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Restoration of a boulder reef in temperate waters: Strategy, methodology and lessons learnt

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ABSTRACT

Anthropogenic impacts on marine habitats are a global problem, particularly in coastal areas. While boulder reefs in temperate waters hold high biomass and biodiversity, and may be unable to recover from anthropogenic stressors without restoration efforts, little is known about how to restore and conserve this important marine habitat. Limited knowledge is a serious impediment to projects aimed at restoring boulder reefs that have been degraded or removed by substrate extraction. In 2008, a boulder reef was restored in Kattegat, the transitional waters between the North Sea and the Baltic Sea, using differently sized boulders. The restored reef covered approximately 27,600 m^2 seafloor and included 100,712 tons of boulders added at depths ranging between 4 and 11 m. This paper describes methodology and lessons learned during the restoration project. Before the restoration, geological and geotechnical surveys confirmed that the sea bed could support added boulders, and high resolution bathymetric surveys provided input for the design of the reef, particularly for numerical modelling of the hydrographic and sediment transport conditions. Numerical modelling was used to derive hydrographic design conditions for boulder placements and further, to ensure that the restored reef would not affect the sea bed morphology and hydrographic conditions at a local harbour and at a protected habitat, both situated in the vicinity of the restoration area. Data on the physical structure of the restored boulder reef, collected in 2009, demonstrated that cavernous structures and shallow reef areas were restored. Moreover, data collected in 2012 confirmed the stability of the restored reef. Finally, results highlighted the importance of stakeholder mapping at the outset, appropriate timing of stakeholder involvement and ongoing consideration of stakeholder perceptions. Charting strategy and introducing a checklist for marine restoration projects, this paper outlines important considerations and methodology needed to ensure that restoration of temperate reef structures meet the objectives, without having undesirable effects on existing hydrographic and morphological conditions, including nearby coastal areas and protected marine habitats.

1. Introduction

Ecological restoration is the "process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed" (Seaman, 2007). Habitat restoration represents an important approach to recover lost functions and services of marine ecosystems (Baggett et al., 2015; Reynolds et al., 2016). Over recent decades, studies have revealed that reefs in cold temperate waters often play important roles in terms of biomass and biodiversity (Nielsen and Dahl, 1992a, 1992b; Pihl and Wennhage, 2002; Stål et al., 2007). For example, high densities of juvenile Atlantic cod (*Gadus morhua*) often occur on gravel or boulder reefs, and the substrates are associated with higher juvenile survival compared to less complex habitats (Lough et al., 1989; Tupper and Boutilier, 1995). Similar effects of hard and complex habitats have been observed in other temperate fish species (Tupper and Boutilier, 1997), highlighting the positive effects of gravel and boulder reefs. With the advent of ecosystem-based marine management (Link and Browman, 2014; Pikitch et al., 2004; Slocombe, 1993), it has

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become imperative to not only understand the importance of temperate reefs in relation to ecosystem functions and services, but also to enable appropriate restoration of degraded and removed temperate reefs.

Extraction of marine substrate has been carried out for decades in many countries (Desprez, 2000; de Groot, 1996, 1986). For example, marine substrates, including gravel and boulders, are extracted in coastal European countries with severe consequences for the biomass and diversity of species depending on hard and complex habitats (Boyd et al., 2005; Desprez, 2000; de Groot, 1980; Kenny and Rees, 1994, 1996; Støttrup et al., 2014). Cessation of the extraction is followed by recolonization, but the developing biological community usually differs significantly from the previous community (Desprez, 2000), unless the original topography and substrate composition are restored (Boyd et al., 2005). In Denmark, large quantities of boulders in shallow (< 10 m) marine waters have been extracted for more than a century (Støttrup et al., 2014), but this activity is now prohibited. While the exact extent and timing of the historic extractions are unknown, it is certain that vast areas of hard and complex habitats have been severely degraded or removed (Dahl et al., 2003). To date, however, methodology and requirements for restoring these important habitats in temperate waters remain uncertain.

Marine reefs represent a type of habitat, which is listed in the EU Habitats Directive (94/36 EU, 1999). The Directive requires EU Member States to maintain or restore protected habitats and associated species listed in the Annexes at a favourable conservation status. To this end, it is important that 1) the area covering the habitat is stable or expanding; 2) the physical structures and ecological functions provided by the habitat continue to exist, and 3) the conservation status of the associated species is favourable. For this reason, coastal EU Member States have designated marine reef areas as part of the EU-wide Natura 2000 network of protected areas. Where marine reefs have been severely degraded or removed, the objectives may be accomplished by restoring the habitat and its functions.

A restored reef will rarely be an exact copy of the original reef. Old bathymetry maps can provide guidance, but may also be inaccurate or unavailable. Moreover, the sizes and shapes of removed boulders are usually unknown, and subsequent erosion may have changed the remaining seabed. Therefore, restored reefs typically constitute novel structures in the marine environment that are exposed to hydrodynamic forces from waves and currents. Restoring a reef should therefore follow the same procedures as most other marine construction works with regards to planning and deployment. Importantly, hydrodynamic forces have the potential to modify a reef or render it unstable, and appropriate precautions should cover reef designs developed with engineering tools including numerical modelling of local conditions. Furthermore, local geotechnical properties may limit the carrying capacity of the sea bed and may therefore constrain the design or the choice of foundation for the restored reef. In the design phase of the restoration process, the stability of the projected reef must be ensured to align with the main objectives of restoring lost ecosystem functions and services. Indeed, unstable reef structures will be prone to degradation over time, possibly precluding that the reef restoration meets the intended objectives.

Potential negative environmental impacts from restored reefs are additional issues to consider during the design phase. Large reef structures may change local current and wave patterns and potentially affect sediment transport and thereby sea bed morphology. Depending on the geometrical properties of the reef, and the location of the reef, impacts may extend to coastal areas (e.g. beaches or harbours), similar to other coastal structures (Kristensen et al., 2013). Importantly, the design phase must ensure that the restored reef will not impact other protected habitats in the vicinity of the restored reef. For example, it is crucial that a restored reef does not cause elevated sedimentation in neighbouring protected habitats.

Finally, stakeholder engagement represents an important issue to consider in the design phase and onwards. Stakeholder participation allows all partners to actively participate in the process of developing plans and projects, including policy options, before decisions are made as encouraged by the Systems Approach (Hopkins et al., 2011; Soma et al., 2014). Stakeholder participation in the early phase of planning scientific projects may, however, in some cases limit project outcomes due to large discrepancies in project perception between managers, scientists and stakeholders (Human and Davies, 2010). On the other hand, interaction with stakeholders may be positive and the scientists may 1) gain local knowledge that improves the project design, 2) get suggestions for policy options which can be simulated in models to aid sustainable management (Dinesen et al., 2011), 3) obtain stakeholder support for field work or data collection (i.e. citizen science), and, 4) stakeholders may gain ownership of the project ensuring the long-term viability of the restored area.

The objective of this study was to restore ecological reef functions and services and achieve a favourable conservation status to fulfil international obligations for the reef habitat type (Mikkelsen et al., 2013; Stenberg et al., 2015; Støttrup et al., 2014). Specifically, the project targeted a Natura 2000 reef site situated in the northern part of Kattegat (Fig. 1), which has been severely degraded by boulder extraction. The project was initiated in 2007 and the boulders deployed in 2008. The restoration objectives were to: 1) stabilize the uppermost part of the study area, 2) restore crevices of different sizes, 3) restore a diverse topography with varying heights and inclinations and 4) restore former shallow reef structures to support functions and services of the habitat. Furthermore, to ensure sustainability and stakeholder support, the project aimed to increase both public awareness and scientific knowledge of protecting and restoring boulder reef habitats. Finally, we provide guidelines for best practice in boulder reef restoration.

The tasks fell into three stages of the project; 1) before the restoration, 2) during the restoration and 3) after the restoration. The chronological flow of tasks is shown in the diagram in Fig. 2.

2. Materials and methods

2.1. The study area

The study area is within a Natura 2000 site (H168 Læsø Trindel and Tønneberg Banke) located about 12 km north-east of the island Læsø in the Kattegat Sea (Fig. 1a). The study area has a highly irregular bathymetry (Fig. 1b) with a plateau extending about 500×1100 m with water depths of 4–11m.

Excavation of boulders took place in the study area for several decades up to the 1990s. Nautical charts from 1831 witness water depths between 1 and 1.5 m, but depths had increased to 4 m in 1990 when biological monitoring began (Dahl et al., 2009), indicating substantial excavation activity in the area. Monitoring of macrophyte communities showed a reef in with unfavourable conservation status revealed by opportunistic species or young specimens of perennial species. This community structure was in contrast to the dominance of well-developed perennial seaweed forests found on nearby reefs with larger stable boulders at similar water depths and exposure levels (Dahl et al., 2009).

A decision was made by the Danish Nature Agency to restore the reef area in 2008 to meet the international obligations according to the EU Habitats Directive (Fredshavn et al., 2014).