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Understanding the conditionality of ecosystem services: The effect of tidal flat morphology and oyster reef characteristics on sediment stabilization by oyster reefs

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ABSTRACT

Ecosystem-based coastal protection by means of conserving, restoring or creating intertidal ecosystems that attenuate waves and stabilize shorelines, offers a promising way to climate proof coastlines for the future. The Pacific oyster (*Crassostrea gigas*) is an ecosystem engineering species, which is known for its wave attenuating and sediment trapping ecosystem services, but it remains unknown to which extent this is conditional. We aim to test the hypothesis that the ecosystem engineering effect concerning sediment trapping and stability by oyster reefs is conditional, and can be predicted based on i) local physical forcing, ii) morphological characteristics of the tidal flat, and iii) biological characteristics of the oyster reef.

Analyses of long-term sediment accretion patterns on natural intertidal oyster reefs at the Oosterschelde basin (The Netherlands) showed that this ecosystem engineering effect is strongest on tidal flats under erosional conditions, lower aspect ratio (i.e., relative long and narrow reefs), relatively closed reefs (i.e., few open patches) and higher coverage of oysters within reef patches. The ability of *C. gigas* to shape the environment thus depends both on biotic and abiotic conditions, meaning that oyster reefs only work under specific conditions for erosion control. Overall, our results provide baseline understanding for ecosystem management aimed at affecting sediment dynamics, thereby contributing to a better understanding for designing ecosystem-based solutions under different abiotic and biotic conditions. In addition, present study provides a clear example of how we need to gain a better understanding of the conditionality of ecosystem services in general, to be able to create and restore ecosystems for obtaining their services.

1. Introduction

Coastal areas are highly important economic zones that are inhabited by rapidly increasing human populations (Masria et al., 2014; Misdorp et al., 2011). Unfortunately, these valuable areas are increasingly threatened by flooding and erosion, due to the combination of anthropogenic activities and climate change (Hallegatte et al., 2013; Hanson et al., 2010; McGranahan et al., 2007). Adaptive measures aimed to reduce flood risk may comprise of constructing new coastal defense structures and/or updating existing ones. Conventional engineering structures, such as sea walls and breakwaters, are commonly used and in some cases the only solution. High construction and maintenance costs and loss of ecosystem services provided by natural coastal systems may, however, defy the application of such structures. Ecosystem-based coastal defense methods – using ecosystems alone or as part of a hybrid solution may offer suitable alternatives in coastal areas (Borsje et al., 2011; de Vriend et al., 2014; Temmerman et al., 2013).

Ecosystem-based coastal defense aims at conserving, restoring or creating natural ecosystems that can contribute to a desired level of coastal safety. Ecosystem-based coastal defense typically makes use of ecosystem engineering species that are capable to modify the physical environment via their own physical structures or biological activities (Jones et al., 1994). Salt marshes, mangroves, sea grass meadows, mussel beds and oyster reefs are well known ecosystem engineering species that can i) attenuate wave energy and ii) stabilize sediment and intertidal areas, thereby contribute to coastal defense (Borsje et al., 2011; Bouma et al., 2014; Temmerman et al., 2013). Ecosystem-based solutions are often posed to be more sustainable and more adaptable to climate change, than conventional coastal engineering (Borsje et al., 2011; de Vriend et al., 2014; Slobbe et al., 2013; Temmerman et al.,

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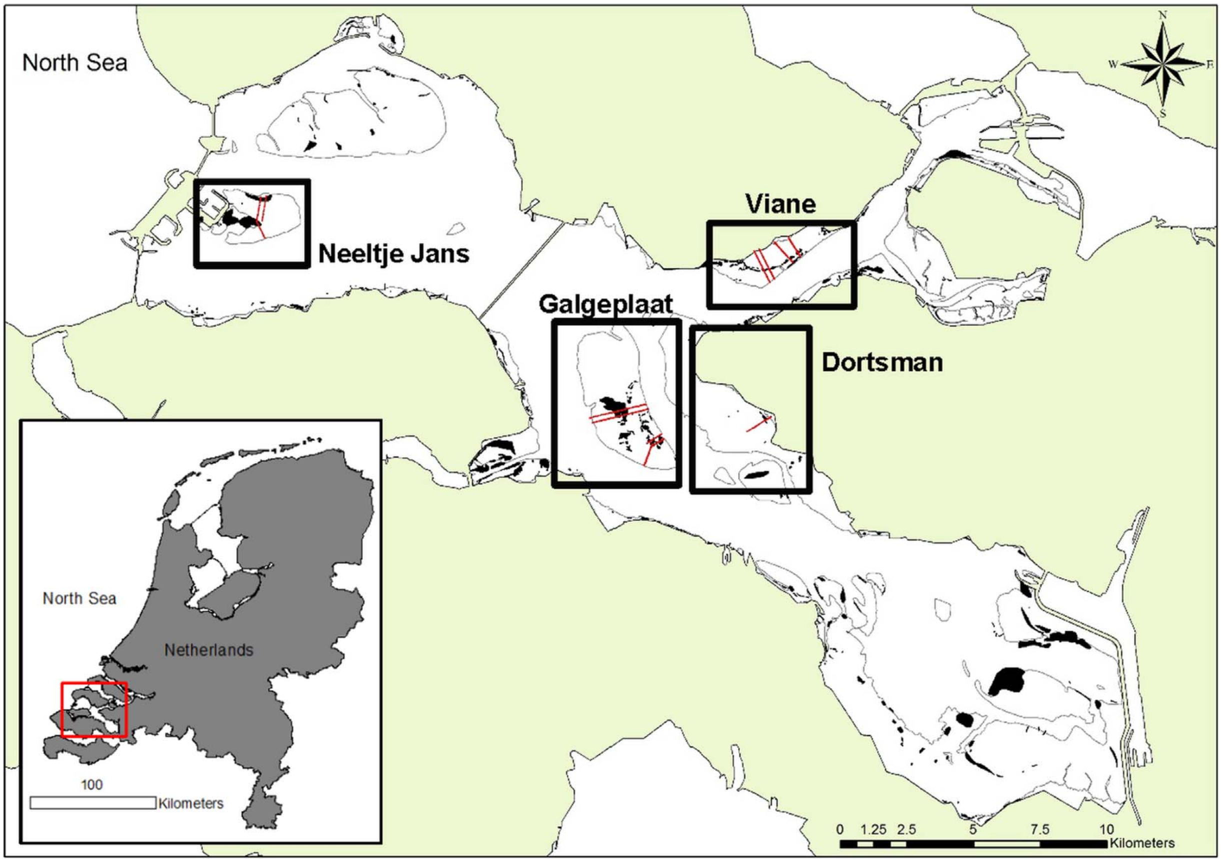

Fig. 1. The Oosterschelde basin (SW Netherlands). The Grey lines indicate the mean low water level, the black areas indicate the oyster reefs present in the intertidal areas (2002) and the red lines indicate the studied transects on four tidal flats (Dortsman, Galgeplaat, Neeltje Jans and Viane). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2013). Large-scale implementation of ecosystem-based solutions is however often hampered by lack of in-depth understanding of the long-term stability and morphological performance of such ecosystem based solutions under different physical conditions (Bouma et al., 2014). In this study we focus on the morphological ecosystem engineering effects of the Pacific oyster *Crassostrea gigas*.

Crassostrea gigas is originally from Russia, Japan and China and was later introduced in many other countries, including the Netherlands (Troost, 2010). As a species it provides numerous ecosystem services, such as, creation of habitats, on which complex food webs are based, enhancement of fishery resources and improvement of water quality (Coen et al., 2007; Grabowski and Peterson, 2007). In addition, *C. gigas* forms extensive three-dimensional reefs, by excretion of cement, which alters flow patterns and attenuate waves (Borsje et al., 2011), enhancing sedimentation and reducing sediment re-suspension (Meyer et al., 1997; Walles et al., 2014). Moreover, as a filter feeder, *C. gigas* increases the local availability of fine sediment in the form of faeces and pseudo-faeces (Crawford et al., 2003). For these reasons, (artificial) oyster reefs have been used both for coastal protection and to reduce erosion (Gregalis et al., 2008; Meyer et al., 1997; Powers et al., 2009). Artificial oyster reefs can be created by offering settling substrate such as e.g. shells, protected or not by gabions or plastic nets, up to active transplantation of oysters (Coen et al., 1999; Walles et al., 2016). These man-made reefs are used as alternative for natural reefs, as the latter are typically not located at the desired places. It remains however a challenge to predict the geomorphological ecosystem engineering effects of such oyster reefs.

Earlier studies on coastal ecosystem engineers demonstrated that alteration of the abiotic environment can be conditional, which means that a particular organism may induce contrasting effects in different environmental settings (Balke et al., 2012; Norkko et al., 2006). As an example, the biogeomorphic shape and long-term development of a *Spartina anglica* tussock is influenced by sediment type and morphodynamics at the landscape scale (Balke et al., 2012). Similarly, the effect of the bivalve *Atrina zelandica* on species abundance and species richness depends on the locally available suspended sediment concentration (Norkko et al., 2006). These types of conditional outcomes of ecosystem engineering may potentially limit the use of ecosystem engineering species for ecosystem-based solutions to specific ranges of physical settings, dependent on the desired outcome. Habitat modification, e.g. the sediment stabilization, by *C. gigas* can occasionally also be much lower than expected, due to specific local abiotic conditions such as water quality or hydrodynamic forcing (Black, 2011; Gregalis et al., 2008; Piazza et al., 2005). But the nature of this relationship remains poorly understood.

The aim of this paper is to understand to which extent ecosystem engineering in terms of sediment accretion by oyster reefs is conditional. We specifically aim to test the hypothesis that the conditional outcome of ecosystem engineering, by oyster reefs, can be predicted based on i) local physical forcing, ii) morphological characteristics of the tidal flat, and iii) biological characteristics of the oyster reef. This was tested by correlating long-term sediment accretion patterns within natural intertidal oyster reefs in the Oosterschelde basin (The Netherlands) to reef characteristics and abiotic conditions.

2. Methods

2.1. Study area

The Oosterschelde basin is a macro-tidal system located in the southwest of the Netherlands. After a major flooding in 1953 the Delta