

Markert, A., Wehrmann, A., Kröncke, I., 2009. Recently established Crassostrea-reefs versus native Mytilus-beds: differences in ecosystem engineering affects the macrofaunal communities (Wadden Sea of Lower Saxony, southern German Bight). Biological Invasions 12, 15–32.

Meyer, D.L., Townsend, E.C., Thayer, G.W., 1997. Stabilization and Erosion Control Value of Oyster Cultch for Intertidal Marsh. Restoration Ecology 5, 93–99.

Molesky, T.J., 2003. Interactions Between Oyster Reefs and Adjacent Sandflats: Effects on Microphytobenthos and Sediment Characteristics. University of North Carolina at Wilmington.

Mulder, J.P.M., Louters, T., 1994. Changes in basin geomorphology after implementation of the Oosterschelde estuary project, in: Nienhuis, P.H., Smaal, A.C. (Eds.), The Oosterschelde Estuary (The Netherlands): a Case-Study of a Changing Ecosystem. Springer Netherlands, Dordrecht, pp. 29–39.

Peterson, C.H., Lipcius, R.N., 2003. Conceptual progress towards predicting quantitative ecosystem benefits of ecological restorations. Marine Ecology Progress Series 264.

Peterson, C.H., Grabowski, J.H., Powers, S.P., 2003. Estimated enhancement of fish production resulting from restoring oyster reef habitat: quantitative valuation. Mar Ecol Prog Ser 264, 249–264.

Piazza, B.P., Banks, P.D., La Peyre, M.K., 2005. The Potential for Created Oyster Shell Reefs as a Sustainable Shoreline Protection Strategy in Louisiana. Restoration Ecology 13, 499–506.

Powers, S.P., Peterson, C.H., Grabowski, J.H., Lenihan, H.S., 2009. Success of constructed oyster reefs in no-harvest sanctuaries: implications for restoration. Marine Ecology Progress Series 389, 159–170.

Rahmstorf, S., 2007. A Semi-Empirical Approach to Projecting Future Sea-Level Rise. Science 315, 368–370.

Schulte, D.M., Burke, R.P., Lipcius, R.N., 2009. Unprecedented Restoration of a Native Oyster Metapopulation. Science 325, 1124–1128.

Scyphers, S.B., Powers, S.P., Heck, K.L., Byron, D., 2011. Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. PloS one 6, e22396.

Slobbe, E. van, E., de Vriend, H.J., Aarninkhof, S., Lulofs, K., de Vries, M., Dircke, P., 2013. Building with nature: in search of resilient storm surge protection strategies. NATURAL HAZARDS.

Smaal, A.C., Nienhuis, P.H., 1992. The eastern Scheldt (The Netherlands), from an estuary to a tidal bay: A review of responses at the ecosystem level. Netherlands Journal of Sea Research 30, 161–173.

Smaal, A.C., Kater, B.J., 2012. Introduction, establishment and expansion of the Pacific oyster Crassostrea gigas in the Oosterschelde (SW Netherlands). Helgoland Marine Research 63, 75–83.

Smith, K.A., North, E.W., Shi, F., Chen, S.-N., Hood, R.R., Koch, E.W., Newell, R.I.E., 2009. Modeling the Effects of Oyster Reefs and Breakwaters on Seagrass Growth. Estuaries and Coasts 32, 748–757.

Speybroeck, J., Bonte, D., Courtens, W., Gheskiere, T., Grootaert, P., Maelfait, J.-P., Mathys, M., Provoost, S., Sabbe, K., Stienen, E.W.M., Lancker, V.V., Vincx, M., Degraer, S., 2006. Beach nourishment: an ecologically sound coastal defence alternative? A review. Aquatic Conservation: Marine and Freshwater Ecosystems 16, 419–435.

Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defence in the face of global change. Nature 504, 79–83.

Troost, K., 2009. Pacific oysters in Dutch estuaries : causes of success and consequences for native bivalves.

Troost, K., 2010. Causes and effects of a highly successful marine invasion: Case-study of the introduced Pacific oyster Crassostrea gigas in continental NW European estuaries. Journal of Sea Research 64, 145–165.

Troost, K., Stamhuis, E.J., Duren, L.A. van, Wolff, W.J., 2009. Feeding current characteristics of three morphologically different bivalve suspension feeders, Crassostrea gigas, Mytilus edulis and Cerastoderma edule, in relation to food competition. Mar Biol 156, 355–372.

Vries, M. de, Bouma, T., Katwijk, M. van, Borsje, B., Wesenbeek, B., 2007. Biobouwers van de kust. Rapport haalbaarheidstudie., Z4158. WL Delft Hydraulics.

Waterman, R.E., Misdorp, R., Mol, A., 1998. Interactions between water and land in The Netherlands. Journal of Coastal Conservation 4, 115–126.

Wijsman, J., Bouma, T., Vries, M. de, 2008. Biobouwers van de kust, fase 2. Deltares, NIOO-CEME, Wageningen Imares, Delft.

Wilson, Costanza, R., Boumans, R., Liu, S., 2005. The intertidal ecosystem. Royal Irish Academy Press, Dublin.

Zanten, E. van, Adriaanse, L.A., 2008. Verminderd getij. Verkenning van de mogelijke maatregelen om de erosie van platen, slikken en schorren in de Oosterschelde te verminderen. (Rappor RSW 2008). Rijkswaterstaat, Middelburg.