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Identifying knowledge gaps hampering application of intertidal habitats in coastal protection: Opportunities & steps to take

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ABSTRACT

Over the last decades, population densities in coastal areas have strongly increased. At the same time, many intertidal coastal ecosystems that provide valuable services in terms of coastal protection have greatly degraded. As a result, coastal defense has become increasingly dependent on man-made engineering solutions. Ongoing climate change processes such as sea-level rise and increased storminess, require a rethinking of current coastal defense practices including the development of innovative and cost-effective ways to protect coastlines. Integrating intertidal coastal ecosystems within coastal defense schemes offers a promising way forward. In this perspective, we specifically aim to (1) provide insight in the conditions under which ecosystems may be valuable for coastal protection, (2) discuss which might be the most promising intertidal ecosystems for this task and (3) identify knowledge gaps that currently hamper application and hence need attention from the scientific community. Ecosystems can contribute most to coastal protection by wave attenuation in areas with relatively small tidal amplitudes, and/or where intertidal areas are wide. The main knowledge gap hampering application of intertidal ecosystems within coastal defense schemes is lack in ability to account quantitatively for long-term ecosystem dynamics. Such knowledge is essential, as this will determine both the predictability and reliability of their coastal defense function. Solutions integrating intertidal ecosystems in coastal defense schemes offer promising opportunities in some situations, but require better mechanistic understanding of ecosystem dynamics in space and time to enable successful large-scale application.

1. Introduction

1.1. Coastal ecosystems for coastal defense

Over the last few decades, the majority of the world population has settled in coastal areas, a trend that is expected to continue in the future (Small and Nicholls, 2003). This global trend has caused increasing anthropogenic activities in coastal areas, with both direct (e.g. coastal engineering) and indirect effects (e.g. land cover change) on coastal ecosystems (e.g., Cohen, 2003; Mora, 2008). As a result, the extent and health of many coastal ecosystems has declined (e.g., seagrasses, Waycott et al., 2009; salt marshes, Adam, 2002; Boorman, 1999; coral reefs, Mumby et al., 2006, 2007; mangrove forests, Valiela et al., 2001). With the decline of these ecosystems, the supporting, provisioning, regulating and/or cultural ecosystem services they provide are also lost (MEA, 2005). One of them is coastal protection by wave attenuation and/or the reduction of flooding risks, which is particularly relevant for the safety in coastal areas (Borsje et al., 2011; Costanza et al., 1997; Koch et al., 2009; Temmerman et al., 2013). Given the combination of increasing storminess (Donat et al., 2011; Young et al., 2011) and accelerating sea-level rise (Donnelly et al., 2004), there is a need to improve coastal defense for the protection of coastal infrastructure and livelihoods. Integrating nature into coastal defense schemes may offer an innovative and cost effective way to achieve this (Borsje et al., 2011; Temmerman et al., 2013). Recent reviews have exemplified this by highlighting the role of coastal wetlands in protecting shore lines (Gedan et al., 2011;

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Shepard et al., 2011). To determine whether a coastal ecosystem may in practice realistically be incorporated in defense schemes, it is required to assess 1) the *coastal defense value* of an ecosystem under relevant storm conditions as may be expected within a specific time-frame and 2) the *long-term persistence* of the ecosystem over a specific time-frame. In this case, the relevant time-frame is the one that is related to the life-time for which a coastal defense structure is designed, without needing major redesigning (i.e., around 50 to 100 years).

In this perspective we do not aim at giving a comprehensive review, but rather aim at specifically pinpointing the most important knowledge gaps that need to be resolved to implement the application of ecosystems in coastal defense schemes. We start with providing an overview which ecosystem properties of intertidal ecosystems are regarded to be most important for *coastal defense values* by wave attenuation and bed stabilization. We then discuss how the *coastal defense value* of an ecosystem may be expected to depend on landscape scale (i.e., tidal and dimensional) settings. We subsequently discuss to which extent we can predict the *long-term persistence* of these ecosystems in the typical highly dynamic coastal environments. Finally, we discuss where the integration of ecology and engineering may be most promising. These considerations reflect the outcome of the authors' joined efforts within the interdisciplinary THESEUS project, which is an EU funded project aimed at developing innovative technologies to create safer European coasts in a changing climate.

2. Factors determining the value of coastal ecosystems for coastal defense

Most ecosystems provide a wide range of ecosystem services (MEA, 2005). Especially (intertidal) coastal ecosystems deliver valuable ecosystem services (Costanza et al., 1997), such as providing food, shelter and nursery areas for numerous species, including commercially important fish (e.g. Nagelkerken, 2000; Valentine and Heck, 1999) and representing an important carbon sink (e.g., Donat et al., 2011; Fourqurean et al., 2012). An increasingly recognized, yet understudied service provided by coastal ecosystems is their ability to contribute to coastal protection by i) attenuating waves, ii) stabilizing shore lines and iii) reducing flood surge propagation.

2.1. Wave attenuation by intertidal coastal ecosystems

Intertidal coastal ecosystems have a defense value by reducing the wave energy reaching the coastline (Koch et al., 2009). This has perhaps been most clearly demonstrated for salt marshes, which can be flooded either from tidal water movement or from rare storm events (Möller, 2006; Möller et al., 1999, 2011). In marshes, wave-attenuating effect is related to a combination of vegetation characteristics like stiffness (Bouma et al., 2005) and standing biomass (Bouma et al., 2010) and physical factors like inundation height (Möller et al., 2011; Yang et al., 2012; Ysebaert et al., 2011) and the characteristics of the incident waves (Shepard et al., 2011). A recent meta-analysis showed that vegetation density, biomass production and marsh size were most relevant in being positively correlated to both wave attenuation and shoreline stabilization (Shepard et al., 2011).

Next to marshes, wave energy can be attenuated by any intertidal ecosystem that creates aboveground structures of significant size, such as biogenic reefs, seagrass, kelp and mangroves. Several studies have described the effect of mangroves for wave attenuation (e.g., see Aziz et al., 2013; Bao, 2011; Barbier et al., 2008). For wave attenuation by seagrass meadows there is also a substantial body of work done (e.g., see Manca et al., 2012; Maza et al., 2013; Paul et al., 2012; Infantes et al., 2011 and references therein), whereas for wave attenuation by reef-building bivalves such as oysters and mussels (e.g., see Borsje et al., 2011; Donker et al., 2013) there seems to be relative few publications available to date.

Studies on seagrasses point out that their value for coastal protection can strongly depend on the environmental boundary conditions such as water depth and seasonal influences on shoot density (Fonseca and Cahalan, 1992; Paul and Amos, 2011; Stratigaki et al., 2011). However, the relatively high flexibility of seagrass makes them less effective in attenuating waves than marsh vegetation (Bouma et al., 2005) unless they have a very high biomass (Bouma et al., 2010; Paul and Amos, 2011). Moreover, seagrass shoots easily bend under currents, thereby losing wave-attenuating capacity (Paul et al., 2012), making them less effective in macro-tidal areas with strong tidal currents. The effect of tidal currents on wave attenuation by flexible coastal vegetation, including seagrass and marsh vegetation, remains understudied, and forms an important knowledge gap. In nutrient rich environments, seagrass plants may become more brittle and easily break when exposed to waves (La Nafie et al., 2012). This decreases their wave attenuation capacity and emphasizes the importance of good water quality management when using ecosystems for coastal defense purposes. The relative lack of knowledge on the indirect effect of water quality on wave attenuation and stability of intertidal ecosystems, by affecting vegetation development, is another important knowledge gap.

Biogenic reefs in temperate climate zones, as created by e.g. oysters, mussels or honeycomb worms, are usually found below mean sea level (Barbier et al., 2008) and may therefore be less effective for the protection of coastal structures from waves. The exact value will depend on the local tidal amplitude and size of the ecosystem, as explained schematically in Fig. 1. However, due to their rigidity, reefs are efficient breakwaters when compared to flexible vegetation (reviewed in Bosje et al. 2011). Furthermore, similar to the effect of vegetation, their active role in stabilizing the substrate might also be important. This is a currently an under-appreciated service, that affects long-term wave forcing of the coastline (Storlazzi et al., 2011). Compared to work done on coastal vegetation, data is scarce on the wave attenuation by biogenic reefs in temperate areas, deserving further study.

The aforementioned aspects are generalized in a conceptual diagram (Fig. 1) and overview table (Table 1) that both were based on simple calculations to extrapolate experimental data as explained in Box 1. The conceptual diagram and overview table demonstrate that ecosystems occurring high in the intertidal zone (i.e. marshes) will be more effective for wave attenuation than ecosystems that occur lower in the intertidal zone (i.e., biogenic reefs and seagrass meadows), because of the lower maximum flooding depth (hw_{max}; Fig. 1). On top of that, tidal range in relation to the elevation where the ecosystem occurs, will affect both the wave-attenuating effect and the point in the tidal cycle where wave attenuation is optimal (by affecting hw_{max}; demonstrated for oyster reefs in Fig. 1). Hence, wave attenuation especially of those ecosystems occurring relatively low in the intertidal (Table 1) will be most beneficial in micro and meso-tidal ecosystems, as inundation height (hw_{max}) will be relatively small, and the time during which the waves are affected by intertidal ecosystems is the longest (Table 1). Estimating the maximum tidal range at which intertidal habitats can still attenuate 50% of the incident wave height over a length of 50 ($MT_{50/50}$) and 100 ($MT_{50/100}$) m shows that especially those ecosystems located high in the intertidal (i.e. salt marshes) can effectively attenuate waves over a much wider spectrum of tidal ranges than ecosystems located at lower elevations (Table 1). For ecosystems lower in the intertidal, it is mainly the wave decay coefficient ($k_{habitat}$; m^{-1}) that determines the tidal range over which waves can be effectively attenuated. The biogenic structures that are situated in the lower intertidal zone should, however, not be fully discarded, as they may at a local scale stabilize the sediment bed and protect ecosystems in the higher intertidal zone from hydrodynamic energy. As these ecosystems higher in the intertidal have a strong attenuating effect on waves, the ecosystems lower in the intertidal may provide an important indirect value for coastal protection (Fig. 2 and see section on ecosystem stability). Such positive interactions via physical processes have since the original paper of Bruno (2000) and Bruno et al. (2003) been intensively studied at the small-scale of the community level (e.g., see Guo