The ecology of natural and artificial hard substrata in marine coastal environments: Substrate characteristics as facilitator of settlement and community stability

Lydia Ricarda Becker

Dissertation

in fulfillment of the requirements for the degree of

Doctor of natural sciences (Dr. rer. nat.)

Faculty 02 – Biology and Chemistry

University of Bremen, Germany

August 2021

Thesis reviewers

First reviewer: Prof. Dr. Kai Bischof (University of Bremen)

Second reviewer: Prof. Dr. Ingrid Kröncke (Senckenberg am Meer, University of Oldenburg)

Defended on 15th October 2021

This research has been conducted within the INTERCOAST ("Integrated Coastal Zone and Shelf-Sea Research") graduate program, a joint collaboration between the Senckenberg Institute in Wilhelmshaven (Germany), the University of Bremen (Germany), and the University of Waikato (New Zealand). INTERCOAST was funded by the Deutsche Forschungsgemeinschaft" (DFG).

Table of Contents

Summary

Natural hard bottom ecosystems worldwide provide unique ecological functions and services within their respective environments. They protect coastlines by dampening large waves, reducing flooding, and preventing erosion. They act as nursery grounds for the associated fauna and play an important role in benthic-pelagic coupling, nutrient cycling and water purification. The rapid growth of the coastal infrastructure due to an ever-increasing population in coastal regions, as well as the growing challenge of global climate change (sea level rise, ocean acidification), are a serious threat to these ecosystems. The management focus on supporting local biodiversity in order to maintain natural ecosystem functioning and services is essential to safeguard a sustainable coastal development. Hence, while there is a strong need in protecting the still remaining natural hard bottom ecosystems, there is also an upcoming demand for reconsidering the way new coastal infrastructure is to be built. Engineering solutions need to focus on the objective to maintain local species richness, while also reducing the demand for natural resources in the production process of new building materials.

The main objective of this doctoral project was to define drivers, which influence benthic community establishment in marine natural and artificial hard bottom systems. The influence of different physical environmental conditions and substrate characteristics in the settlement processes and community establishment was evaluated. Risks of invasion by neobiota in natural and artificial structures and options to implement natural ecosystem services in artificial environments as protection against invasion were discussed.

The first part of this dissertation focusses on habitat characteristics of natural hard bottom systems of the southern North Sea, Germany. The southern North Sea is a marine environment with relatively low proportion of natural hard bottom ecosystems. Observation and monitoring of these protected grounds is often difficult due to the heterogeneous habitats and overall low visibility. Chapter 2 shows how video sampling methods in combination with environmental distribution maps on sediments, currents, and depth can help to model the status quo of biotic and abiotic conditions within a German nature conservation area, the "Helgoländer Steingrund" (HSG; 54°14.00N and 8°03.00W). Within this study, a new approach using species distribution models was tested on presence/absence data of nine benthic species (*Echinus esculentus, Metridium senile, Cancer pagurus, Phymatolithon spp., Axinella polypoides, Homarus gammarus*, *Flustra foliacea, Alcyonidium diaphanum, Alcyonium digitatum*). The species distribution models revealed good evaluation measures (true skill statistic >0.7; area under the receiver operation characteristic curve >0.90), implying that the model shows a good predictive performance. The outcome of this study is a clear recommendation on SDM application in further environmental monitoring programs on the HSG and other protected hard ground areas. Chapter 3 compares different hydroacoustic and hydrodynamic measurement tools to improve the assessments of the environmental conditions in the study area. Sonar systems, underwater videos, and bottom samples were used for mapping and classifying the abiotic and biotic components of the habitat. Based on acoustic backscatter data three main seabed types (sand, gravel, and hard substrate) were identified. The additional information from underwater videos and sediment samples lead to an expansion to six seabed types with different abiotic and biotic components. The flanks of the ridge of the HSG and their transition to the surrounding soft-ground areas were characterized by a distinct dominance of the bryozoa *Flustra foliacea* and *Alcyonidium diaphanum*. Acoustic Doppler Current Profiler data showed a uniform flow pattern across the ridge, and even resolved the local variability of current patterns, dependent of the tidal stage and bottom relief. Flow patterns are likely responsible for the zonation of the two benthic species.

The second part of this dissertation focusses on habitat characteristics and succession on artificial substrates and environments. Those were in the focus of one-year succession studies presented in chapter 4 and chapter 5. The experiments described the establishment of benthic communities on concrete cubes (15 x 15 x 15 cm) made from five different concrete mixtures. The concrete mixtures contained various cements (Portland cement and blast furnace cements) and aggregates (sand, gravel, iron ore and blast furnace slag). Depending on their mixture, natural resources were saved, and CO_2-emissions were reduced. This makes the materials "environmentally friendly". All cubes were deployed in April 2017. After 12 months, they were examined regarding species composition and coverage, followed by statistical analysis (PERMANOVA, SIMPER, DIVERSE). One succession study was carried out in a natural hard bottom ecosystem near the island of Helgoland (chapter 4). The second study was conducted at the JadeWeserPort, Wilhelmshaven, as an example of a recently erected artificial habitat with high anthropogenic impact (chapter 5).
Chapter 4 showed differences in settlement communities for different surface orientation of the cubes. Significant differences in settlement communities of the Front/Back side were present depending on the used concrete mixtures. Chapter 5 indicated marked differences in settled communities at the Port site compared to the natural environments of Helgoland. At the Port site community composition did not differ between the concrete mixtures. However, surface

orientation of the cubes again revealed significant differences in species abundances and compositions. Cubes hold more neobiota in the Port site than in natural hard ground environments. Recommendations for the usage of “environmentally friendly” produced concrete mixtures are given.

Regarding new coastal constructions, a sustainable production process of the required building materials should always be considered. As long as no significant difference in succession patterns and establishment of benthic communities between the “environmentally friendly” produced concrete mixtures and those that are commonly provided is present, “environmentally friendly” produced mixtures should be used. Anyhow, this is not sufficient to help maintaining ecosystem services under future scenarios of climate change. On the one hand, a protection of natural hard bottom systems is essential to maintain natural ecosystem service and functioning. On the other hand, the potential of artificial structures in restoring ecosystem services should not be underestimated. Artificial structures, if they fulfill certain criteria, as the use of environmentally friendly produced materials and combine those for instance with an enhanced habitat complexity, can, to certain extent compensate for natural habitat losses. If they host high biodiversity of native species, they can also be used to protect natural coasts from invasion by neobiota.

Zusammenfassung

Marine Hartbodenökosysteme erbringen einzigartige Ökosystemfunktionen und Dienstleistungen. Sie bieten einen natürlichen Schutz für Küstensysteme weltweit, indem sie große Wellen brechen, Überschwemmungen abfangen und Erosionen vermindern. Hartbodenökosysteme sind die Kinderstube zahlreicher Organismen und spielen eine wichtige Rolle bei benthisch-pelagischen Kopplungsprozessen, Nährstoffkreisläufen und bei der natürlichen Reinigung von Meereswasser. Der starke Bevölkerungsanstieg in Küstenregionen und das damit einhergehende schnelle Wachstum der Küsteninfrastruktur, zusammen mit den Herausforderungen des globalen Klimawandels (Meeresspiegelanstieg, Ozeanversauerung), sind eine Bedrohung für diese einzigartigen Ökosysteme. Um eine nachhaltige Küstenentwicklung zu fördern und natürliche Ökosystemfunktionen und Dienstleistungen zu gewährleisten, ist es wichtig einen Fokus auf die Unterstützung und den Erhalt lokaler Biodiversität zu legen. Während auf der einen Seite ein dringender Bedarf besteht, die noch verbliebenen natürlichen Hartbodenökosysteme zu schützen, ist andererseits ein Umdenken der Art und Weise wie neue Küsteninfrastrukturen gebaut werden sollten unumgänglich. Technische Lösungen sollten den Erhalt des lokalen Artenreichtums zum Ziel haben, während gleichzeitig eine Ressourcen schonende Produktion neuer Baustoffe angestrebt werden muss.

Das Hauptziel der vorliegenden Arbeit lag darin, Einflüsse für die Etablierung benthischer Gemeinschaften in natürlichen und künstlichen Hartbodensystemen zu definieren. Es wurde der Einfluss unterschiedlicher physikalischer Umweltbedingungen und Substrateigenschaften auf die Besiedlungsprozesse und die Gründung von Artgemeinschaften untersucht. Darüber hinaus wurden die Risiken der Etablierung invasiver Arten auf natürlichen und künstlichen Strukturen sowie die Möglichkeit, natürliche Ökosystemleistungen als Invasionsschutz in künstliche Umgebungen zu implementieren, diskutiert.

Der erste Teil der vorliegenden Dissertation beschäftigt sich mit den Habitateigenschaften natürlicher Hartbodenökosysteme der deutschen Bucht. Im diesem Teil der Nordsee kommen natürliche Hartbodenökosysteme nur zu einem sehr geringen Anteil vor. Die Beobachtung und das Monitoring in diesen Gebieten gestaltet sich aufgrund der Heterogenität und schlechten Sichtverhältnisse am Meeresgrund oft schwierig.

Kapitel 2 zeigt, wie durch die Messung abiotischer Parameter (Tiefe, Sediment, Strömung) und biotischer Daten aus Videotransektfahrten Artverbreitungskarten im Naturschutzgebiet „Helgoländer Steingrund“ (45°14.00 N; 8°03.00 W) modelliert wurden. Es wurde ein neuer

Ansatz der Verwendung von Artverbreitungsmodellen durch die Analyse der An-/ Abwesenheitsdaten von neun benthischen Arten getestet (*Echinus esculentus*, *Metridium senile*, *Cancer pagurus*, *Phymatolithon spp.*, *Axinella polypoides*, *Homarus gammarus*, *Flustra foliacea*, *Alcyonidium diaphanum*, *Alcyonium digitatum*). Die Artverbreitungsmodelle zeigten gute Bewertungsmaße (true skill statistic >0.7; area under the receiver operation characteristic curve >0.90). Dies bedeutet, dass die Modelle eine gute Vorhersageleistung zeigten. Daraus ergibt sich eine klare Empfehlung zur Anwendung von Artverbreitungsmodellen im weiteren Monitoring des „Helgoländer Steingrund“ und anderer geschützter Hartbodengebiete der deutschen Bucht.

Kapitel 3 vergleicht verschiedene hydroakustische und hydrodynamische Messmethoden, um die Aufnahme von Umweltbedingungen im Untersuchungsgebiet zu verbessern. Sonarsysteme, Unterwasservideos und Bodenproben wurden zur Kartierung und Klassifizierung der abiotischen und biotischen Komponenten des Habitats verwendet. Basierend auf akustischen Rückstreudaten wurden drei Meeresbodentypen (Sand, Kies und hartes Substrat) identifiziert. Die zusätzlichen Informationen aus Unterwasservideos und Sedimentbodenproben führten zu einer Erweiterung auf sechs Meeresbodentypen mit verschiedenen abiotischen und biotischen Komponenten. Der Übergang zwischen Hartsubstrat und Sand in den Randbereichen des „Helgoländer Steingrund“ zeigte eine deutliche Dominanz der Bryozoen *Flustra foliacea* und *Alcyonidium diaphanum*. Die Dominanz dieser Arten wurde durch Strömungsmuster erklärt, die durch die Auswertung der Daten eines akustischen Doppler-Strömungsprofilers identifiziert wurden. Die Daten des Profilers zeigten ein gleichmäßiges Strömungsmuster über den Kamm des Steingrunds, sowie eine lokale Variabilität in Abhängigkeit der Gezeitenphase.

Der zweite Teil dieser Dissertation beschäftigt sich mit Habitateigenschaften und Sukzession auf künstlichen Substraten und in anthropogenen Umgebungen. Künstliche Substrate standen im Fokus von einjährigen Besiedlungsstudien, die in Kapitel 4 und Kapitel 5 vorgestellt werden. Die Experimente beschreiben die Etablierung benthischer Gemeinschaften auf Betonwürfeln (15 x 15 x 15 cm) aus fünf verschiedenen Betonmischungen. Die Mischungen enthielten verschiedene Zemente (Portlandzement und Hochofenzemente) und Zuschlagstoffe (Sand, Kies, Eisenerz und Hochofenschlacke). Je nach Herstellungsart wurden natürliche Ressourcen eingespart und der CO_2-Ausstoß im Herstellungsprozess der Materialien verringert. Dies macht die Baustoffe „umweltfreundlicher“. Alle Würfel wurden im April 2017 im Meer ausgebracht. Nach 12 Monaten wurden sie auf Artenzusammensetzung und -bedeckung untersucht und anschließend statistisch ausgewertet (PERMANOVA, SIMPER, DIVERSE). Eine Besied-

lungsstudie wurde in einem natürlichen Hartbodenökosystem in der Nähe der Insel Helgoland durchgeführt (Kapitel 4). Die zweite Studie wurde am JadeWeserPort, Wilhelmshaven, einem Raum mit hohem anthropogenen Einfluss durchgeführt (Kapitel 5).
In Kapitel 4 wurden Unterschiede in den Artgemeinschaften für die unterschiedlichen Oberflächenorientierungen der Würfel aufgezeigt. Zusätzlich wurden signifikante Unterschiede in den Artgemeinschaften der Vorder- und Rückseiten, jeweils abhängig von den verwendeten Betonbeimischungen, nachgewiesen. In Kapitel 5 wurden deutliche Unterschiede zwischen den Artgemeinschaften des Hafenstandorts JadeWeserPort im Vergleich zur natürlichen Umgebung vor Helgoland gezeigt. Während die Oberflächenorientierung der Würfel signifikante Unterschiede in der Häufigkeit und Zusammensetzung der Arten aufwies, zeigten sich keine Unterschiede in Abhängigkeit der Betonbeimischungen. Im JadeWeserPort fanden sich mehr Neobiota auf den Betonwürfeln, als vor Helgoland. Das Kapitel schließt mit Empfehlungen für den Einsatz von „umweltfreundlich“ hergestellten Betonmischungen.

Wird in Küstenregionen neu gebaut, sollte immer auf eine nachhaltige Herstellung der benötigten Baustoffe geachtet werden. Solange kein signifikanter Unterschied in der Sukzession und Etablierung benthischer Artgemeinschaften zwischen den „umweltfreundlich“ hergestellten Betonmischungen und den üblicherweise bereitgestellten Mischungen besteht, sollte auf die „umweltfreundlich“ hergestellten Mischungen zurück gegriffen werden. Dies allein wird jedoch nicht ausreichen, um in zukünftigen Szenarien des Klimawandels zur Erhaltung der Ökosystemdienstleistungen von Hartbodenhabitaten beizutragen. Einerseits ist der Schutz natürlicher Hartbodensysteme unerlässlich, um die natürlichen Ökosystemdienstleistungen und -funktionen aufrechtzuerhalten, andererseits ist das Potenzial künstlicher Strukturen zur Wiederherstellung von Ökosystemdienstleistungen nicht zu unterschätzen. Künstliche Strukturen können, durch die Erfüllung bestimmter Kriterien wie beispielsweise die Verwendung von „umweltfreundlich“ hergestellter Materialien, kombiniert mit einer erhöhten Habitatkomplexität, natürliche Habitatverluste bis zu einem gewissen Grad kompensieren. Wenn anthropogene Lebensräume beispielsweise eine hohe Artenvielfalt einheimischer Arten beherbergen, können sie so zum natürlichen Schutz der Küsten vor invasiven Arten beitragen.

Versicherung an Eides Statt

Ich, Lydia Ricarda Becker (geb. Kohlmorgen),

versichere an Eides Statt durch meine Unterschrift, dass ich die vorstehende Arbeit selbständig und ohne fremde Hilfe angefertigt und alle Stellen, die ich wörtlich dem Sinne nach aus Veröffentlichungen entnommen habe, als solche kenntlich gemacht habe, mich auch keiner anderen als der angegebenen Literatur oder sonstiger Hilfsmittel bedient habe.

Ich versichere an Eides Statt, dass ich die vorgenannten Angaben nach bestem Wissen und Gewissen gemacht habe und dass die Angaben der Wahrheit entsprechen und ich nichts verschwiegen habe.

Die Strafbarkeit einer falschen eidesstattlichen Versicherung ist mir bekannt, namentlich die Strafandrohung gemäß § 156 StGB bis zu drei Jahren Freiheitsstrafe oder Geldstrafe bei vorsätzlicher Begehung der Tat bzw. gemäß § 161 Abs. 1 StGB bis zu einem Jahr Freiheitsstrafe oder Geldstrafe bei fahrlässiger Begehung.

Ort, Datum Unterschrift

CHAPTER 1
General introduction

1.1. Marine hard bottom communities

Marine hard bottom ecosystems represent an evolutionary heritage. Species richness of these systems is comparable to tropical rainforests, but its functional diversity is superior (Wahl 2009). Thus, hard bottoms belong to the most productive and diverse ecosystems on our planet. Through their taxonomical and functional diversity as well as their internal dynamics, communities in hard bottom systems provide irreplaceable ecosystem services such as nutrient cycling, water purification, benthic-pelagic coupling, or nursery grounds for juveniles (Little and Kitching 1996; Wahl 2009).

Since a large proportion of hard bottom communities worldwide is located in shallow and near-shore regions (Little and Kitching 1996; Halpern et al. 2008; Wahl 2009) they are particularly prone to impacts of human activities (Firth et al. 2014). With ongoing climate change, and anthropogenic pressures like over-fishing, eutrophication, invasions or restructuring of coastlines, marine hard bottom ecosystems will structurally reorganize over the coming decades as well (Thompson et al. 2002; Airoldi et al. 2008, 2021; Wahl 2009). Consequences will be shifts in ecosystem services and functions (Thompson et al. 2002; Branch et al. 2008; Wahl 2009; Firth et al. 2014; Bishop et al. 2017).

Mobile forms are not exclusively restricted to one substratum type, therefore most studies on species of hard bottom communities concentrate on sessile taxa (Witman and Dayton 2001; Bonnici et al. 2018). Sessile taxa include all major macroalgal groups, sponges, most cnidarians, few bivalves and sessile gastropods, most bryozoans and phoronids, few boring urchins, tube building annelids, and all ascidians (Wahl 2009).

Hard bottom systems can be subdivided into three different types of substratum: (1) Natural substrate – mineral substrata: natural rock surfaces or surfaces of organic origin e.g. valves or dead clams; (2) Artificial substrate – all of anthropogenic origin; (3) Biogenic (living) surfaces (Davis 2009). This dissertation focuses on the first and second type of substratum.

1.2. Establishment and stability of benthic communities

Community establishment is a continuous succession process which is characterized by both physical and biological interactions (Noël et al. 2009). Succession as such is defined as replacement of species during recolonization following a disturbance or the creation of new substrata (Noël et al. 2009; Sousa and Connell 1992). The colonization of completely new substrate, occurring naturally after an earthquake or by volcanic action, or artificially by the building of new constructions, creating new space for species to settle is called primary succession. Secondary succession follows physical disturbances e.g. waves, ice or sediment scouring, or follows the relaxation of grazing pressure and is defined as the colonization of substrate which may still be partly occupied (Noël et al. 2009).

In marine benthic communities, primary succession starts with physiochemical events, occurring on a very small spatial scale and is followed by biological colonization by bacteria and diatoms (Wahl 1989). The observation of species communities after one year of deployment is often described or seen as a temporary “final stage” of succession as most of the substrata should be covered by macrofauna organisms >1 cm, and subsequently only small changes in community structure should occur (Noël et al. 2009) (Fig 1). However, succession time vary within different regions, and is highly dependent on material and substrate (Sousa and Connell 1992; Benedetti-Cecchi 2000a, b; Lukens and Selberg 2004).

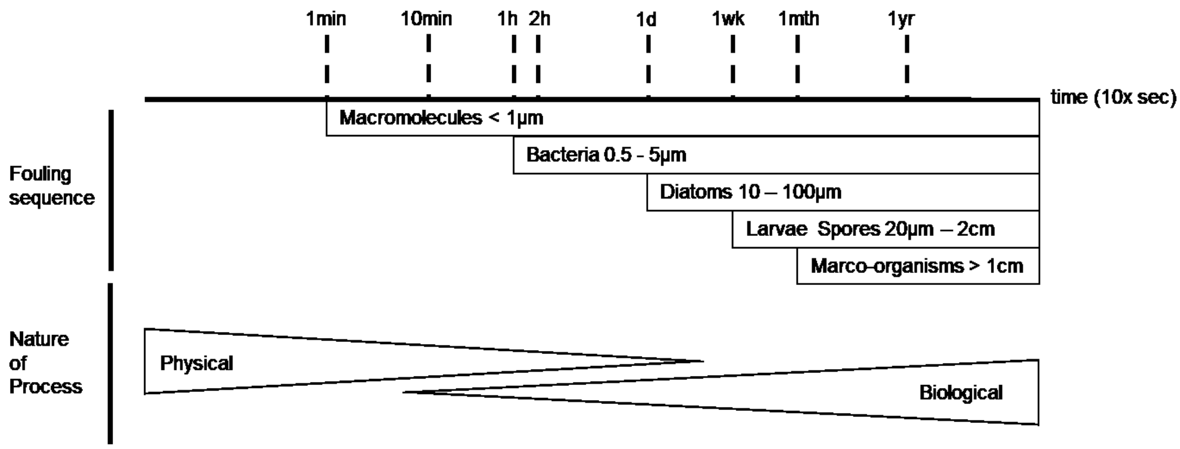


Fig. 1 Generalized schematic model of the succession process (fouling sequence) leading to community establishment (modified from Wahl 1989). Macromolecules were nearly instantaneously adsorbed followed by prokaryote fouling. Diatoms typically settle from the first to second day onward. Larvae and algal spores follow with a lag of one to several weeks (Noël et al. 2009)

Three different succession models describe the interaction between different species during their settlement on open space: facilitation, tolerance, and inhibition (Connell and Slatyer 1977).

Facilitation describes the importance of early settlers. The settlement of propagules of species is necessary for subsequent development of other species. Tolerance suggests that succession is independent of interspecific interaction effect between early and late colonizers. However, a more efficient resource use might exclude early colonizers by their competitors. Inhibition means that early settlers block the colonization of later stages. This is due to an increased

biodiversity in early succession stages. Here, superior competitors dominate over the colonization of new species.
Even though the models of Connell and Slatyer (1977) are criticized for their oversimplification of nature, and for offering little predictive power (Benedetti-Cecchi 2000a), they have given a useful classification on succession processes and have had an enormous influence on subsequent experimental studies (Noël et al. 2009).

1.3. Natural hard bottom habitats in marine coastal environments

Natural stony and coarse-grained habitats, also often referred to as rocky reefs (Taylor 1998), provide important ecological functions for the marine environment. The complexity of seabed characteristics and their surface structures provide different microhabitats leading to a high biodiversity compared to surrounding soft bottom areas (Wenner et al. 1983; de Kluijver 1991; Kühne 1992; Kühne and Rachor 1996; Kostylev et al. 2005; Diesing et al. 2009). Diversity and community structure can differ among regions, but hard bottom habitats worldwide show broad similarities in their distribution patterns of subtidal species (Little and Kitching 1996). Habitats of temperate-boreal rocky coastlines tend to be dominated by macroalgae at shallow depth, giving way to sessile invertebrates as light levels diminish or grazing increases (Witman and Dayton 2001). Macroalgae, which are structuring rocky coastlines and hard grounds in temperate regions, are far less dominant in tropical regions. Here, habitats are rather fringed with coral reefs or dominated by sessile invertebrates such as sponges, gorgonians, anemones, bryozoans, and ascidians (Santileces et al. 2009). Marine subtidal hard substrates provide essential functions in marine ecosystems (Taylor 1998; Firth et al. 2016). They act as settling grounds, shelter, feeding and nursery grounds for diverse sessile and mobile marine animal communities. The scattered occurrence of such habitats represent stepping stones for the dispersal and potential biogeographical range shifts of organisms, e.g. in response to environmental change (Firth et al. 2016; Airoldi et al. 2021).

1.3.1. Natural hard bottom habitats in the German Bight, southern North Sea

The southern North Sea is a marine environment with relatively low proportion of natural hard bottom habitats (Pratje 1951; Bartholomä et al. 2019; Michaelis et al. 2019a). The majority is regarded as residues of the end moraines of the Saalian and Weichselian stages of the last

Glacial Period (Pratje 1951). Coarse-grained areas with very coarse boulders are rare in the German North Sea (Fig 2).

Strong geomorphological gradients have been described for hard substrates in the closer vicinity of Helgoland Island, located 50 km from the nearest mainland (Eidersterdt) in the German Bight (Mielck et al. 2014; Hass et al. 2016; Holler et al. 2017). Grain size up to boulders, and a smoother topographic relief occur in the "Sylter Außenriff" area (Feldens et al. 2018; Papenmeier and Hass 2018). An even smoother relief characterizes the "Helgoländer Steingrund", which is known as one of the rare hard substrates consisting of cobblestone-size to small boulders deposits. In contrast to the widespread and spatially distributed deposits of the "Sylter Außenriff", the "Helgoländer Steingrund" is shaped as a half-moon hard substrate ridge, with different hydrodynamic regimes characterizing the western and the eastern flanks.

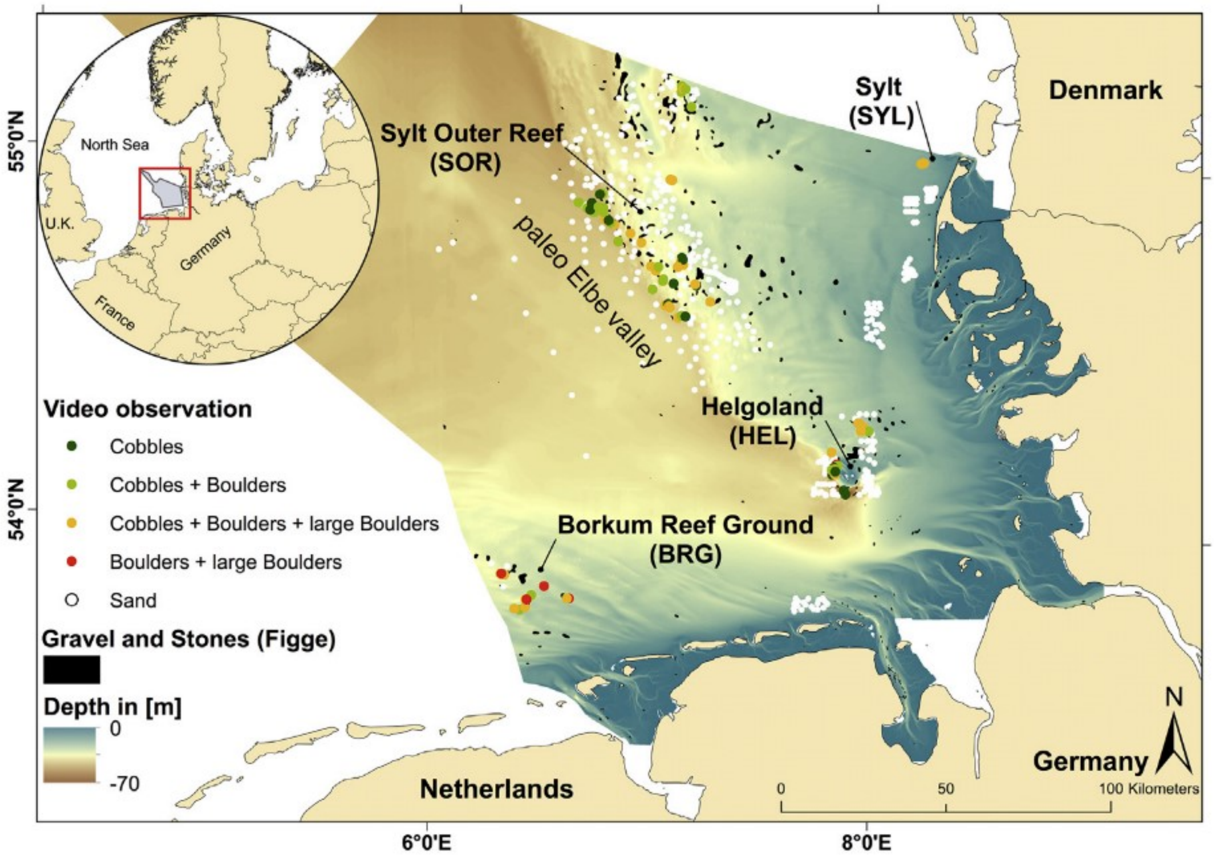


Fig. 2 Hard ground areas in the German Bight (Michaelis et al. 2019a): Areas containing gravel and stones (black areas) in the German Bight. Colored dots indicate the presence of substrate sizes in the range of cobbles to large boulders. White dots show stations with sand only. Bathymetric data were provided by the German Federal Maritime and Hydrographic Agency (BSH, 2018).

Hard substrates located in the southern North Sea hold important ecological habitat functions, as they are nursery and feeding grounds for various fishes, and provide substrate for sessile taxa to settle. The consequences of anthropogenic disturbances, due to an increase in oil and gas exploitation, sand extraction, stone extraction, fisheries, and by the installation of offshore wind farms, are still unclear (Gray 1997; Crowe et al. 2000; Airoldi and Beck 2007; Wahl 2009).
Investigations on epibenthic reef communities in the German Bight (SE North Sea), are to date mostly performed in intertidal zones and in sites dominated by macroalgae around the island of Helgoland (e.g. Schultze et al. 1990; Bartsch and Tittley 2004; Franke and Gutow 2004; Reichert et al. 2008). Studies on subtidal hard substrates are rare (de Kluijver 1991; Kühne and Rachor 1996; Coolen et al. 2015; Michaelis et al. 2019a, b). Settlement of macrofauna communities is influenced by the availability of solar radiation for photosynthesis of macroalgae and by the exposition to water currents (de Kluijver 1991). Kühne and Rachor 1996 and Coolen et al. 2015 highlight the importance of different substrates for the establishment of benthic communities. The latter studies provide extensive species lists including e.g. anthozoans, bryozoans and polychaetes, but mapping of species distribution in heterogeneous habitats has not occurred. Recently, the distance to shore lines as well as the importance of the size of the colonized hard substrate was discussed by non-destructive video sampling methods (Michaelis et al. 2019b).

1.3.2. Natural hard bottom study site – Helgoland Island

Helgoland represents a geologically and ecologically unique location in the south-eastern part of the North Sea (Fig. 2) with a rocky intertidal and subtidal area covering about 35 km^2, designated as a nature reserve since 1981 (Franke and Gutow 2004). Helgoland is geographically and ecologically isolated from similar areas in Norway and Britain by some hundred kilometers of sandy or muddy soft bottoms (Franke and Gutow 2004). The marine environment displays an offshore character, influenced by the North Sea water body (Martens 1978). The area is considered relatively unpolluted, compared to more inshore localities in the southern North Sea (de Kluijver 1991).
While the intertidal areas of Helgoland have been subject to many studies on the composition and interaction of benthic macrofauna and algal communities, relatively little is known from its subtidal areas (Kühne and Rachor 1996; Bartholomä et al. 2019; Becker et al. 2019; Michaelis et al. 2019a). A long-term study on the benthic macrofauna was carried out for the years 1900-2004 for monitoring purposes. Here, 402 taxa were found in all tidal and subtidal regions around

Helgoland between 1950-2004 (Boos et al. 2004). However, only one study was capturing macrofauna and algal communities with subtidal sampling points in close proximity to Helgoland Island (de Kluijver 1991). Since then, no comparable studies have been carried out in these regions (Bartsch and Tittley 2004; Boos et al. 2004). As significant changes were found within the distribution and composition of algal species as result of increasing water transparency since 1975 (Pehlke and Bartsch 2008), it is likely that changes due to the changing environments have also occurred in macrofauna communities.

1.3.3. Natural hard bottom study site – “Helgoländer Steingrund”

The “Helgoländer Steingrund” (HSG; 54°14.00N and 8°03.00W, Fig. 3), an area of ~159 ha, is located approx. 11 km east-northeast of the Helgoland main island in the German Bight, North Sea (Fig. 3) (Stocks 1955; Schulz 1983; Kühne 1992; Kühne and Rachor 1996; Dederer and Schneider 2015). It is included in the Flora-Fauna-Habitat guidelines established in 1992 and is part of BFN nature conservation areas (Schleswig-Holstein Ministerium für Energiewende 2016; BFNReport477 2018). Geologically, the HSG is part of a crescent-shaped end moraine, dated back to the Warthe and partly to the Vistula stages of the Saale glaciation (Pratje 1951; Schulz 1983). The sediment is composed of medium to coarse sands, locally mixed with boulders and pebbles; shallower parts are mainly covered by boulders (Schulz 1983; Kühne 1992). The HSG is formed by several smaller elevations and ground depressions (Schulz 1983). Its shallowest parts lie at depth around 9 m, while surrounding areas are 15-18 m deep (Stocks 1955; Schulz 1983; Kühne 1992; Dederer et al. 2015). Semi-diurnal tide occurs with a range of ~1.5 m. The tidal current model of the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH) shows surface currents velocities between decimeters and more than 1 m/s.

The fauna and flora of the HSG is clearly separated from other areas of the German Bight. The heterogeneity and complexity of the habitat and the otherwise limited availability of natural hard grounds in the German Bight has led to its high biodiversity (Kühne 1992; Kühne and Rachor 1996; Dederer et al. 2015). Dederer et al. 2015 have published a detailed taxa list. A total of 128 hard ground associated taxa have been identified by scuba diving methods, for instance in situ sampling with counting frames, and usage of different photo and video systems (Dederer et al. 2015). Earlier studies with taxonomic background were published by de Kluijver (1991) and Kühne and Rachor (1996). Communities are dominated by the keelworm *Spirobranchus triqueter* (Polychaeta), dead man’s fingers *Alcyonium digitatum (*Anthozoa), encrusting red algae *Phymatolithon* spp., and hornwrack *Flustra foliacea* (Bryozoa) (de Kluijver 1991; Kühne and Rachor 1996; Dederer et al. 2015).

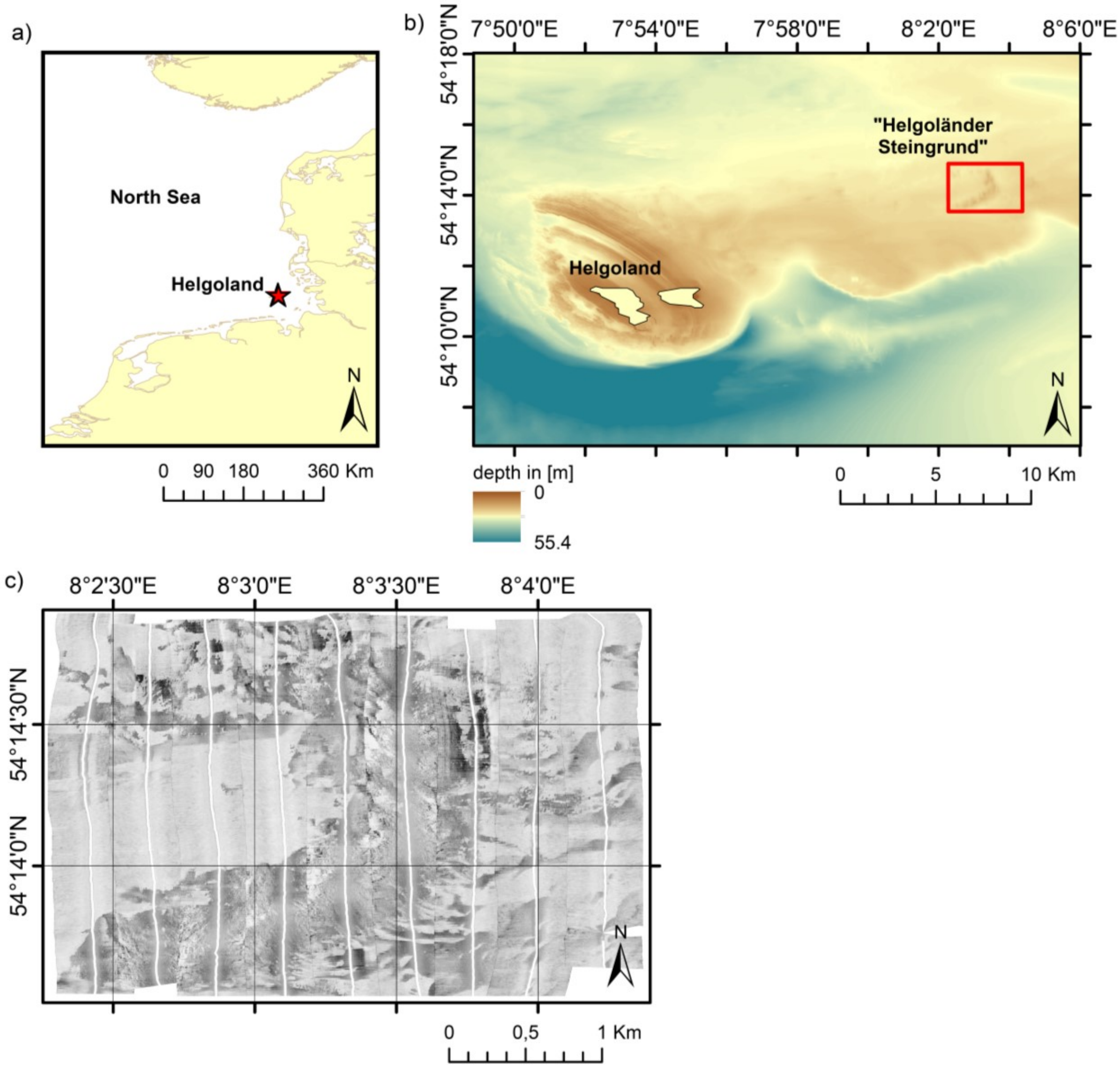


Fig. 3 Study site "Helgoländer Steingrund", North Sea, Germany. a) The red star marks the location of the study site (54° 14.00 N and 8° 03.00 W) within the German North Sea; b) Location of the "Helgoländer Steingrund", about 11 km east-northeast of Helgoland; (Bathymetry data: Sievers et al. 2020) c) Topography of the study area "Helgoländer Steingrund", shown by backscatter mosaic data retrieved from Sidescan Sonar backscatter measurements.

1.4. Artificial substrates in marine coastal environments

Coastal development is a burning issue worldwide (Firth et al. 2020; O'Shaughnessy et al. 2020; Airoldi et al. 2021; Strain et al. 2021). The exponential growth of human populations as well as global changes, such as sea-level rise and an increased frequency of extreme meteorological events (e.g. storms), will further accelerate the transformation of coastal habitats (McGranahan et al. 2007; Halpern et al. 2008; Bulleri and Chapman 2010; Tessler et al. 2015; Firth et al. 2020; Airoldi et al. 2021; Strain et al. 2021). Coastlines globally have been transformed to sustain human activity, with the consequence of irreversible modification of natural systems (Halpern et al. 2008; Knights et al. 2016; O'Shaughnessy et al. 2020). Human activities include shipping and transportation, residential and commercial development, as well as the creation of artificial defense structures to protect urban infrastructure (i.e. seawalls, breakwaters, groynes). The term "ocean sprawl" describes the proliferation of artificial structures in marine and coastal environments, and the subsequent modification and loss of natural substrata (Duarte et al. 2013; Firth et al. 2016; Bishop et al. 2017; Heery et al. 2017).

In most cases artificial structures directly replace natural habitats (Airoldi and Beck 2007). In urbanized centers, artificial structures even form their own intertidal and subtidal habitats (Russel et al. 1983; Davis et al. 2002; Chapman and Bulleri 2003; Airoldi et al. 2005; Airoldi and Beck 2007; Bulleri and Chapman 2010). The result of a replacement of natural habitats by artificial structures is habitat fragmentation (Krauss et al. 2010) and a disruption of natural ecological connectivity (Firth et al. 2016; Bishop et al. 2017). Changes in the geomorphology and hydrodynamics of the surrounding habitats are known consequences of ocean sprawl (Dugan et al. 2008; Nordstrom 2014). In sandy bottom habitat for instance, the morphology of coastlines in close proximity to artificial structures can be modified by a change in longshore sediment transport though changes in wave activity by artificial structures (Dugan et al. 2008; Nordstrom 2014). Runoff from roads and buildings facilitate an increased input of nutrients and pollutants in adjacent water bodies (Barnes et al. 2002; Arnold and Gibbons 2007; Wicke et al. 2012) The loss of natural ecosystem functions and services is highly controversial (Bulleri and Chapman 2010; Todd et al. 2019; Airoldi et al. 2021).

Studies on ecological issues connected to the introduction of artificial structures have to date received relatively little attention (Southward and Orton 1954; Glasby and Connell 1999; Hawkins et al. 2002; Chapman 2003; Bulleri 2006; Bulleri and Chapman 2010; Assi et al. 2018; Bonnici et al. 2018). Bulleri and Chapman (2010) explained: "Compared to artificial reefs, coastal infrastructure has never been built with the objective to enhance populations of certain marine species or particular taxa." Thus, changes caused to biota have long time been considered a side effect. However, present coastal infrastructures do not function as surrogate for natural marine habitats. In contrast to natural hard ground environments, artificial substrata support species typical to hard bottoms but are not analogues of natural rocky or biogenic habitats (Glasby and Connell 1999; Bulleri 2005a). Ecological impacts of coastal infrastructure vary according to the nature of surrounding habitats (Bulleri 2005b).

Impacts of artificial surfaces in natural hard ground environments are considered not to alter the fundamental nature of the natural habitat, especially when surfaces consist of natural stones (Southward and Orton 1954; Hawkins et al. 1983; Thompson et al. 2002; Branch et al. 2008). But there is mounting evidence that structure and functioning of communities associated with artificial structures differ from natural habitats (Glasby and Connell 1999; Rilov and Benayahu 2000; Perkol-Finkel and Benayahu 2004; Moschella et al. 2005; Clynick et al. 2009; Lam et al. 2009; Perkol-Finkel and Sella 2015; Sella and Perkol Finkel 2015). While natural habitats slope gently or have heterogeneous topography, artificial constructions frequently provide vertical habitat (Chapman 2003; Perkol-Finkel and Benayahu 2004; Moschella et al. 2005; Lam et al. 2009). This can lead to highly increased densities of certain species and to an increased strength of interspecific interactions (Moreira et al. 2006; Bulleri and Chapman 2010).

In the case of coastal infrastructure being built in areas which otherwise are characterized as soft bottom habitats, artificial substrate create strong changes in species composition, abundance and diversity (Bacchiocchi and Airoldi 2003). Here, especially the proximity to natural rocky coastlines or reefs influence community characteristics (Airoldi et al. 2009; Clynick et al. 2009). Coastal constructions within ecosystems dominated by soft bottoms typically show a high biomass but consist of few non-specialist macrofauna species. Communities on artificial structures adjacent to areas where natural hard grounds and reefs are present are much more diverse. However, they still never reach the diversity of its surrounding natural hard ground habitats (Airoldi et al. 2008).

1.4.1. Neobiota in artificial construction sites

It is known that especially artificial structures seem to be susceptible to invasion (Bulleri and Airoldi 2005; Glasby et al. 2007; Neves et al. 2007; Tyrrell and Byers 2007). Especially globalization and extended marine traffic together with an increasing infrastructure on coasts worldwide increase the risk of introducing non-indigenous species, so-called neobiota (Bulleri and Chapman 2010). Artificial structures in big ports, which are connected to shipping routes worldwide, hold potential risks for the introduction of neobiota. They appear in greater proportions on artificial structures than in adjacent natural habitats (Glasby et al. 2007). Reasons might entail a higher tolerance to environmental stressors (Dafforn et al. 2009), reduced competitive interaction with extant species, or lower mortality because of predation (Elton 1958; Keane and Crawley 2002).

Closely connected systems of artificial structures, for instance along the European coastlines, provide additional dispersal routes for neobiota, causing drastic changes also to natural environments close by (Glasby and Connell 1999; Glasby et al. 2007). Environmental agencies worldwide closely monitor species causing such changes to the natural marine environment, particularly under the European Water Framework Directive (Mostert 2003) and the Marine Strategy Framework Directive (Olenin et al. 2010).

1.4.2. Impact of material types – The example of concrete

Coastal constructions often consist of "unnatural material". Concrete, plastic, or metal are expected to influence settlement and recruitment of benthic species by differences in their physical properties compared to natural materials (Svane and Petersen 2001; Perkol-Finkel and Benayahu 2004; Chapman and Clynick 2006; Bulleri and Chapman 2010).

Material structure plays an important role for species settlement and diversity. Small microhabitats, like those formed by natural rock pools or overhangs are mostly missing in artificial structures. However, these structures are important for post-settlement survival of plant or animal propagules. Adding microhabitat complexity to an otherwise smooth vertical wall enhances biodiversity and raises the ecological value of artificial structures (Dyson and Yocom 2015). The awareness of the positive effects of so-called "ecological designs" in urban environments is just starting off (Dyson and Yocom 2015; Perkol-Finkel and Sella 2019). However, over the past decades several new approaches were tested with the goal to recover neglected ecosystem services by integrating knowledge of ecosystem processes and functions into urban design practices (Firth et al. 2014; Perkol-Finkel and Sella 2014; Dyson and Yocom 2015; Sella and Perkol Finkel 2015). The process to successfully integrate human society into the natural environment for the benefit of both is labelled "ecological engineering" (O'Shaughnessy et al. 2020). Ecological engineering techniques combine the fixed environmental context of artificial structures (e.g. tidal position, geographic position), their associated biodiversity (i.e., the variety of living organisms) and their role in ecological functioning (O'Shaughnessy et al. 2020). A catalogue for ecological engineering of coastal artificial structures suggesting a multifunctional approach for stakeholders and end-users has been published recently (O'Shaughnessy et al. 2020).

Concrete has been used in seawater-exposed artificial structures (e.g. harbors, causeways, dikes, piers, locks and breakwaters) for decades and is one of the most common materials in coastal constructions worldwide (Bijen 1996; Kosmatka et al. 2008). Due to its availability, durability (50-100 years), formability, and low price, concrete has become one of the most common construction materials worldwide (Jensen and Glavind 2002).

Concrete is a mixture of cement, aggregates, water and small quantities of additives. The cement-water paste "glues" the aggregates into a rocklike mass as the paste hardens because of the hydration process forming Calcium-Silicate-Hydrates (Locher 2006). The quality of the hardened concrete (strength, durability for 50-100 years) depends upon the quality of its constituents, mainly upon cement and aggregates, as well as the quality of the execution of construction work.

The present concrete manufacturing industry is under pressure. Cement production makes up 5-8% of the total anthropogenic CO_2-emissions worldwide, due to the calcination process of limestone and the thermal energy demand for Portland cement clinker production (Humphreys and Mahasenan 2002; Crow 2008; Assi et al. 2018). Portland-cement clinker is a solid material produced in the manufacture as an intermediary product in cement production (Kosmatka et al. 2008). Due to an exploding demand and non-acceptance of additional mining activities, the availability of natural resources commonly used for the aggregates (usually sand and gravel or crushed stone) is limited (Crow 2008; Assi et al. 2018; United Nations Envionment Programme 2019). This makes the reduction of Portland cement production and the increase of supplementary cementitious materials, like granulated blast furnace slags, a byproduct of pig iron production, a dominant topic in the cement industry (Schneider et al. 2011; Ehrenberg 2015; bbs 2016). It is increasingly important to substitute natural aggregates by industrial by-products, also for the concrete producers (bbs 2016).

Within the construction industry, the term “environmentally friendly concrete” refers mainly to the production process (raw materials demand, CO_2 emission) and technical aspects (long term durability). Promising is the use of slags from metal production (e.g. steel, copper). These offer technical advantages due to their mineral properties and have been used in road construction and armor stones for decades (EC 1988). For that purpose, technical and environmental requirements are defined in standards and delivery terms. However, for the aquatic environments, their usage is controversially discussed as there might be unforeseen problems due to uncontrolled leaching of heavy metals out of pure slag stones (BfG 2008).

Regarding environmental aspects, the leaching behavior of concrete has been analyzed in order to protect mainly the groundwater (Dijkstra and van der Sloot 2013). However, due to the binding capacity of the Calcium-Silicate-Hydrates and a very dense pore structure, the leaching of heavy metals should be negligible. In general, and also to protect the marine environment, the usage of alternative materials is regulated depending on the place of its usage, because the European concrete standard EN 206 is not universally aligned. While e.g. the Netherlands allow the use of slags as concrete aggregates, in Germany their use is linked to strong requirements regarding the solid content of heavy metals, in particular Chromium.

Hitherto, little is known on how marine species react to differences in the composition of concrete materials. Species composition and settlement processes might still provide important information on the appropriateness of the use of alternative concrete materials. The few existing international studies show that species react and respond to differences in concrete mixtures (Perkol-Finkel et al. 2008; Perkol-Finkel and Sella 2015; Sella and Perkol Finkel 2015). Encrusting species, e.g. barnacles or tube building Polychaeta can even improve the strength of concrete materials (Perkol-Finkel and Sella 2015).

Positive experiences exist in Japan and Korea for using pure (unbound) steel slags for the construction of artificial seaweed beds (Nakagawa et al. 2010). Some investigations were conducted related to a potential impact of pure electric arc furnace slag being used as armor stones in the Elbe river (Karbe and Ringelband 1995). The results indicate that heavy metal content of algae growing on the slags might increase. However, for some elements like Vanadium this was only observed for the first algal generation. After removing the plants and during a new storing period of the slag samples under water, there was no difference detected in the Vanadium content of algae growing on slags and on natural stones. A report from the German Federal Institute for Hydrology (BfG 2008) reviewed further studies on pure armor stones made from different types of metallurgical slags in German rivers, indicating an accumulation of heavy metals in macrofauna. However, more systematic investigations are required. In contrast, investigations in the Netherlands on the use of steel slags in mesocosm experiments and in the field revealed that heavy metal concentrations increased in short term but, under the condition of fresh water exchange, no negative impact of heavy metals on the ecosystems became apparent (Oosterschelde region; (Foekema et al. 2016).

The experiments from the Netherlands also indicate that the leaching behavior of pure by-products can have different impacts depending on the surrounding environment (Foekema et al. 2016). Under conditions of low turbulence, like in a channel, the water exchange and thus the water/slag ratio is much lower than in a river or the open ocean. Therefore, the impact on the environment will be more drastic in a small channel than in a bigger floating system.

1.4.3. Study site for artificial materials – The JadeWeserPort

Fig. 4 Study site – JadeWeserPort, Wilhelmshaven, southern North Sea, Germany a) Location of the Port b) Overview on the port facilities c) deployment site, service port (Photographs are used with permission of the JadeWeserPort)

The JadeWeserPort is the easternmost deep-water port from the Nordrange, meaning a list of the most important continental European Ports of the North Sea. It is tide-independent till 18 m water depth (Fig 4) (JWP 2020a). Port construction started in 2008. In April 2012 its trial operation started and the port has been running official business since September 2012 (JWP 2020a). It holds 130 hectares of Container Terminals out of 340 hectares total area. It has a turnover capacity of 2.7 million TEU/year (JWP 2020b). In 2019, transfers of 29.29 million t were documented which is +7 % compared to 2018 (Jahrespressekonferenz Niedersächsiche Seehäfen 2020).

The neobiota report of the German coast lines 2014 (Rhode et al. 2015) reports a total of 116 taxa for the JadeWeserPort, of which 17 were neobiota to the German North Sea coastline. Swimming pontoons, located in the so-called service port, were reported as the species richest habitat of the harbor (Rhode et al. 2015). Here, a total of 63 Taxa were found; 14 of them were neobiota (Rhode et al. 2015).

1.5. Objectives of the thesis

Multitudes of environmental aspects influence the ecology of natural and artificial hard bottom systems in marine coastal environments. Substrate characteristics influence for instance settlement and community stability. This dissertation will specifically address the following objectives:

a. define key roles of natural and artificial substrates with regard to production and ecosystem services
b. characterise how natural and artificial substrates affect the establishment of benthic communities
c. analyse the significance of artificial substrates as stepping stones for biological invaders

For this, the following questions were addressed:

1. What kind of ecosystem services are provided by natural coastal systems and how can they be implemented into marine artificial environments?
2. What are the main drivers in benthic community establishment of natural and artificial habitats?
3. What is an "environmentally friendly" artificial material?
4. What are the risks of natural and artificial structures regarding invasion by neobiota and which measures can be taken to protect natural and artificial grounds?

1.6. Thesis outline

All studies presented in this dissertation were conducted in the southern North Sea areas of the German Bight. The target of **Chapter 2** and **Chapter 3** was to observe and combine biotic and abiotic environmental conditions of a natural hard bottom system of the German Bight. Two interdisciplinary studies were conducted in the "Helgoländer Steingrund", a subtidal natural hard bottom area off Helgoland Island. In the field, different tools of hydroacoustic (Side Scan Sonar, sediment sampling), and hydrodynamic systems (ADCP), as well as the relatively new tool of non-destructive video analysis were applied to provide a comprehensive understanding of environmental conditions in an area with low visibility and high habitat complexity.

Chapter 2 describes the use of presence/absence data of species, generated by ground truth video sampling as the basis for modeling high quality small-scale distribution maps of benthic species. Since available datasets on the distribution of sediments and local current conditions were not up-to-date, hydroacoustic grids on sediments, depth and velocities needed to be generated in advance. Challenging was the heterogeneity and low visibility of the "Helgoländer Steingrund".

Chapter 3 further adds and discusses information on hydrodynamic and hydroacoustic measurements in the area of the "Helgoländer Steingrund". Special focus was laid on the comparison of different hydroacoustic and hydrodynamic measurement tools adding information to peculiarities of the environmental conditions in the study area. The difficulties and limitations of hydrodynamic and hydroacoustic tools in gaining precise information while working in an area with high habitat complexity and low visibility are discussed.

Chapter 4 and **Chapter 5** describe the establishment of benthic communities on cubes (15 x 15 x 15 cm) made of five different concrete mixtures, containing different cements (Portland cement and blast furnace cements) and aggregates (sand, gravel, iron ore and metallurgical slags) after one year of deployment. The emphasis here was to find out whether there are differences in established community composition, depending on differences in concrete constitutes. Consequences for the usability of alternative concrete constituents in marine constructions are discussed.

Chapter 4 describes the outcome of the settlement experiment conducted in a natural hard ground experimental field near to Helgoland Island (German Bight).

Chapter 5 focuses on the outcome of succession experiments conducted in the JadeWeserPort, Wilhelmshaven, Germany, as an example of a recently erected artificial habitat with high anthropogenic impact. Results are compared to the natural study site of Helgoland. In addition, the influence of artificial materials on the introduction of neobiota are the focal point of this chapter.

1.7. List of publications and declaration of contributions

Publication I

<u>Title:</u> Small-scale distribution modeling of benthic species in a protected natural hard ground area in the German North Sea (Helgoländer Steingrund)

<u>Authors:</u> **L. R. Becker**, A. Bartholomä, A. Singer, K. Bischof, S. I. I. Coers, I. Kröncke

<u>Journal:</u> Geo-Marine Letters (2020) 40:167–181
https://doi.org/10.1007/s00367-019-00598-8

<u>Contribution of the candidate in % of the total workload</u>
Experimental concept and design: 70%
Experimental work and acquisition of the data: 70%
Data analysis and interpretation: 80%
Preparation of figures and tables: 100%
Drafting of the manuscript: 95%

Publication II

<u>Title:</u> Hydrodynamics and hydroacoustic mapping of a benthic seafloor in a coarse grain habitat of the German Bight

<u>Autors:</u> A. Bartholomä, R. M. Capperucci, **L. R. Becker**, S. I. I. Coers, C. N. Battershill

<u>Journal:</u> Geo-Marine Letters (2020) 40:183–195
https://doi.org/10.1007/s00367-019-00599-7

<u>Contribution of the candidate in % of the total workload</u>
Experimental concept and design: 40%
Experimental work and acquisition of the data: 60%
Data analysis and interpretation: 30%
Preparation of figures and tables: 10%
Drafting of the manuscript: 20%

Publication III

Title: The role of artificial material for benthic communities – establishing different concrete materials as hard bottom environments

Autors: **L. R. Becker**, A. Ehrenberg, V. Feldrappe, I. Kröncke, K. Bischof

Journal: Marine Environmental Research (2020) 161
https://doi.org/10.1016/j.marenvres.2020.105081

Contribution of the candidate in % of the total workload:
Experimental concept and design: 70%
Experimental work and acquisition of the data: 70%
Data analysis and interpretation: 80%
Preparation of figures and tables: 100%
Drafting of the manuscript: 90%

Publication IV

Title: Benthic community establishment on different concrete mixtures introduced to a German deep-water port

Autors: **L.R. Becker**, I. Kröncke, A, Ehrenberg, V. Feldrappe, K. Bischof

Journal: Helgoland Marine Research (2021) 75:5 https://doi.org/10.1186/s10152-021-00550-3

Contribution of the candidate in % of the total workload:
Experimental concept and design: 70%
Experimental work and acquisition of the data: 70%
Data analysis and interpretation: 85%
Preparation of figures and tables: 100%
Drafting of the manuscript: 95%

CHAPTER 2 – Publication I

2.1. Small-scale distribution modeling of benthic species in a protected natural hard ground area in the German North Sea (Helgoländer Steingrund)

Becker, L.R., Bartholomä, A., Singer, A., Bischof, K., Coers, S., Kröncke, I

Becker, L.R., Bartholomä, A., Singer, A., Bischof, K., Coers, S., Kröncke, I. (2019). Small-scale distribution modeling of benthic species in a protected natural hard ground area in the German North Sea (Helgoländer Steingrund). Geo-Marine Letters 40:167–181 doi:10.1007/s00367-019-00598-8

Geo-Marine Letters (2020) 40:167–181
https://doi.org/10.1007/s00367-019-00598-8

ORIGINAL

Small-scale distribution modeling of benthic species in a protected natural hard ground area in the German North Sea (Helgoländer Steingrund)

Lydia R. Becker[1,2,3] · Alexander Bartholomä[2] · Anja Singer[1] · Kai Bischof[3] · Susanne Coers[1,2] · Ingrid Kröncke[2,4]

Received: 14 February 2019 / Accepted: 23 September 2019 / Published online: 24 October 2019

Abstract
Natural stony and coarse-grained habitats entail important ecological features for the marine environment. Due to the complexity of their bottom characteristics, they host a high biodiversity compared to surrounding soft bottom areas. The German nature conservation area "Helgoländer Steingrund" (HSG; 54°14.00 N and 8°03.00 W) is subject to regular monitoring but lacks information on the spatial distribution of benthic species. Within this study, a new approach using species distribution models (SDM) was tested to fill these gaps of knowledge. Newly recorded environmental data (depth, sediments, current velocities) in the HSG and information on the presence and absences of nine benthic species (*Echinus esculentus*, *Metridium senile*, *Cancer pagurus*, *Phymatolithon* spp., *Axinella polypoides*, *Homarus gammarus*, *Flustra foliacea*, *Alcyonidium diaphanum*, *Alcyonium digitatum*), collected using video analysis of drop camera records, was used to perform SDMs. The models revealed good evaluation measures (true skill statistic > 0.7; area under the receiver operation characteristic curve > 0.90), implying that the model showed good predictive performance for the potential distribution of the tested species. The outcome of this study is a clear recommendation on SDM application in further environmental monitoring programs on the HSG and other protected hard ground areas.

Introduction

In recent years, the demand for developing standards for seafloor and benthic habitat mapping has significantly increased from governmental organizations as well as from the scientific community. As such, standards need to be implemented for monitoring programs and coastal resource management (Robinson et al. 1996; Forster-Smith et al. 1999; Davies et al. 2001; Bartholomä 2006; Ehrhold et al. 2006; Reiss et al. 2014; Hass et al. 2016). Much of the information on the spatial distribution of marine species and habitats needed for robust decision making is currently lacking (Ehrhold et al. 2006; Pearson 2010; Reiss et al. 2014; Hass et al. 2016; Singer et al. 2016). Lately, substantial progress in the development of predictive species distribution modeling (SDM) has been made (Mouquet et al. 2015). Within terrestrial ecology, information from SDM studies is already used for conservation and management purposes, but also forecasting the effects of environmental or climate changes via SDM is becoming more and more important (Guisan and Thuiller 2005; Reiss et al. 2011). In marine science, predictive models have addressed a variety of research goals, with a focus on the design of conservation strategies, but still represent novel tools (Robinson et al. 2011, 2017; Reiss et al. 2014). The development of SDMs in the marine environment is facilitated by increasing availability of large-scale environmental data (Degraer et al. 2008; Glockzin et al. 2009; Gogina et al. 2010; Reiss et al. 2011). SDMs in marine ecosystems mostly deal with the distribution of commercial fish species (Venables and Dichmont 2004; Maxwell et al. 2009; Moore et al. 2010; Lenoir et al. 2011; Reiss et al. 2014). Only few studies have applied SDMs to the distribution of marine invertebrate benthos (Reiss et al.

✉ Lydia R. Becker
lkohlmorgen@marum.de; lydia@uni-bremen.de

1 INTERCOAST Research Training Group, University of Bremen, Leobener Strasse, 28359 Bremen, Germany

2 Senckenberg am Meer, Department for Marine Research, Südstrand 40, 26382 Wilhelmshaven, Germany

3 Department of Marine Botany, University of Bremen, Leobener Str. NW2, 28359 Bremen, Germany

4 Institute for Chemistry and Biology of the Marine Environment, University of Oldenburg, Carl-von-Ossietzky-Straße 911, 26133 Oldenburg, Germany

2014; Neumann et al. 2017). For example, local-scale studies for polychaete distributions and other benthic communities have been carried out in German North Sea and Belgium waters (Degraer et al. 2008; Willems et al. 2008; Meißner et al. 2008). Macrofauna distribution in soft substrates has been modeled for the intertidal of the Jade Bay in the southern North Sea (Singer et al. 2016, 2017). However, to date, no studies are available where subtidal hard ground areas in the German North Sea have been modeled, even though most hard grounds were included in German and EU nature conservation programs (Michaelis et al. 2019a).

Natural stony and coarse-grained habitats, also often referred to as rocky reefs (Taylor 1998), provide important ecological features for the marine environment. Their complexity of seabed characteristics and their surface structures provide different microhabitats leading to a high biodiversity, compared to surrounding soft bottom areas (Wenner et al. 1983; de Kluijver 1991; Kühne 1992; Kühne and Rachor 1996; Kostylev et al. 2005; Diesing et al. 2009). Diversity and community structure can differ among regions, but stony and coarse-grained habitats worldwide show broad similarities in the distribution patterns of subtidal species (Little and Kitching 1996). Habitats of temperate-boreal rocky coastlines tend to be dominated by macroalgae at shallow depth, giving way to sessile invertebrates as light levels diminish or grazing increases (Witman and Dayton 2001). Macroalgae, which are structuring rocky coastlines and hard grounds in temperate regions, are far less dominant in tropical regions. In which case, habitats are fringed with coral reefs or dominated by sessile invertebrates such as sponges, gorgonians, anemones, bryozoans, and ascidians (Santileces et al. 2009).

To cover large-scaled spatial distribution patterns, seafloor mapping by underwater remote sensing technology coupled with automatic seabed classification has developed rapidly within the last decade (e.g., Kendall et al. 2005; Bartholomä 2006; Bartholomä et al. 2011; Hass et al. 2016; Holler et al. 2017). Hydroacoustic methods enable extensive seafloor mapping in a short time period (Kenny et al. 2000). The acoustic backscatter signals reflect abiotic and biotic properties such as surface roughness and grain size (e.g., Wienberg and Bartholomä 2005; Bartholomä 2006; Bartholomä et al. 2011; Markert et al. 2013), as well as coverage by benthic communities. Mussel beds and shell debris (Wienberg and Bartholomä 2005; Van Overmeeren et al. 2009), coral reefs (Gleason 2009; Foster et al. 2019), macroalgae (Preston 2006; Hass and Bartsch 2008; Mielck et al. 2014), and reefs of tube-building polychaetes (e.g., Degraer et al. 2008; Kröncke et al. 2018) can be mapped by hydroacoustic measurements. However, there are some challenges to overcome in generating small-scale environmental data within heterogeneous hard ground areas. To support underwater remote sensing technology, ship supported drift camera systems are used (Kendall et al. 2005). These camera systems operate well in areas with high visibility and low suspension loads that occur for instance in tropical regions. Only a few studies have used ship-based drift camera systems within areas of low visibility and high suspension loads, like the North Sea (Michaelis et al. 2019a, b). Here, ground-truthing and the investigation of macrofauna distribution by video analysis are still in its early stages.

The following study combines methods of seafloor habitat mapping (by Sidescan Sonar, single-beam echosounder, acoustic Doppler current profiler, bottom grab samples) and drift video tracks in a natural hard ground area of low visibility within the German North Sea, the "Helgoländer Steingrund" (HSG). Information was used to generate species distribution maps via SDM modeling. The HSG, one of few natural stony and coarse-grained habitat within the German Bight (Michaelis et al. 2019a, b), comprises an area of about 159 ha and is located about 11 km east-northeast off the island of Helgoland (Dederer et al. 2015). The HSG is included in the Flora-Fauna-Habitat guidelines and is part of the German nature conservation areas (Schleswig-Holstein Ministerium für Energiewende 2016; BFN Report 477 2018), which are interlinked network areas within the European Union. As such, the HSG represents a protected area and is subject to regular monitoring (Dederer and Schneider 2015). Former studies have shown that benthic species populating the HSG developed their environmental niche over a long time period of relatively stable environmental conditions (de Kluijver 1991; Kühne and Rachor 1996). This makes them appropriate indicators for long-term ecological studies and for SDM, where a robust database on species presences as well as on the environmental context is essential for reliable verification of the model output (Robinson et al. 2017).

This study addresses the questions:

(1) Are hydroacoustic-based environmental grids sufficient to represent the distribution of sediments, depth, and velocities in the HSG area, as example of a heterogeneous natural stony and coarse-grained habitat?

(2) Is ground truth video sampling a good tool to represent species presences and absences in an area of low visibility as a basis for high-quality species distribution maps of the HSG area?

Material and methods

Study site and physical settings

The "Helgoländer Steingrund" (HSG; 54°14.00 N and 8°03.00W) is a natural hard ground area of ~ 159 ha, approx. 11 km east-northeast of the Helgoland main island in the German Bight, North Sea (Fig. 1) (Stocks 1955; Schulz

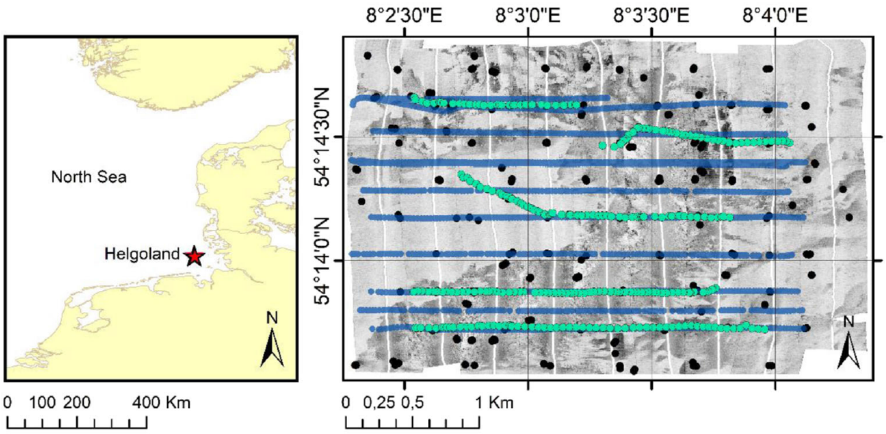


Fig. 1 Left: The red star marks the location of the study site Helgoländer Steingrund (54° 14.00 N and 8° 03.00 W) within the German North Sea; right: HSG study area, showing Sidescan Sonar backscatter mosaic by Sidescan Sonar measurements, location of sediment sampling (black dots), location of the five sampled video profiles (green lines), and location of the ADCP measurements (blue lines)

1983; Kühne 1992; Kühne and Rachor 1996; Dederer and Schneider 2015). It is included in the Flora-Fauna-Habitat guidelines established in 1992 by the German government and is part of the BFN nature conservation areas (Schleswig-Holstein Ministerium für Energiewende 2016; BFN Report 477 2018). The HSG is formed by several smaller elevations and ground depressions from NNW to SSW direction, often described as half-moon-shape structure (Schulz 1983). The shallowest parts are located at around 9 m depth, while surrounding areas are at depths from 15 to 18 m (Stocks 1955; Schulz 1983; Kühne 1992; Dederer and Schneider 2015). Geologically, the HSG is part of a crescent-shaped end moraine, dated back to the Warthe and partly to the Vistula stages of the Saale glaciation (Pratje 1951; Schulz 1983). Its sediment is composed of medium to coarse sands, locally mixed with boulders and pebbles; shallower parts are mainly covered by boulders (Schulz 1983; Kühne 1992). The water temperature of the HSG varies seasonally from 2 to 19 °C, the salinity varies from 30 to 33, influenced by the fluctuating estuarine water inflow from the river Elbe (Kühne and Rachor 1996). Tidal currents mean velocity of 0.6 kt enables almost saturated concentrations of oxygen 8–10 mg/l^{-1} in the bottom waters (Kühne and Rachor 1996).

The fauna and flora of the HSG are clearly separate from other areas of the German Bight. The heterogeneity and complexity of the habitat and the otherwise limited availability of natural hard grounds in the German Bight has led to a high biodiversity compared to the surrounding soft bottom habitats (Kühne 1992; Kühne and Rachor 1996; Dederer and Schneider 2015). A detailed taxa list of the HSG has been published recently (Dederer et al. 2015). A total of 128 hard ground associated taxa have been identified by scuba diving methods, for instance in situ sampling with counting frames, and usage of different photo and video systems (Dederer et al. 2015). Earlier studies describing taxa present in the HSG were published by de Kluijver (1991) and Kühne and Rachor (1996). Communities of the HSG are dominated by the keel worm *Spirobranchus triqueter* (Polychaeta), dead man's fingers *Alcyonium digitatum* (Anthozoa), encrusting red algae *Phymatolithon* spp., and hornwrack *Flustra foliacea* (Bryozoa) (de Kluijver 1991; Kühne and Rachor 1996; Dederer et al. 2015).

Surveys—sampling procedure and analysis

Sampling took place during five 1-week cruises over summer and autumn with the RV "SENCKENBERG" in 2016 and one cruise in November 2018. The five sampling campaigns in 2016 included Sidescan Sonar measurements in May (1 cruise), sediment sampling from June to August (3 cruises), and video sampling on August 31 (1 cruise). Acoustic Doppler current profiler (ADCP) measurements were performed during the cruises in 2016 and 2018.

Sidescan Sonar recordings

A Benthos SIS-1624 dual frequency Sidescan Sonar system (SSS) was used to collect data along nine north-south oriented profiles (Fig. 1), which were 250 m apart from each other and 2500 m long. The SSS system was operated at frequencies of 123 kHz and 382 kHz. A swath range of 300 m was selected, which resulted in an overlap of 50 m between adjacent profiles.

Sediment sampling

Sediment samples were taken with a 0.2-m^2 Shipek grab. Once sufficient sediment material was present in the grab, a subsample for grain size analysis was taken after a photographic documentation of the grab contents. Stations at which the Shipek grab was empty were marked as hard bottom grounds, with the assumption that no sediment material was present on these grounds. In total, 356 sediment samples were taken in the HSG area. One hundred ninety-eight samples were taken on a predefined grid (66 sites, 3 replicates each). The other 158 samples were taken in selected morphologically distinct areas based on the SSS mosaic (Fig. 1). Grain size measurements of sediments were performed by measurements of settling velocities. In the lab, the samples were desalted in semi-permeable hoses over 24 h. The desalted samples were then washed through a 63-μm mesh size sieve to separate the mud fraction (< 63 μm) from the sand fraction (> 63 μm). Grain size distribution was calculated using settling velocities to provide hydraulic grain sizes. The sand fraction (2000–63 μm) was measured in the settling tube MacroGranometer (Brezina 1979), and the finer fractions of silt and mud were analyzed in a Micrometrics Sedigraph. The settling velocities were transformed into hydraulic grain sizes.

ADCP measurements

Current velocities were measured over tidal cycles by means of a vessel mounted Teledyne ADCP (acoustic Doppler velocity profiler) Rio Grande 1200 kHz system and with an installation depth of 1.1 m below the water surface. The system has been coupled with D-GPS positioning (also for heading). Compass calibration achieved a good fit with less than 5° angle variation in direction between the bottom track and D-GPS track. Because of the water depth of almost 20 m, the system has been configured in high-frequency mode (Water Mode 12) with a bin size of 25 cm to cover the entire water column. To reduce the noise of individual ensembles, the data were smoothed by an average of 10 ensembles. The tracks were orientated parallel and perpendicular to the ridge of the half-moon-shaped structure of the HSG. For the time series analysis, the W-E-orientated tracks were considered (Fig. 1).

Video recordings

A drop camera (Kongsberg 1366 MKII-0321), protected by a stainless steel drop-down frame, was used to collect data on the biotic communities and on sediment distribution. Five profiles were chosen from the analysis of hydroacoustic backscatter data from previous surveys. The profiles covered areas of low and high backscatter, as well as transition zones (see Fig. 1). Depending on the time span of the profile camera, drops lasted from 35 to 70 min. While recording, the video and the position of the camera GPS (error value ± 5 m) were transmitted on a live screen. Recordings were saved for further visual analysis.

Data processing

Macrofauna data: extraction and selection

For data extraction, the video of each profile was separated into segments of 1 min. We logged GPS coordinates at the start of each 1-min sequence as reference point for the presence and absence of nine benthic species (*Echinus esculentus*, *Metridium senile*, *Cancer pagurus*, *Phymatolithon* spp., *Axinella polypoides*, *Homarus gammarus*, *Flustra foliacea*, *Alcyonidium diaphanum*, *Alcyonium digitatum*). *E. esculentus*, *F. foliacea*, *A. digitatum*, *Phymatolithon* spp., and *H. gammarus* were chosen as the characterizing species for the HSG according to the FFH guidelines (Dederer et al. 2015). In addition, *A. polypoides* represents one sponge, and *M. senile* one cnidarian species. *A. diaphanum* was present with similar high abundances as *F. foliacea,* thus represents another dominant bryozoan species. *C. pagurus*, like *H. gammarus*, represents a mobile predator of the HSG. Since, the video profile lines cut through the HSG areas of low and high backscatter, as well as transition zones, we assumed that we captured all parts of the study site that relate to the environmental characteristics. The resulting maximum distance between the sampling points varied from 10 to 50 m, representing an adequate distance for benthic species and full spatial coverage. Each transect was evaluated individually by two persons to guarantee representativeness of data.

Environmental data: processing and selection

In total, nine grids were generated from the collected environmental data of the HSG, six from the sediment samples, one from Sidescan Sonar measurements, one from bathymetry measurements, and one from the ADCP surveys. Data were further processed in ArcGIS10.2 © Esri by using the Bayesian Kriging interpolation method for bathymetry data and local polynomial interpolation for sediments. The environmental sediment grids include the percentage of sand, gravel, mud, shell < 2 mm, shell > 2 mm, and "hard ground". The side scan data was post-processed into mosaics using *SonarWiz Vers 7.2* and georeferenced by ArcGIS10.2 © Esri. The bathymetry data were measured with a single-beam echosounder coupled with a motion sensor and Differential Global Positioning System (DGPS). The ADCP mean current velocities were averaged over a depth of 0 to 2 m above bed over the 0.25 m bin size intervals using the USGS Velocity Mapping Toolbox (Parsons et al. 2013). The tide correction was made on the basis of the water level of Helgoland port provided by the German Federal Institute of Hydrology BfG. All grids were converted with ArcGIS10.2 to have the same extent (5.75 km^2), coordinate system (WSG_1984), and resolution (5 m).

Prior to modeling, all environmental variables were tested for predictor collinearity (Pearson's correlation coefficient, $r \pm 0.7$, Booth et al. 1994; Dormann et al. 2013). Only predictors were implemented that fell below the critical threshold of $r \pm 0.7$. Because of high collinearity ($r = 0.76$) with "hard grounds", the sand layer was omitted. "Hard grounds" were regarded as a more important variable for model species. We also omitted the Sidescan layer, since measurement quality is poor and does not improve the quality of the model output.

SDM "Biomod2"—modeling statistical analyses

Model algorithms, settings, and evaluation

Within this study, the ensemble forecasting platform "biomod2" v.3.3-7 (Thuiller et al. 2016) was applied for SDM, implemented in R v.3.3.2 (R Development Core Team 2015). Numerous SDM studies have successfully applied both "biomod" and its updated version "biomod2" to terrestrial and marine grounds (Thuiller et al. 2009, 2016). The model runs up to 10 commonly used modeling algorithms; classification, regression, and machine learning techniques can be applied. The modeling algorithms that were used were chosen from Singer et al. (2016, 2017). Here, the model setup was selected for four highly recommended presence-absence SDM techniques, which resulted in excellent small-scale distribution model performance: random forest (RF, Breiman 2001) and generalized boosting models (GBM, Ridgeway 1999) as two machine learning techniques, and multivariate adaptive regression splines (MARS, Friedman 1991) and generalized linear models (GLM, McCullagh and Nelder 1998) as two regression-based methods. A short description of the four applied and merged SDM algorithms and their respective key literature can be found in Singer et al. (2016, 2017).

Further, "biomod2" gives the possibility of calculating and comparing different evaluation measures, like the true skill statistic (TSS) and the area under the receiver operating characteristic curve (AUC) (Thuiller et al. 2009, 2016). To account for inter-model variabilities and single-algorithm uncertainties, multiple modeling algorithms are merged in "ensemble models" (EM). "Biomod2" provides several techniques to generate these EM. This study applied the "mean of probabilities" ensemble building technique, which results in a more robust prediction than other techniques like "committee averaging" (Marmion et al. 2009). Default parameter modeling settings (Georges and Thuiller 2013) were modified. For GBMs, 3000 trees were used as fitting basis; for RF, 500 trees were built (see Reiss et al. 2011).

"Biomod2" uses a randomization procedure that is independent of the applied modeling algorithm to calculate the importance of each employed variable in the ensemble model. Pearson's correlation between the standard predictions (or fitted values) and randomly permuted environmental variable predictions are used. High values of the predictor variable indicate high importance of the predictor (Thuiller et al. 2009, 2016). Each variable importance score is given as a rank value, i.e., 1 minus the correlation score. To compare species-specific models, raw variables importance scores were standardized. The score of each predictor was divided by the sum of all predictor scores.

EM response curves were calculated within biomod2 after Elith et al. (2005), using the algorithm-independent evaluation strip method; $n - 1$ variables were set constant to the mean value. The resulting curve shows the sensitivity of the model to the specific variable (Thuiller et al. 2016).

Model evaluation

Species presences were randomly split into test data (30%) and training data (70%). Ten replicate runs per algorithm (40 runs per species) were performed to account for model variability. For model evaluation, TSS and AUC, two highly recommended evaluation measures (Fielding and Bell 1997; Allouche et al. 2006), were calculated. They account for the proportion of the two prediction types of correctly predicted presences "sensitivity," and correctly predicted absences "specificity" in the error matrix. Thus, all four elements of the error matrix derived from the test data were considered (Pearson 2010). A threshold and prevalence-independent measure is given by the AUC value, which is defined by plotting sensitivity versus the corresponding proportion of false positives ('1-specificity) across the range of possible thresholds (Pearson 2010). AUC gives values from 0 to 1, 0.7 indicating a statistically reliable model performance (Hosmer and Lemeshow 2000).

The TSS is prevalence independent but needs a specific threshold level (Allouche et al. 2006). The TSS values range from − 1 to + 1 (formula: "sensitivity + specificity − 1"). A statistically reliable model performance is given by values above 0.4 (Allouche et al. 2006; Landis and Koch 2013). For the HSG model output, only the best fitted model runs above critical thresholds of > 0.4 TSS and > 0.7 AUC as implemented in the final ensemble model. Maps show the EM result from the test data based on the mean TSS values.

Results

Present habitat conditions in 2016

The environmental grids of depth, sediment distribution, and current velocities are shown in Fig. 2. Depth ranged from − 18 to − 6 m, and the characteristic half-moon-shape structure of elevations and ground depressions is apparent. The distribution of pure hard ground areas, not covered by layers of gravel, shell, or mud, is located at the northern and southwestern parts of the half-moon-shape structure. However, the study site sediments are dominated by the sand and gravel fraction, laterally mixed with shell fragments in some parts. The highest gravel content of ~ 30 weight% was present within the southeastern parts of the HSG, adjacent to the half-moon-shape structure. The maximum amount of very fine sediment consisting of the mud fraction (silt and clay) is less than 2 weight%. The highest

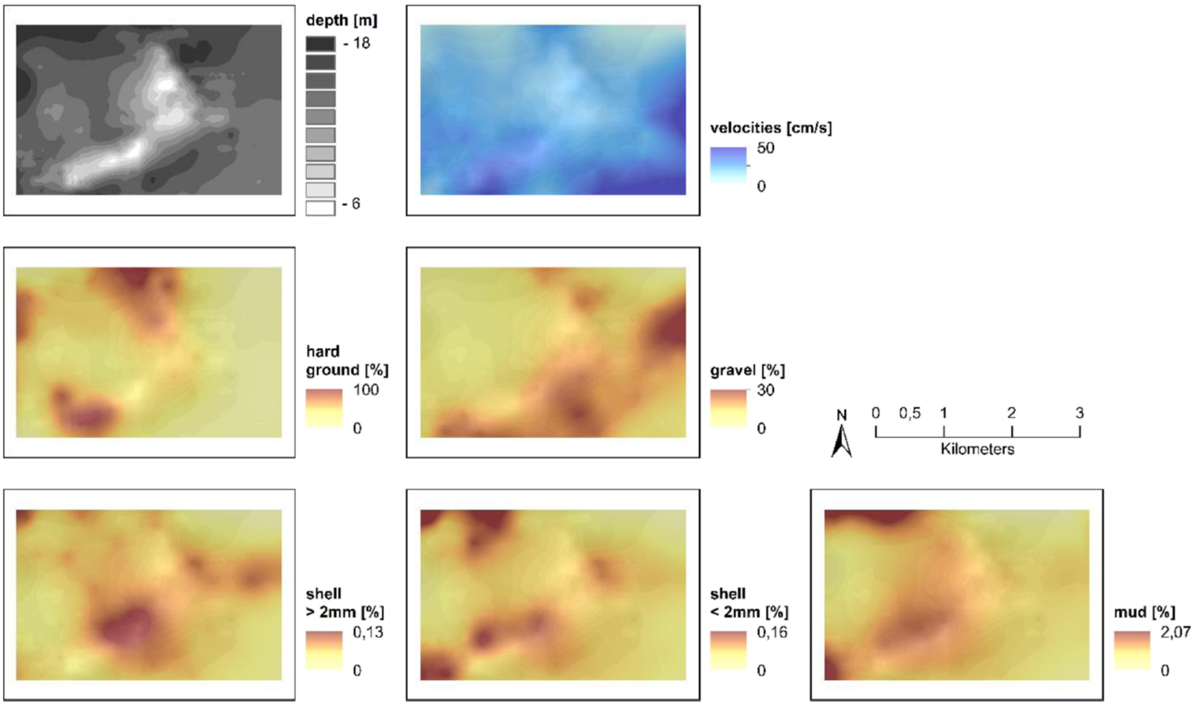


Fig. 2 Interpolated grids of all 7 environmental variables employed in the SDM: depth [m], gravel weight [%], hard ground [%], mud weight [%], shell< 2 mm weight [%], shell > 2 mm weight [%], and depth-averaged velocities [cm/s] (averaged over depth 0 to 2 m above bed). Grids have the same extent (5.75 km^2), coordinate system (WSG_1984), and resolution (5 m). For orientation, all environmental grids show the depth layer in the background

mud content of ~ 2 weight% was present in the southwestern part right before the elevation of the half-moon-shape structure, as well as in the deeper northwestern part of the HSG. Shell content (< 2 mm; > 2 mm; > 0.1 weight%) was also highest in the southwestern parts of the HSG. In contrast to the distribution of mud, higher shell content was also found in the eastern parts of the HSG.

The highest velocities (averaged over depth 0 to 2 m above bed) of 50 cm/s were located in the southeastern parts of the HSG. High velocities were also partly present in the southeastern parts of the HSG. Lowest velocities were found in the northern part of the HSG.

Present macrofauna distribution (2016)

Model evaluation

True skill statistic (TSS) and area under the receiver operation characteristic curve (AUC) values of the chosen species indicate good to excellent performances for the predicted ensemble models. All TSS values were > 0.7 and all AUC values were > 0.90 (Table 1). The prediction of the species *M. senile* (TSS = 0.94, AUC = 0.99), *Phymatolithon* spp. (TSS = 0.91, AUC = 0.99), and *H. gammarus* (TSS = 0.92, AUC = 0.98) was predicted with the most accuracy. *Cancer pagurus* (TSS = 0.70, AUC = 0.91) predictions revealed the lowest model accuracy. Hard ground (7 species), gravel (3 species), and depth (3 species) correlated most significantly with the macrofauna distribution in the HSG (≥ 0.10 standardized variables of importance [VI] scores). The variables shell > 2 mm (2 species), shell < 2 mm (2 species), current velocities (2 species), and mud (1 species) were less important predictors for species distribution in the HSG.

Metridium senile (gravel: VI = 0.44 + hard ground: VI = 0.17 + depth: VI = 0.15) and *H. gammarus* (hard ground: VI = 0.35 + shell > 2 mm: VI = 0.32, gravel: VI = 0.2 + velocities: VI = 0.11) showed the highest model response of VI > 0.7 (adding up its explaining VI ≥ 0.1). However, *H. gammarus* only reached the high response by adding up four explanatory VIs. That indicates a more general response by this species to the tested environmental parameters. Furthermore, only 16 out of 40 total runs were included in the EM. *Alcyonium digitatum*, with only one significant VI, showed a high response to hard ground: VI = 0.61. *Axinella polypoides* also revealed only one significant VI (depth: VI = 0.43). *Flustra foliacea* revealed the lowest response value of 0.49 by adding up its explaining VI ≥ 0.1 (hard ground: VI = 0.25 + shell <2 mm: VI = 0.24). All other species showed VIs ≥ 0.6 by adding

Table 1 Modeled benthic species' biological traits (feeding mode: *SUS* suspension feeder, *SD* surface deposit feeder, *PD* predator; mobility), presences and absences used for SDM, mean variables of importance (VI): of depth [m], gravel weight [%], hard ground [%], mud weight[%], shell < 2 mm weight [%], shell > 2 mm weight [%], and depth-averaged velocities [cm/s] (averaged over depth 0 to 2 m above bed), the calculated values of TSS and AUC, and the number of included ensemble model runs (*x* out of 40). Predictor variables with VI ≥ 0.1 are shown in bold

Species	Taxa	Biological trait		Presence (2016)	Absence (2016)	Mean Variable importance (TSS)	Evaluation measures (ensemble model)		included ensemble model runs
		Feeding mode	Mobility				TSS	AUC	
Flustra foliacea	Bryozoa	SUS	Sessile	129	159	1) **Hard ground (0.25)** 2) **Shell < 2 mm (0.24)** 3) Depth (0.09) 4) Gravel (0.02) 5) Mud (0.02) 6) Velocities (0.02) 7) Shell >2 mm (0.01)	0.82	0.97	40
Alcyonidium diaphanum	Bryozoa	SUS	Sessile	166	122	1) **Gravel (0.37)** 2) **Mud (0.12)** 3) **Velocities (0.12)** 4) Shell < 2 mm (0.07) 5) Shell > 2 mm (0.07) 6) Hard ground (0.03) 7) Depth (0.01)	0.75	0.94	38
Alcyonium digitatum	Anthozoa	SUS	Sessile	134	154	1) **Hard ground (0.61)** 2) Shell < 2 mm (0.06) 3) Depth (0.03) 4) Shell > 2 mm (0.03) 5) Gravel (0.01) 6) Mud (0.01) 7) Velocities (0.01)	0.81	0.97	40
Echinus esculentus	Echinodermata	SD, PD	Free living	108	180	1) **Hard ground (0.64)** 2) **Shell > 2 mm (0.11)** 3) Depth (0.06) 4) Shell<2 mm (0.04) 5) Gravel (0.03) 6) Mud (0.04 7) Velocities (0.02)	0.85	0.98	40
Metridium senile	Anthozoa	SUS	Sessile	45	243	1) **Gravel (0.44)** 2) **Hard ground (0.17)** 3) **Depth (0.15)** 4) Mud (0.09) 5) Velocities (0.08) 6) Shell > 2 mm (0.03) 7) Shell < 2 mm (0.01)	0.94	0.99	30
Cancer pagurus	Crustacea	PD	Free living	127	161	**1) Hard ground (0.43)** **2) Shell > 2 mm (0.21)** **3)** Depth (0.06) **4)** Shell<2 mm (0.05) **5)** Mud (0.03) **6)** Gravel (0,02) **7)** Velocities (0.01)	0.70	0.91	29
Phymatolithon spp.	Rhodophyta		Sessile	76	212	1) **Hard ground (0.40)** 2) **Depth (0.32)** 3) Gravel (0.06) 4) Shell > 2 mm (0.04) 5) Velocities (0.03) 6) Mud (0.003) 7) Shell < 2 mm (0.02)	0.91	0.99	40
Axinella polypoides	Porifera	SUS	Sessile	51	237	1) **Depth (0.43)** 2) Hard ground (0.08) 3) Mud (0.07) 4) Shell > 2 mm (0.05) 5) Velocities (0.04) 6) Shell < 2 mm (0.03) 7) Gravel (0.01)	0.80	0.97	40
Homarus gammarus	Crustacea	PD	Free living	19	269	1) **Hard ground (0.35)**	0.92	0.98	16

Table 1 (continued)

Species	Taxa	Biological trait		Presence (2016)	Absence (2016)	Mean Variable importance (TSS)	Evaluation measures (ensemble model)		included ensemble model runs
		Feeding mode	Mobility				TSS	AUC	
						2) **Shell < 2 mm (0.32)** 3) **Gravel (0.20)** 4) **Velocities (0.11)** 5) Depth (0.06) 6) Mud (0.05) 7) Shell > 2 mm (0.03)			

up two or more VI (see Table 1). Besides *H. gammarus*, also *C. pagurus* (29 EM), *M. senile* (30 EM), and *A. diaphanum* (38 EM) do not include all 40 EM runs in the analysis.

Prediction maps

The small-scale distribution of the nine species in the HSG is shown by the ensemble prediction maps (Fig. 3). All of the chosen modeled species are known to be associated with hard ground areas. Consequently, for almost all species, the models predict the main occurrences within the half-moon-shape structure of the HSG. However, predictions of the chosen species revealed differences in their individual spatial distribution. Comparing, for instance, the distribution of the two bryozoan species *F. foliacea* and *A. diaphanum*, predictions showed a broader distribution of *A. diaphanum* towards the eastern, northeastern, and southern parts of the observed area. *Flustra foliacea* spread all across the half-moon-shape of the HSG and within the northwestern edge of the area (Fig. 3a, b). Both species partly dominated the surface structure of the sea bottom, meaning coverage of nearly 100%, when they occurred in high abundances (Fig. 3a, b). Predictions for the occurrence of the anthozoan species *A. digitatum* and the edible sea urchin *E. esculentus* were restricted to the half-moon-shape structure of the HSG and to the northwestern edge of the surrounding area. Species of *A. digitatum* were mostly growing on bigger stones and boulders (Fig. 3c, d). *Echinus esculentus* was found grazing in the HSG (Fig. 3c, d). Similar to *A. digitatum*, specimens of the sea anemone *M. senile* were observed to be present on stones and boulders and in areas where shell fragments and coarse sediments dominated the surface (Fig. 3e). In contrast to all other species, their probability of occurrence was predicted to be restricted to the eastern ridge of the HSG and the eastern areas (Fig. 3e). The edible crab *C. pagurus* was predicted to a broader distribution across the area of the HSG, also to the eastern areas (Fig. 3f). It was found within areas of coarse sediments, but also often hidden in gaps and rifts of gravels and boulders (Fig. 3f). Encrusting coralline red alga of the genus *Phymatolithon* spp. showed a sharp limitation in their predicted occurrences within the half-moon-shape structure of the HSG (Fig. 3g). Partly, they dominated the surface of stones and boulders, especially in the shallower parts of the HSG (Fig. 3g). Predictions for the occurrences of the sponge *A. polypoides* were even more restricted to the inner parts of the half-moon-shape of the HSG (Fig. 3h), including its shallowest parts (Fig. 2). *Axinella polypoides* was mainly found on the top of bigger stones, enabling the species to filter the water column (Fig. 3h). Presences of the European lobster *H. gammarus* were predicted in the north and southwestern areas of the HSG (Fig. 3i). Specimens were often found to hide in gaps under or behind boulders (Fig. 3i). Mostly, they were detected in gravely areas adjacent to areas where shell fragments and coarse sediments dominated the surface. They were not found by video sampling within the main hard ground area of the HSG.

Species-specific response curves

Significant species-environmental relationships in the HSG were shown in the species-specific response curves (Fig. 4). Most significant correlations occurred by probabilities above 70%. Species-specific VI values are shown in Table 1. *Flustra foliacea* had a significant positive correlation with hard ground more than 25% and shell < 2 mm more than 0.05 weight%. *Alcyonidium. diaphanum* had a significant positive correlation with gravel more than 7.5 weight%, mud less than 1.15 weight%, and velocities less than 29 cm/s. *Alcyonium digitatum* had a significant positive correlation with hard ground greater than 22%. *Echinus esculentus* had a significant positive correlation with hard ground greater than 19%, and shell > 2 mm more than 0.04 weight%. *Metridium senile* had a significant positive correlation with gravel between 12 and 20 weight%, hard ground more than 27%, and depth between 14 and 15 m. *Cancer pagurus* had a significant correlation with hard ground more than 23% and depths less than 11.5 m. *Phymatolithon* spp. had a significant positive correlation with hard ground more than 20% and depth less than 11.5 m. *Axinella polypoides* had a significant positive correlation with depth less than 10.5 m. *Homarus gammarus* showed no significant correlation of its VIs over 70%.

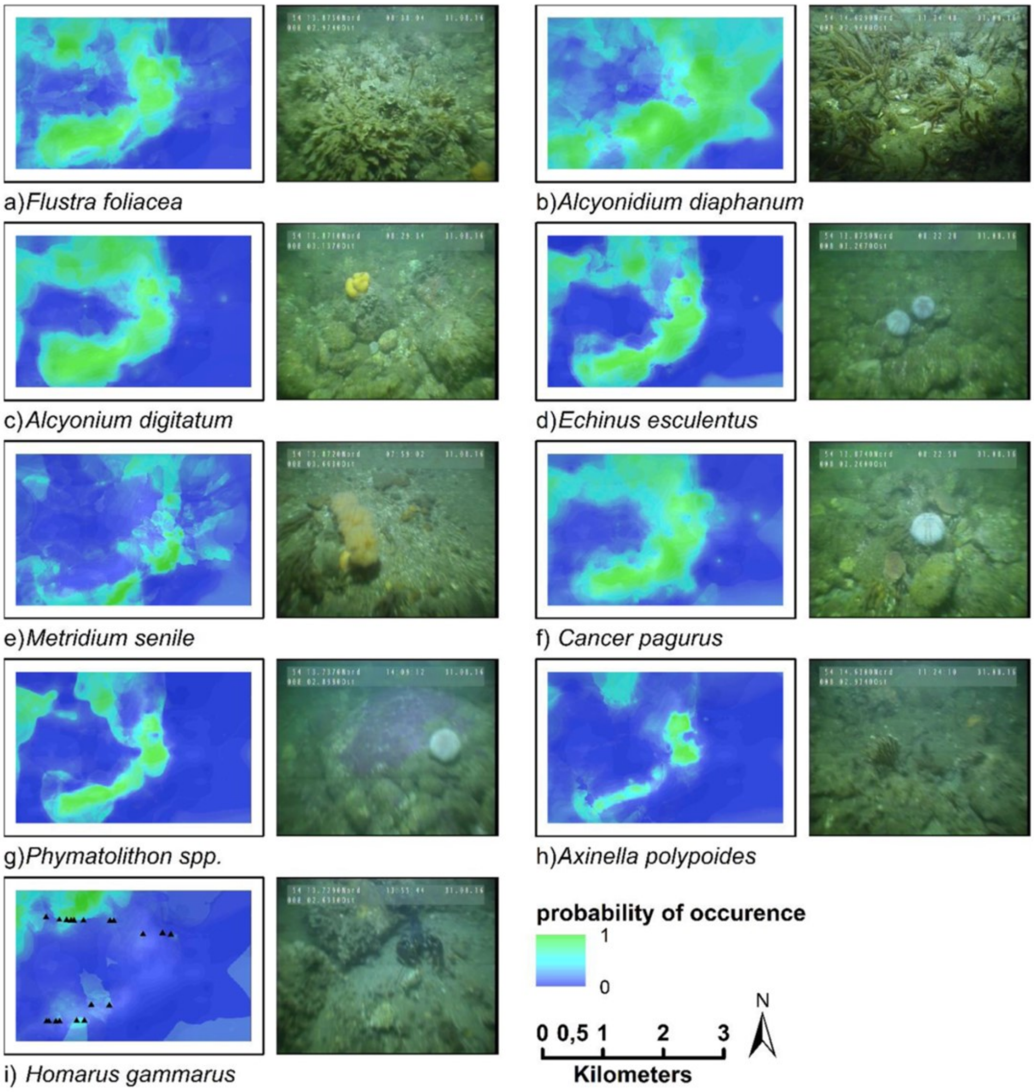


Fig. 3 Probability of occurrence as determined from predicted species distribution in the HSG. **a** *F. foliacea*, **b** *A. diaphanum*, **c** *A. digitatum*, **d** *E. esculentus*, **e** *M. senile*, **f** *C. pagurus*, **g** *Phymatolithon* spp., **h** *A. polypoides*, **i** *H. gammarus* (presences for *H. gammarus* were additionally shown as black triangles in the prediction map). Snapshots of the drop camera videos were shown for each modeled species

Discussion

Environmental grids

The data coverage used for the interpolation of environmental grids play a central role for generating reliable SDM especially for heterogeneous distribution patterns of sediments and topographic reliefs of hard substrates. The quality of the SDM strongly depends on the grid size, which means the data density of the field data. Besides the spatial distribution, the temporal resolution in tide-driven systems has a high importance. Applying the average velocity of the ADCP data for example simplifies the complexity of the current pattern on the vertical resolution. In contrast to other SDM studies on marine and terrestrial ground communities (Thuiller et al. 2009, 2016), nearly no former information on environmental conditions of the study area HSG and no high-resolution hydrodynamic model was available. Interpolation of data however brings its own difficulties as the procedure is based on the principles of spatial autocorrelation, which assumes that closer points are more similar compared to farther ones (Tobler 1970; Habib et al. 2018). Interpolations, thus, just give an approximation to the actual conditions in the field. For sediment conditions in the studied system, Schulz (1983) published a map showing sediment distribution based on profile measurements with Sidescan Sonar. However, this study used

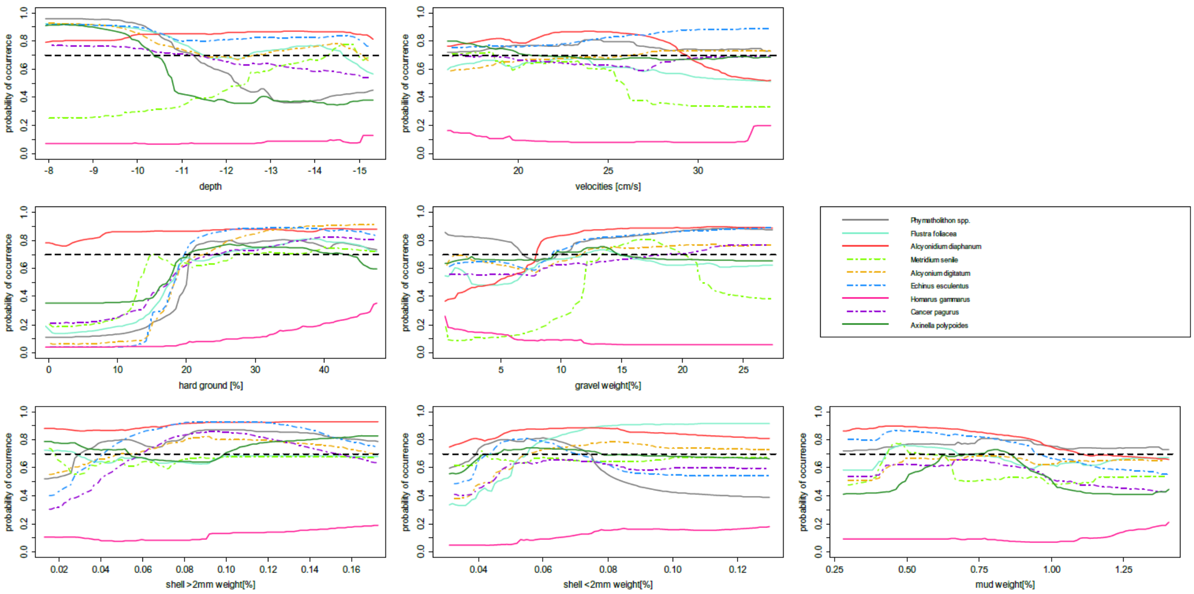


Fig. 4 Probability of occurrence determined by response curves of all macrofauna species for the correlated environmental variables of the ensemble model: depth [m], hard ground [%] gravel weight [%], mud weight [%], shell < 2 mm weight [%], shell > 2 mm weight [%], velocities [cm/s] derived with R package 'biomod2'. Significant species-environmental relationships occur when species probabilities of occurrence cross the black dotted line 0.7 = 70%

a different classification of the sediments than the distribution maps generated in the current study (based on grab samples). However, rough matches between both studies are apparent in the interpolated distribution of sand and coarse-grained material. This indicates stable and persistent environmental conditions over a long time period within the observed area. For the interpolated depth layer, similar to the sediment grids, a visual comparison to older maps (Stocks 1955; Schulz 1983) revealed a good fit of the recorded data to previous investigations. Thus, it can be assumed that interpolation was successful for both: sediments and depth.

Thus far, almost no information on current velocities was available for the HSG. For this study, we already integrated velocity data of six transects with in total 73 time slots, allowing detailed information on high vertical and lateral resolution for a short time period at a specific site. Implementing these data into SDM, six to ten bins above the sea bottom were averaged. The horizontal resolution over the entire area always integrates different point-based survey transects which have been carried during a given time period of the tidal range. The natural changing velocity during tides and the change of time and space during measurements might have weakened the relevance of hydrodynamics in the model. Further measurements have to be conducted to improve the quality of data.

Video sampling

For this study, video sampling provided sufficient information on the presences and absences of the chosen species to successfully model their distribution within the HSG area. Merely, the European lobster *H. gammarus* was difficult to spot (19 presences to 269 absences). Dederer et al. (2015) faced similar problems, spotting *H. gammarus* by records of a drop camera. They postulated that *H. gammarus*, as nocturnally active species, escapes the lights of the camera and hides in rock crevices. Thus, these authors have never spotted *H. gammarus* in drop camera records (Dederer et al. 2015). With our results, we were able to refute this. However, the probability to overlook species hiding behind rocks and in rock crevices is still given. Indeed, the fact that *H. gammarus* is nocturnally active and as we conducted sampling during day time, maximizes the chance of overlooking species (Skerritt et al. 2015), underestimating their presences and raising the uncertainty of the model output (Pearson 2010). This is a problem, not only for specimens of *H. gammarus*, but also for all other mobile taxa investigated, like for instance *C. pagurus*. The example of *H. gammarus* clearly shows that such limitations should be considered, when using video sampling for species distribution maps. SDMs always represent two aspects, which are not easy to distinguish: firstly, they represent the probability of sampling species in a proposed area, which is limited by the sampling gear, and secondly, they give a hint on species occurrences, which is modeled and, thus, not perfect.

Even though, considering all limitations, video analysis by drop camera can be used as a cost-effective alternative to recent methods. In the case of this study, it provides possibilities to sample all indicator species, and more taxa, named by Dederer et al. 2015. For example, Kendall et al. (2005) also used a video transect approach in Gray's Reef National Marine Sanctuary off Georgia (USA) for creating benthic maps. They came to the same conclusion: that a video transect approach maximizes the spatial area covered during field operations in deeper waters. However, their approach required modified procedures for accuracy assessment (Kendall et al. 2005). The results of the present study on the HSG confirm that video sampling is sufficient to gain usable information on the presence and absence of biota to successfully model species distribution.

Small-scale species distribution modeling

According to the resulting variables of importance and the resulting response curves, the model results reflect well the possible distribution range of the chosen species, with the exception of *H. gammarus*. With *H. gammarus*, one major constraint in SDM becomes obvious: model overfitting by few presences of specimens against many predictor variables. As stated above, this species was difficult to spot by drop camera records; absences were much higher than presences. This overfitting leads to reduced model generalizability and reduced transferability to new data (Vaughan and Ormerod 2005; Breiner et al. 2015). Harrell et al. (1996) state that species presences should be 10 times larger than the number of environmental variables used for SDM, meaning for this study, a minimum of 70 species presences would be required for precise modeling. The number of 16 included EM for *H. gammarus* out of 40 model runs is also low, indicating that one could not trust the predicted distribution here. The study of Singer et al. (2016) as template for the present study set the minimum to 40 species presences with also seven explaining environmental variables. This proved to be sufficient for good model results there (Singer et al. 2016, 2017).

For seven out of nine modeled species, hard ground was the most important predictor variable. This is reasonable, since this study mainly deals with species associated to stony and coarse grain habitats. For example, the bryozoan species *F. foliacea* and the anthozoa *A. digitatum* need to attach to stones and boulders to grow (Hartnoll 1975; de Kluijver 1991; Bitschofsky et al. 2011). Red algae of the genus *Phymatolithon* spp. encrust on stones and boulders (Dederer et al. 2015; Fortunato 2015), while crustacean species like *C. pagurus* and *H. gammarus* hide in rock crevices between and within rocks (Dederer et al. 2015; Skerritt et al. 2015).

Depth was named as an important predictor variable for three out of nine species. Depth is correlated to other environmental parameters, i.e., light availability (Häder et al. 1998). Encrusting red algae like *Phymatolithon* spp. (predicted only in depths to 11.5 m) conduct photosynthesis, thus need light to grow (Ballesteros 2006; Fortunato 2015). Around Helgoland, light availability is limited within depth 10 m onward (de Kluijver 1991), which fits to the predicted and restricted presences of *Phymatolithon* spp. For the sponge species *A. polypoides*, which revealed depth as its only statistically relevant variable of importance, the connection is not that obvious. Within the HSG area, their probability of occurrence is clearly restricted to its upper parts. Sponges of the family *Axinellidae* are suspension feeders, which, amongst other organisms, rely on plankton feeding (Schmidt 1862). Food availability might be one limiting factor here; however, due to the measured environmental variables, we cannot validate if food availability is limiting.

SDM revealed gravel as important predictor variable for *M. senile*, *A. diaphanum*, and *H. gammarus*. *Metridium senile* is a conspicuous member of invertebrate communities, found in cold temperate waters across the northern hemisphere (Nelson and Craig 2011). Within the HSG, *M. senile* appeared mainly in the eastern ridge. Its predicted occurrences were different to the other species, not restricted to the half-moon-shape structure. The probability of occurrence for *M. senile* was highest in areas with a medium range of 12 to 22% gravel and low mud contents 0.4 to 0.65%. *Metridium senile* as a suspension feeder feeds on planktonic larvae (Anthony 1997). In the HSG, it appears in smaller areal ranges than all other suspension-feeding types, especially the bryozoan species. The predicted species distribution maps show that only *A. diaphanum* is present in areas where high abundances of *M. senile* were present. From fouling communities, it is known that *M. senile* has a strong potential to be a dominant competitor and structuring force (Nelson and Craig 2011; Martin et al. 2015). The HSG might hold best suitable environmental conditions for this species in the eastern ridge of the area. However, again, this cannot be proven by the measured environmental variables.

According to the model output, *A. diaphanum* occurred in areas with low mud contents less than 1.15%, gravel more than 7.5%, and velocities less than 29 cm/s. *Alcyonidium diaphanum* is a very common bryozoan species (Howson and Picton 1997; Porter et al. 2001, 2002). As suspension feeder, it attaches to rocks, shells, or stones, of the lower intertidal zone, and occurs in shelly sands and coarse grounds offshore (Porter et al. 2001, 2002). *Alcyonidium diaphanum* and *H. gammarus* were the only species revealing velocities as a significant predictor variable. This is somehow surprising, as hydrodynamic conditions (current velocities) together with sediment characteristics are major determinants for the presence of benthic species in sublittoral communities (Kröncke et al. 2004; Markert et al. 2015; Schückel et al. 2015a; Gutperlet et al. 2017; Holler et al. 2017; Kröncke et al. 2018). As mentioned above, the grid data for current velocities show just a general trend in the observed area. With the recorded ADCP data, interpolation held too many uncertainties to make a solid statement to which extent current velocities influence presences or absences of benthic species in the HSG. Further sampling is necessary.

Conclusion and outlook

SDM represented a good tool to generate full coverage and high-quality species distribution maps within the HSG area. The model revealed good evaluation measures based on the sampled environmental parameters. SDM provides a fast and reliable tool to generate maps for species distribution with a limited amount of environmental variables. However, abiotic and biotic input variables should be proven carefully with regard to the heterogeneity of the area. The relation of species presences to the number of environmental variables has to be kept in mind (Vaughan and Ormerod 2005; Breiner et al. 2015). Further studies could improve the quality of the environmental input data by adding more explaining environmental variables of different types, not only bathymetry, sediments, and velocities. One additional variable for the improvement of environmental information might for instance be food availability as assessed by chlorophyll a measurements or measurements of the total organic carbon and nitrogen contents (e.g., Wieking and Kröncke 2003; Dederer et al. 2015; Schückel et al. 2015a, b; Singer et al. 2016). ADCP measurements on more profiles at the same tidal conditions might improve environmental input grids on the velocities in the HSG area. Based on the outcome of this study, a recommendation towards SDM application in further monitoring of natural stony and coarse-grained habitats, like the HSG, can be given. Further, management and monitoring programs will benefit from the information given by the output of SDM.

Acknowledgments We thank the captains and crews of RV "Senckenberg" for the help with sampling. We are grateful to Maik Wilsenack, Astrid Raschke, and students for the technical support in the field and in the lab.

Funding information This research was funded by the DFG ("German Research Foundation") within the INTERCOAST ("Integrated Coastal Zone and Shelf-Sea Research") graduate program, a joint collaboration between the Senckenberg Institute in Wilhelmshaven (Germany), the University of Bremen (Germany), and the University of Waikato (New Zealand).

References

Allouche O, Tsoar A, Kadmon R (2006) Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). J Appl Ecol 43:1223–1232. https://doi.org/10.1111/j.1365-2664.2006.01214.x

Anthony KRN (1997) Prey capture by the sea anemone Metridium senile (L.): effects of body size, flow regime, and upstream neighbors. Biol Bull 192:73–86. https://doi.org/10.2307/1542577

Ballesteros E (2006) Mediterranean coralligenous assamblages: a synthesis of present knowledge. Oceanogr Mar Biol 44:123–195

Bartholomä A (2006) Acoustic bottom detection and seabed classification in the German Bight, southern North Sea. 177–184. https://doi.org/10.1007/s00367-006-0030-6

Bartholomä A, Holler P, Schrottke K, Kubicki A (2011) Acoustic habitat mapping in the German Wadden Sea – comparison of hydro-acoustic devices. J Coast Res 1–5

BFNReport477 (2018) Die Meeresschutzgebiete in der deutschen ausschließlichen Wirtschaftszone der Nordsee – Beschreibung und Zustandsbewertung – Die Meeresschutzgebiete in der deutschen ausschließlichen Wirtschaftszone der Nordsee

Bitschofsky F, Forster S, Scholz J (2011) Regional and temporal changes in epizoobiontic bryozoan-communities of Flustra foliacea (Linnaeus, 1758) and implications for North Sea ecology. Estuar Coast Shelf Sci 91:423–433. https://doi.org/10.1016/j.ecss.2010.11.004

Booth GD, Niccolucci MJ, Schuster EG (1994) Identifying proxy sets in multiple linear regression: an aid to better coefficient interpretation. Ogden, UT US Dept Agric For Serv Intermt Res Stn no.470:20

Breiman L (2001) Random forests. Kluwer Academic Publishers, Netherlands

Breiner FT, Guisan A, Bergamini A, Nobis MP (2015) Overcoming limitations of modelling rare species by using ensembles of small models. Methods Ecol Evol 6:1210–1218. https://doi.org/10.1111/2041-210X.12403

Brezina J (1979) Particle size and settling rate distributions of sand-sized materials. In: PARTEC - 2nd European Symposium on Particle Characterization. Nürnberg, pp 1–47

Davies J, Baxter J, Bradley M, et al (2001) Marine monitoring handbook. UK Mar SACs Proj 221

de Kluijver MJ (1991) Sublittoral hard substrate communities off Helgoland. Helgoländer Meeresun 45:317–344. https://doi.org/10.1007/BF02365523

Dederer G, Schneider C (2015) Der Helgoländer Steingrund

Dederer G, Boos K, Kanstinger P, et al (2015) Tauch-Untersuchung des "Steingrund" bei Helgoland (FFH DE 1714-391) und Konzeptentwicklung eines Tauch-Monitorings für den FFH Lebensraumtyp Riff. Abschlussbericht

Degraer S, Moerkerke G, Rabaut M et al (2008) Very-high resolution side-scan sonar mapping of biogenic reefs of the tube-worm Lanice conchilega. Remote Sens Environ 112:3323–3328. https://doi.org/10.1016/j.rse.2007.12.012

Diesing M, Coggan R, Vanstaen K (2009) Widespread rocky reef occurrence in the central English Channel and the implications for predictive habitat mapping. Estuar Coast Shelf Sci 83:647–658. https://doi.org/10.1016/j.ecss.2009.05.018

Dormann CF, Elith J, Bacher S, et al (2013) Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. https://doi.org/10.1111/j.1600-0587.2012.07348.x

Ehrhold A, Hamon D, Guillaumont B (2006) The REBENT monitoring network, a spatially integrated, acoustic approach to surveying near-shore macrobenthic habitats: application to the Bay of Concarneau (South Brittany, France). ICES J Mar Sci 63:1604–1615. https://doi.org/10.1016/j.icesjms.2006.06.010

Elith J, Ferrier S, Huettmann F, Leathwick J (2005) The evaluation strip: a new and robust method for plotting predicted responses from species distribution models. Ecol Model 186:280–289. https://doi.org/10.1016/J.ECOLMODEL.2004.12.007

Fielding AH, Bell JF (1997) A review of methods for the assessment of prediction errors in conservation presence/absence models. Environ Conserv 24:38–49. https://doi.org/10.1017/s0376892997000088

Forster-Smith RL, Davies J, Sotheran I (1999) Broad scale remote survey and mapping of sublittoral habitats and biota. Report on sublittoral mapping methodology Sea Map Res Gr 157

Fortunato H (2015) Coralline red algae: a proxy in climate and ocean acidification studies. Neues Jahrb Geol Palaontol Abh 277:189–208. https://doi.org/10.1127/njgpa/2015/0498

Foster AG, Walker BK, Riegl BM, et al (2019) Interpretation of single-beam acoustic backscatter using lidar-derived topographic complexity and benthic habitat classifications in a coral reef environment Interpretation of Single-Beam Acoustic Backscatter Using Lidar-Derived Topographic Complexity and 2009:16–26. https://doi.org/10.2112/SI53-003.1

Friedman J (1991) Multivariate adaptive regression splines. Ann Stat 11:416–431

Georges D, Thuiller W (2013) Multi-species distribution modeling with biomod2. R-CRAN Proj 11

Gleason ACR (2009) Single-beam accoustic seabed classification in coral reef environments with application to the assessment of grouper and snapper habitat in the upper florida keys, USA. Univ Miami 190

Glockzin M, Gogina M, Zettler ML (2009) Beyond salty reins - modelling benthic species ' spatial response to their physical environment in the Pomeranian Bay (Southern Baltic Sea) benthic Zone in Słupsk Beyond salty reins - Modeling benthic species ' spatial response to their physical environ

Gogina M, Glockzin M, Zettler ML (2010) Distribution of benthic macrofaunal communities in the western Baltic Sea with regard to near-bottom environmental parameters . 1 . Causal analysis. J Mar Syst 79:112–123. https://doi.org/10.1016/j.jmarsys.2009.07.006

Guisan A, Thuiller W (2005) Predicting species distribution: offering more than simple habitat models. Ecol Lett 8:993–1009. https://doi.org/10.1111/j.1461-0248.2005.00792.x

Gutperlet R, Capperucci RM, Bartholomä A, Kröncke I (2017) Relationships between spatial patterns of macrofauna communities, sediments and hydroacoustic backscatter data in a highly heterogeneous and anthropogenic altered environment. J Sea Res 121:33–46. https://doi.org/10.1016/j.seares.2017.01.005

Habib A, Khoshelham K, Akdim N, el Ghandour FE, Labbassi K, Menenti M (2018) Impact of spatial resolution, interpolation and filtering algorithms on DEM accuracy for geomorphometric research: a case study. MESE 4:1537–1554. https://doi.org/10.1007/s40808-018-0512-3

Häder D-P, Kumar HD, Smith RC, Worrest RC (1998) Effects on aquatic ecosystems. JPPA 1344:53–68. https://doi.org/10.1111/j.1365-2761.1990.tb00803.x

Harrell FE, Lee KL, Mark DB (1996) Multivariable prognostic models: issues in developing models, evaluating assumptions and adequacy, and measuring and reducing errors. Statistics in Medicine 15:361–387. https://doi.org/10.1002/(SICI)1097-0258(19960229)15:4<361::AID-SIM168>3.0.CO;2-4

Hartnoll RG (1975) The annual cycle of Alcyonium digitatum. Estuar Coast Mar Sci 3:71–78. https://doi.org/10.1016/0302-3524(75)90006-7

Hass HC, Bartsch I (2008) Acoustic kelp bed mapping in shallow rocky coasts - case study Helgoland. 50–53 , In: Doerffer R, Colijn F, van Beusekom J (eds.). Observing the Coastal Sea - an Atlas of Advanced Monitoring Techniques. LOICS Reports & Studies 33. Geesthacht, Germany: GKSS Research centre.

Hass HC, Mielck F, Fiorentino D, Papenmeier S, Holler P, Bartholomä A (2016) Seafloor monitoring west of Helgoland (German Bight, North Sea) using the acoustic ground discrimination system RoxAnn. Geo-Marine Letters 37:125–136. https://doi.org/10.1007/s00367-016-0483-1

Holler P, Markert E, Bartholomä A, et al (2017) Tools to evaluate seafloor integrity: comparison of multi-device acoustic seafloor classifications for benthic macrofauna-driven patterns in the German Bight, southern North Sea. 93–109. https://doi.org/10.1007/s00367-016-0488-9

Hosmer DW, Lemeshow S (2000) Applied logistic regression, Second Edition. John Wiley & Sons, Inc

Howson CM, Picton BE (1997) The species directory of the marine fauna and flora of the British Isles and surrounding seas 28

Kendall MS, Jensen OP, Alexander C et al (2005) Benthic mapping using sonar, video transects, and an innovative approach to accuracy assessment: a characterization of bottom features in the Georgia Bight. J Coast Res 21:1154–1165. https://doi.org/10.2112/03-0101R.1

Kenny AJ, Andrulewicz E, Bokuniewicz H, et al (2000) An overview of seabed mapping technologies in the context of

Kostylev VE, Erlandsson J, Yiu M, Williams GA (2005) The relative importance of habitat complexity and surface area in assessing biodiversity: fractal application on rocky shores. 2:272–286. https://doi.org/10.1016/j.ecocom.2005.04.002

Kröncke I, Stoeck T, Wieking G, Palojärvi A (2004) Relationship between structural and trophic aspects of microbial and macrofaunal communities in different areas of the North Sea. Mar Ecol Prog Ser 282:13–31. https://doi.org/10.3354/meps282013

Kröncke I, Becker LR, Badewien TH, et al (2018) Near- and offshore macrofauna communities and their physical environment in a South-Eastern North Sea Sandy Beach System 5:1–11. https://doi.org/10.3389/fmars.2018.00497

Kühne S (1992) Die Fauna des Steingrundes in der Deutschen Bucht - unter besonderer Berücksichtigung der Epifauna. Bonn

Kühne S, Rachor E (1996) The macrofauna of a stony sand area in the German Bight (North Sea). Helgol Mar Res 50:433–452. https://doi.org/10.1007/bf02367159

Landis JR, Koch GG (2013) The measurement of observer agreement for categorical data Data for Categorical of Observer Agreement The Measurement. Society 33:159–174

Lenoir S, Beaugrand G, Lecuyer É (2011) Modelled spatial distribution of marine fish and projected modifications in the North Atlantic Ocean. Glob Chang Biol 17:115–129. https://doi.org/10.1111/j.1365-2486.2010.02229.x

Little C, Kitching J (1996) The biology of the rocky shores. Oxford University Press, New York

Markert E, Holler P, Kröncke I, Bartholomä A (2013) Benthic habitat mapping of sorted bedforms using hydroacoustic and ground-truthing methods in a coastal area of the German Bight/ North Sea. Estuar Coast Shelf Sci 1–11. https://doi.org/10.1016/j.ecss.2013.05.027

Markert E, Kröncke I, Kubicki A (2015) Small scale morphodynamics of shoreface-connected ridges and their impact on benthic macrofauna. J Sea Res 99:47–55. https://doi.org/10.1016/j.seares.2015.02.001

Marmion M, Parviainen M, Luoto M et al (2009) Evaluation of consensus methods in predictive species distribution modelling. Divers Distrib 15:59–69. https://doi.org/10.1111/j.1472-4642.2008.00491.x

Martin JP, Garese A, Sar A, Acuña FH (2015) Fouling community dominated by Metridium senile (Cnidaria: Anthozoa: Actiniaria) in Bahía San Julián (southern Patagonia, Argentina). 79:211–221

Maxwell DL, Stelzenmüller V, Eastwood PD, Rogers SI (2009) Modelling the spatial distribution of plaice (Pleuronectes platessa), sole (Solea solea) and thornback ray (Raja clavata) in UK waters for marine management and planning. J Sea Res 61:258–267. https://doi.org/10.1016/J.SEARES.2008.11.008

McCullagh P, Nelder J (1998) Generalized linear models. Chapman and Hall, London New York

Meißner K, Darr A, Rachor E (2008) Development of habitat models for Nephtys species (Polychaeta: Nephtyidae) in the German Bight

(North Sea). J Sea Res 60:276–291. https://doi.org/10.1016/J.SEARES.2008.08.001

Michaelis R, Hass HC, Mielck F et al (2019a) Hard-substrate habitats in the German Bight (South-Eastern North Sea) observed using drift videos. J Sea Res 144:78–84. https://doi.org/10.1016/j.seares.2018.11.009

Michaelis R, Hass HC, Mielck F et al (2019b) Epibenthic assemblages of hard-substrate habitats in the German Bight (south-eastern North Sea) described using drift videos Continental Shelf Research Epibenthic assemblages of hard-substrate habitats in the German Bight (south-eastern North Sea) des. Cont Shelf Res 175:30–41. https://doi.org/10.1016/j.csr.2019.01.011

Mielck F, Bartsch I, Hass HC, et al (2014) Estuarine, Coastal and Shelf Science Predicting spatial kelp abundance in shallow coastal waters using the acoustic ground discrimination system RoxAnn 143:1–11. https://doi.org/10.1016/j.ecss.2014.03.016

Moore CH, Harvey ES, Van Niel K (2010) The application of predicted habitat models to investigate the spatial ecology of demersal fish assemblages. Mar Biol 157:2717–2729. https://doi.org/10.1007/s00227-010-1531-4

Mouquet N, Lagadeuc Y, Devictor V et al (2015) Predictive ecology in a changing world. J Appl Ecol 52:1293–1310. https://doi.org/10.1111/1365-2664.12482

Nelson ML, Craig SF (2011) Role of the sea anemone Metridium senile in structuring a developing subtidal fouling community 421:139–149. https://doi.org/10.3354/meps08838

Neumann H, Diekmann R, Emeis KC et al (2017) Full-coverage spatial distribution of epibenthic communities in the south-eastern North Sea in relation to habitat characteristics and fishing effort. Mar Environ Res 130:1–11. https://doi.org/10.1016/j.marenvres.2017.07.010

Parsons DR, Jackson PR, Czuba JA et al (2013) Velocity Mapping Toolbox (VMT): A processing and visualization suite for moving-vessel ADCP measurements. Earth Surf Process Landf 38:1244–1260. https://doi.org/10.1002/esp.3367

Pearson R (2010) Species ' Distribution modeling for conservation educators and practitioners. 3:54–89

Porter JS, Hayward PJ, Jones MES (2001) The identity of Alcyonidium diaphanum (Bryozoa: Ctenostomatida). JMBA 81:1001–1008. https://doi.org/10.1017/S0025315401004970

Porter JS, Ellis JR, Hayward P et al (2002) Geographic variation in the abundance and morphology of the bryozoan Alcyonidium diaphanum (Ctenostomata: Alcyonidiidae) in UK coastal waters. JMBA 82:529–535. https://doi.org/10.1017/S0025315402005842

Pratje O (1951) Die Deutung der Steingruende der Nordsee als Endmoraenen. Deutsche Hydrographische Zeitschrift 4(3):106–114

Preston JM (2006) Acoustic classification of seaweed and sediment with depth-compensated vertical echoes. 0–4

R Development Core Team (2015) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. www.r-project.org

Reiss H, Cunze S, König K, et al (2011) Species distribution modelling of marine benthos: a North Sea case study 442:71–86. https://doi.org/10.3354/meps09391

Reiss H, Birchenough S, Borja A et al (2014) Benthos distribution modelling and its relevance for marine ecosystem management. ICES J Mar Sci 72:297–315

Ridgeway G (1999) The state of boosting. 172–181

Robinson CLK, Hay DE, Booth J, Truscott J (1996) Standard methods for sampling resource and habitats in coastal subtidal regions of British Columbia. 2. Review of sampling with preliminary recommendations. Can Tech Rep Fish Aquat Sci XII:119

Robinson LM, Elith J, Hobday AJ, et al (2011) Pushing the limits in marine species distribution modelling: lessons from the land present challenges. 789–802. https://doi.org/10.1111/j.1466-8238.2010.00636.x

Robinson NM, Nelson WA, Costello MJ et al (2017) A systematic review of marine-based species distribution models (SDMs) with recommendations for best practice. Front Mar Sci 4:1–11. https://doi.org/10.3389/fmars.2017.00421

Santileces B, Bolton J, Meneses I (2009) Marine algal communities. In: Witman J, Roy K (eds) Marine macroecology. University of Chicago Press, Chicago

Schleswig-Holstein Ministerium für Energiewende LU und ländliche R (2016) Managementplan für das Flora-Fauna-Habitat-Gebiet „ DE - 1714-391 Steingrund “. 1–29

Schmidt O (1862) Die Spongien des adriatischen Meeres. Wilhelm En, Leipzig

Schückel U, Beck M, Kröncke I (2015a) Macrofauna communities of tidal channels in Jade Bay (German Wadden Sea): spatial patterns, relationships with environmental characteristics, and comparative aspects. Mar Biodivers 45:841–855. https://doi.org/10.1007/s12526-014-0308-2

Schückel U, Kröncke I, Baird D (2015b) Linking long-term changes in trophic structure and function of an intertidal macrobenthic system to eutrophication and climate change using ecological network analysis. Mar Ecol Prog Ser 536:25–38. https://doi.org/10.3354/meps11391

Schulz HD (1983) Der Steingrund bei Helgoland - Restsediment einer saalezeitlichen Endmoräne. Meyniana 35:43–53

Singer A, Schückel U, Beck M et al (2016) Small-scale benthos distribution modelling in a North Sea tidal basin in response to climatic and environmental changes (1970s-2009). Mar Ecol Prog Ser 551:13–30. https://doi.org/10.3354/meps11756

Singer A, Millat G, Staneva J, Kröncke I (2017) Modelling benthic macrofauna and seagrass distribution patterns in a North Sea tidal basin in response to 2050 climatic and environmental scenarios. Estuar Coast Shelf Sci 188:99–108. https://doi.org/10.1016/j.ecss.2017.02.003

Skerritt DJ, Robertson PA, Mill AC, Polunin NVC (2015) Fine-scale movement , activity patterns and home-ranges of European lobster Homarus gammarus. https://doi.org/10.3354/meps11374

Stocks T (1955) Der Steingrund bei Helgoland. Deutsche Hydrographische Zeitschrift 8:112–118. https://doi.org/10.1007/BF02019797

Taylor RB (1998) Density, biomass and productivity of animals in four subtidal rocky reef habitats: the importance of small mobile invertebrates

Thuiller W, Lafourcade B, Engler R, Araujo MB (2009) BIOMOD - a platform for ensemble forecasting of species distribution. Ecography 32:369–373. https://doi.org/10.1111/j.1600-0587.2008.05742.x

Thuiller CW, Georges D, Engler R, Breiner F (2016) Package 'biomod2.' R package:104

Tobler WR (1970) A computer movie simulating urban growth in the detroit region. Econ Geogr 46:234–240

van Overmeeren R, Craeymeersch J, van Dalfsen J, Fey F, van Heteren S, Meesters E (2009) Acoustic habitat and shellfish mapping and monitoring in shallow coastal water – Sidescan sonar experiences in The Netherlands. Estuarine, Coastal and Shelf Science 85(3):437–448

Vaughan IP, Ormerod SJ (2005) The continuing challenges of testing species distribution models. J Appl Ecol 42:720–730. https://doi.org/10.1111/j.1365-2664.2005.01052.x

Venables WN, Dichmont CM (2004) GLMs , GAMs and GLMMs: an overview of theory for applications in fisheries research 70:319–337. https://doi.org/10.1016/j.fishres.2004.08.011

Wenner EL, Knott DM, Van Dolah RF, Burrell VG Jr (1983) Invertebrate communities associated with hard bottom habitats in the South Atlantic Bight. Estuar and Coast Shelf Sci 17:143–158. https://doi.org/10.1016/0272-7714(83)90059-8

Wieking G, Kröncke I (2003) Macrofauna communities of the Dogger Bank (central North Sea) in the late 1990s: spatial distribution, species composition and trophic structure. Helgol Mar Res 57:34–46. https://doi.org/10.1007/s10152-002-0130-2

Wienberg C, Bartholomä A (2005) Acoustic seabed classification in a coastal environment (outer Weser Estuary, German Bight)—a new approach to monitor dredging and dredge spoil disposal. Cont Shelf Res 25:1143–1156. https://doi.org/10.1016/j.csr.2004.12.015

Willems W, Goethals P, Van den Eynde D et al (2008) Where is the worm? Predictive modelling of the habitat preferences of the tube-building polychaete Lanice conchilega. Ecol Model 212:74–79. https://doi.org/10.1016/j.ecolmodel.2007.10.017

Witman J, Dayton P (2001) Rocky subtidal communities. In: Bertness M, Gaines S, Hay M (eds) Marine Community ecology. Sinauer Press, Sunderland, pp 339–366

CHAPTER 3 – Publication II

3.1. Hydrodynamics and hydroacoustic mapping of a benthic seafloor in a coarse grain habitat of the German Bight

Bartholomä, A., Capperucci, R.M., **Becker, L.R.**, Coers, S.I.I., Battershill, N.

Bartholomä, A., Capperucci, R.M., **Becker, L.R.**, Coers, S.I.I., Battershill, N. (2019). Hydrodynamics and hydroacoustic mapping of a benthic seafloor in a coarse grain habitat of the German Bight. Geo-Marine Lett. 40:183–195 doi:10.1007/s00367-019-00599-7

Geo-Marine Letters (2020) 40:183–195
https://doi.org/10.1007/s00367-019-00599-7

ORIGINAL

Hydrodynamics and hydroacoustic mapping of a benthic seafloor in a coarse grain habitat of the German Bight

A. Bartholomä[1] · R. M. Capperucci[1,2] · L. Becker[1] · S. I. I. Coers[1,2] · C. N. Battershill[3]

Received: 19 February 2019 / Accepted: 23 September 2019 / Published online: 24 October 2019

Abstract

Coarse-grained hard substrate areas with grain sizes up to very coarse boulder (> 2 m) are very rare in the German North Sea. The "Helgoländer Steingrund" is one of such highly biodiverse areas: it is characterized by a half-moon-shaped hard substrate ridge, which subdivides the site into a more exposed (westerly) and a less exposed (easterly) flank, characterized by a mixture of sand and gravel deposits. Sonar systems, underwater videos, and bottom samples were used for mapping and classifying the abiotic and biotic components in such very patchy and coarse-grained habitat. Three main seabed types (sand, gravel, and hard substrate) were identified, based on acoustic backscatter data. The additional information coming from underwater videos and sediment bottom sample analysis allowed the description of six different seabed types, which included both the abiotic (sediments, morphology, etc.) and biotic components. The flanks of the ridge and their transition to the surrounding soft-ground areas were characterized by a distinct dominance of the bryozoa *F. foliacea* and *A. diaphanum* on the western and on the eastern side, respectively. Morphology and hydrodynamics are likely responsible for such zonation. This is proved by the outcomes of the Acoustic Doppler Current Profiler data, which showed the general flow pattern across the ridge and even resolved the local variability of current pattern, dependent on the tidal stage and bottom relief.

Introduction

Most parts of the seafloor in the German Bight consist of reworked Holocene and Pleistocene sand, with a small amount of silt and clay (Schwarzer et al. 2008; Zeiler et al. 2008). In contrast, coarse-grained hard substrate areas with grain sizes up to very coarse boulder (following the extended nomenclature of Terry and Goff 2014) are very rare in the German North Sea. Hard substrates with strong geomorphological gradients have been described in the closer vicinity of the Helgoland Island (Mielck et al. 2014; Hass et al. 2017; Holler et al. 2017). A different kind of hard ground, with grain size up to boulders and a smoother topographic relief occurs in the "Sylter Aussenriff" area (Papermeier and Hass 2018; Feldens et al. 2018). An even smoother relief characterizes the "Helgoländer Steingrund" (HSG), which is known as one of the rare hard substrates made by cobble-size to small boulders deposits. In contrast to the widespread and spatially distributed deposits of the "Sylter Aussenriff", the HSG is shaped as a half-moon hard substrate ridge, with different hydrodynamic regimes characterizing the westerly and the easterly flanks. The HSG is part of the nature conservation areas (BFN 2018) due to its high biodiversity, whose preservation requires a detailed mapping and a monitoring.

As highlighted by Dyrynda (1994), the colonization pattern of benthic communities largely depends on the substrate type. Rachor and Nehmer (2003) pointed out the relevance of hard substrates for the biodiversity and for the biodiversity and the lateral variability of such patterns.

The HSG ridge was firstly surveyed and described in 1908 (Stocks 1955). A former study of the abiotic ensemble characterizing the HSG site was carried out by Schulz (1983), who analyzed side-scan sonar (SSS) images and classified the seafloor in five different sediment types. Several studies focused on the epibenthic communities living on the hard ground (de Kluijver 1991; Kühne and Rachor 1996), while a more comprehensive overview of the organisms living in and on the HSG

✉ A. Bartholomä
alexander.bartholomae@senckenberg.de

[1] Senckenberg am Meer, Südstrand 40, 26382 Wilhelmshaven, Germany

[2] Department of Geosciences, University of Bremen, P.O. Box 330440, 28359 Bremen, Germany

[3] Environmental Research Institute, Faculty of Science & Engineering, University of Waikato, Private Bag 3105, Hamilton 3040, New Zealand

hard substrate was given by Dederer et al. (2015). They showed that the cobble and boulder deposits are mainly colonized by different bryozoan species. Moreover, they pointed out the importance of understanding the colonization mechanism of the bryozoans, in order to be able to preserve such a rare environment. However, the study did not provide a detailed geographical distribution of the different taxa and did not take into account the abiotic and the hydrodynamic characteristics of the area.

In situ investigations, like seafloor sampling and scuba diving observations, can offer detailed information about single spots, while a different approach is required for the areal characterization (i.e., composition and lateral distribution) of both the abiotic and the biotic components of an ecosystem. On the other hand, backscatter from hydroacoustic devices (e.g., SSS, echo sounder systems) allows to spatially cover large areas in a short time, but lacks a direct investigation of the seafloor nature. The backscatter summarizes information about, for example, grain size, suspended sediments, morphological elements, fauna, and flora. A combination of acoustic sources and seafloor ground-truthing is therefore helpful in resolving the habitat distribution pattern on different scales, depending of the acoustic configuration (frequency, swath angle, etc.). In addition, the knowledge of the local current hydrodynamic conditions can provide useful information for understanding the colonization pattern and mechanisms of the hard ground-related biocommunities (Michaelis et al. 2019). Acoustic current measurements (e.g., by means of Acoustic Doppler Current Profiler) can be used for such purpose.

Many studies investigated the hydroacoustic response of sonar systems to different habitat types (e.g., Freitas et al. 2003; Quintino et al. 2010; Bartholomä et al. 2011; Freitas et al. 2011; Arendartchuk et al. 2017; Greene et al. 2018). At the North Sea, Mielck et al. (2014) investigated the spatial abundance of kelp around the Helgoland Island, by means of a single-beam echo sounder (SBES) system. A combination of SBES data and underwater videos was used by Hass et al. (2017) for distinguishing seafloor substrate types in the southern North Sea. Holler et al. (2017) used different acoustic sources for differentiating between hard and soft grounds and for studying the modification of the acoustic signal due to soft sediment-related communities (brittle stars). However, there are still significant gaps in mapping the hard substrate biotic and abiotic components in the North Sea region (specifically regarding the aeral composition and distribution on a small scale) and in understanding the factors, which are driving the colonization mechanisms.

The general current regime in the North Sea is well known (e.g., Staneva et al. 2009; Callies et al. 2017). Under regular conditions, westerly winds cause a counterclockwise circulation in the North Sea (Sündermann and Pohlmann 2011), which results in mainly northwards currents in the HSG area. Occasionally, the main wind direction changes which causes in a reversion or stagnation of the currents.

The present study aims to offer a new glimpse about the small-scale distribution pattern of both abiotic and biotic components of a highly protected and rare hard-ground environment, particularly regarding the different communities living on the hard substrates. For this purpose, a new high-resolution morpho-bathymetry of the area was produced, together with a new classification of the seafloor in sediment types (based on SSS, SBES, underwater videos, and bottom sample data), which made use of the acoustic data for spatially extending the point-based information coming from the in situ investigations. In addition, the local dynamic conditions were estimated by means of repeated SSS surveys (for the mobility of the sandy soft ground) and by means of ADCP measurements for the influence of the currents in the development of different bryozoan association along the two flanks of the HSG ridge.

Physical settings

The "Helgoländer Steingrund" (HSG) is located in the German Bight (southern North Sea), 11 km east-northeast of the Helgoland Island, and covers an area of nearly 1.6 km^2 (Fig. 1a).

The area consists of patches of very coarse grain deposits, the size of which ranges from pebbles to boulders, and surrounded by sand (Schulz 1983). The very coarse-grained sediments were transported during the Warthe Stage (140 kyr BP, Lambeck et al. 2006) of the Saalian Ice Age, as a result of an end moraine deposit (Pratje 1951; Schulz 1983). Due to its broad spectrum of grain sizes, the HSG area offers a set of physical substrates, potentially suitable to many different biocommunities. The HSG is listed in the flora-fauna habitat guidelines, and it is part of the German natural conservation areas (BFN report 477 2018). Kühne and Rachor (1996) counted 289 different species, while Dederer et al. (2015) pointed out the heterogeneous spatial distribution of the very densely and very sparsely colonized areas. Visual ground-truthing by scuba diving showed significant distribution patterns of benthic coverage, which represent an ecosystem with high biodiversity (Dederer et al. 2015).

The water depth ranges between 9 and 20 m, with the minimum depth in the shallow part of the central ridge. Semi-diurnal tide occurs with a range of ~ 1.5 m; the flood flow enters from the southwest. Westerly winds are dominant, with the largest fetch length from the northwest. The tidal current model of the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH) shows surface current velocities between decimeters and more than 1 m/s. During the field work, the weather conditions included periods of strong wind (up to 8 Bft.) with wave height > 2 m, which affected the quality of some dataset.

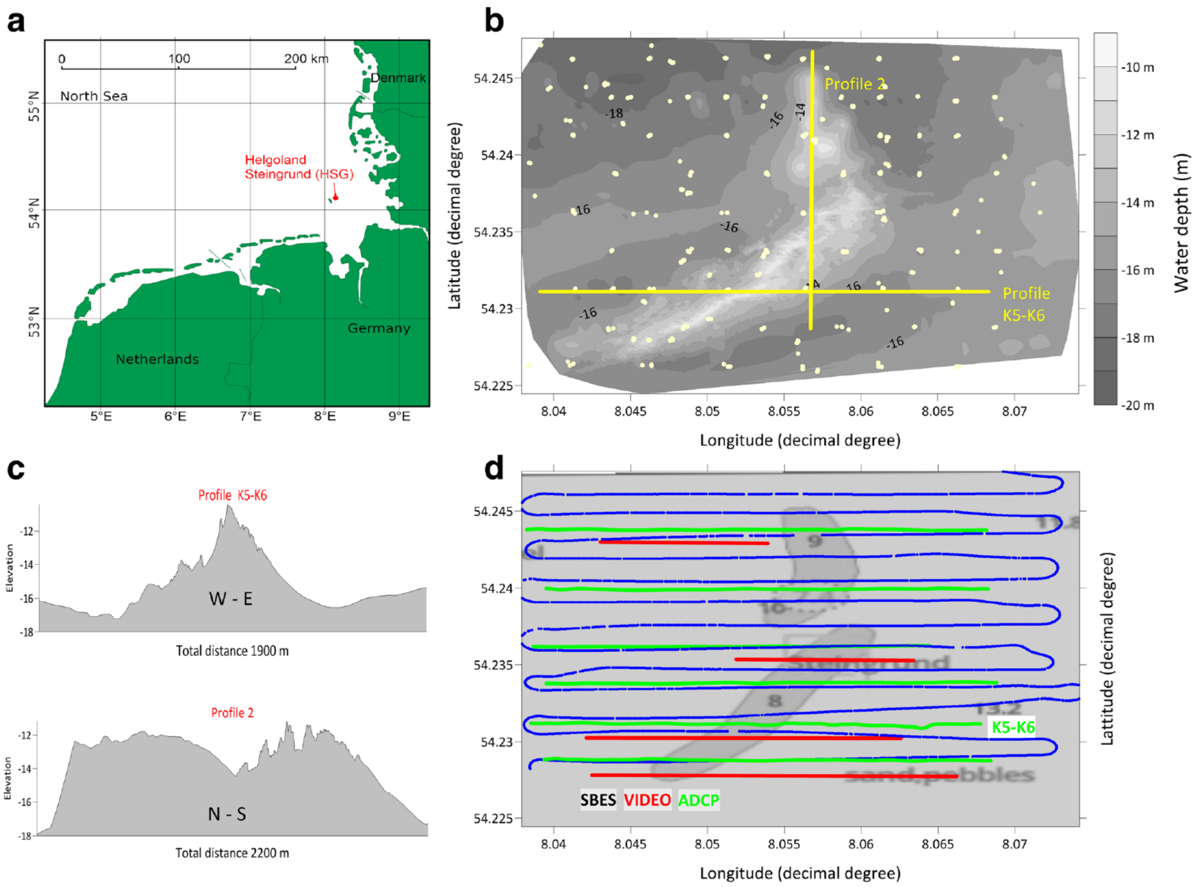


Fig. 1 **a** Location map of the study site "Helgoländer Steingrund," east of the Helgoland Island, in the southern North Sea. **b** Bathymetry map from multibeam echo sounder and subbottom profiler data (SBP). Sampling stations are showed as yellow dots; the yellow lines (profile 1 and profile K5-K6) correspond to the transect showed in **c**. **c** Elevation profiles in west-east (K5-K6 = ADCP time series transect) and north-south directions. **d** Nautical chart with the survey lines for the single-beam echo sounder (SBES, blue), underwater video (red), and Acoustic Doppler Current Profiler (ADCP, green). SBP survey lines correspond to the SBES ones

Data collection and processing

The field measurements have been carried out aboard the RV Senckenberg and RV Heincke during three cruises in September 2016, November 2016, and November 2018. The survey site encloses an area of 6.1 km^2 east of the Helgoland Island, in the German Bight (Fig. 1a). Hydroacoustic data were recorded with an average vessel speed of 5 knots.

Bathymetry and acoustic seafloor mapping—single-beam echo sounder (SBES), subbottom profiler (SBP), and multibeam echo sounder (MBES)

Individual acoustic sources have been used for the seafloor acoustic classification because vertical and oblique angle operating hydroacoustic devices differ in their acoustic backscatter characteristics (e.g., Lurton 2002). During the surveys, a combination of SBES Furuno FCV 1000, 50/200 kHz) and SBP (SES-Innomar 2000 standard plus) was used for collecting bathymetric and seafloor backscatter data (Fig. 1d). The SBP was coupled with a motion sensor (IXblue Octans) for ship movement compensations and corrections. Positioning was achieved by means of a Trimble D-GPS system (Helgoland Beacon). Tide corrections were calculated using tide gauge values recorded at the Helgoland port station ("Helgoland Binnenhafen," seven nautical miles away from the study site). The tide- and motion-corrected high-frequency signal (100 kHz) of the SBP was used for extracting the bottom depth information and, together with the multibeam echo sounder (MBES) data, for producing the bathymetric map.

In order to dense the coarse bathymetric grid based on SBP data, a MBES dataset (from 2016, with 0.5 m grid size, kindly provided by the BSH) was further processed, in particular for the central region of the study site. Bathymetry data of SES and MBES has been contoured by means of the triangulation algorithm of Golden Software Surfer™ 15. The 200-kHz signal of the SBES system was used for the waveform analysis. In a water depth of 15 m, the footprint has a beam radius of almost 1 m and a beam area of nearly 3 m^2, given a beam angle of 7.4° (Bartholomä 2006). The SBES signal was processed with the QTC IMPACT software (Quester Tangent 2004), which analyzes the full waveform of the received acoustic wave by means of a principal component analysis (PCA). The PCA finds the three most significant descriptors (so-called Q values), which describe the best statistical similarity of the echoes (e.g., Preston and Collins 2000; Bartholomä 2006; Freitas et al. 2011). These values identify a vector in a 3D Q-space. The cloud of points can be subdivided into different classes (splitting process), which ends up with a number of classes depending on the optimal splitting level (based on statistical function, e.g., cluster performance index and the chi^2).

Acoustic seafloor mapping-side-scan sonar (SSS)

SSS data were collected in November 2016 by means of a Benthos SIS-1624 dual-frequency system (110 kHz and 390 kHz). Nine north-south profiles were recorded, with a length of 2500 m and a spacing of 250 m. A swath range of 300 m was set, with 50 m overlap between the lines. For this study, only the low-frequency data were processed, as the high-frequency dataset resulted to be adversely affected by the severe weather conditions. In November 2018, a second SSS dataset was collected by means of a Klein 4000 (100 and 400 kHz), along 11 transects west-east oriented, 200 m spaced, and with a swath range of 300 m (i.e., 100 m overlap between the lines). The low frequency was used for the seafloor classification.

The SonarWiz software (v7.04) was used for producing the final mosaics (after applying geometric and radiometric corrections) and for segmenting the dataset in acoustic classes (only for the November 2018 dataset). SonarWiz allows choosing among different algorithm and classification functions (Seabed Characterization Tool, SonarWiz UserGuide 2017). For this study, a combination of Gray-Level Co-occurrence Matrix (GLCM) functions was used (contrast, homogeneity, energy, and entropy; Haralick et al. 1973). Due to its larger coverage, the SSS mosaic of November 2016 (in 1 m resolution, Fig. 3b, c) was used as a base for the interpretation of the bottom samples and video results (Fig. 3a, b) and, therefore, for spatially extending these point information on an areal scale. This process was performed on ArcGIS (v10.2). The November 2018 dataset (Fig. 3d), instead, resulted to be more suitable for the classification, due to the larger overlap between the lines and to its west-east orientation, which better fits to the main morphological structures of the area.

Ground-truthing—bottom samples

Seafloor samples were collected for grain size analysis from 128 stations, in series of 3 replicates, by means of a 0.2-m^2 Shipek grab sampler. A total amount of 353 samples were recovered (Fig. 1b), as many attempts to sample the hard-ground locations failed (empty grabs). Due to the vessel drifting and to the positioning error connected to the vessel-sampling device offsets, the replicates from the same sampling station presented a distance up to 50 m from the planned position. The sediment samples were macroscopically described on board, a photo was taken for each sample, and for soft sediments, a subsample was collected for grain size analysis.

The sediments were desalinated in the lab and wet-sieved on a 63-μm mesh, and the shell content for the fraction coarser than 2 mm were removed. The sand fraction (2000–63 μm) was analyzed by means of a settling tube (Brezina 1979) and the mud fraction (< 63 μm) by means of a Sedigraph particle analyzer. The sediment classes were named after Folk (1954).

Ground-truthing—underwater videos

The underwater videos were recorded along five west-east tracks (total length ~ 5500 m) (Fig. 1d). The tracks were designed to fit with the sampling positions. A drop camera (Kongsberg 1366 MKII- 0321) was deployed, frame-mounted, and slowly towed behind the vessel at the average speed of 0.8 knots. The videos were replayed on an Adobe Premiere Pro CC software to visually identify the main seabed types (e.g., seafloor sediments, structures, and biota). The videos were therefore split accordingly, and the position of each class reported as a vector line on ArcGIS. In regard to the hard ground, a semi-quantitative estimation of the spatial coverage of the bryozoa was given.

Hydrography—Acoustic Doppler Current Profiler

A vessel-mounted Teledyne Rio Grande ADCP with 1200 kHz frequency was deployed in November 2017 and 2018, in order to measure the current velocity and direction over tidal cycles. The system was coupled with a D-GPS positioning (also for heading); the compass calibration achieved a good fit in direction between bottom track and D-GPS track (< 5° variation). The high-frequency mode (Water Mode 12) with a bin size of 25 cm was set, in order to cover the entire water column (max. depth ~ 20 m). The raw data were then smoothed using an average of 10 ensembles, in order to reduce the noise and to increase the signal/noise ratio.

Nine ADCP transects parallel and perpendicular to the ridge were recorded over more than one tidal cycle and in both directions. For the time series analysis, only the east-west tracks of November 2018 were considered (Fig. 1d). One of these east-west transects (named K5-K6 in Fig. 1b, d) was used for comparison with the overlaying underwater video. Tidal data recorded at the Helgoland port gauge ("Helgoland Binnenhafen" in Fig. 4 approximately 7 nautical miles southwest of the study site) were used for relating the ADCP measurements to the tidal phase. The tidal curve was provided by the German Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde BfG), in 1 min interval (Fig. 4). The ADCP data were processed by means of the USGS Velocity Mapping Toolbox (Parsons et al. 2013).

The vessel movements produced an interference with the ADCP records, in regard to the close-to-surface bins (the first 1–1.5 m from the water surface). As a result, the uppermost bins showed often a higher current velocity, randomly changing in values and direction, depending on the orientation of the transect's respect to the ship movement, the currents, and the wave action.

Results

Bathymetry and morphology

The morpho-bathymetric map (Fig. 1b and Fig. 2) confirms the presence of a half-moon-shaped structure, which in this new high-resolution version shows a morphological complexity particularly in the southwestern end. Three morphological sections can be recognized, separated by the ridge, which in its central region is ~ 450 m wide and 6 m higher than its margins (Fig. 1b). The cross section shows the asymmetric profile of the ridge, with the steeper side on the western flank (Fig. 1c). The shallowest part of the ridge reaches a water depth of ~ 9 m. The complex topographic pattern (surface roughness), which distinguishes the central and southwestern part of the ridge, decreases along the flanks, where they gradually merge with the smooth and soft ground-covered regions (Fig. 1b, c).

Bottom samples

Based on the first macroscopic description of the grab samples, on the photos taken on board, and on the grain size analysis results, the sediments were grouped into 3 classes (Fig. 2):

- Sandy sediments (yellow dots)
- Gravelly sediments (orange dots)
- Hard substrate (purple dots)

The sandy sediments (125 samples) are composed by sand (90–100 wt%), small amounts of gravel (0–10 wt%), and shell fragments (0–10 wt%). Mud content is negligible. The gravelly sediments (92 samples) show higher amount of gravel (> 10 wt%) and a sand content < 90 wt%. The hard substrate class (136 samples) includes the coarser material, which could be characterized, based on the bottom samples, only in its gravel-to-cobble-size fraction, due to the limitation of the sampler (occasionally, cobbles were recovered in the Shipek grab). The soft-ground regions (west and east of the central ridge) differ in their main sedimentological components: the western one is dominated by sandy sediments, while the eastern area is mainly composed by a mixture of both sand and gravel. The hard substrate class (purple dots, Fig. 2) overlaps the central ridge and extends to the northwest area

Underwater video analysis

The analysis and segmentation of the underwater videos revealed the presence of seafloor structures (e.g., bedforms, hardground) and of different benthic assemblages (Fig. 3a). Six seabed types (Fig. 3a, b) were distinguished, based on such characteristics:

- Seabed type 1, ripple-shaped sand—sand with bedforms, rare epifaunal organisms, and small shell debris.
- Seabed type 2, gravel and shell fragments–gravelly and sandy sediments (without bedforms), with a higher content of shell debris.
- Seabed type 3, sand and gravel—sand with bedforms, the troughs of which are filled by fine gravelly sediments and shell fragments.
- Seabed type 4, colonized hard substrate—hard substrate mainly made by cobbles and boulders, totally covered by epifaunal communities, with a dominance of the two bryozoa species *Flustra foliacea* (Fig. 3b, green-colored area) and *Alcyonidium diaphanum* (Fig. 3b, brown-colored area), each of them dominating a specific region of the ridge.
- Seabed type 5, non-colonized hard substrate—hard substrate mainly made by cobbles and boulders, poorly covered or not covered by epifauna.
- Seabed type 6, mixed substrate—a very heterogeneous mix of small sand patches with individual coarse-grained particles (from gravel to boulder size).

The hard substrate seabed types (4, 5, and 6) can mainly be found in the ridge area, while the sandy and gravelly seabed types (1, 2, and 3) occur in the western and eastern regions (Fig. 3b). Spatial distribution and coverage density of the bryozoa show a geographic zonation of the two main species: the western and central parts are characterized by the bryozoa *F. foliacea*, while the *A. diaphanum* become dominant along the transition zone of the eastern flank, till the beginning of the large eastern sand field (with a spatial density of > 70%) (Fig. 3b).

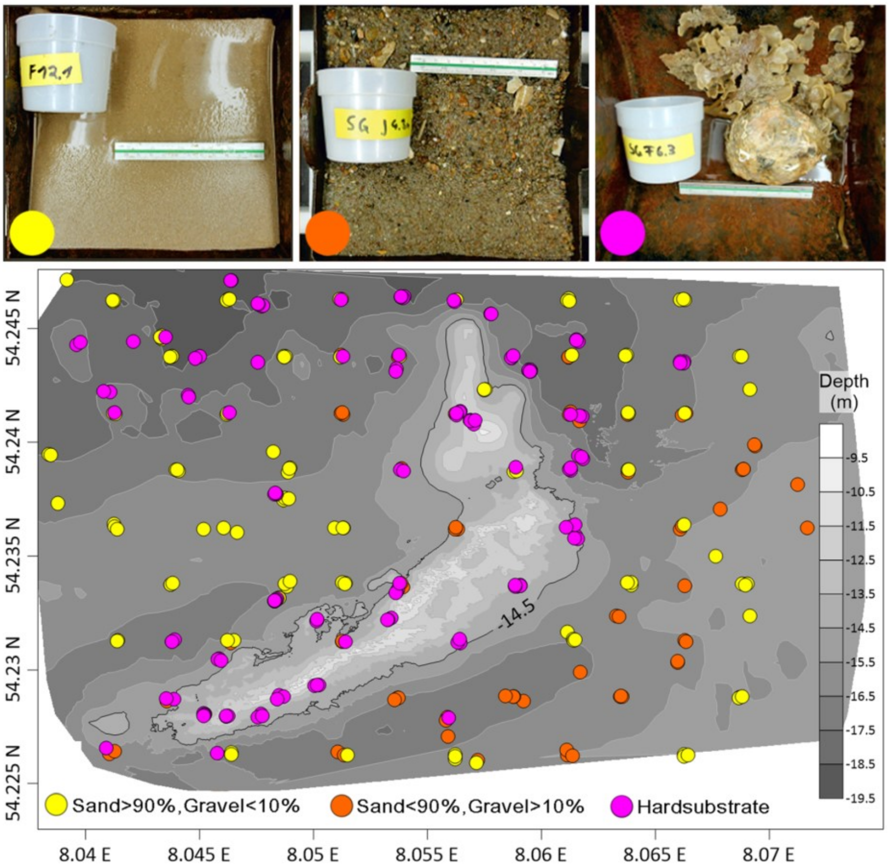


Fig. 2 The three main sediment types and the sediment distribution map in the Helgoländer Steingrund area. The colored dots (and the related photos) correspond to sandy sediments (yellow), gravelly sediments (orange), and hard substrate (purple). The high-resolution morpho-bathymetric map in the background shows in detail the complex topography characterizing the half-moon-shaped ridge, especially in its central and southwestern parts

Hydroacoustics—side-scan sonar

SSS data shows a clear distinction between hard substrate (darker grayscale tones, Fig. 3c, d) and soft-ground regions (light grayscale tones). The comparison of the two SSS mosaics (November 2016, Fig. 3c; November. 2018, Fig. 3d) shows no significant difference in the backscatter distribution pattern: minor changes occur only along the outer rim of the ridge.

November 2018 was used for the acoustic classification. The spatial backscatter pattern was split into 3 classes (Fig. 3e): Class 1 (~ 50% of the total area) occurs mostly on the western region (soft ground) and, associated with both class 2 and class 3, in the eastern one. Class 2 and class 3 correspond to the ridge and its flanks, with class 3 (~ 30%) which covers the ridge crest and its surroundings and class 2 (~ 20%) which appears in the transition zones between class 1 and class 3.

Hydroacoustics—single beam

At the beginning of the statistical analysis, the SBES data were split into five acoustic classes, according to the optimal splitting level suggested by the software statistics. Two classes stood out among the others, both for the statistic relevance (class 1 37%, class 3 28%; yellow and purple in Fig. 3e, respectively) and, in regard to class 1, for the distinctive area of occurrence (it appeared mostly in the western region, characterized by sandy sediments). The remaining three classes, instead, were subrepresented (e.g., class 3 3%), and moreover, they occurred always in association and were not distinguishable as separated classes. Therefore, these three classes were merged into a new one (named class 2 35%; orange dots in Fig. 3e), which still occurred in association with class 3, but with a distinctive presence along the ridge flanks and rim.

Hydrography—Acoustic Doppler Current Profiler

A selection of the 73 original ADCP records, chosen among the most representative and of better quality datasets, was used for giving a picture of the current velocity and direction over the entire area (6 east-west transect, Fig. 1D) and, more specifically, along the southern K5-K6 profile (Fig. 1D). The time stamp for each transect is given in the water level curve of the Helgoland port (Fig. 4). During slack water time, the recorded current velocity over the entire water column was < 0.1 m/s, while at maximum flow, the average velocity was ~ 0.8 m/s, with peaks up to 1.2 m/s. For the near-to-seafloor region, the

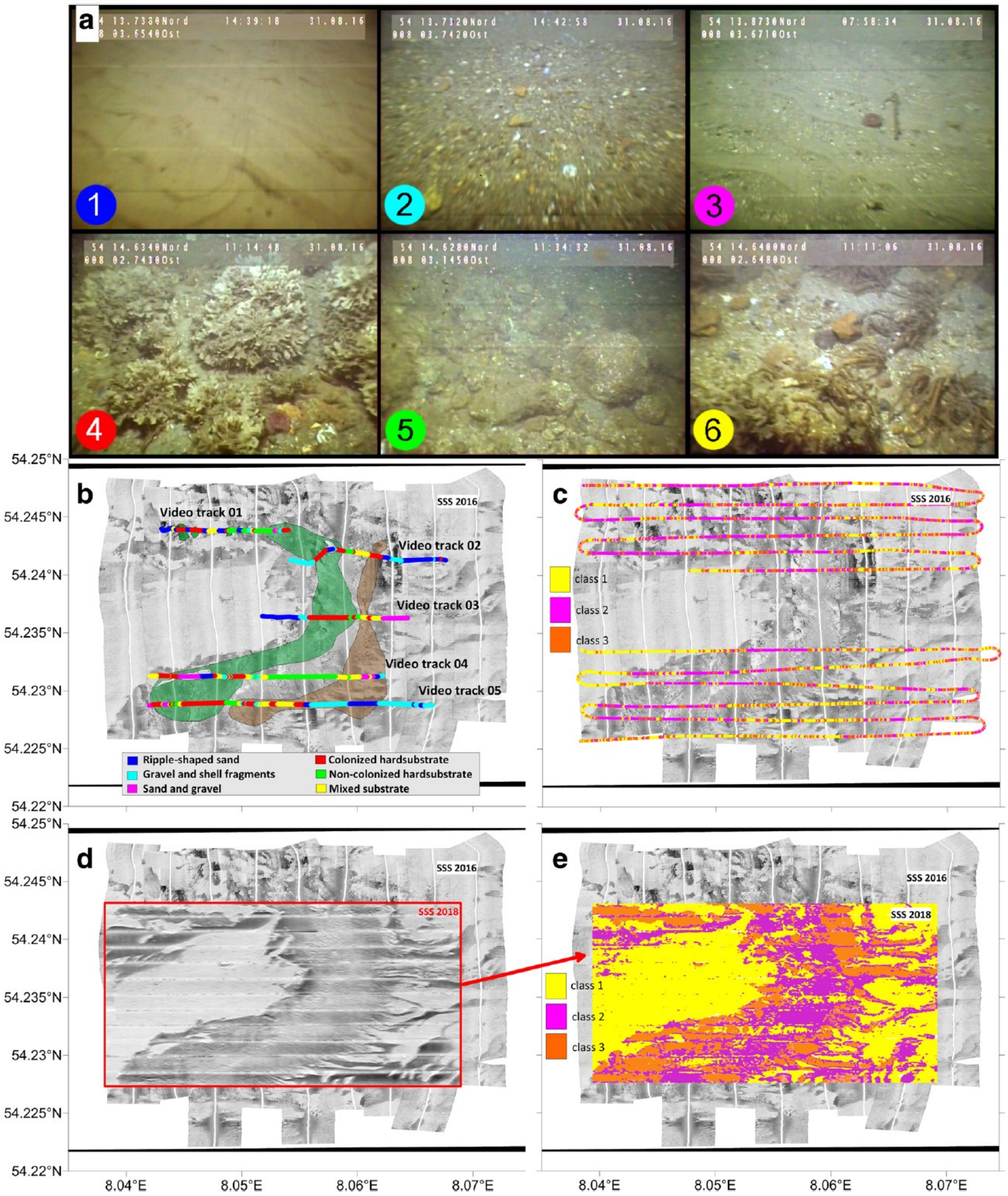
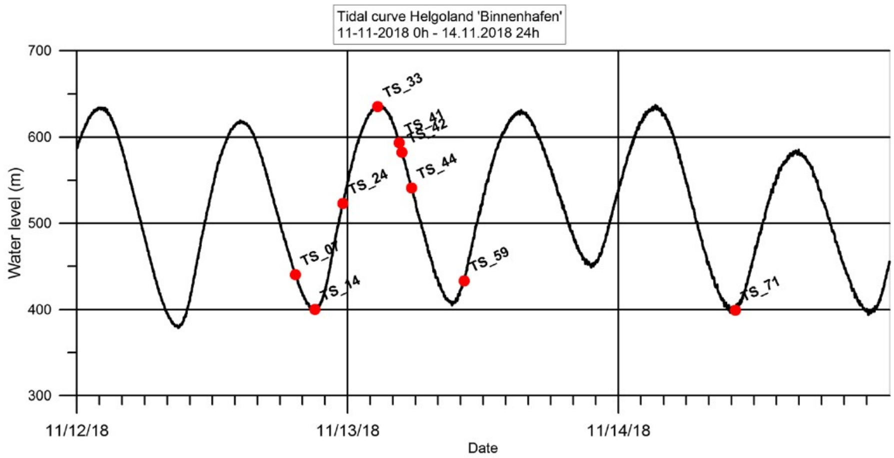


Fig. 3 Seafloor classification based on underwater videos and acoustic data. **a** Video classification: (1) ripple-shaped sand, (2) gravel and shell fragments, (3) sand and gravel, (4) colonized hard substrate, (5) non-colonized hard substrate, and (6) mixed substrate. **b** Segmentation of the video tracks into the six seabed types (see above); the zones of high abundance of the two bryozoan species have been highlighted with polygons: green = *F. foliacea* and brown = *A. diaphanum.* **c** Single-beam (SBES) acoustic classification (three classes). Background: side-scan sonar (SSS) backscatter mosaic (2016 dataset). **d** SSS backscatter mosaic (2018 dataset), on top of the 2016 one. **e** Acoustic seafloor classification of the 2018 SSS data. The color code of the three classes corresponds to the colors of the SBES ones

current data of the first two meters above sea bottom (8 bin cells) were integrated. During maximum ebb flow, near-to-seafloor current velocities ≥ 0.5–0.6 m/s were recorded (Fig. 5). During maximum flood flow, the near-to-seafloor velocity rose up to ~ 0.7 m/s (Fig. 5). The flow direction followed the general current pattern of the German Bight (westerly/easterly for ebb/flood). According to the complex seafloor morphology, the local flow pattern showed strong variations across the water column.

The times series of transect K5-K6 (corresponding to video track 4) pointed out such complex flow pattern (Fig. 6). The flow direction rotated from 250° (K5-K6_TS07 in Fig. 6) to 300°

Fig. 4 Tidal curve recorded at the Helgoland harbor gauge during the Acoustic Doppler Current Profiler (ADCP) survey (transect K5-K6). The red dots correspond to the current velocity/direction measurements showed in Fig. 5



from flood to maximum ebb flow (K5-K6_TS41 and K5-K6_TS44, Fig. 6). The flow direction moved westward and further to southeast during the ebb flow. The averaged maximum velocity increased from to 0.5 to 0.8 m/s at maximum ebb flow and decreased again to less than 0.5 m/s. The east-west transect across the central ridge clearly showed the influence of the HSG ridge on the flow pattern. In fact, during the higher flow phases (both ebb and flood), the ridge altered the flow, as shown by the

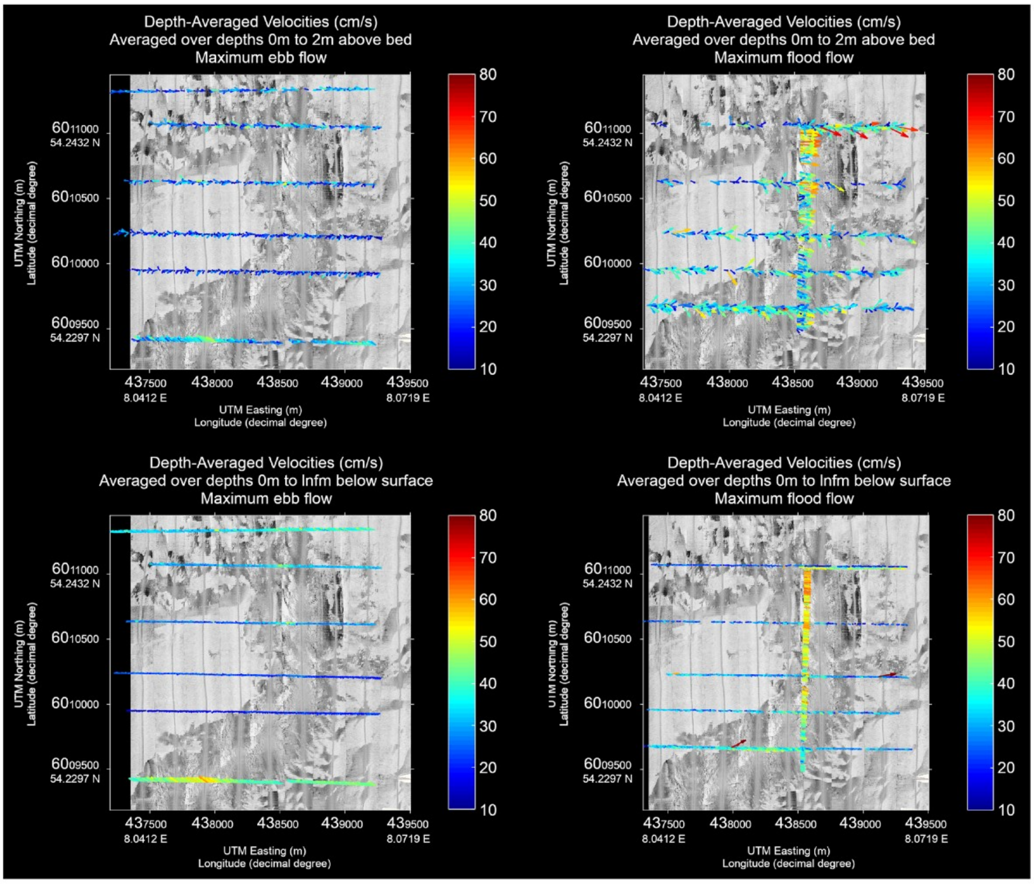


Fig. 5 Averaged velocity vectors of the six ADCP (Acoustic Doppler Current Profiler) transects of November 2018 (positions in Fig. 1d). Ebb flow 2 m above sea bottom (upper left) and over the entire water column (lower left). Flood flow 2 m above sea bottom (upper right) and over the entire water column (lower right)

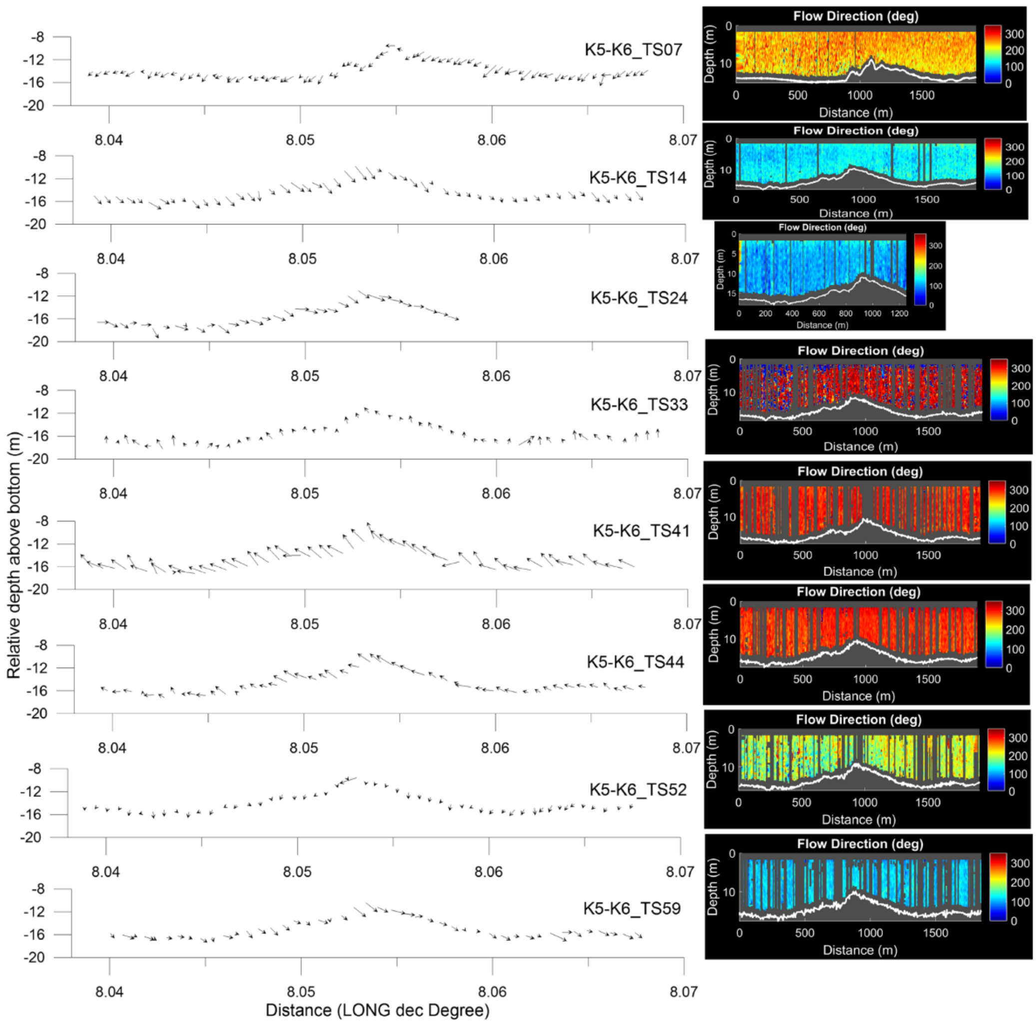


Fig. 6 Time series of the transect K5-K6 (position in Fig. 1d) during different tidal stages (shown in Fig. 4). The left column shows the averaged velocity vector for the first 2 m above sea bottom, and the right column gives the velocity direction (in geographic orientation) over the entire water column

scattering of the current values (velocity and direction) in Fig. 6 and in Fig. 7. At flood flow, the eastern part of the transect shows a south running current in the deeper part of the water column; meanwhile, the upper part shows into the opposite direction (Fig. 7). Around slack water, the pattern is heterogeneous; only at the western flank a weak flow zonation can be observed (Fig. 6). During ebb flow on top of the ridge, a stronger north-directed current separates the current regime into three spatial sections following the morphology (Fig. 7).

Discussion

The "Helgoländer Steingrund" area belongs to a small number of hard substrate sites in the German Bight, which are highly regarded due to their ecological value. It includes a very broad spectrum of sediment grain sizes, ranging from sand to large boulders, with a high spatial patchiness, which offers a potential suitable substratum for benthic communities. Such a high complexity of the substrate and its related hydrodynamic conditions influences the patchy distribution pattern of colonized and non-colonized areas. The outcomes from underwater video analysis confirmed the high biodiversity showed by Dederer et al. (2015). In comparison to former works, the hydroacoustic mapping showed in the present study provided a small-scale description of such complex patchiness. As similarly showed by Freitas et al. (2011), the wave analysis of the SBES signal allowed to discriminate the main different seabed types, which fit the grain size classes present in the area (sand, gravel, and coarser deposits). Ellingsen et al. (2002) stated that "seabed homogeneity is important if each acoustic class should represent on single seabed type." An attempt to use a higher amount

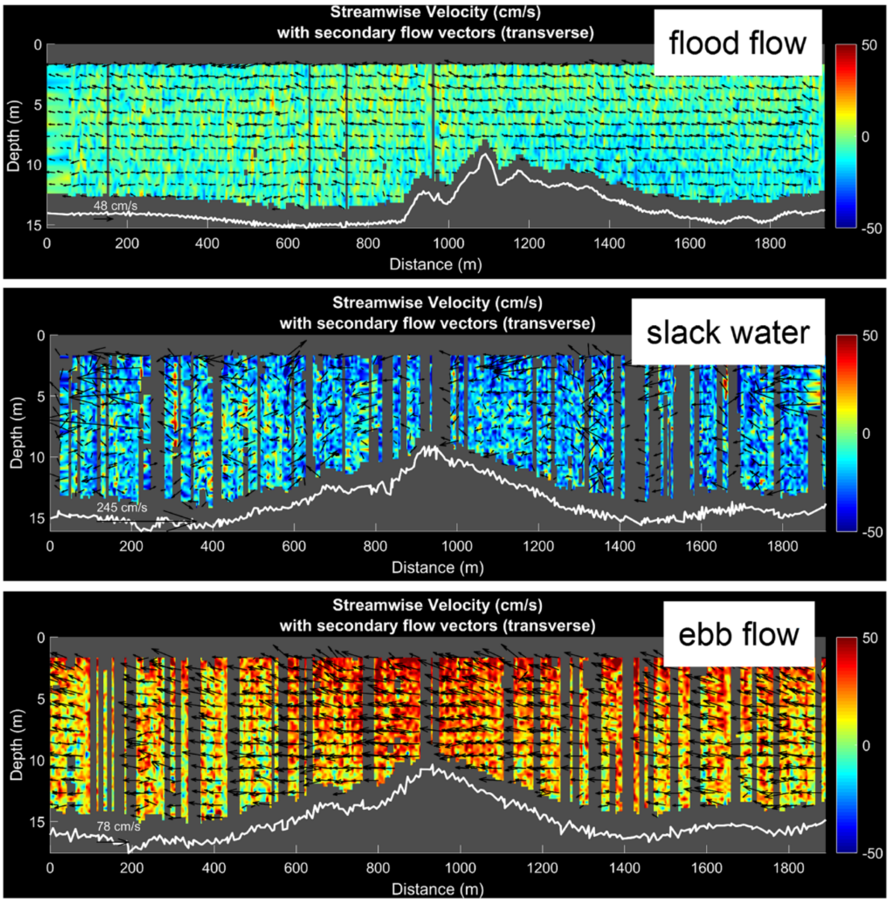


Fig. 7 Time slots of the different tidal stages of transect K5-K6 during ebb flow, slack water, and flood flow. The colored pattern shows the two flow direction perpendicular to the transect direction. In such a west-east-oriented transect, positive values indicate the north-directed component and negative values the south-directed component

of classes (respect to the ones indicated as optimal splitting level by the QTC statistics) failed to reveal a connection to the benthic coverage. While the SBES-QTC approach was successfully used in previous studies (e.g., Holler et al. 2017) to detect the presence of biogenic assemblages over soft-ground substrates, in the HSG area, the SBES classification was mainly driven by the sediments and the related seafloor roughness. The main reason can be found in the relationship between the density and size of the epibenthic fauna at our study site and the size of the area investigated by a single echo (foot print size). In fact, while the beams collected from homogeneous areas (both hard or soft grounds) reflect the interaction of the acoustic wave with one sediment type, the echoes covering patchy areas average the influence of different components and their spatial relationship. This effect is even more significant due to the wave form processing, which stacks up to 5 echoes in one signal before performing the PCA. In contrast to this study, Anderson et al. (2002) analyzed SBES-QTC data along the coast of Newfoundland and distinguished “rocks” and “rocks with macrofauna,” but on a steeper depth gradient of more than 200 m water depth. Their successful discrimination of macrofauna implies a much broader depth range, and in fact, the same approach was successfully followed by Mielck et al. (2014), which used the hardness/roughness values of a SBES RoXAnn system in order to map the dense kelp forests around the western underwater outcrops of the Helgoland Island.

In several studies, the SSS was used as a successful tool for habitat mapping (e.g., Collier and Brown 2005). Besides, the recent trend moved from the manual segmentation to semi-automatic detection tools for classifying the SSS signal, especially in coarse grain habitats (Papermeier and Hass 2018, Michaelis et al. 2019). The results of our GLCM-based semi-automatic classification showed a similar distribution pattern as Schulz (1983). The comparison of the two SSS datasets (November 2016 and November 2018) showed only minor changes around the ridge rim, which can be interpreted as mobile sediment layers, the mobility of which is likely controlled by storm events. The movement of these sand layers and the interaction with the rocks can act as a driving factor in preventing the colonization of such transitional areas (Michaelis et al. 2019). The strong contrast change of sandy sediments, gravelly sediments, and hard substrates is consistent with the spatial distribution pattern of the SBES classification (Fig. 3c).

However, our study points out the importance of using an integrated approach (hydroacoustic mapping and in situ seafloor ground-truthing) in order to be able to spatially resolve the lateral variability of extremely patchy environments, characterized by a combination of seafloor substrates and communities, which varies on a meter-size scale. In fact, the combination of acoustic and ground truth data made possible to work out the spatial separation of the bryozoa *Flustra foliacea* and *Alcyonidium diaphanum*. While *F. foliacea* dominates the western flank and the ridge, *A. diaphanum* is the most abundant in the more patchy gravel-to-boulder area (eastern flank of the ridge). Such a region forms a transition zone, where the relict moraine deposits (cobbles, boulders, etc.) gradually fade into the easternmost sandy soft ground, forming individual and isolated stones among gravel and sandy sediments. Such a strong zonation of the bryozoan communities could be likely linked to the local micro- and macrohydrodynamic conditions: the former could be related to the surface roughness, as the relict moraine deposits are denser and steeper on the western flank than on the eastern one; the latter could reflect the general hydrodynamic conditions of the water column (e.g., exposure, nutrients), as a result of the interaction between the general circulation and the local morphology of the seafloor (ridge; Dyrynda 1994).

The ADCP data shows a general flow pattern with current velocities of almost 1 m/s during flood flow, in accordance with the major current regime of the tidal driven circulation of the North Sea (Sündermann and Pohlmann 2011; Staneva et al. 2009). However, the presence of the half-moon-shaped ridge had a strong influence in modifying temporal and spatial current flow pattern. In fact, during the different tidal stages, the ridge divides the current flow in opposite directions. The maximum flow velocities show a slightly stronger impact of the flood current, which helps explaining the dominance of *F. foliacea* in this region. A closer look into the current profiles shows a stronger variation in direction and velocity close to the near-seafloor-section of the ridge and in the transition zone to the east (Fig. 6 and Fig. 7). Such a flow pattern shows a behavior similar to the one occurring over bedforms (e.g., ripples or dunes). Kwoll et al. (2014) analyzed the relationship between mobile bedforms and tides. Dunes with height of up to 8 m (comparable in size to the HSG hard substrate topography) show that the flow velocity strongly increases when the flood flow hits the steep site of the dune and then decreases on the less steep lee side. On the contrary, during ebb flow, the water hits the less steep site first and decelerates significantly at the steep lee side of the ridge. This can explain the general difference of both sides of the ridge, but the patchiness along the transition zone needs to be downscaled. This locally sheltered area is the preferred place of *A. diaphanum*, which avoids stronger currents (Porter et al. 2001). Migné and Davoult (2002) showed, in fact, that such species prefer strong tidal current exposed areas (as in the English Channel). That contradicts with our observation of currents, with estimated velocity of 0.3 m/s close to the sea bottom. It has to be considered that the resolution of our ADCP is limited (due to a 0.25-m bin size), but still, the data represents a phase of higher hydrodynamic conditions of the fall period in the North Sea.

Conclusion

At the hard substrate area "Helgoländer Steingrund" (HSG), hydroacoustic devices, underwater videos, and bottom samples were used for mapping and classifying such very patchy and coarse-grained habitat. The SBES and SSS data allowed a clear distinction of the morphological units, including the rocky ridge, its flanks, and the transition zones toward the gravelly-sandy surrounding areas. The major challenge in the hydroacoustic data was the identification of colonized and non-colonized hard substrates in the small-scale patchy areas composed of the full range of grain sizes, from gravel to boulder. Three classes of sediment types were identified. While the acoustic-based approach could only partially resolve the biotic components (colonized vs non-colonized substrates) or their specific fingerprints (the difference between bryozoan species), the use of underwater videos allowed a more detailed classification into six different seabed types, which took into account both the abiotic (sediments, morphology, etc.) and biotic components. The two flanks of the ridge and the transition to the surrounding soft ground areas resulted to be differentiated into two regions, with a distinct dominance of the bryozoa *F. foliacea* and *A. diaphanum* on the western and on the eastern side, respectively. The comparison between SBES and SSS dataset showed a similar distribution of the main three acoustic classes (corresponding to sand, gravel, and hard substrate); however, the SSS overrated the sand and the SBES the hard substrate areas. Although the presence of distinct benthic communities was not detected in the hydroacoustic data, SSS images can be successfully used for a high-resolution mapping of hard substrates, which can be used as a surrogate for the presence of bryozoan assemblages. The occurrence of bedforms in the northeastern part of the study site and the strong heterogeneity in colonization of the hard substrate reflect complex hydrodynamic conditions. This is proved by the outcomes of the ADCP data which could show the general flow pattern at this side but even resolved the local variability of current pattern dependent on tidal stage and bottom relief. At this stage, the influence of waves were not considered, which is in addition an important driver for local hydrodynamics. More small-scaled hydrodynamic data and the use of habitat models will help resolving the complexity of the patchy habitat in future.

Acknowledgments This study is financed by the German Research Foundation (DFG) and is part of the INTERCOAST project, which is a collaboration of the University of Bremen, the Senckenberg Institute in Wilhelmshaven, and the University of Waikato.

The authors would like to thank the crew of the RV Senckenberg for the support on the vessel.

Many thanks go to the Federal Maritime and Hydrographic Agency (BSH) Hamburg which provided the (MBES) multibeam data for the bathymetry.

The authors are grateful to Astrid Raschke for the grain-size analysis, to Maik Wilsenack for the technical support, and to our student assistant Vanessa Köhler.

The data reported in this paper will be archived in Pangaea (www.pangaea.de).

References

Anderson JT, Gregory RS, Collins WT (2002) Acoustic classification of marine habitats in coastal Newfoundland. ICES J Mar Sci 59:156–167

Arendartchuk F, Prado MFV, Bonetti J (2017) Classification of geomorphological in Pântano do Sul Bay (SC) from side-scan sonar images. 2017 IEEE/OES Acoustics in Underwater Geosciences Symposium (RIO Acoustics)

Bartholomä A (2006) Acoustic bottom detection and seabed classification in the German Bight. Geo-Mar Lett 26(3):177–184. https://doi.org/10.1007/s00367-006-0030-6

Bartholomä A, Holler P, Schrottke K, Kubicki A (2011) Acoustic habitat mapping in the German Wadden Sea - comparison of hydro-acoustic devices. J Coast Res Spec Issue 64:1–5

BFN (Federal Agency for Nature Conservation) (2018) Die Meeresschutzgebiete in der deutschen ausschließlichen Wirtschaftszone der Nordsee - Beschreibung und Zustandsbewertung, (2. überarb. Auflage). BfN-Report, 477, 486 p

Brezina J (1979) Particle size and settling rate distributions of sand-sized materials. PARTEC - 2nd European Symposium on Particle Characterization. Nürnberg, 1-47

Callies U, Gaslikova L, Kapitza H, Scharfe M (2017) German Bight residual current variability on a daily basis: principal components of multi-decadal barotropic simulations. Geo-Mar Lett 37(2):151–162. https://doi.org/10.1007/s00367-016-0466-2

Collier JS, Brown CJ (2005) Correlation of sidescan backscatter with grain size distribution of seabed sediments. Mar Geol 214:431–449

de Kluijver MJ (1991) Sublittoral hard substrate communities off Helgoland. Helgoländer Meeresun 45:317–344

Dederer G, Boos K, Kanstinger P, Krone R, Schneider C, Beher J, Kuhlenkamp R, Kind B (2015) Tauchuntersuchung des "Steingrund" bei Helgoland (FFH DE 1714 - 391) und Konzeptentwicklung eines Tauch Monitorings für den FFH Lebensraumtyp Riff. Final report, 74 p

Dyrynda P (1994) Hydrodynamic gradients and bryozoan distributions within an estuarine basin (Poole Harbour,UK). Olsen & Olsen, Fredensborg

Ellingsen KE, Gray JS, Bjørnbom E (2002) Acoustic classification of seabed habitats using the QTC VIEW system. J Mar Sci 59(4):825–835

Feldens P, Schulze I, Papenmeier S, Schönke M, Schneider von Deimling J (2018) Improved interpretation of marine sedimentary environments using multi-frequency multibeam backscatter data. Geosciences

Folk RL (1954) The distinction between grain size and mineral composition in sedimentary-rock nomenclature. J Geol 62(4):344–359

Freitas R, Silva S, Quintino V, Rodrigues AM, Rhynas KP, Collins WT (2003) Acoustic seabed classification of marine habitats: studies in the western coastal-shelf area of Portugal. J Mar Sci 60:599–608

Freitas RF, Ricardo F, Pereira L, Sampaio S, Carvalho M, Gaspar V, Quintino V, Rodrigues AM (2011) Benthic habitat mapping: concerns using a combined approach (acoustic, sediment and biological data). Estuar Coast Shelf Sci 92:598–606

Greene A, Rahman AF, Kline R, Rahman MS (2018) Side scan sonar: a cost-efficient alternative method for measuring seagrass cover in shallow environments. Estuar Coast Shelf Sci 207:250–258

Haralick RM, Shanmugam S, Dinstein S (1973) Textural features for image classification. IEEE Trans Syst Man Cybern 3(6):610–620

Hass C, Mielck F, Fiorentino D, Papenmeier S, Holler P, Bartholomä A (2017) Seafloor monitoring west of Helgoland (German Bight, North Sea) using the acoustic ground discrimination system RoxAnn. Geo-Mar Lett 37:125–136. https://doi.org/10.1007/s00367-016-0483-1

Holler P, Markert E, Bartholomä A, Capperucci R, Hass CH, Kröncke I, Mielk F, Reimers CH (2017) Tools to evaluate seafloor integrity: comparison of multi-device acoustic seafloor classifications for benthic macrofauna-driven patterns in the German Bight, southern North Sea. Geo-Mar Lett 37(2):93–109

Kühne S, Rachor S (1996) The macrofauna of a stony sand area in the German Bight (North Sea). Helgoländer Meeresun 50(4):433–452

Kwoll E, Becker M, Winter C (2014) With or against the tide: the influence of bed form asymmetry on the formation of macroturbulence and suspended sediment patterns. Water Resour Res 50(10):7800–7815. https://doi.org/10.1002/2013WR014292

Lambeck K, Purcell A, Funder S, KjæR KH, Larsen E, Moller PER (2006) Constraints on the Late Saalian to early Middle Weichselian ice sheet of Eurasia from field data and rebound modelling. Boreas 35(3):539–575

Lurton X (2002) An introduction to underwater acoustics. Principle and applications, Springer, 347 pp

Michaelis R, Hass CH, Mielck F, Papenmeier S, Sander L, Ebbe B, Gutow L, Wiltshire KH (2019) Hard-substrate habitats in the German Bight (South-Eastern North Sea) observed using drift videos. J Sea Res 144:78–84. https://doi.org/10.1016/j.seares.2018.11.009

Mielck F, Bartsch I, Hass HC, Wölfl AC, Bürk D, Betzler C (2014) Predicting spatial kelp abundance in shallow coastal waters using the acoustic ground discrimination system RoxAnn. Estuar Coast Shelf Sci 143:1–11

Migné A, Davoult D (2002) Experimental nutrition in the soft coral Alcyonium digitatum (Cnidaria: Octocorallia): removal rate of phytoplankton and zooplankton. Cah Biol Mar 43(1):9–16

Papermeier S, Hass CH (2018) Detection of stones in marine habitats combining simultaneous hydroacoustic surveys. Geosciences 8(8):279. https://doi.org/10.3390/geosciences8080279

Parsons DR, Jackson PR, Czuba JA, Engel FL, Rhoads BL, Oberg KA, Best JL, Mueller DS, Johnson KK, Riley JD (2013) Velocity mapping toolbox (VMT): a processing and visualization suite for moving-vessel ADCP measurements. Earth Surf Process Landf 38:1244–1260

Porter JS, Hayward PJ, Spencer Jones ME (2001) The identity of Alcyonidium diaphanum (Bryozoa: Ctenostomatida). J Mar Biol Assoc 81(6):1001–1008. https://doi.org/10.1017/S0025315401004970

Pratje O (1951) Die Deutung der Steingründe in der Nordsee als Endmoränen. Deutsche Hydrographische Zeitschrift 4(3):106–114. https://doi.org/10.1007/bf02027271

Preston JM, Collins WT (2000) Bottom classification in very shallow water by high-speed data acquisition. Oceans Conference Record (IEEE), 2, 1277, 1282 vol.2. https://doi.org/10.1109/OCEANS.2000.881778

Quester Tangent (2004) QTC IMPACT user manual

Quintino V, Freitas R, Mamede R, Ricardo F, Rodrigues AM, Mota J, Perez-Ruzafa A, Marcos C (2010) Remote sensing of underwater vegetation using single-beam acoustics. ICES J Mar Sci 67:594–605. https://doi.org/10.1093/icesjms/fsp251

Rachor E & Nehmer P (2003) Erfassung und Bewertung ökologisch wertvoller Lebensräume in der Nordsee-Abschlussbericht für das F + E-Vorhaben FKZ 899 85 310. Report, Bundesamt für Naturschutz, 175 pp

Schulz H (1983) Der Steingrund bei Helgoland - Restsedimente einer saaleeiszeitlichen Endmoräne. Meyniana 35:43–53

Schwarzer K, Ricklefs K, Bartholomä A, Zeiler M (2008) Geological development of the North Sea and the Baltic Sea. Die Küste 74:1–17

Staneva J, Stanev E, Wolff J-O, Badewien T, Reuter R, Flemming BW, Bartholomä A, Bolding K (2009) Hydrodynamics and sediment dynamics in the German Bight: a focus on observations and numerical modelling. Cont Shelf Res 29(1):302–319

Stocks T (1955) Deutsche-Hydrographische Zeitschrift 8: 112. https://doi.org/10.1007/BF02019797

Sündermann J, Pohlmann T (2011) A brief analysis of North Sea physics. Oceanologia 53(3):663–689

Terry JP, Goff J (2014) Megaclasts: proposed revised nomenclature at the coarse end of the Udden-Wentworth grain-size scale for sedimentary particle. J Sediment Res 84:192–197

Zeiler M, Schwarzer K, Bartholomä A, Ricklefs K (2008) Seabed morphology and sediment dynamics. Die Küste 74:31–44

CHAPTER 4 – Publication III

4.1. The role of artificial material for benthic communities – establishing different concrete materials as hard bottom environments

Becker L.R., Ehrenberg A., Feldrappe V., Kröncke I., Bischof K.

Becker L.R., Ehrenberg A., Feldrappe V., Kröncke I., Bischof K. (2020). The role of artificial material for benthic communities – establishing different concrete materials as hard bottom environments. Marine Environmental Research 161 doi.org/10.1016/j.marenvres.2020.105081

Marine Environmental Research 161 (2020) 105081

Contents lists available at ScienceDirect

Marine Environmental Research

journal homepage: http://www.elsevier.com/locate/marenvrev

The role of artificial material for benthic communities – Establishing different concrete materials as hard bottom environments

Lydia R. Becker[a,b,c,*], Andreas Ehrenberg[d], Volkert Feldrappe[d], Ingrid Kröncke[b,e], Kai Bischof[c]

[a] University of Bremen, INTERCOAST Research Training Group, Leobener Strasse, 28359, Bremen, Germany
[b] Senckenberg am Meer, Dept. for Marine Research, Südstrand 40, 26382, Wilhelmshaven, Germany
[c] University of Bremen, Department of Marine Botany, Leobener Str. NW2, 28359, Bremen, Germany
[d] FEhS – Institut für Baustoff-Forschung e.V., Bliersheimer Straße 62, 47229, Duisburg, Germany
[e] Institute for Chemistry and Biology of the Marine Environment, University of Oldenburg, Schleusenstr 1, 26382, Wilhelmshaven, Germany

ARTICLE INFO

Keywords:
Coastal constructions
Succession
Fouling communities

ABSTRACT

Concrete is used in marine coastal constructions worldwide. These structures are colonized by specialized hard-bottom biota consisting of macroalgae and benthic macrofauna. As concrete manufacturers face challenges such as limited natural resources and high CO2-emissions, the need for supplementary materials increases. Still, there has been little research on the reaction of species to the differences in concrete composition and what ecological impact these reactions could have. This study addresses the questions (1) if there are differences in settlement communities, depending on differences in concrete constitutes and (2) if so, what are the consequences for the usability of alternative concretes in marine constructions. For the experiment 15 cubes (15 × 15 × 15 cm) made of five different concretes, containing different cements (Portland cement and blast furnace cements) and aggregates (sand, gravel, iron ore and metallurgical slags) were deployed in a natural hard bottom experimental field near Helgoland Island (German Bight) in April 2016. After 12 months, all cubes were examined regarding species composition and coverage, followed by statistical analysis (PERMANOVA, SIMPER, DIVERSE). Results indicate differences in settlement communities for different surface orientation (Top, Front/Back) of the cubes. Significant differences in settlement communities of the Front/Back side were present depending on the used material type. However, the found differences in settlement between the concrete types tested are not sufficiently clear to provide recommendations for their usability in coastal constructions.

1. Introduction

Concrete has been used in artificial structures exposed to seawater (e.g. harbors, causeways, dikes, piers, locks and breakwaters) for decades and is one of the most common materials in coastal constructions worldwide (Bijen, 1996; Kosmatka et al., 2008). However, from an ecological perspective there is large controversy on how marine algae and benthic macrofauna species respond to and behave within these introduced artificial habitats. It remains unresolved as to what extent species within these habitats can benefit from the newly introduced materials, or whether they represent a threat as potential stepping-stones for invasive species to settle on (Airoldi et al., 2009; Glasby et al., 2007). Several previous studies observed and discussed settlement processes on artificial structures (Airoldi et al., 2009, 2015; Chapman and Underwood, 2011; Connell and Glasby, 1999; Ido and Shimrit, 2015) yet the consolidation of coastlines is an important issue in current coastal ecology (Airoldi et al., 2009). From a civil engineering perspective, durability aspects of the respective concrete structures are critical for its use in offshore and harbour constructions. It has further been shown, that specifically the use of cements containing granulated blast furnace slag from pig iron production processes offer technological advantages (Bijen, 1996).

Concrete is mostly colonized by specialized hard-bottom biota consisting of macroalgae and associated macrofauna, but settlement is typically less diverse than in natural hard bottom communities (Ido and Shimrit, 2015). However, depending on where and how artificial structures are introduced, they can potentially provide a benefit to the surrounding marine environments. Positive effects, for instance, were recorded on the abundance of commercially important crustacean species in offshore wind farms, suggesting a potential for the incorporation

* Corresponding author. University of Bremen, Department of Marine Botany, Leobener Str. NW2, 28359, Bremen, Germany.
E-mail address: lkohlmorgen@marum.de (L.R. Becker).

https://doi.org/10.1016/j.marenvres.2020.105081
Received 16 March 2020; Received in revised form 29 June 2020; Accepted 9 July 2020
Available online 10 July 2020

of these areas as no fishing, or restricted activity zones (Ashley et al., 2014). The biomass and diversity of benthic macrofauna communities can differ significantly, depending on whether the concrete structures were placed in highly anthropogenically influenced habitats or introduced in to less influenced areas. Furthermore, the proximity to natural rocky coastlines or reefs can influence community characteristics on coastal constructions (Airoldi et al., 2009; Clynick et al., 2009). Coastal constructions within ecosystems dominated by soft bottom typically show a high biomass but consist of fewer non-specialist macrofauna species. In contrast, communities on artificial structures adjacent to areas where natural hard bottoms and reefs are present are much more diverse. Yet, neither reach the diversity of their surrounding natural bottom habitats (Airoldi et al., 2008).

On a global scale, concrete is the most important construction material due to its availability, formability and low cost efficiency. It is estimated that around 15 km^3 of concrete are used annually (Jensen and Glavind, 2002). Concrete is a mixture of cement, aggregates, water and small quantities of chemical additives. Due to the formation of Calcium-Silicate-Hydrates (through the hydration process) the aggregates are encased into a rocklike mass by the cement-water mixture (Locher, 2006). The quality of the hardened concrete (strength, durability for 50–100 years) depends on the quality of its components, mainly the cement and the aggregates, as well as the quality of the construction work (Crow, 2008; Kosmatka et al., 2008).

The concrete manufacturing industry is under pressure these days. Cement production makes up 5–8% of the total anthropogenic CO_2-emissions worldwide due to the calcination process of limestone and the thermal energy demand for Portland cement clinker production (Assi et al., 2018; Crow, 2008; Humphreys and Mahasenan, 2002). Portland-cement clinker is a solid material produced in the manufacture as an intermediary product in cement production (Kosmatka et al., 2008). Moreover, the availability of natural resources commonly used for the aggregates (usually sand and gravel or crushed stone) are limited due to a rising demand and the non-acceptance of additional mining activities (Assi et al., 2018; Crow, 2008; United Nations Envionment Programme, 2019). Thus, the dominant topic of the cement industry is to reduce the Portland cement production and to increase the use of supplementary cementitious materials, like granulated blast furnace slag, a by-product of pig iron production (Ehrenberg, 2015; Schneider et al., 2011). For the concrete producers there has also been an increasing pressure to substitute natural aggregates with industrial by-products. (bbs, 2016). In particular, slags from metal production (e.g. steel, copper) offer opportunities due to their mineral properties. These materials are already used for road construction and armor stones for decades (EC, 1988). Technical and environmental requirements are defined in standards and delivery terms. There are still challenges to overcome, like the leaching of heavy metals out of pure slag stone, especially within the aquatic environment (BfG, 2008).

Within the construction industry, the term “environmental friendly concrete” refers mainly to the production process (raw materials demand, CO_2 emission) and technical aspects (long term durability). Regarding environmental aspects, the leaching behavior of concrete has been analyzed in order to protect the groundwater (Dijkstra and van der Sloot, 2013). However, due to the binding capacity of the Calcium-Silicate-Hydrates and the very dense pore structure the leaching of heavy metals bound in concrete should be negligible. The use of alternative materials is strongly region dependent, as the European concrete standard EN 206 is not universally accepted. While e.g. the Netherlands allow the use of slags as concrete aggregates, in Germany their use is regulated in regards to the solid content of heavy metals, in particular Chromium.

The creation of new, open space by releasing artificial substrate initiates primary succession. This process starts with physiochemical events, occurring on a very small spatial scale and is followed by a biological colonization by bacteria and diatoms (Noel et al., 2009). From this point on succession is regarded as a continuous process with changing trajectories, reflect both physical and biological processes. The observation of species communities after one year of deployment is often described or seen as a temporary “final stage” of succession as most of the substrata should be covered by macrofauna organisms >1 cm, and subsequently only small changes in community structure should occur (Noel et al., 2009). However, succession time vary within different regions, and is highly dependent on material and substrate (Benedetti-Cecchi, 2000a, 2000b; Lukens and Selberg, 2004; Sousa and Connell, 1992). Succession on marine coastal infrastructure is unintended as extensively discussed in biofouling literature (Haderlie, 1984; Hole, 1952; Howell and Behrends, 2006; Yan and Yan, 2003).

Hitherto, little is known on how species react to differences in the composition of concrete materials. Although, species composition and settlement processes might provide important information on the appropriateness of the use of alternative concrete materials. Some few international studies show that species react and respond to differences in concrete mixtures (Ido and Shimrit, 2015; Perkol-Finkel et al., 2008; Perkol-Finkel and Sella, 2015). Encrusting species, e.g. barnacles or tube building Polychaeta can even improve the strength of concrete materials (Perkol-Finkel and Sella, 2015).

In Japan and South Korea pure (unbound) steel slags as bottom grounds were used successfully for the construction of artificial seaweed beds (Nakagawa et al., 2010). Some investigations were conducted related to the potential impact of pure electric arc furnace slag being used as armor stones in the Elbe river (Karbe and Ringelband, 1995). The results indicate that there might be an increase in the heavy metal content of algae growing on the slags. For certain elements like Vanadium this was only observed for the first algal generation. No difference in Vanadium content of algae growing on slags and on natural stones was detected after removing plants and starting a new storing period. A report from the German Federal Institute for Hydrology (BfG, 2008) reviewed further studies on pure armor stones made from different types of metallurgical slags in German rivers with results indicating an accumulation of heavy metals in macrofauna. However, more systematic investigations are required. In contrast, investigations in the Netherlands on the use of steel slags in mesocosm experiments and in the field revealed that heavy metal concentrations increased in short term but, under the condition of freshwater exchange, no negative impact of heavy metals on the ecosystems became apparent (Oosterschelde region) (Foekema et al., 2016).

The experiments from the Netherlands also indicate that the leaching behavior of pure by-products can have different impacts depending on the surrounding environment (Foekema et al., 2016). Under conditions of low turbulence, like in a channel, the water exchange and thus the water/slag ratio is much lower than in a river or the open ocean. Therefore, the impact on the environment will be more drastic in a small channel than in a bigger floating system.

In natural hard bottom communities, it is well known that sessile benthic macrofauna species and algae are highly specialized and can thus be used to indicate the health of their habitats (Wahl, 2009). Settlement experiments, can therefore provide important information on the applicability of new materials.

Within this study five different concretes were deployed, containing different cements (Portland cement and blast furnace cements) and aggregates (natural sand, gravel, iron ore and metallurgical slags). To study related differences in settlement by sessile benthic macrofauna and algae, 15 cubes were exposed to a natural hard bottom environment near Helgoland Island in the German North Sea. The main questions of this study were:

(1) Are there differences in settlement communities between different types of concretes after one year of deployment in a natural hard bottom environment?
(2) What consequences result from differences in settlement between the materials and what does this mean for the usability of the alternative concrete constituents in marine constructions?

2. Material and methods

2.1. Concretes

Concrete in structures exposed to seawater faces several challenges, like in the intertidal repeated cycles of wetting and drying and/or freezing and thawing. In seawater the use of low permeability concrete is required minimize corrosion and sulfate attack and to increase durability. The not universally accepted European concrete standard EN 206 and - based on it - the different national concrete standards (e.g. DIN 1045–2 in Germany) define different exposure classes and the corresponding minimum requirements for the concrete recipe (e.g. max. water/cement ratio, min. cement content). The concretes used in the experiment fulfilled the requirements for the exposure class "XS2" (marine structures being permanently under water). In all cases the cement content was 320 kg/m^3 and the water/cement ratio was 0.5.

A Portland cement CEM I 42.5 R and two blast furnace cements CEM III/A 42.5 N and CEM III/B 42.5 N were used as binders. All cements fulfilled the requirements of the European cement standard EN 197–1. Blast furnace cements are well known for providing a dense structure with low capillary porosity resulting in a high resistance against Chloride and Sulphur erosion. Thus, for decades they have been the established material for durable concrete marine structures (Bijen, 1996; Eckhardt and Kronsbein, 1950; Schröder et al., 1975).

To replace natural aggregates with industrial by-products is not only advantageous regarding resource efficiency (recycling economy) but also for economical (limited availability of natural materials) aspects. From a technical point of view it might be useful to use aggregates with a higher apparent density compared to natural gravel. For our study we used natural sand (2.64 kg/dm^3), gravel (2.64 kg/dm^3) and iron ore "MagnaDense" (4.90 kg/dm^3) and two metallurgical slags (a copper slag "Iron Silicate" and an electric arc furnace slag "EOS" with 3.80 kg/m^3 and 3.60 kg/m^3, respectively).

In February 2017 three cubes (15 × 15 × 15 cm^3) of five different concretes Material 1 – Material 5 (M1 - M5) (Fig. 1.) were produced at the "Institut für Baustoffforschung, FEhS Duisburg" according to EN 12390–2. The compositions given in Fig. 1 are given in wt.-%. However, concrete recipes are based on volumetric calculations. The cubes were stored 1 day in their mold, 6 days under water and then under consistent climate conditions at 20 °C and 65% relative moisture. In March 2017 they were transported to Helgoland.

The concrete compressive strength of the cubes was measured after 2 and 28 days of storage, according to EN 12390–3. The results are given in Table 1. Only M5 with the electric arc furnace slag aggregate had a significant higher strength after 28 days. The reason could be that EOS itself has a very high grain strength.

Table 1
Compressive strength $f_{c,\ cube}$ of the concretes M1-M5 in N/mm^2 after 2 and 28 days under constant climate conditions at 20 °C and 65% relative moisture.

	M1	M2	M3	M4	M5
2 days	43.5	40.1	41.1	41.7	43.5
28 days	59.1	58.4	56.4	60.4	72.0

2.2. Deployment site and experimental set up

The southern North Sea is a marine environment with relatively low proportion of natural hard-substrate areas (Bartholomä et al., 2019; Michaelis et al., 2019b; Pratje, 1951). The majority is regarded as residues of the end moraines of Saalian and Weichselian stages of the Glacial Period (Pratje, 1951). Helgoland Island is located 50 km from the nearest mainland (Eidersterdt) in the German Bight. It represents a geologically and ecologically unique locality in the south-eastern part of the North Sea with a rocky intertidal and subtidal area covering about 35 km^2, designated as a nature reserve since 1981 (Franke and Gutow, 2004). It is geographically and ecologically isolated from similar areas in Norway and Britain by some hundreds kilometers of sandy or muddy soft bottoms (Franke and Gutow, 2004). The marine environment displays an offshore character, influenced by the North Sea water body (Martens, 1978). The area is considered relatively unpolluted, compared to more inshore localities in the southern North Sea (de Kluijver, 1991).

Little is known on the composition and interactions of subtidal benthic macrofauna and algal communities around Helgoland (Bartholomä et al., 2019; Becker et al., 2019; Kühne and Rachor, 1996; Michaelis et al., 2019a). For monitoring purposes, a long-term study on the benthic macrofauna was carried out for the years 1900–2004. Here, 402 taxa were found in all tidal and subtidal regions around Helgoland between 1950 and 2004 (Boos et al., 2004). However, only one study captured macrofauna and algal communities with subtidal sampling points in close proximity to Helgoland Island (de Kluijver, 1991). Since then no comparable studies have been carried out in these regions (Bartsch and Tittley, 2004; Boos et al., 2004), even though significant changes were found within the distribution and composition of algal species as a result of increasing water transparency since 1975 (Pehlke and Bartsch, 2008). It is likely that changes due to the changing environments are also present in macrofauna communities.

The 15 concrete cubes were mounted onto five PVC frames, with each frame fitting three cubes (1 m x 0.3 m) (Fig. 2b). Each frame was fit with three cubes. The placement of the cubes was random, with an emphasis put on ensuring no frame had multiple cubes of the same material. (Fig. 2b). The frames were installed by divers at the AWI MarGate underwater experimental field, an underwater experimental area and test facility off Helgoland on March 28, 2017 (Fig. 2a). The concrete cubes were deployed at a water depth of ~7 m. Distance

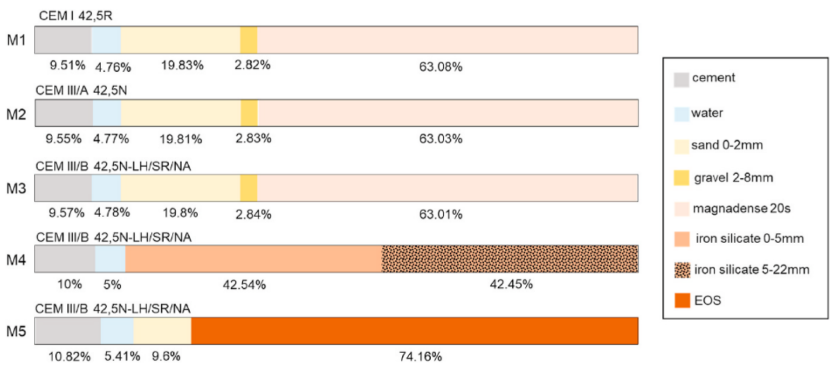


Fig. 1. Composition of the different concretes M1-M5. Ingredients of cements (CEM I 42,5R; CEM III/A 42,5N; CEM III/B 42.5N-LH/SR/NA) and aggregates (sand, gravel, mangnadense, iron silicate, EOS) are given in wt.-%.

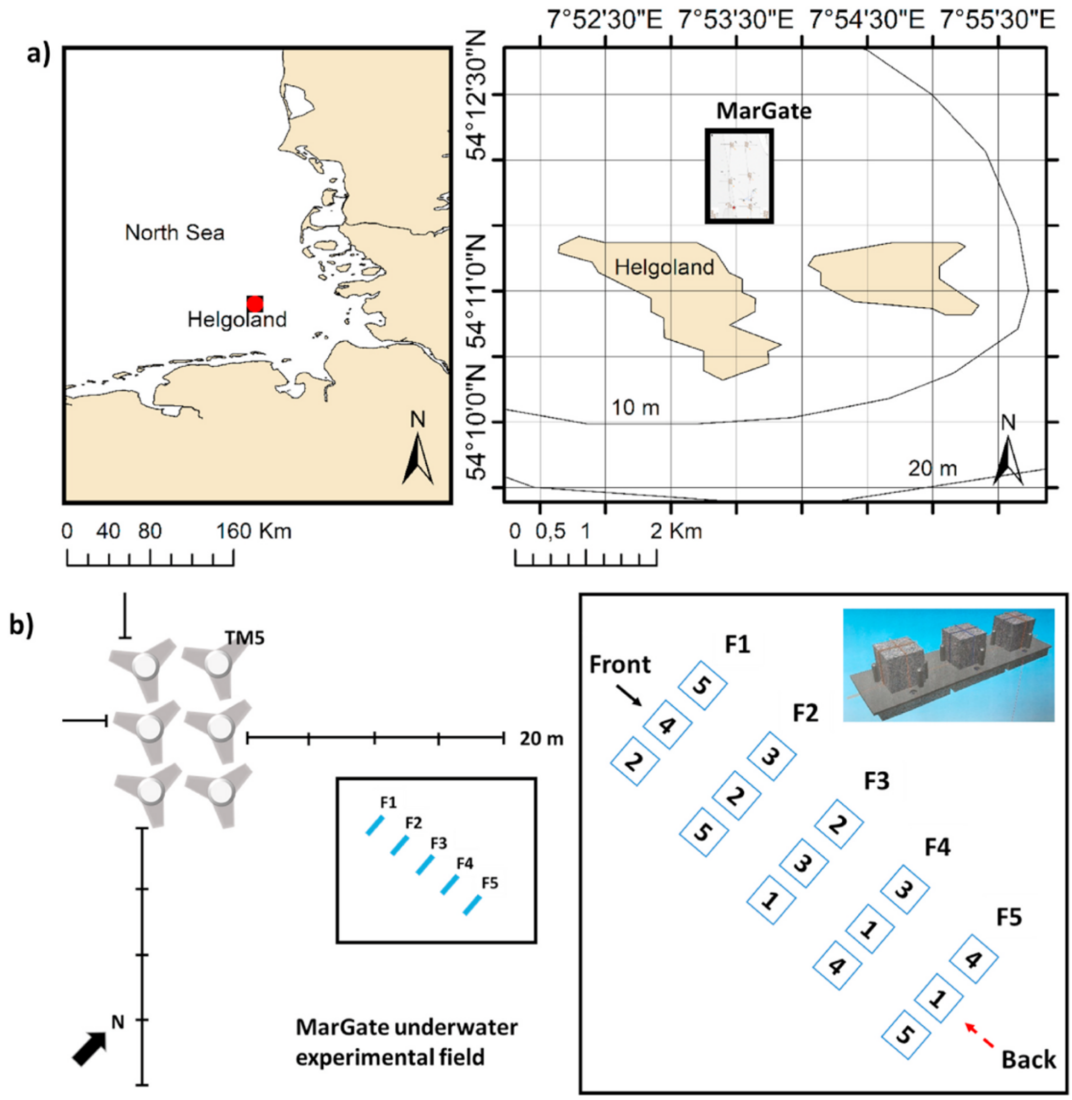


Fig. 2. a) Location of the deployed concrete cubes at the MarGate underwater experimental field, Helgoland Island, North Sea b) The picture bottom left shows the location of the experimental set up in the MarGate underwater experimental field. The set up was installed at 6–7 m depth, 10 m apart from the nearest tetrapod. Distance between the Frames (F1–F5) was ~2 m, frames orientate northwards. The picture bottom right shows how materials (1–5) are fitted in the frames (F1–F5). Arrows indicate the Front and Back side of the blocks.

between the frames was 2 m, with frames orientate northwards. The nearest artificial constructed tetrapod was 10 m apart from the experimental set up (Fig. 2b). de Kluijver (1991) found two different communities within the range of the study area. The first community occurs in depth from 4.5 to 6.5 m and holds up to 93 taxa. Kluijver separated the communities in to three different layers: The first community held a well-developed top layer of brown algae *Laminaria hyperborea*. The middle layer is dominated by red algae (*Ceramium rubrum* and *Delesseria sanguinea*), brown algae (*Laminaria hyperborea*) and tuberculous organisms (Amphipods and Corophiids as well as Spionidae for instance *Polydora ciliata*). Amongst red algae *Membranoptera alata* was named characteristic for the community. Bryozoa consist of *Membranipora membranacea* and *Electra pilosa*, which are epiphytic on *Laminaria hyperborea*. The third layer (encrusting layer) was dominated by the red algae *Phymatolithon* spp. and *Hildenbrandia rubra*. The second community occurs in a depth from 8 to 10.5 m and holds up to 51 taxa. Here the top layer is not developed. The middle layer is mainly dominated by the anthozoa *Metridium senile* and the polychaete *Spirobranchus triqueter*. The encrusting layer is formed by *Phymatolithon* spp..

2.3. Sampling procedure and analysis

The concrete cubes were retrieved on April 2, 2018, after an exposure time of one year. Until further analyses, they were stored without light in a saltwater tank at 10 °C. Cubes were evaluated in the lab from April 9, 2018 to April 13, 2018. All macrofauna and algal species present on the top, front and backside of the concrete cubes (15 × 15 cm) were recorded. Additionally, each side was photographed. Species were determined to the lowest possible taxonomic level. Species abundance and coverage were recorded using of a smaller grid (1 cm^2 = 0.44% coverage of the total area). Areas, where no macrofauna and algal species settled, were recorded as uncovered areas.

For comparison of the different sides and materials only coverage data were used in the statistical analysis. Mobile macrofauna species or species with less than five individuals per site were excluded from the analysis. One community was summed up as "black carpet", including species of juvenile Phaeophyceae and cyanobacterial communities. They formed a visible black crust on the cubes.

2.4. *Data processing and statistical analysis*

Statistical analyses were performed using the statistical PRIMER package, v6 (Clarke and Gorley, 2006) and PERMANOVA + add on PRIMER v6 (Anderson et al., 2008). Univariate 1-way PERMANOVA tests, based on square root transformed coverage data, as well as multivariate analysis of the transformed data via PERMANOVA pair-wise tests, based on Bray-Curtis similarity were performed. P-values yield the exact test of the null hypothesis. That means the probability of rejecting the null hypothesis is exactly equal to the chosen significant level of 0.05. The chance of false positive findings (type I error) is 5% (Anderson et al., 2008). MDS plots were used to show trends in multivariate data. DIVERSE tool and similarity percentage routine (SIMPER) analyses were used to determine differences in species communities. Mean coverage and standard deviations were calculated in R v.3.3.2 (R Development Core Team, 2016). Coverage values over 100% were found due to the horizontal and partially overlapping distribution of species. Comparison of the general descriptors of DIVERSE analysis (mean taxa per side, Shannon-Wiener index H' (log base e), Simpson's index (1-λ) and evenness J′) were also done in R. Depending on the outcome of pre-tests (Shapiro Wilk-test; Levene's test) one-way ANOVA or Mann-Whitney-U were performed.

3. Result

3.1. *Benthic flora and fauna*

After one year of deployment, 51 macrofauna and algal taxa in total were identified on all concrete cubes. With 13 different taxa, Rhodophyta represent the most diverse group, followed by Phaeophyceae (10 taxa), Cnidaria (7 taxa), Polychaetes (6 taxa), and Bryozoa (5 taxa). Other taxonomic groups represented two or less taxa per group (Table 2). The following statistical analyses include %-coverage of 20 taxa, as well as one taxa, named "black carpet" (which includes 9 taxa of juvenile species of Phaeophycacea), and the % of uncovered concrete (see Table 2).

3.2. *Differences between the observed sides*

The MDS plot of square root transformed coverage data revealed differences between the observed sides of the concrete cubes (Fig. 3). Permanova pair-wise test confirmed highly significant differences ($P = 0.0001$) between macrofauna and algal communities on the top sides (T) to communities on the front (F) and back (B) sides of the cubes. No significant difference was found between the front and back sides ($P = 0.31$). Therefore, they were further handled as one side (F/B).

3.3. *Differences between the sides "top" and "front/back"*

Permanova statistical analysis on square root transformed coverage data of the Top side and Front/Back side, showed significant differences between Top and Front/Back sides ($p = 0.0001$) and between the five materials ($p = 0.0235$). Interaction between sides and materials was also significant ($p = 0.0503$), meaning that the significant effect of sides and materials is different within the tested groups (Table 3).

3.4. *Side effect*

Permanova pair-wise test on square root transformed coverage data showed significant differences ($p < 0.01$) between the Top side and the Front/Back side for all five materials. Further comparison showed that

Table 2
List of macrofauna and algal taxa found on the concrete cubes. Species, which %-coverage is included in the analysis, are marked in bold. Species of the Phylum Phaeophyceae (excluding *Petalonia fascia*) built a black carpet cover on the cubes, and were included as such in the statistical analysis.

phylum/class	Order	family	Species
Arthropoda	Decapoda	Porcellanidae	*Pisidia longicornis*
		Balanidae	*Balanus* spp
Bryozoa	Cyclostomatida	**Crisiidae**	***Crisia aculeata***
		Plagioeciidae	***Plagioecia patina***
		Tubuliporidae	***Tubulipora plumosa***
	Cheilostomatida	**Cryptosulidae**	***Cryptosula pallasiana***
	undef.	**undef.**	***white Bryozoa***
Chlorophyta	Ulvales	Ulvaceae	*Ulva* spp
Chordata	Aplousobranchia	**Didemnidae**	
	Stolidobranchia	**Styelidae**	***Botryllus schlosseri***
Cnidaria	Actiniaria	Actiniidae	*Urticina* juv.
			Urticina felina
		Metridiidae	*Metridium senile*
	Anthoathecata	Eudendriidae	*Eudendrium capillare*
	Leptothecata	**Sertularellidae**	***Sertularella polyzonias***
		Campanulariidae	*Clytia gracilis*
			Obelia geniculata
Hydrozoa	Anthoathecata	Tubulariidae	*Tubularia indivisa*
Mollusca	Nudibranchia	Cuthonellidae	*Cuthonella concinna* + Gelege
	Trochida	Trochidae	*Steromphala cineraria*
Phaeophyceae **(black carpet)**	Desmarestiales	Desmarestiaceae	*Desmarestia viridis*
	Ectocarpales	Acinetosporaceae	*Pilayella* spp
			Pilayella littoralis
		Scytosiphonaceae	***Petalonia fascia***
	Laminariales	Chordaceae	*Chorda tomentosa*
	Sphacelariales	Cladostephaceae	*Cladostephus* spp
		Sphacelariaceae	*Sphacelaria nana*
			Sphacelaria plumosa
	Tilopteridales	Tilopteridaceae	*Haplospora globosa*
			Tilopteris mertensii
Polychaeta	Phyllodocida	Hesionidae	*Nereimyra punctata*
		Phyllodocidae	*Eulalia viridis*
			Phyllodoce rosea
	Sabellida	**Serpulidae**	***Spirorbis spirorbis***
			Spirobranchus triqueter
	Terebellida	Terebellidae	*Lanice conchilega*
Pycnogonida	Pantopoda	Nymphonidae	*Nymphon brevirostre*
Rhodophyta	Bonnemaisoniales	Bonnemaisoniaceae	*Bonnemaisonia hamifera*
	Ceramiales	Delesseriaceae	*Delesseria sanguinea*
		Rhodomelaceae	*Brongniartella byssoides*
			Ceramium rubrum
		Rhodomelaceae	***Polysiphonia elongata***
			Polysiphonia nigrescens
			Polysiphonia urceolata
			Rhodomela confervoides
			Rhodomela virgata
	Corallinales	Corallinaceae	*Corallina officinalis*
	Corallinales	**Lithothamniaceae**	***Phymatolithon spp***
	Hildenbrandiales	**Hildenbrandiaceae**	*Hildenbrandia* spp
	Plocamiales	**Plocamiaceae**	*Plocamium cartilagineum*
Tube dwelling diatoms			

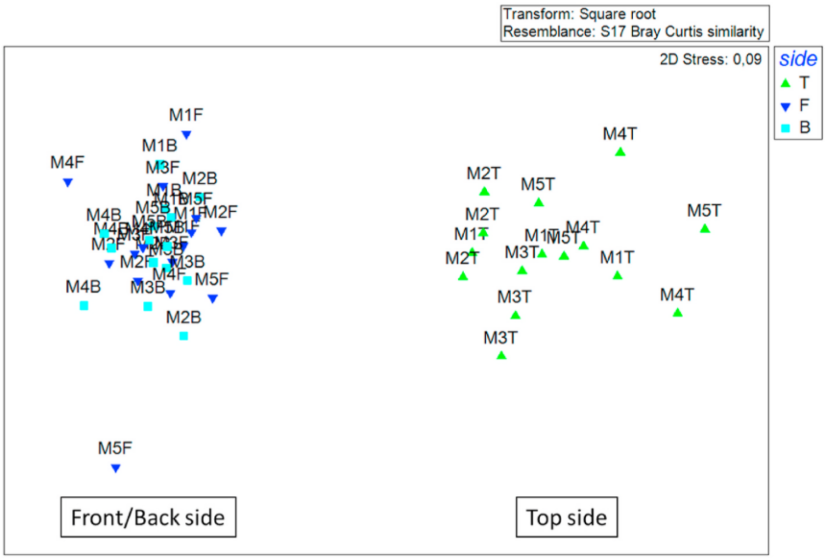


Fig. 3. MDS plot of square root transformed coverage data indicating differences in species communities between different cube sites. Given label capture Material type (M1-M5) and sites (F=Front; B=Back, T = Top).

Table 3
Results of Permanova on square root transformed coverage data showing differences in macrofauna and algal communities between different sides (Top vs F/B) and materials (M1-M5). Analysis implies interaction between side effect and material effect. Meaning that the effect within side and material differ within the tested groups. Abbreviations: df = degrees of freedom, SS = sum of squares, MS = mean sum of squares, Pseudo F = pseudo-F ratio. Significance levels P (perm) are based on 9999 permutations (significance levels: *significant ($p \leq 0.05$), **highly significant ($p \leq 0.005$)). Unique perms indicate how many unique values of the test statistic were obtained under permutation.

Source	df	SS	MS	Pseudo-F	P (perm)	Unique perms
sides	1	30,518	30,518	89,605	0,0001**	9945
material	4	3367,2	841,8	2,4716	0,0235*	9947
Sides x material	4	2778,8	694,7	2,0397	0,0503*	9935
res	35	11,920	340,58			
total	44	48,387				

mean taxa numbers, as well as diversity indices were quite similar between the Top and Front/Back sides of the concrete cubes (see Table 4). Only evenness J' revealed significant differences between the Top (0.9 ± 0.04) and Front/Back sides (0.93 ± 0.02; Mann-Whitney-U W = 371, p = 0.0005). The Top sides of the cubes also revealed significantly higher mean coverages of 137.27 (±18.60) %, compared to the Front/Back sides (107.37 ± 25.43%; one-way ANOVA df = 1, F = 16.97, p = 0.0002). SIMPER analysis indicates differences in species communities between the sides. While the Top communities were dominated by diatoms (31.74%), and by the red algae *Polysiphonia urceolata* (10.97), the Front/Back side communities were dominated by species of the "black carpet" (22.55%) and by the bryozoa *Tubularia plumosa* (17.36%) (see. Table 4). These differences can also be seen in the example pictures of the final photographic documentation of the cubes (Fig. 5).

3.5. Material effect

Permanova pair-wise test on square root transformed coverage data revealed no differences in communities between materials on the Top side of the cubes (Table 5). Significant differences between the materials were found within the Front/Back sides. Material M4 showed significant differences ($p < 0.05$) to all other materials, excluding M5 (for exact values see Table 5). A trend towards significant difference can be seen between M4 and M5 ($p = 0.067$). Material M1 differed significantly from all other materials, excluding Material M2 (Table 5).

Table 4
Results of DIVERSE and SIMPER Analysis for the Top and Front/Back sites. Shown are mean taxa, mean coverage, Shannon-Wiener index H' (log base e), Simpson's index (1-λ) and Evenness J'. Standard deviations are shown in brackets. Depending on the pre-tests one-way ANOVA or Mann-Whitney-U was performed. Given are p-values. Significances are marked in bold ('tendency towards significance ($p \leq 0.07$) *significant ($p \leq 0.05$), **highly significant ($p \leq 0.005$)). SIMPER analysis shows characterizing macrofauna and algal species and to which percentage they contribution to the communities (in brackets) on the different sites.

site	Top	Front/Back	Significance test one-way ANOVA	Significance test Mann-Whitney-U
Mean taxa per side	11.4 (2.59)	10.8 (1.45)	0.31	–
Mean coverage [%]	137.27 (18.60)	107.37 (25.43)	**0.0002 ****	-
Shannon-Wiener index H' (log base e)	2.16 (0.29)	2.21 (0.13)	–	0.66
Simpson's index (1-λ)	0.88 (0.05)	0.9 (0.02)	–	0.08
Evenness J'	0.9 (0.04)	0.93 (0.02)	–	**0.0005****
Species communities resulting from SIMPER analysis	Diatoms (31.74). *Polysiphonia urceolata* (10.97) black carpet (10.9) *Spirobis spirobis* (7.89) *Phymatholithon* spp. (6.3)	black carpet (22.55) *Tubulipora plumosa* (17.36) *Spirobis spirobis* (14.21). uncoverd (11.04) *Spirobranchus triqueter* (7.28) *Phymatolithon* spp. (7.18)		

Table 5
Resulting p-values from Permanova pair-wise test (sides x material for pairs of levels of factor material) on square root transformed coverage data. Tests revealed significant differences for materials within the Front/Back side level while no differences where observed in the Top side level. Significances are marked in bold ('tendency towards significance ($p \leq 0.07$) *significant ($p \leq 0.05$), **highly significant ($p \leq 0.005$)).

Groups	Unique perms = 10	Unique perms = 462
	T	Front/Back
M1,M2	0,094	0138
M1,M3	0,100	**0019***
M1,M4	0,097	**0002****
M1,M5	0,297	**0007***
M2,M3	0,097	0633
M2,M4	0,097	**0037***
M2,M5	0,097	0266
M3,M4	0,102	**0025***
M3,M5	0.098	0.546
M4,M5	0.695	**0,067'**

3.6. Differences in the front/back side

Material M4 revealed lower mean taxa numbers (9.67 ± 1.5) than all other materials, resulting in a lower Shannon-Wiener index H' (2.10 ± 0.18). However, evenness J′ is similar to the other materials. Mean coverage is highest for Material M1 (128.83 ± 24.09), Material M4 and M5 showed lower mean coverage (M4: 100.83 ± 32.06, M5: 92.67 ± 27.13). Evenness J' is similar in all five materials (Table 6). SIMPER analysis showed, that species named for the main communities on the materials were quite similar. Still, there were differences in the quantity and order of their appearances (Fig. 4). The community of the "black carpet" and the bryozoa *Tubularia plumosa* were mostly found as top characterizing species. Except in Material M5 where the tube building polychaete *Spirobis spirobis* is named amongst the top characterizing species. Within Material M1 the tube building polychaete *Spirobranchus triqueter* appeared in similar high abundances as *S. spirobis* which is different to all other materials (Fig. 4). *S. triqueter* is absent within the named characterizing species communities of Material M4 (Fig. 4). Material M1 is the only community where the group of Didemnidae appeared as a characteristic species. Material M4 is the only community where the bryozoan species *Cryptosula pallasiana* is named as a characteristic specie M4 (Fig. 4). Differences can also be seen in the example pictures of the final photographic documentation of the cubes (Fig. 5).

4. Discussion

The results of the study clearly indicate differences in settlement of macrofauna and algal communities for the different sites of the cubes (Top vs Front/Back sides). These differences are expected due to the different microclimatic conditions on the sides e.g. light intensity, currents, and horizontal vs vertical distribution preferences. Particularly the preference between horizontal and vertical distribution is well studied and discussed in literature (Bulleri and Airoldi, 2005; Bulleri and Chapman, 2010; Chapman, 2003; Lam et al., 2009; Moschella et al., 2005; Perkol-Finkel and Benayahu, 2004; Siddik et al., 2019). Further differences between settlement communities of the Front/Back side were found depending on the used material type. Especially settlement on M1 and M4 differed significantly from the other cubes. M1 showed higher mean coverages and counted the tube building polychaete *Spirobranchus triqueter* amongst the three most contributing species to the community.

S. triqueter is known to be an important component of the hard bottom ecosystems of the German Bight (Becker et al., 2019; de Kluijver, 1991; Dederer et al., 2015; Kühne and Rachor, 1996). Species do not seem to be sensitive to "pollution or chemical harming substances" (Dederer et al., 2015). In fact, ocean acidification seems to be the only major threat to this species (Dıáz-Castañeda et al., 2019). *S. triqueter* is a sessile filter-feeding tube worm which occurs on solid substrata such as rocks or shells, and is quite common to Helgoland waters. It appears frequently on all hard substrates in all parts below the low water line. High abundances are reached on natural stones and boulders often forming their own habitat structure (Klöckner, 1976). *S. triqueter* belongs to the main group of marine fouling organism (Nelson-Smith, 1967), particularly in tropic and subtropical waters.

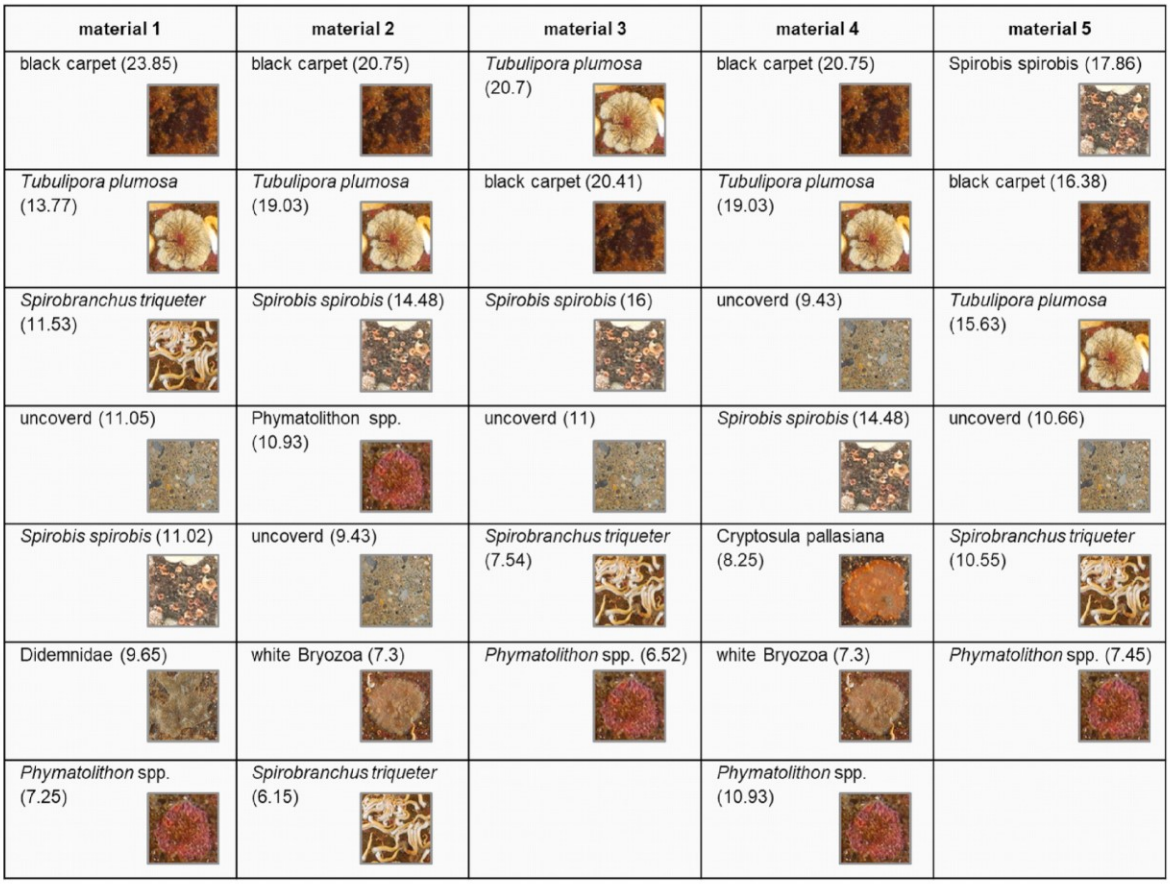
Material 1 is made with Portland cement, which is the most common binder in concrete (Crow, 2008; Kosmatka et al., 2008). It is a fine powder made from Portland cement clinker mainly from limestone and clay in combination with sulphates as setting retarders (Locher, 2006). Blast furnace cements, which are used as binders in all other concretes used in this experiment (M2-M5), consist of a mixture of Portland cement clinker, granulated (quenched) blast furnace slag and sulphates. To date there are no comparable studies on the preferences of hard bottom organisms to Portland cement or to blast furnace cement concretes in marine infrastructure. In fact, few studies deal with the understanding of species communities on artificial concrete marine constructions (Connell and Glasby, 1999; Dugan et al., 2012; Ido and Shimrit, 2015; Perkol-Finkel and Sella, 2014). Knowledge of their effect on the environment is limited (Perkol-Finkel and Sella, 2014). Studies mostly discuss negative effects of Portland cement to marine coastal environments, stating that costal marine infrastructure never reaches the diversity of natural hard bottom environments (Airoldi et al., 2008; Airoldi et al., 2009; Glasby et al., 2007). Over 50% of coastal marine infrastructure is made of Portland cement (Perkol-Finkel and Sella, 2014), which is known as a poor substrate in terms of biological recruitment, presumably due to high surface alkalinity (pH ~13 compared to ~8 of seawater) and presence of compounds that are toxic to marine life (EBM, 2004; Lukens and Selberg, 2004). Adding to that, coastal marine infrastructure often includes highly inclined, homogeneous surfaces with minimal surface complexity supporting only species highly tolerant to these conditions (Chapman and Underwood, 2011).

It is striking that M4 as well as M5 showed lower mean coverages than M1 to M3. The metallurgical slags used in M4 and M5 are "industrial particle sized aggregates". In combination with blast furnace cements M4 and M5 should provide a very dense structure with a low capillary porosity resulting in a high resistance against Chloride and Sulphur attacks. Since the hydraulic reaction is faster in Portland cement, which is used in M1, compared to slag cements, the internal structure of the cubes made of M1 might already differ after one year of deployment. This can, but does not necessarily have to take influence on settlement processes between the different cubes. Several antifouling experiments, have shown that surface roughness plays an important role in settlement of marine organisms (Howell and Behrends, 2006).

Experiments in the Alboran Sea on early benthic assessment of subtidal and intertidal communities, tracked on five artificial substrata differing in origin, roughness, and chemical composition: Oyster

Table 6
Results of DIVERSE Analysis for the Front/Back site of the different materials M1-M5. Shown are mean taxa, mean coverage [%], Shannon-Wiener index H' (log base e), Simpson's index (1-λ) and evenness J'. Standard deviations are shown in brackets.

material	M1	M2	M3	M4	M5
Mean taxa	11.17 (2.13)	11 (1.55)	10.67 (0.89)	9.67 (1.5)	11.5 (1.15)
Mean coverage [%]	128.83 (24.09)	107.17 (26.76)	107.33 (15.97)	100.83 (32.06)	92.67 (27.13)
Shannon-Wiener index H' (log base e)	2.24 (0.17)	2.22 (0.11)	2.20 (0.08))	2.10 (0.18)	2.29 (0.10)
Simpson's index (1-λ)	0.9 (0.02)	0.9 (0.01)	0.9 (0.01)	0.89 (0.03)	0.92 (0.01)
Evenness J′	0.93 (0.02)	0.93 (0.03)	0.93 (0.01)	0.93 (0.03)	0.94 (0.02)



material 1	material 2	material 3	material 4	material 5
black carpet (23.85)	black carpet (20.75)	*Tubulipora plumosa* (20.7)	black carpet (20.75)	Spirobis spirobis (17.86)
Tubulipora plumosa (13.77)	*Tubulipora plumosa* (19.03)	black carpet (20.41)	*Tubulipora plumosa* (19.03)	black carpet (16.38)
Spirobranchus triqueter (11.53)	*Spirobis spirobis* (14.48)	*Spirobis spirobis* (16)	uncoverd (9.43)	*Tubulipora plumosa* (15.63)
uncoverd (11.05)	Phymatolithon spp. (10.93)	uncoverd (11)	*Spirobis spirobis* (14.48)	uncoverd (10.66)
Spirobis spirobis (11.02)	uncoverd (9.43)	*Spirobranchus triqueter* (7.54)	Cryptosula pallasiana (8.25)	*Spirobranchus triqueter* (10.55)
Didemnidae (9.65)	white Bryozoa (7.3)	*Phymatolithon* spp. (6.52)	white Bryozoa (7.3)	*Phymatolithon* spp. (7.45)
Phymatolithon spp. (7.25)	*Spirobranchus triqueter* (6.15)		*Phymatolithon* spp. (10.93)	

Fig. 4. Results from Permanova SIMPER analysis for the Front/Back sides, showing species and the percentage to which they contribute to the communities on each material (in brackets).

Sandstone, Limestone, Gabbro, Slate and Concrete showed that species richness was highest on sandstone correlating with surface roughness. This again highlights the importance of artificial surface types and structures (Sempere-Valverde et al., 2018).

Howell and Behrends (2006) reviewed the bioenergetic argument of the attachment point theory. It states that attachment of a sphere (spore) to a flat substratum leads to a net increase in total surface area, which leads to an increase in work or energy exerted on the system (Hoipkemeier-Wilson et al., 2004). Valleys that are of similar dimensions to the body size of the spore and surfaces that have a certain number of attachment points will be preferred. This results in a net decrease in surface area and to reduction of hydrodynamic stress.

Ulva (Chlorophyta) spores, for example, preferentially settle on surfaces that provide a topography with dimensions of the same order as the maximum width of the free-swimming spore, ca.5 μm (Callow et al., 2002; Hoipkemeier-Wilson et al., 2004). Settlement of the barnacles was reported to be reduced, when surface mean roughness increased, compared to smooth controls (Berntsson et al., 2000; Hills and Thomason, 1998; Petronis et al., 2000).

Still, M4 differs from the other materials. Early experiments with *S. triqueter* could show that surface roughness does not influence settlement of this species (Klöckner, 1976). It remains unclear why this species is missing here.

M4 and M5 used a copper slag "Iron Silicate" and an electric arc furnace slag "EOS". Leaching of heavy metals might have a negative impact on settlement (BfG, 2008). The results from an ecotoxicology experiment with pure slags and undiluted samples revealed that all organisms were fatally injured by the released eluates. Eluate sample was taken after 24 h leaving 100 g slag dry mass in 1 l distillated water. However, the effect was negligible in diluted samples (Manz, 2008). Other studies report an accumulation of heavy metals in organisms growing on pure slag stones. But, abundances and diversity did not differing from natural stones (basalt and greywacke) (Koop, 2008). Yet, these studies did not compare community composition, which is important due to the ecological importance of certain species to the environment (Koop, 2008).

Concrete shows a comparably low leaching capacity compared to pure slags (Dijkstra and van der Sloot, 2013, DAfStb, 1996). The leaching velocity of heavy metals is more or less independent on their concentration in the solid concrete. The dominant parameters are the solubility of the elements, the chemical binding capacity of the hydrated cement phases and the diffusion coefficient of the cement stone matrix. Thus, in concrete, the combination of slag aggregates and any cement should to a certain point act as a protection against the release of harmful substances. But even if the leaching effect is not that high, there is still a chance that heavy metals are released in the environment close by or even measurable just on the surface of the cubes. If so, this might have an effect on the settlement of organisms. Still, the rate of water exchange will significantly influence the measurable concentration of heavy metals.

For M4, one Bryozoan species *Cryptosula pallasiana* was found to contribute considerable numbers to the community. *C. pallasiana* is known as cosmopolitan cheilostome bryozoan and an inhabitant of harbours worldwide (Bock and Gordon, 2020; Ryland, 1965). It

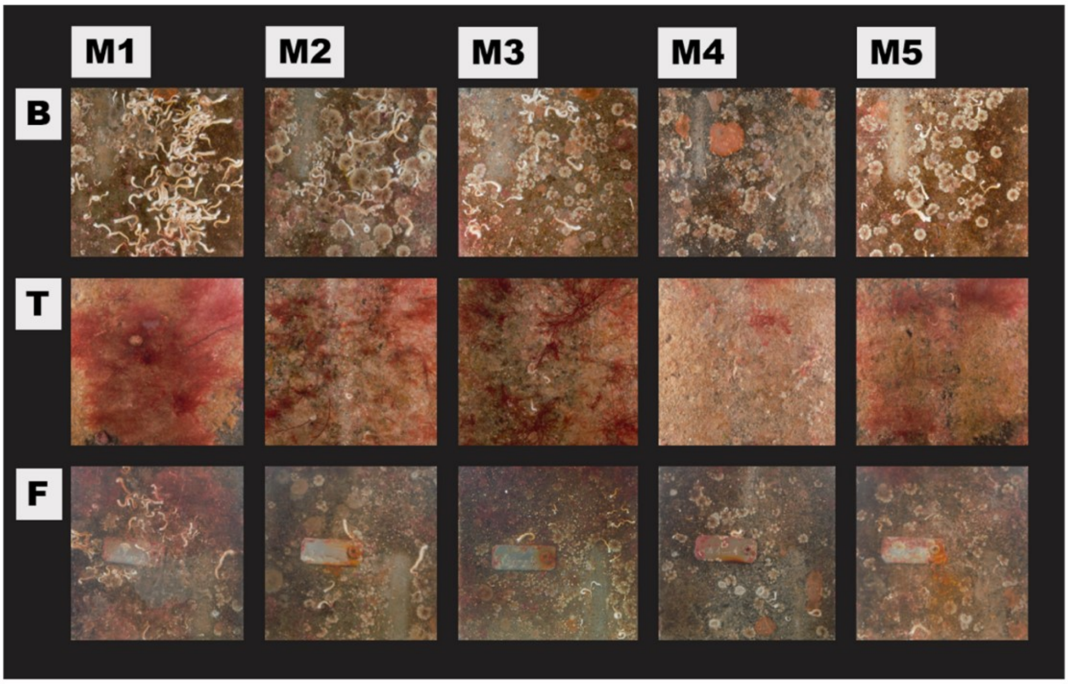


Fig. 5. Example from the final documentation, showing exemplarily the back (B), top (T) and front (F) side of each material M1-M5.

colonises a range of algal and hard substrata and is distributed from Norway to the Mediterranean and Black Sea and on the Atlantic coast of Canada and the USA to Florida. *C. pallasiana* frequently fouls boat hulls and has been reported from docks and harbours in New Zealand (Gordon and Mawatari, 1992). It feeds on small microorganisms, including diatoms and other unicellular algae. Further information on this species is rare.

Studies from the red sea coast could show that bryozoan species in general react to heavy metal concentrations in soil by a clear decrease in diversity (El-Sorogy et al., 2016). This implies a sensitive reaction of this group to heavy metal pollution. But it is likely that not all species react to pollution to the same level.

However, if bryozoan species generally react sensitively to heavy metals, it has to be assumed that concentrations released by M4 must be at a minimum. Further experiments have to be conducted.

5. Conclusions

Based on the results of this study, it has to be concluded that from an ecological point of view it is not possible to give clear recommendations for or against the usage of the materials under investigation in coastal constructions. There are many uncertainties that have to be considered. Experiments on the leaching effect of "slag concretes" in marine conditions have to be conducted. It is known that during Portland cement clinker hydration, Portlandite (calcium hydroxide) is formed resulting in pH levels of 10–11. This is significantly more basic than seawater, which has a pH of 8.3. The low pH can render the surface an inhospitable or even toxic microenvironment to invertebrate organisms for 3–12 months (Lukens and Selberg, 2004). This would mean that studying succession patterns over one year is not enough. It is important to observe the early stages of succession on the cubes as critical differences in settlement may appear in that time span (Noel et al., 2009). But, with respect to the operational life of concrete, which can be 50–100 years (Crow, 2008; Kosmatka et al., 2008), it is interesting to see if differences observed at the early stage are levelled out after two to three years' time. Besides ecological considerations, from the technical point of view there is no alternative to concrete as a construction material in marine environment.

Within the current experiment, we only observed the behavior of concrete in a natural marine environment. Differences might be negligible in anthropogenically influenced harbour sites where it is most likely that additional marine coastal infrastructure will be built and further anthropogenic influences are to be expected. Data on experiments conducted in the Jade-Weser-Port, a German deep-sea harbour located in Wilhelmshaven, will be evaluated soon to give a basis for further discussions on that point.

Funding

This research was funded by the DFG ('German Research Foundation') within the INTERCOAST ('Integrated Coastal Zone and Shelf-Sea Research') graduate program, a joint collaboration between the Senckenberg Institute in Wilhelmshaven (Germany), the University of Bremen (Germany), and the University of Waikato (New Zealand) and by the FEhS Institute Duisburg.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Lydia R. Becker: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Project administration, Visualization. **Andreas Ehrenberg:** Conceptualization, Methodology, Resources, Writing - review & editing. **Volkert Feldrappe:** Methodology, Resources, Writing - review & editing. **Ingrid Kröncke:** Validation, Writing - review & editing, Supervision. **Kai Bischof:** Conceptualization, Writing - review & editing, Supervision.

Acknowledgements

We thank the diving team of the Alfred-Wegener-Institut (Helmholtz-Zentrum für Polar- und Meeresforschung, Germany) for support of our work. We thank the crews of RV "Senckenberg" for help with logistics. Thanks to Vanessa Köhler, Karin Springer, Gesine Lange and students for their help with identifying species and photographic documentations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2020.105081.

References

Airoldi, L., Balata, D., Beck, M.W., 2008. The Gray Zone: relationships between habitat loss and marine diversity and their applications in conservation. J. Exp. Mar. Biol. Ecol. 366, 8–15. https://doi.org/10.1016/j.jembe.2008.07.034.

Airoldi, Laura, Connell, S.D., Beck, M.W., 2009. The loss of natural habitats and the addition of artificial substrata. In: Wahl, M. (Ed.), Marine Hard Bottom Communities, Ecological Studies 206. Springer-Verlag, Berlin Heidelberg, pp. 269–280.

Airoldi, L., Turon, X., Perkol-Finkel, S., Rius, M., 2015. Corridors for aliens but not for natives: effects of marine urban sprawl at a regional scale. Divers. Distrib. 21, 755–768. https://doi.org/10.1111/ddi.12301.

Anderson, M.J., Gorley, R.N., Clarke, K.R., 2008. PERMANOVA+ for PRIMER Guide to Software and Statistical Methods, pp. 1–217. Prim. Plymouth, UK.

Ashley, M.C., Mangi, S.C., Rodwell, L.D., 2014. The potential of offshore windfarms to act as marine protected areas - a systematic review of current evidence. Mar. Pol. 45, 301–309. https://doi.org/10.1016/j.marpol.2013.09.002.

Assi, L., Carter, K., Deaver, E., Eddie), Anay, R., Ziehl, P., 2018. Sustainable concrete: building a greener future. J. Clean. Prod. 198, 1641–1651. https://doi.org/10.1016/j.jclepro.2018.07.123.

Bartholomä, A., Capperucci, R.M., Becker, L., Coers, S.I.I., Battershill, N., 2019. Hydrodynamics and hydroacoustic mapping of a benthic seafloor in a coarse grain habitat of the German Bight. Geo Mar. Lett. https://doi.org/10.1007/s00367-019-00599-7.

Bartsch, I., Tittley, I., 2004. The rocky intertidal biotopes of Helgoland: present and past. Helgol. Mar. Res. 58, 289–302. https://doi.org/10.1007/s10152-004-0194-2.

bbs, 2016. The Demand for Primary and Secondary Raw Materials in the Mineral and Building Materials Industry in Germany up to 2030, pp. 1–5.

Becker, L.R., Bartholomä, A., Singer, A., Bischof, K., Coers, S., Kröncke, I., 2019. Small-scale distribution modeling of benthic species in a protected natural hard ground area in the German North Sea (Helgoländer Steingrund). Geo Mar. Lett. https://doi.org/10.1007/s00367-019-00598-8.

Benedetti-Cecchi, L., 2000a. Priority effects, taxonomic resolution, and the prediction of variable patterns of colonisation of algae in littoral rock pools. Oecologia 123, 265–274. https://doi.org/10.1007/s004420051013.

Benedetti-Cecchi, L., 2000b. Predicting direct and indirect interactions during succession in a mid-littoral rocky shore assemblage. Ecol. Monogr. 70, 45–72.

Berntsson, K.M., Jonsson, P.R., Lejhall, M., Gatenholm, P., 2000. Analysis of behavioural rejection of micro-textured surfaces and implications for recruitment by the barnacle Balanus improvisus. J. Exp. Mar. Biol. Ecol. 251, 59–83. https://doi.org/10.1016/S0022-0981(00)00210-0.

BfG (Bundesanstalt für Gewässerkunde), 2008. Umweltaspekte des Einsatzes von industriell hergestellten Wasserbausteinen in Bundeswasserstraßen. Koblenz. 17. Chemisches Kolloquium am 11./12. Juni 2008 in Koblenz, Druckpartner Moser. Druck + Verlag GmbH, Rheinbach.

Bijen, J., 1996. Blast Furnace Slag Cement for Durable Marine Structures. Stichting Betonprisma (Association of the Netherlands Cement Industry), s'Hertogenbosch, Netherlands.

Bock, P., Gordon, D.P., 2020. World List of Bryozoa. Cryptosula Pallasiana (Moll,1803) [WWW Document]. World Regist. Mar. Species. http://www.marinespecies.org/aphia.php?p=taxdetails&id=111343 2020-01-27.

Boos, K., Buchholz, C., Buchholz, F., Gutow, L., 2004. Bericht über die Zusammensetzung des Helgoländer Makrozoobenthos im Vergleich historischer und aktueller Quellen Klassifizierungsvorschlag nach der WRRL und Empfehlungen zum Monitoring.

Bulleri, F., Airoldi, L., 2005. Artificial marine structures facilitate the spread of a non-indigenous green alga, Codium fragile ssp. tomentosoides, in the north Adriatic Sea. J. Appl. Ecol. 42, 1063–1072. https://doi.org/10.1111/j.1365-2664.2005.01096.x.

Bulleri, F., Chapman, M.G., 2010. The introduction of coastal infrastructure as a driver of change in marine environments. J. Appl. Ecol. 47, 26–35. https://doi.org/10.1111/j.1365-2664.2009.01751.x.

Callow, M.E., Jennings, A.R., Brennan, A.B., Seegert, C.E., Gibson, A., Wilson, L., Feinberg, A., Baney, R., Callow, J.A., 2002. Microtopografic cues for settlement of zoospores of the green fouling alga enteromorpha. Biofouling 18, 237–245. https://doi.org/10.1080/08927010290014908.

Chapman, M.G., 2003. Paucity of mobile species on constructed seawalls: effects of urbanization on biodiversity. Mar. Ecol. Prog. Ser. 264, 21–29. https://doi.org/10.3354/meps264021.

Chapman, M.G., Underwood, A.J., 2011. Evaluation of ecological engineering of "armoured" shorelines to improve their value as habitat. J. Exp. Mar. Biol. Ecol. 400, 302–313. https://doi.org/10.1016/j.jembe.2011.02.025.

Clarke, R.K., Gorley, R.N., 2006. Primer V6: user manual - tutorial. Prim. Plymouth Mar. Lab. 1–190.

Clynick, B.G., Blockley, D., Chapman, M.G., 2009. Anthropogenic changes in patterns of diversity on hard substrata: an overview. In: Wahl, M. (Ed.), Marine Hard Bottom Communities, Ecological Studies 206. Springer-Verlag, Berlin Heidelberg, pp. 247–256.

Connell, S.D., Glasby, T.M., 1999. Do urban structures influence local abundance and diversity of subtidal epibiota? A case study from Sydney Harbour, Australia. Mar. Environ. Res. 47, 373–387. https://doi.org/10.1016/S0141-1136(98)00126-3.

Crow, M.J., 2008. The concrete conundrum. Chem. World 62–66.

DAfStb, 1996. Sachstandsbericht Umweltverträglichkeit zementgebundener Baustoffe. Schriftenreihe des Deutschen Ausschusses für Stahlbeton Heft 458.

de Kluijver, M.J., 1991. Sublittoral hard substrate communities off Helgoland. Helgol. Meeresunters. 45, 317–344. https://doi.org/10.1007/BF02365523.

Dederer, G., Boos, K., Kanstinger, P., Krone, R., Schneider, C., Beher, J., Kuhlenkamp, R., Kind, B., 2015. Tauch-Untersuchung des "Steingrund" bei Helgoland (FFH DE 1714-391) und Konzeptentwicklung eines Tauch-Monitorings für den FFH Lebensraumtyp Riff (Abschlussbericht).

Dijkstra, J.J., van der Sloot, H.A., 2013. Dossier of Information Justifying that Concrete Qualifies for the Potential Release of Regulated Dangerous Substances Without-Further-Testing (WFT) by the Producer. Petten (The Netherlands).

Díaz-Castañeda, V., Erin Cox, T., Gazeau, F., Fitzer, S., Delille, J., Alliouane, S., Gattuso, J.P., 2019. Ocean acidification affects calcareous tube growth in adults and reared offspring of serpulid polychaetes. J. Exp. Biol. 222 https://doi.org/10.1242/jeb.196543.

Dugan, J.E., Airoldi, L., Chapman, M.G., Walker, S.J., Schlacher, T., 2012. Estuarine and Coastal Structures: Environmental Effects, A Focus on Shore and Nearshore Structures, Treatise on Estuarine and Coastal Science. Elsevier Inc. https://doi.org/10.1016/B978-0-12-374711-2.00802-0.

EBM, 2004. Environmental Best Management Practice Guideline for Concreting Contractors.

EC, 1988. Information Day on Utilization of Blast Furnace and Steelmaking Slags. Commission of the European Communities, Liège Belgium.

Eckhardt, A., Kronsbein, W., 1950. Beton und Zement in Seewasser.

Ehrenberg, A., 2015. Granulated blast furnace slag - from laboratory into practice. Proceedings 14th International Congress on the Chemistry of Cements, Beijing (China) (13.-16.10.2015).

El-Sorogy, A., Abdel-Wahab, M., Ziko, A., Shehata, W., 2016. Impact of some trace metals on bryozoan occurrences, Red Sea coast, Egypt. Indian J. Geo-Marine Sci. 45, 86–99.

Foekema, A.E.M., Sonneveld, C., Hoornsman, G., Blanco, A., 2016. Uitloging en effecten van metalen uit staalslakken beoordeeld in mesocosms (Lelystad).

Franke, H.-D., Gutow, L., 2004. Long-term changes in the macrozoobenthos around the rocky island of Helgoland (German Bight, North Sea). Helgol. Mar. Res. 58, 303–310. https://doi.org/10.1007/s10152-004-0193-3.

Glasby, T.M., Connell, S.D., Holloway, M.G., Hewitt, C.L., 2007. Nonindigenous biota on artificial structures: could habitat creation facilitate biological invasions? Mar. Biol. 151, 887–895. https://doi.org/10.1007/s00227-006-0552-5.

Gordon, D.P., Mawatari, S.F., 1992. Atlas of marine-fouling bryozoa of New Zealand ports and habours. Misc. Publ. 107, 1–52. https://doi.org/10.20595/jjbf.19.0_3.

Haderlie, E.C., 1984. A brief overview of the effects of marofouling. In: Costlow, J.D., Tipper, R.C. (Eds.), Marine Biodeteroration: an Interdisciplinary Study. Naval Institute Press, Annapolis, Maryland, pp. 163–166.

Hills, J.M., Thomason, J.C., 1998. The effect of scales of surface roughness on the settlement of barnacle (Semibalanus balanoides) cyprids. Biofouling 12, 57–69. https://doi.org/10.1080/08927019809378346.

Hoipkemeier-Wilson, L., Schumacher, J.F., Carman, M.L., Gibson, A.L., Feinberg, A.W., Callow, M.E., Finlay, J.A., Callow, J.A., Brennan, A.B., 2004. Antifouling potential of lubricious, micro-engineered, PDMS elastomers against zoospores of the green fouling alga Ulva (Enteromorpha). Biofouling 20, 53–63. https://doi.org/10.1080/08927010410001662689.

Hole, W., 1952. Marine Fouling and its Prevention (Annapolis, Maryland).

Howell, D., Behrends, B., 2006. A review of surface roughness in antifouling coatings illustrating the importance of cutoff length. Biofouling 22, 401–410. https://doi.org/10.1080/08927010601035738.

Humphreys, K., Mahasenan, M., 2002. Towards a Sustainable Cement Industry. Substudy 8 Climate Change. Conches-Geneva (Switzerland).

Ido, S., Shimrit, P.F., 2015. Blue is the new green - ecological enhancement of concrete based coastal and marine infrastructure. Ecol. Eng. 84, 260–272. https://doi.org/10.1016/j.ecoleng.2015.09.016.

Jensen, B.L., Glavind, M., 2002. Consider the environment - why and how. Sustainable concrete production. In: Proceedings of the Int. Conf. Held at the Univerity of Dundee, p. 14. UK, on 9-11 September 2002.

Karbe, L., Ringelband, U., 1995. Auswirkungen von in der Elbe im Wasserbau eingesetzter Elektroofenschlacke(sEOS) der Hamburger Stahlwerke auf aquatische Lebensgemeinschaften (Hamburg).

Klöckner, K., 1976. Zur Ökologie von Pomatoceros triqueter (Serpulidae, Polychaeta) - I. Reproduktionsablauf, Substratwahl, Wachstum und Mortalität. Helgoländer Wissenschaftliche Meeresuntersuchungen 28, 352–400. https://doi.org/10.1007/BF01610588.

Koop, J.H.E., 2008. Besiedlung von Schlackensteinen und Akkumulation von Schwermetallen in auf Schlacke lebenden Organismen. In: Umweltaspekte Des

Einsatzes von Industriell Hergestellten Wasserbausteinen in Bundeswasserstraßen. BfG, Koblenz, p. 154.
Kosmatka, S.H., Kerkhoff, B., Panarese, W.C., 2008. Design and Control Design and Control of Concrete Mixtures, fourteenth ed.
Kühne, S., Rachor, E., 1996. The macrofauna of a stony sand area in the German Bight (North Sea). Helgol. Mar. Res. 50, 433–452. https://doi.org/10.1007/bf02367159.
Lam, N.W.Y., Huang, R., Chan, B.K.K., 2009. Variations in intertidal assemblages and zonation patterns between vertical artificial seawalls and natural rocky shores: a case study from Victoria Harbour, Hong Kong. Zool. Stud. 48, 184–195.
Locher, F.W., 2006. Cement. Düsseldorf.
Lukens, R.R., Selberg, C., 2004. Guidelines for Marine Artificial Reef Materials.
Manz, W., 2008. Ökotoxikologische untersuchungen von Wasserbaustein-eluaten. In: Umweltaspekte Des Einsatzes von Industriell Hergestellten Wasserbausteinen in Bundeswasserstraßen. BfG, Koblenz, p. 154.
Martens, P., 1978. Contribution to the hydrographical structure of the eastern German Bight. Helgol. Meeresunters. 31, 414–424.
Michaelis, R., Hass, H.C., Mielck, F., Papenmeier, S., Sander, L., 2019a. Epibenthic assemblages of hard-substrate habitats in the German Bight (south-eastern North Sea) described using drift videos Continental Shelf Research Epibenthic assemblages of hard-substrate habitats in the German Bight (south-eastern North Sea) des. Continent. Shelf Res. 175, 30–41. https://doi.org/10.1016/j.csr.2019.01.011.
Michaelis, R., Hass, H.C., Mielck, F., Papenmeier, S., Sander, L., Ebbe, B., Gutow, L., Wiltshire, K.H., 2019b. Hard-substrate habitats in the German Bight (South-Eastern North Sea) observed using drift videos. J. Sea Res. 144, 78–84. https://doi.org/10.1016/j.seares.2018.11.009.
Moschella, P.S., Abbiati, M., Åberg, P., Airoldi, L., Anderson, J.M., Bacchiocchi, F., Bulleri, F., Dinesen, G.E., Frost, M., Gacia, E., Granhag, L., Jonsson, P.R., Satta, M.P., Sundelöf, A., Thompson, R.C., Hawkins, S.J., 2005. Low-crested coastal defence structures as artificial habitats for marine life: using ecological criteria in design. Coast. Eng. 52, 1053–1071. https://doi.org/10.1016/j.coastaleng.2005.09.014.
Nakagawa, M., Tsutsumi, N., Kato, T., Kiso, E., 2010. Technology of Constructing Seaweed Beds by Steel-Making Slag (Madrid).
Nelson-Smith, A., 1967. Catalogue of Main Marine Fouling Organisms (Found on Ships Coming into European Waters), Serpulids. OECD,Working Group of Experts on Fouling and Corrosion of Ships' Hulls, vol. 3 (Paris).
Noel, L.M.-L.J., Griffin, J.N., Moschella, P.S., Jenkins, S.R., Thompson, R.T., Hawkins, S. J., 2009. Changes in diversity and ecosystem functioning during succession. In: Wahl, M. (Ed.), Marine Hard Bottom Communities, Ecological Studies 206. Springer-Verlag, Berlin Heidelberg, pp. 213–223.
Pehlke, C., Bartsch, I., 2008. Changes in Depth Distribution and Biomass of Sublittoral Seaweeds at Helgoland (North Sea) between 1970 and 2005 37, pp. 135–147. https://doi.org/10.3354/cr00767.
Perkol-Finkel, S., Benayahu, Y., 2004. Community structure of stony and soft corals on vertical unplanned artificial reefs in Eilat (Red Sea): comparison to natural reefs. Coral Reefs 23, 195–205. https://doi.org/10.1007/s00338-004-0384-z.
Perkol-Finkel, S., Sella, I., 2015. Harnessing urban coastal infrastructure for ecological enhancement. Proc. Inst. Civ. Eng. Marit. Eng. 168, 102–110. https://doi.org/10.1680/jmaen.15.00017.
Perkol-Finkel, S., Sella, I., 2014. Ecologically active concrete for coastal and marine infrastructure: innovative matrices and designs. From Sea to Shore - Meet. Challenges Sea 1139–1149. https://doi.org/10.1680/fsts597571139.
Perkol-Finkel, S., Zilman, G., Sella, I., Miloh, T., Benayahu, Y., 2008. Floating and fixed artificial habitats: spatial and temporal patterns of benthic communities in a coral reef environment. Estuar. Coast Shelf Sci. 77, 491–500. https://doi.org/10.1016/j.ecss.2007.10.005.
Petronis, Š., Berntsson, K., Gold, J., Gatenholm, P., 2000. Design and microstructuring of PDMS surfaces for improved marine biofouling resistance. J. Biomater. Sci. Polym. Ed. 11, 1051–1072. https://doi.org/10.1163/156856200743571.
Pratje, O., 1951. Die deutung der Steingruende der Nordsee als endmoraenen. Dtsch. Hydrogr. Zeitschrift 4 (3), 106–114.
R Development Core Team, 2016. R: a Language and Environment for Statistical Computing.
Ryland, J.S., 1965. Catalogue of Main Marine Fouling Organisms. Polyzoa, Paris.
Schneider, M., Romer, M., Tschudin, M., Bolio, H., 2011. Sustainable cement production-present and future. Cement Concr. Res. 41, 642–650. https://doi.org/10.1016/j.cemconres.2011.03.019.
Schröder, H.T., Hallauer, O., Scholz, W., 1975. Beständigkeit verschiedener Betonarten in Meerwasser und in sulfathhaltigem Wasser.
Sempere-Valverde, J., Ostalé-Valriberas, E., Farfán, G.M., Espinosa, F., 2018. Substratum type affects recruitment and development of marine assemblages over artificial substrata: a case study in the Alboran Sea. Estuar. Coast Shelf Sci. 204, 56–65. https://doi.org/10.1016/j.ecss.2018.02.017.
Siddik, A.A., Al-Sofyani, A.A., Ba-Akdah, M.A., Satheesh, S., 2019. Invertebrate recruitment on artificial substrates in the Red Sea: role of substrate type and orientation. J. Mar. Biol. Assoc. U. K. 99, 741–750. https://doi.org/10.1017/S0025315418000887.
Sousa, W., Connell, S.D., 1992. Grazing and succession in marine algae. In: John, D., Hawkins, S., Price, J. (Eds.), Plant-Animal Interactions in the Marine Benthos. Oxford University Press, New York, pp. 425–441.
United Nations Envionment Programme, 2019. Sand and Sustainability: Finding New Solutions for Environmental Governance of Global Sand Resources (Geneva, Switzerland).
Wahl, M. (Ed.), 2009. Marine Hard Bottom Communities. Springer-Verlag, Berlin Heidelberg.
Yan, T., Yan, W.X., 2003. Fouling of offshore structures in China-a review. Biofouling 19, 133–138. https://doi.org/10.1080/0892701021000057927.

CHAPTER 5 – Publication IV

5.1. Benthic community establishment on different concrete mixtures introduced to a German deep-water port

Becker L.R., Kröncke I., Ehrenberg A., Feldrappe V., Bischof K.

Becker L.R., Kröncke I., Ehrenberg A., Feldrappe V., Bischof K., (2021). Benthic community establishment on different concrete mixtures introduced to a German deep-water port. Helgoland Marine Research 75:5 doi.org/10.1186/s10152-021-00550-3

Becker *et al. Helgol Mar Res* (2021) 75:5
https://doi.org/10.1186/s10152-021-00550-3

Helgoland Marine Research

ORIGINAL ARTICLE

Open Access

Benthic community establishment on different concrete mixtures introduced to a German deep-water port

Lydia R. Becker[1,2,3*], Ingrid Kröncke[2,4], Andreas Ehrenberg[5], Volkert Feldrappe[5] and Kai Bischof[3*]

Abstract

Concrete is a widely used building material in coastal constructions worldwide. However, limited natural resources used in the production process, as well as high CO_2-emission due to the calcination process of limestone and the thermal energy demand for Portland cement clinker production, raise the demand for alternative constituents. Alternative mixture types should be environmentally friendly and, at best, mimic natural hard substrates. Here five different concrete mixtures, containing different cements (Portland cement and blast furnace cements) and aggregates (sand, gravel, iron ore and metallurgical slags) were made. Three replicate cubes (15 × 15 × 15 cm) of each type were then deployed in a German deep-water Port, the JadeWeserPort, to study benthic community establishment after one year. Results are compared to a similar experiment conducted in a natural hard ground environment (Helgoland Island, Germany). Results indicate marked differences in settled communities in the Port site compared to natural environments. At the Port site community composition did not differ with the concrete mixtures. Surface orientation of the cubes (front/top/back) revealed significant differences in species abundances and compositions. Cubes hold more neobiota in the Port site than in natural hard ground environments. Implications for the usage of new concrete mixtures are discussed.

Keywords: Coastal constructions, Succession, Fouling communities

Introduction

Coastal infrastructures do not function as surrogate for natural marine habitats. Even though artificial structures act as key anthropogenic drivers of environmental change to coastal habitats worldwide [1], ecological consequences of their introduction to the marine environment, to date, have received relatively little attention [2–8]. However, there is a growing consensus that artificial structures are different to natural rocky shores or biogenic reefs [1, 2, 9–13]. In most instances, coastal infrastructure is built in areas which otherwise are characterised as soft bottom habitats; here the change in species composition, abundance and diversity through the change of the natural habitat origin becomes particularly clear [14].

While natural habitats slope gently or have heterogeneous topography, artificial constructions frequently provide vertical habitat [6, 15–17]. This can lead to increased densities of certain species and to an increasing strength of interspecific interactions [1, 18]. Understanding of how species do or do not use artificial structures is still in its infancy. To date, the characteristics of communities that are likely to establish on or near artificial structures are not predictable [1]. Observation of the community establishment on newly introduced artificial structures

*Correspondence: lkohlmorgen@marum.de; kai.bischof@uni-bremen.de
[1] INTERCOAST Research Training Group, University of Bremen, Leobener Strasse, 28359 Bremen, Germany
[3] Department of Marine Botany, University of Bremen, Leobener Str. NW2, 28359 Bremen, Germany
Full list of author information is available at the end of the article

thus helps to understand the ecological value of a structure itself.

The release of artificial substrata initiates primary succession. Primary succession starts with physiochemical events and occurs on very small spatial scales. Physiochemical events are followed by a biological colonization by bacteria and diatoms [19]. From this point on, succession is regarded as a continuous process with changing trajectories, deflected by both physical and biological processes. A temporary "final stage" of succession, where most of the substrata is covered by macrofauna organisms > 1 cm and subsequently only small changes occur, is reached after approximately one year of deployment in most cases [19]. Further studies on succession of coastal infrastructure can be found, for instance, in biofouling literature, where processes are extensively discussed [20–23].

Newly raised artificial structures are susceptible to invasion, first of all, because of the new, open space [24–27]. Further reasons for invasion can be poor environmental conditions, frequent disturbances, or support of activities linked to the introduction of exotic species (e.g. shipping, aquaculture) [1]. Especially globalization and extended marine traffic within the last century, together with an increase in infrastructure on coasts worldwide, increase the risks of introducing non-indigenous species, so called neobiota [1]. This is especially true for artificial structures in big ports, which are connected to shipping routes worldwide. Neobiota generally appear in greater proportions on artificial structures than in adjacent natural habitats [25] potentially due to a higher tolerance to environmental stressors [28], reduced competitive interactions with extant species and or by lower mortality by predation [29, 30].

Closely connected systems of artificial structures for example along the European coastlines, provide additional dispersal routes for neobiota, also causing drastic changes to natural environments close by [2, 25]. For example, *Undaria pinnatifida*, a brown algae species native to East Asian shores, was introduced into the Mediterranean in 1971 with Pacific oysters. Intentional introduction from there to the French Atlantic coast 12 years later led to a gradual spread to the British Isles and recently to the North Sea [31]. Environmental agencies worldwide are monitoring species causing such changes to the natural marine environment, particularly under the European Water Framework Directive and the Marine Strategy Framework Directive.

European coastlines are covered by 22.000 km^2 of concrete or asphalt [32–34]. Due to its availability, durability (50–100 years), formability and low in price, concrete has become one of the most important construction materials worldwide [35]. However, the availability of natural resources, commonly used in aggregates, are limited [36–38]. The reduction of Portland cement production and the increase of supplementary cementitious materials, like granulated blast furnace slags, a byproduct of pig iron production, is a desired achievement in the cement industry [39–41]. The use of slags from metal production (e.g. steel, copper) is promising. These offer technical advantages due to their mineral properties, and have been used in road construction and armor stones for decades [42]. For aquatic environments, their usage is controversial because of the potential for uncontrolled leaching of heavy metals out of pure slag stones [43]. The European concrete standards regulations are not standardized on the usage of aggregates, thus the usage depends on assessments in specific projects.

The following study closely relates to the results of a succession experiment on concrete cubes made of different mixtures which contained different cements (Portland cement and blast furnace cements) and aggregates (natural sand, gravel, iron ore and metallurgical slags). The cubes for this study were deployed in an underwater experimental area and test facility within a natural hard ground environment near Helgoland Island in the German Bight [44]. In order to compare succession on natural and artificial structures, we report here on a settlement experiment on concrete cubes made of the same mixtures and deployed in the same time span as in Becker et al. [44], but in a completely different environment; the JadeWeserPort as an example of a recently erected artificial habitat (Wilhelmshaven, Germany). Here, it is most likely that additional marine coastal infrastructure will be built, and further anthropogenic influences are to be expected.

Taking the JadeWeserPort as a representative example of a recently established artificial infrastructure with high anthropogenic impact, this study focuses on the following questions:

(1) Are there differences in the benthic communities settled on different mixture types after one year of deployment in an anthropogenically influenced area?
(2) Are observed patterns different to succession studies in a natural hard ground area (e.g. near Helgoland Island)? How do both areas differ in terms of species composition on the concrete blocks?
(3) Are there implications for the usability of alternative concrete constituents in marine constructions?

Material and methods

Deployment site and experimental design

The JadeWeserPort is the most eastern deep-water port from the "Nordrange", it is the most important continental European Ports of the North Sea [45] and is tide-independent up to 18 m water depth (Fig. 1a). Port construction started in 2008; in April 2012 its trial operation started and it has been running official business since September 2012 [45]. It holds 130 hectare of Container Terminal out of 340 hectare total area. It has a turnover capacity of 2.7 million TEU/Year [46]. In 2019, transfer of 29.29 Mio t were documented, which is + 7% compared to 2018 [47]. The neobiota report of the German coast line 2014 [48] reports a total of 116 taxa for the JadeWeserPort, of which 17 were neobiota to the German North Sea coastline.

The deployment site of the concrete cubes was in a separated part of the harbor, the service port. In total, 15 concrete cubes (15 × 15 × 15 cm) made of five different concrete mixtures, were fixed on five steel—PVC-frames (1 m × 0.25 × 0.30 m). Each frame was rigged with three cubes. The different mixtures were randomly placed in the frames, with the exception that none of the different mixtures were present in the same frame twice (Fig. 1b). The frames were deployed from swimming pontoons in April 9th, 2017 and submerged ~ 1.5 m beneath the surface and fixed by ropes.

The swimming pontoons had previously been reported as the species richest habitat of the harbor [48]. Here, a total of 63 Taxa was found, 14 of them were neobiota [48]. It was further reported that eight out of the 14 neobiota were only found at the JadeWeserPort pontoons.

Concrete mixtures

Concretes used in the experiments fulfill the requirements for exposure class "XS2" (marine structures being permanently under water) defined in the non-standardised EU concrete standard EN 206. The cement content was 320 kg/m^3 and the water/cement ratio was 0.5 in all cases.

Mixtures differed in the used cement types and aggregates. In mixture 1—mixture 3, a Portland cement CEM I 42.5 R and two blast furnace cements CEM III/A 42.5 N and CEM III/B 42.5 N were used as binders. Natural sand (2.64 kg/dm^3), gravel (2.64 kg/dm^3) and iron ore "MagnaDense" (4.90 kg/dm^3) were used in slightly different concentrations (Table 1). In mixture 4 and 5, blast furnace cement (CEM III/B 42.5 N) was combined with two metallurgical slags (a copper slag "Iron Silicate" and an electric arc furnace slag "EOS" with 3.80 kg/m^3 and 3.60 kg/m^3) as aggregates (Table 1). All cements used fulfilled the requirements of the European cement standard EN 197-1. Since blast furnace cements provide a very dense structure with a low capillary porosity, they are commonly used for durable concrete structures in the marine environment [33, 49, 50].

In accordance with EN 12390-2, the "Institut für Baustoffforschung FEhS Duisburg" produced three cubes (15 × 15 × 15 cm^3) of each of the five different mixtures (M1–M5) in February 2017. The cubes were stored 1 day in their mold, 6 days under water, and then under constant climate conditions at 20 °C and 65% relative moisture. At the end of March 2017, they were transported to Wilhelmshaven.

The concretes' compressive strengths were measured in accordance with EN 12390-3 after 2 and 28 days of casting. The results are shown in Table 2. M5, the mixture with the electric arc furnace slag aggregate, had a significantly higher strength after 28 days, due to the very high grain strength of EOS.

Fig. 1 Deployment site and experimental set up—**a** Location of the JadeWeserPort; tiles were deployed in the service port. **b** Order of frames **a**–**e**; numbers 1–5 show the location of the different concrete mixtures

Table 1 Composition of the different concrete mixtures M1–M5

Mixture	Cement type	[kg/m³]	Water [kg/m³]	w/c—ratio	Aggregates					
					Type	[kg/m³]	Art	[kg/m³]	Art	[kg/m³]
M1	CEM I 42,5R	320	160	0.5	Sand 0–2 mm	667	Gravel 2–8 mm	95	Magnadens 20 s	2122
M2	CEM III/A 42,5 N	320	160	0.5	Sand 0-2 mm	664	Gravel 2–8 mm	95	Magnadens 20 s	2112
M3	CEM III/B 42,5 N-LH/SR/NA	320	160	0.5	Sand 0–2 mm	662	Gravel 2–8 mm	95	Magnadens 20 s	2107
M4	CEM III/B 42,5 N-LH/SR/NA	320	160	0.5	Iron silicate 0–5 mm	1361	Iron silicate 5–22 mm	1358	–	–
M5	CEM III/B 42,5 N-LH/SR/NA	320	160	0.5	Sand 0–2 mm	284	EOS	2193	–	–

Ingredients of cements (CEM I 42,5R; CEM III/A 42,5 N; CEM III/B 42.5 N-LH/SR/NA) and aggregates (sand, gravel, magnadens, iron silicate, EOS) are given in kg/m³

Sampling procedure and analysis

The concrete cubes were retrieved on April 16th, 2018, after a one year deployment (April 9th, 2017–April 16th, 2018). Until evaluation, they were stored in darkness in saltwater at ~ 10 °C. The cubes were examined in the lab from April 16th 2018 to April 19th 2018. Three cube sides, the top, front and backside, were evaluated. The front side is defined as the cube side, which points in the direction of the open water, the back side is defined as the cube side, which points to the pontoon (Fig. 1b). All macrofauna and algal species present on the top, front and backside of the concrete cubes (15 × 15 cm) were recorded. Additionally, each side was photographically documented. Species were determined to the lowest possible taxonomic level and for smaller species, abundance and coverage were recorded using a smaller grid (1 cm^2 = 0.44% coverage of the total area).

For comparison of the different sides and mixture types, only coverage data was used in the statistical analysis. Mobile macrofauna species or species with less than five individuals per cube side were excluded from the analysis. One community was summed up as "mat", including species of juvenile Phaeophyceae and cyanobacterial communities, as well as diatoms species. They formed a visible crust on the cubes.

All neobiota were identified according to neobiota catalogues [51, 52]. Categories (K1–K3) were assigned accordingly: K1 Neobiota with a known strong impact on the environment. K2 Neobiota with a known strong impact on the environment, but this impact is still not present on regional coasts. K3 Neobiota with to date unknown consequences to the environment [51].

Data processing and statistical analysis

Statistical analysis were performed using the statistical PRIMER package, v6 [53] and PERMANOVA + add on PRIMER v6 [54]. Univariate 1-way PERMANOVA tests, based on square root transformed coverage data, as well as multivariate analysis of the transformed data via PERMANOVA pair-wise tests, based on Bray–Curtis similarity, were performed. P-values yield the exact test of the null hypothesis. This means, the probability of rejecting the null hypothesis is exactly equal to the chosen significant level of 0.05. The chance of false positive findings (type I error) is 5% [54]. MDS plots were used to show trends in multivariate data. DIVERSE tool and similarity percentage routine (SIMPER) analysis were used to determine differences in species communities. Mean coverage and standard deviations were calculated in R v.3.3.2 [55]. Coverage values over 100% were found due to the horizontal and partially overlapping distribution of species.

Table 2 Compressive strength $f_{c,\ cube}$ of the concrete mixtures M1–M5 in N/mm^2 after 2 and 28 days under constant climate conditions at 20 °C and 65% relative moisture

	M1	M2	M3	M4	M5
2 days	43.5	40.1	41.1	41.7	43.5
28 days	59.1	58.4	56.4	60.4	72.0

Results

Benthic flora and fauna

After one year of deployment, 32 macrofauna and algal taxa were identified in total on all concrete cubes. Five of these taxa belong to the group of neobiota (K1 = 1 species and two species classified as K2 and K3). With five different taxa, Mollusca represented the most diverse group, followed by Arthropoda (4), Phaeophyceae (4), and Rhodophyta (4). Other taxonomic groups were represented two or less taxa per group (Table 3). The following statistical analysis include %-coverage of nine taxa and one taxa named "mat" (which includes 3 juvenile species of Phaeophycaea and diatoms).

Differences between the observed mixtures and sides

Permanova revealed no differences in community composition for the different mixtures (M1–M5), but confirmed highly significant differences (P = 0.0001) between macrofauna and algal communities of the top side (T), the front side (F), and the back side (B) of the cubes (Table 4).

Differences between the observed sides of the concrete cubes were also shown by the MDS plot of square root transformed coverage data (Fig. 2). Permanova pair-wise test confirmed significant differences between all sides (T-F P = 0.0001, T-B P = 0.0001, F-B P = 0.0001).

Side effect

Taxa numbers are similar between the Top and Front sides (T: 4.31 ± 0.91; F: 4.62 ± 0.62), only the Back differed with one taxa less (B: 3.31 ± 0.46). The Top sides of the cubes revealed lower mean coverages (51.23 ± 19.04%) compared to the Front (118.54 ± 21.69%) and Back (97.38 ± 29.77%) sides (Table 5). Shannon–Wiener index H' was highest for the Top sides (1.07 ± 0.15). For the Front sides, a Shannon–Wiener index of 0.97 ± 0.19, and for the Back sides, a Shannon–Wiener index H' of 0.88 ± 0.13 was calculated. Eveness J' was 0.75 ± 0.15 for the Top sides, 0.63 ± 0.1 for the Front sides, and 0.74 ± 0.11 for the Back sides of the cubes (Table 5). SIMPER analysis indicated differences in species communities between the sides. While the Top communities were dominated by red algae *Polysiphonia nigrescens* (46.33%), followed

Table 3 List of macrofauna and algal taxa found on the concrete cubes

Phylum/class	Order	Family	Species	Neobiota
Arthropoda	Amphipoda	Gammaridae	*Gammarus spec*	
	Decapoda	Cancridae	*Cancer pagurus*	
	Sessila	Austrobalanidae	*Austrominius modestus*	K2
			Balanus crenatus	
Bryozoa	Cheilostomatida	Bugulidae	***Crisularia purpurotincta***	
		Electridae	*Electra pilosa*	
Chlorophyta	Ulvales	Ulvaceae	*Ulva* spp	
	Ulvales	Ulotrichaceae	*Acrosiphonia arcta*	
Chordata	Stolidobranchia	Styelidae	*Botryllus schlosseri*	K3
Cnidaria	Actiniaria	Actiniidae	*Urticina* juv	
			Urticina felina	
Echinodermata	Forcipulatida	Asteriidae	*Asterias rubens*	
Hydrozoa	Anthoathecata	Tubulariidae	*Tubularia indivisa*	
			"Club polyp"	
Mollusca	Littorinimorpha	Calyptraeidae	*Crepidula fornicata*	K2
	Mytilida	Mytilidae	*Mytilus edulis*	
	Nudibranchia	Onchidorididae	*Onchidoris bilamellata + Gelege*	
	Ostreida	Ostreidae	*Crassostrea gigas*	K1
	Trochida	Trochidae	*Gibbula spec*	
Phaeophyceae	Ectocarpales	Acinetosporaceae	***Hincksia hincksiae***	
(mat)			***Pilayella* spp**	
			Pilayella littoralis	
		Ectocarpaceae	***Ectocarpus siliculosus***	
Polychaeta	Phyllodocida	Polynoidae	*Harmothoe glabra*	
			Harmothoe antilopes	
	Terebellida	Terebellidae	***"Polychaete mud tube"s***	
Porifera	Suberitida	Halichondriidae	*Halichondria (Halichondria) panicea*	
Rhodophyta	Bonnemaisoniales	Bonnemaisoniaceae	*Bonnemaisonia hamifera*	K3
	Ceramiales	Rhodomelaceae	*Ceramium rubrum*	
		Rhodomelaceae	***Polysiphonia nigrescens***	
	Corallinales	Lithothamniaceae	*Phymatolithon* spp	
Tube dwelling diatoms				

Species %-coverage included in the JadeWeserPort analysis are shown in bold. Species of the Phylum Phaeophyceae and diatoms built a mat cover on the cubes and were included as such in the statistical analysis. Risk categories are given (K1–K3) [51]

Table 4 Results of Permanova on square root transformed coverage data showing differences in macrofauna and algal communities between different sides (Top vs Front vs. Back)

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Sides	2	23,183	11,592	27.763	0.0001**	9940
Mixture	4	2094	523.5	1.2539	0.275	9929
Sides × mixture	8	1603.3	200.41	0.48002	0.955	9923
Res	24	10,020	417.52			
Total	38	38,455				

No differences were present for mixtures (M1–M5). Analysis implies no interaction between side effect and mixtures effect. Meaning that the effect within side and mixtures is the same within the tested groups

df degrees of freedom, *SS* sum of squares, *MS* mean sum of squares, *Pseudo F* pseudo-F ratio. Significance levels P(perm) are based on 9999 permutations (significance levels: *significant ($p \leq 0.05$), **highly significant ($p \leq 0.005$)). Unique perms indicate how many unique values of the test statistic were obtained under permutation

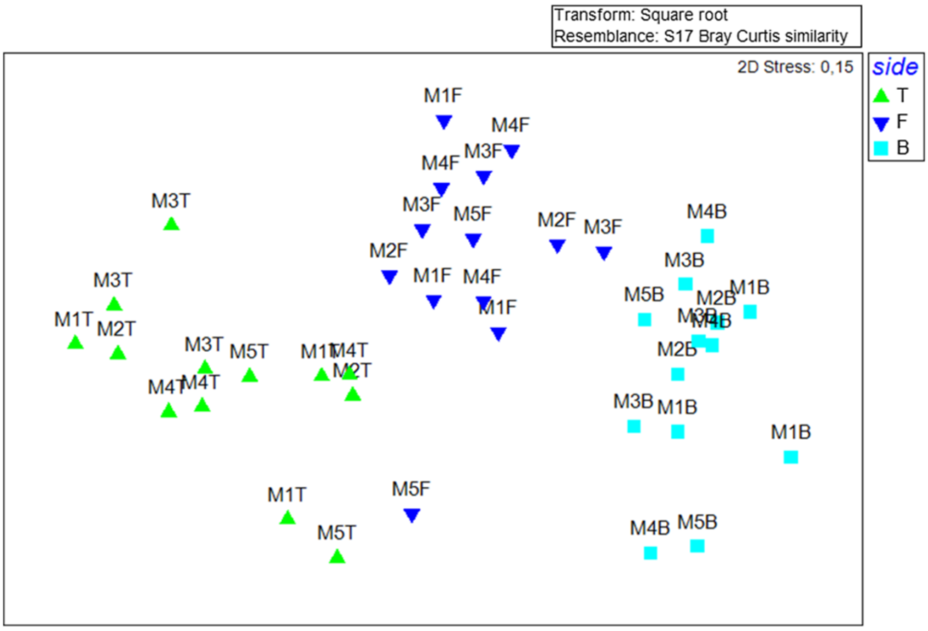


Fig. 2 MDS plot of square root transformed coverage data indicating differences in species communities between different cube sides. Given label capture mixture type (M1–M5) and sites (*F* Front, *B* Back, *T* Top)

Table 5 Results of DIVERSE and SIMPER analysis for the top, front and back sides of the cubes

Site	Top	Front	Back
Mean taxa per side	4.31 (0.99)	4.62 (0.68)	3.31 (0.5)
Mean coverage [%]	51.23 (20.63)	118.54 (23.5)	97.38 (32.25)
Shannon–Wiener index H′	1.07 (0.29)	0.97 (0.21)	0.88 (0.14)
Eveness J′	0.75 (0.16)	0.63 (0.1)	0.74 (0.12)
Species communities resulting from SIMPER analysis	*Polysiphonia nigrescens* (46.33) mat (26.20) *Balanus crenatus* (14.23) *"Polychaete mud tubes"* (10.17)	mat (56.39) *Polysiphonia nigrescens* (22.93) *Balanus crenatus* (10.52) *Crisularia purpurotincta* (7.28)	mat (48.47) *Balanus crenatus (29.94)* *Crisularia purpurotincta (21.07)*

Shown are mean taxa, mean coverage, Shannon–Wiener index H′ and Eveness J′. Standard deviations are shown in brackets. SIMPER analysis shows characterizing macrofauna and algal species, and to which percentage they contribution to the communities (in brackets) on the different sites

by mat species (26.20%), *Balanus crenatus* (14.23%) and "*Polychaete mud tubes*" (10.17%), the Front sides were dominated by the mat species (56.39%), *Polysiphonia nigrescens* (22.93%), *Balanus crenatus* (10.52%), and *Crisularia purpurotincta* (7.28). The Back sides, like the Front sides, were also dominated by mat species (48.47%) but then followed by *Balanus crenatus* (29.94%) and *Crisularia purpurotincta* (21.07%) (Table 5).

Neobiota in the JadeWeserPort

Five out of the total of 32 taxa found on the concrete cubes were recorded as neobiota, belonging to all of the three different risk categories: K1—*Crassostera gigas*; K2—*Austrominius modestus*, *Crepidula fornicata*; K3—*Botryllus schlosseri*, *Bonnemaisonia hamifera* (Table 3). Abundances of *Crassostera gigas* were low being found on 6 out of 45 cube sides, with less than five individuals per side. Abundances of *Austrominius modestus* were also low being found on 1 out of 45 cube sides, with less than five individuals per side. In 26 out of 45 cube sides, individuals of *Crepidula fornicata* were present at densities of 1–4 individuals per side, however on three sides, 10–25 individuals were present. Abundances of *Botryllus schlosseri* were low with three small colonies found on 5 sides. *Bonnemaisnia hamifera* was found on 13 out of 45 cube sides, with coverage mostly less than 5% per side but one side was found with 30%.

Discussion

The findings within this study contribute to a better understanding of the process of settlement of benthic communities on artificial constructions, and further highlight that these structures cannot act as surrogates to natural grounds. In the context of a continuously increasing activity of constructing new marine coastal infrastructure [32–34], the investigation of new concrete mixtures is necessary with regards to resource efficiency, sustainability and economical aspects. There is more than one concrete type which can be used in coastal constructions, to safeguard natural resources. Testing different mixtures in the natural environment, is not only important for the evaluation of ecological impacts, but also concerning durability and static requirements.

In the JadeWeserPort, concrete mixture type made no differences to settled communities after one year. However, surface orientation of the cubes (Front/Top/Back) revealed significant differences in species abundances and community compositions. In a similar experimental setting, however in a less anthropogencially shaped environment, Becker et al. [44] observed different results. Here, the same concrete mixtures were exposed within the same period of time to the natural subtidal hard ground conditions of Helgoland Island. Becker et al. [44] also observed significant differences of settlement communities depending on the surface orientation of the cubes, but also significant differences in settled communities between mixture types. They suggests that concrete mixture type is negligible in anthropogenically influenced sites but more study sites are needed to confirm this. Impacts of artificial material in inshore coastal hard bottom communities might not necessarily be the same as for Helgoland, which, due to its relatively isolated location in the German Bight is offshore character [56].

Constructions of marine artificial infrastructure have been influencing natural environmental conditions for decades, for instance by changes in water flow, contamination loads, noise etc., and have impacted species richness and diversity which cannot be readily reversed [1, 57]. In nearshore environments, fragmentation of rocky shore habitats by replacing natural rock with artificial substrata, leads to a loss of habitat and changes the characteristics of the remaining assemblages [58]. The subdivision into numerous smaller habitat patches results in an overall reduction in species richness [59]. Species present in anthropogenically influenced sites are characterized by a generally broad range of tolerance [1]. Changes, for instance in concrete ingredients, will probably be of minor importance to those species. Natural hard grounds, in contrast, hold higher numbers of propagules, species that are more specialized and react more sensitive to small range environmental changes [1, 13, 57]. This might result in more drastic and visible changes in the settling community structures depending on mixture types.

Species composition and abundances in anthropogenically influenced and natural sites

Artificial constructions like ports, are known to differ from natural hard grounds in terms of community composition and species densities [57, 60]. Studies on artificial constructions found reduced species richness compared to the neighbouring natural communities [1, 61–63].

For the cubes deployed in the JadeWeserPort, a total of 32 taxa was found. This is low, compared to a total of 51 taxa found on the cubes of the natural hard ground study site in Helgoland by Becker et al. [44]. Comparing results of taxa numbers given by other studies conducted in the JadeWeserPort and Helgoland, the trend towards lower species diversity in the port site is also observed. For the JadeWeserPort a total of 116 taxa [48] is reported where at the natural site Helgoland, up to 402 taxa can be found [64]. Other studies show similar results. For instance, a recent comparison of concrete jetties versus natural rocky shores of the Mediterranean revealed a total of 150 algal and faunal taxa, 77 were recorded on jetties while 140 were recorded on natural rocky shores [65].

The floating pontoons in the JadeWeserPort were reported as the habitat of the harbor richest in species [48]. With a total of 63 taxa, they held more than half of all taxa found in the port site. Studies on floating and fixed artificial structures suggest, that the motion of floating structures, like pontoons, influence species composition and abundances [66, 67]. In temperate regions, differences between floating and fixed structures were mainly due to increased abundances of species [25, 66–69]. For tropical environments, changes in community composition were observed as well, for instance, more filter feeding organisms were found on floating structures, compared to fixed habitats [66, 67]. This might be explained by higher water flow and turbulence through these structures. This trend is also reflected by community composition found for the pontoons in the JadeWeserPort by Rhode et al. [48].

Regarding species composition, only eight red and brown algal species were found in the JadeWeserPort. The red alga *Polysiphonia nigrescens* dominated over all others covering most of the front sites of the cubes after the second month of deployment. *Polysiphonia nigrescens* was missing on the back side of the cubes, and here, barnacles dominated the surface. The back side of the cubes is shaded by the pontoons and since algae species need light for growth, it is reasonable that they preferred the open water side. However, taxa numbers of algae found on the concrete cubes in the port are considerably lower, compared to the natural study site, where cubes were covered by 23 algal taxa after one year of deployment. The proximity to natural rocky coastlines or reefs influence community characteristics on artificial constructions [57, 60]. The JadeWeserPort is surrounded by a mud flat environment. Thus, the pool of reproductive spores potentially reaching artificial structures to settle is low compared to the natural hard ground environments [13].

Water transparency in anthropogenic port sites is often considerably low, especially when a mud flat environment surrounds them. This is critical, as light availability is a main factor limiting the growth of algal species. Regular dredging activities in the port and in the channels close by, in combination with the regular tide flow, can increase the percentage of small mud particles in the water column [70–73]. In the JadeWeserPort, water transparency is already low in 0.5 to 1 m [48], as measured by Secchi depth. For the North Sea areas, water transparency increases with distance to the shore lines [74]. For the natural site Helgoland, mean water transparency lies already around 4–5 m Secchi depth [75, 76], a value which can hardly be measured in the proximity of anthropogenic construction sites.

Apart from a higher diversity of algae, more Bryozoan species were found at the natural study site as well, compared to the JadeWeserPort [44]. In addition to water transparency, water contamination levels influence species diversity. The southern parts of the North Sea are under the influence of the rivers Elbe, Weser, Ems, Rhein, Schelde and Thames. Hence, contamination levels with respect to brackish water inflow and industrial loads through these rivers are higher compared to the isolated position of Helgoland Island [56]. Studies from the Red Sea coast show that bryozoan species react sensitively to environmental pollution, mainly heavy metal contamination in soils. Diversity of Bryozoan species was higher in unpolluted areas than in anthropogenically influenced coastal sites [77]. Although we did not assess heavy metal load at the study site, it is likely that a higher contamination level in port sites may influence species diversity.

For the JadeWeserPort, the barnacle *Balanus crenatus* were among the characteristic species, especially for the cubes' back sides. Barnacles are typical settling organisms on artificial structures worldwide [20–23, 78]. Within artificial constructions, barnacles prefer vertically orientated structures, but this can vary depending on sediment loads [79]. Other species typical for artificial constructions can be tube building polychaetes, like *Spriobranchus triqueter* or *Spirobis spirobis* for temperate regions, both missing from the JadeWeserPort study site [65, 79].

Neobiota

The experiments in the JadeWeserPort affirm a high invasion risk of artificial structures, as argued, for instance, in Glasby et al. [80]. All five neobiota found in this study were also included in the total of 14 neobiota found on the pontoon site in the JadeWeserPort by Rhode et al. [48]. However, abundances of neobiota were still low, compared to dominating native species. A fast succession of native competitors, for instance *Polysiphonia nigrescen*s might have prevent the settlement by neobiota.

Since 1954, the barnacle *Austominius modestus* has been one of the main fouling species in German coastal waters [51]. After a series of mild winters and warm summers, exponential population growth was observed in several North Sea regions [51, 81]. This might become problematic with further increasing temperature due to climate change. A model on two competing barnacle species with different reproduction times (as would the case for *Austrominius modestus* and *Balanus crenatus*) revealed a positive impact of warming waters for invasive species due to a reduced time period between the reproductive peaks of the species [82]. However, native species can be supported and positively influenced by the precise timing of the introduction of new substrates [82]. In the present study, the native barnacle *Balanus crenatus* still dominated on the cubes of the JadeWeserPort. The slipper snail *Crepidula fornicata,* also introduced from England where it spread to most European ports, has been established as part of the German marine fauna since 1934. Its abundance is still strongly reduced by cold winters [51]. On the cubes in the JadeWeserPort, the pacific oyster *Crassostera gigas* was also found being introduced to the North Sea waters in the middle of the twentieth century where in the Wadden Sea, it replaced native mussel beds of *Mytilus edul*is. Hitherto, *Crassostera gigas* can be found along almost all European coastlines [51]. At the natural study site of Helgoland Becker et al. [44] observed two neobiota (*Botryllus schlosseri* and *Bonnemaisonia hamifera*) but they do not seem to have a negative impact on the natural environment [51].

There are several reasons given as to why artificial structures are particularly vulnerable to invasion. Those reasons entail a generally lower diversity of native species, reduced competitive interaction and predation risk, but also changes in environmental conditions, like a reduced water flow in more sheltered conditions [1]. For breakwaters along the coasts of Italy a spread of introduced green macroalgae has been found [12, 24]. Algae benefit from the wave-sheltered environments on the shoreward side of the breakwaters [12, 24]. Dafforn et al. [28] argue that filter-feeding invaders, which are often transported on ship hulls, could take advantage of being adapted to high shear stress by colonizing open space on moving substrata, for instance floating docks. Regarding reduced competitive interactions and predation risk, as postulated by the biotic resistance theory [29] and enemy release hypotheses [30], it also needs to be taken into account that artificial structures always initiate primary succession when they are built or released to marine environments. It is difficult to predict, if neobiota will manage to replace native competitors in the long term. However, with ongoing climate change and global trade and transport it is likely that neobiota will succeed over native species [83, 84].

In conclusion, a general recommendation can be given with respect to the use of new concrete mixtures in marine constructions. As long as there is no significant difference in succession patterns and establishment of benthic communities between the new concrete mixtures and those which are commonly provided, and that leakage of environmental pollutants can be excluded, the new mixtures should be used for new constructions. This way, at least a more environmentally friendly production would be guaranteed. However, it is important to balance between costs and benefits of new concrete mixtures and building solutions may differ from case to case.

Acknowledgements
We thank the JadeWeserPort for support of our work. We thank Maik Wilsenack, Ralf Kuhlmann, Hermann Neumann, and Michael Becker for help with logistics. Thanks to Vanessa Köhler, Karin Springer, Gesine Lange and students for help with identifying species and doing photographic documentations. Thanks to Prof. Dr. Conrad Pilditch for linguistic revisions.

Authors' contributions
L. R. Becker: conceptualization, methodology, validation, formal analysis, investigation, writing—original draft, writing—review and editing, project administration, visualization. K. Bischof: conceptualization, writing—review and editing, supervision. I. Kröncke: validation, writing—review and editing, supervision. A. Ehrenberg: conceptualization, methodology, resources, writing—review and editing. V. Feldrappe: methodology, resources, writing—review and editing. All authors read and approved the final manuscript.

Funding
Open Access funding enabled and organized by Projekt DEAL. This research was funded by the DFG ('German Research Foundation') within the INTERCOAST ('Integrated Coastal Zone and Shelf-Sea Research') graduate program, a joint collaboration between the Senckenberg Institute in Wilhelmshaven (Germany), the University of Bremen (Germany), and the University of Waikato (New Zealand) and by the FEhS Institute Duisburg.

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Author details
[1]INTERCOAST Research Training Group, University of Bremen, Leobener Strasse, 28359 Bremen, Germany. [2]Department for Marine Research, Senckenberg Am Meer, Südstrand 40, 26382 Wilhelmshaven, Germany. [3]Department of Marine Botany, University of Bremen, Leobener Str. NW2, 28359 Bremen, Germany. [4]Institute for Chemistry and Biology of the Marine Environment, University of Oldenburg, Schleusenstr. 1, 26382 Wilhelmshaven, Germany. [5]FehS-Institut Für Baustoff-Forschung E.V., Bliersheimer Straße 62, 47229 Duisburg, Germany.

Received: 12 June 2020 Accepted: 8 June 2021
Published online: 19 June 2021

References

1. Bulleri F, Chapman MG. The introduction of coastal infrastructure as a driver of change in marine environments. J Appl Ecol. 2010;47:26–35.
2. Glasby TM, Connell SD. Urban structures as marine habitats. Ambio. 1999;28:595–8.
3. Southward AJ, Orton JH. The effects of wave-action on the distribution and numbers of the commoner plants and animals living on the Plymouth breakwater. J Mar Biol Assoc UK. 1954;33:1–19.
4. Connell SD. Urban structures as marine habitats: an experimental comparison of the composition and abundance of subtidal epibiota among pilings, pontoons and rocky reefs. Mar Environ Res. 2001;52:115–25.
5. Hawkins SJ, Allen JR, Ross PM, Genner MJ. Marine and coastal ecosystems. In: Perrow MR, Davy AJ, editors. Handbook of ecological restoration in practice. Cambridge: Cambridge University Press; 2002. p. 121–48.
6. Chapman MG. Paucity of mobile species on constructed seawalls: effects of urbanization on biodiversity. Mar Ecol Prog Ser. 2003;264:21–9.
7. Bulleri F. Is it time for urban ecology to include the marine realm? Trends Ecol Evol. 2006;21:656–8.
8. Airoldi L, Abbiati M, Beck MW, Hawkins SJ, Jonsson PR, Martin D, et al. An ecological perspective on the deployment and design of low-crested and other hard coastal defence structures. Coast Eng. 2005;52:1073–87.
9. Bulleri F. The introduction of artificial structures on marine soft- and hard-bottoms: ecological implications of epibiota. Environ Conserv. 2005;32:101–2.
10. Firth LB, Thompson RC, Bohn K, Abbiati M, Airoldi L, Bouma TJ, et al. Between a rock and a hard place: environmental and engineering considerations when designing coastal defence structures. Coast Eng. 2014;87:122–35.
11. Firth LB, Knights AM, Bridger D, Evans AJ, Mieszkowska N, Moore PJ, et al. Ocean sprawl: challenges and opportunities for biodiversity management in a changing world. Oceanogr Mar Biol Annu Rev. 2017;2016(54):193–269.
12. Vaselli S, Bulleri F, Benedetti-Cecchi L. Hard coastal-defence structures as habitats for native and exotic rocky-bottom species. Mar Environ Res. 2008;66:395–403. https://doi.org/10.1016/j.marenvres.2008.06.002.
13. Bulleri F. Role of recruitment in causing differences between intertidal assemblages on seawalls and rocky shores. Mar Ecol Prog Ser. 2005;287:53–64.
14. Bacchiocchi F, Airoldi L. Distribution and dynamics of epibiota on hard structures for coastal protection. Estuar Coast Shelf Sci. 2003;56:1157–66.
15. Perkol-Finkel S, Benayahu Y. Community structure of stony and soft corals on vertical unplanned artificial reefs in Eilat (Red Sea): comparison to natural reefs. Coral Reefs. 2004;23:195–205.
16. Moschella PS, Abbiati M, Åberg P, Airoldi L, Anderson JM, Bacchiocchi F, et al. Low-crested coastal defence structures as artificial habitats for marine life: Using ecological criteria in design. Coast Eng. 2005;52:1053–71.
17. Lam NWY, Huang R, Chan BKK. Variations in intertidal assemblages and zonation patterns between vertical artificial seawalls and natural rocky shores: a case study from Victoria Harbour. Hong Kong Zool Stud. 2009;48:184–95.
18. Moreira J, Chapman MG, Underwood AJ. Seawalls do not sustain viable populations of limpets. Mar Ecol Prog Ser. 2006;322 Smallwood 2001:179–88.
19. Noël LM-LJ, Griffin JN, Moschella PS, Jenkins SR, Thompson RT, Hawkins SJ. Changes in diversity and ecosystem functioning during succession. In: Wahl M, editor. Marine hard bottom communities, ecological studies 206. Berlin Heidelberg: Springer-Verlag; 2009. p. 213–23.

20. Haderlie EC. A brief overview of the effects of marofouling. In: Costlow JD, Tipper RC, editors. Marine biodeteroration: an interdisciplinary study. Annapolis: Naval Institute Press; 1984. p. 163–6.
21. Hole W. Marine fouling and its prevention. Maryland: Annapolis; 1952.
22. Howell D, Behrends B. A review of surface roughness in antifouling coatings illustrating the importance of cutoff length. Biofouling. 2006;22:401–10.
23. Yan T, Yan WX. Fouling of offshore structures in China—a review. Biofouling. 2003;19:133–8.
24. Bulleri F, Airoldi L. Artificial marine structures facilitate the spread of a non-indigenous green alga, Codium fragile ssp. tomentosoides, in the north Adriatic Sea. J Appl Ecol. 2005;42:1063–72.
25. Glasby TM, Connell SD, Holloway MG, Hewitt CL. Nonindigenous biota on artificial structures: could habitat creation facilitate biological invasions? Mar Biol. 2007;151:887–95.
26. Neves CS, Rocha RM, Pitombo FB, Roper JJ. Use of artificial substrata by introduced and cryptogenic marine species in Paranaguá Bay, southern Brazil. Biofouling. 2007;23:319–30.
27. Tyrrell MC, Byers JE. Do artificial substrates favor nonindigenous fouling species over native species? J Exp Mar Bio Ecol. 2007;342:54–60.
28. Dafforn KA, Johnston EL, Glasby TM. Shallow moving structures promote marine invader dominance. Biofouling. 2009;25:277–87.
29. Elton CS. The ecology of invasion by animals and plants. London: Methuen; 1958.
30. Keane RM, Crawley MJ. Exotic plant invasions and the enemy release hypothesis. Trends Ecol Evol. 2002;17:164–70.
31. Schiller J, Lackschewitz D, Buschbaum C, Reise K, Pang S, Bischof K. Heading northward to Scandinavia: Undaria pinnatifida in the northern Wadden Sea. Bot Mar. 2018;61:365–71.
32. Airoldi L, Beck M. Loss, status and trends for coastal marine habitats of Europe. Oceanograph Marine Biol. 2007;45:345–405.
33. Bijen J. Blast furnace slag cement for durable marine structures. Stichting Betonprisma (Association of the Netherlands Cement Industry), s'Hertogenbosch, Netherlands; 1996.
34. Kosmatka SH, Kerkhoff B, Panarese WC. Design and control of concrete mixtures. EB001, 14th edition, Portland Cement Association, Skokie, Illinois, USA, 2002.
35. Jensen BL, Glavind M. Consider the environment - why and how. Sustainable concrete production - Proceedings of the International Conference held at the University of Dundee, UK, on 9–11 September; 2002. p. 14.
36. Assi L, Carter K, Deaver E (Eddie), Anay R, Ziehl P. Sustainable concrete: building a greener future. J Clean Prod. 2018;198:1641–51. https://doi.org/10.1016/j.jclepro.2018.07.123.
37. Crow MJ. The concrete conundrum. Chem World. 2008;March:62–66.
38. United Nations Envionment Programme. Sand and sustainability: finding new solutions for environmental governance of global sand resources. Geneva: Switzerland; 2019.
39. Ehrenberg A. Granulated blast furnace slag - from laboratory into practice. 14th Int Congr Chem Cem. 2015. http://www.iccc2015beijing.org/dct/page/1.
40. Schneider M, Romer M, Tschudin M, Bolio H. Sustainable cement production-present and future. Cem Concr Res. 2011;41:642–50. https://doi.org/10.1016/j.cemconres.2011.03.019.
41. bbs. The demand for primary and secondary raw materials in the mineral and building materials industry in Germany up to 2030. 2016; p. 1–5.
42. EC. Information day on utilization of blast furnace and steelmaking slags. Liège Belgium: Commission of the European Communities; 1988.
43. BfG. Umweltaspekte des Einsatzes von industriell hergestellten Wasserbausteinen in Bundeswasserstraßen. Koblenz; 2008.
44. Becker LR, Ehrenberg A, Feldrappe V, Kröncke I, Bischof K. The role of artificial material for benthic communities—establishing different concrete materials as hard bottom environments. Mar Environ Res. 2020. https://doi.org/10.1016/j.marenvres.2020.105081.
45. JWP. Basis-Information JadeWeserPort. Wilhelmshaven; 2020.
46. JWP. Imagebroschüre JadeWeserPort-Das GVZ JadeWeserPort. Wilhelmshaven; 2020.
47. Jahrespressekonferenz Niedersächsiche Seehäfen. Niedersachsens Seehäfen erzielen mit 53,5 Mio. Tonnen das beste Ergebnis der letzten 10 Jahre. 2020. https://www.jadeweserport.de/presse-media/news/4764/. Accessed 19 Mar 2020.
48. Rhode S, Schupp P, Markert A, Wehrmann A. Neobiota - Basislinie in niedersächsischen Küstengewässern. 2015. Bericht erstellt im Auftrag des NLWKN und NLPV.
49. Eckhardt A, Kronsbein W. Beton und Zement in Seewasser. 1950.
50. Schröder HT, Hallauer O, Scholz W. Beständigkeit verschiedener Betonarten in Meerwasser und in sulfathaltigem Wasser. 1975.
51. Lackschewitz D, Reise K, Buschbaum C, Karez R. Neobiota in deutschen Küstengewässern. 2014.
52. BLANO. Neobiota-Plattform. by Fach AG Neobiota. 2020. https://www.neobiota-plattform.de/english/neobiota-platform/. Accessed 19 Mar 2020.
53. Clarke RK, Gorley RN. PRIMER V6: User Manual - Tutorial. Prim Plymouth Mar Lab. 2006; p. 1–190.
54. Anderson MJ, Gorley RN, Clarke KR. PERMANOVA+ for PRIMER guide to software and statistical methods. Prim Plymouth, UK. 2008; p. 1–217.
55. R Development Core Team. R: a language and environment for statistical computing. 2016. www.r-project.org.
56. de Kluijver MJ. Sublittoral hard substrate communities off Helgoland. Helgoländer Meeresuntersuchungen. 1991;45:317–44.
57. Airoldi L, Connell SD, Beck MW. The loss of natural habitats and the addition of artificial substrata. In: Wahl M, editor. Marine hard bottom communities, ecological studies 206. Berlin Heidelberg: Springer-Verlag; 2009. p. 269–80.
58. Fahrig L. Effects of habitat fragmentation on biodiversity. Annu Rev Ecol Evol Syst. 2003;34:487–515.
59. Debinski DM, Holt RD. A survey and overview of habitat fragmentation experiments. Conserv Biol. 2000;14:342–55.
60. Clynick BG, Blockley D, Chapman MG. Anthropogenic changes in patterns of diversity on hard substrata: an overview. In: Wahl M, editor. Marine hard bottom communities, ecological studies 206. Berlin Heidelberg: Springer-Verlag; 2009. p. 247–56.
61. Airoldi L, Balata D, Beck MW. The Gray Zone: relationships between habitat loss and marine diversity and their applications in conservation. J Exp Mar Bio Ecol. 2008;366:8–15. https://doi.org/10.1016/j.jembe.2008.07.034.
62. Sella I, Perkol FS. Blue is the new green—ecological enhancement of concrete based coastal and marine infrastructure. Ecol Eng. 2015;84:260–72. https://doi.org/10.1016/j.ecoleng.2015.09.016.
63. Gacia E, Satta MP, Martin D. Low crested coastal defence structures on the Catalan coast of the Mediterranean Sea: how they compare with natural rocky shores. Sci Mar. 2007;71:259–67.
64. Boos K, Buchholz C, Buchholz F, Gutow L. Bericht über die Zusammensetzung des Helgoländer Makrozoobenthos im Vergleich historischer und aktueller Quellen - Klassifizierungsvorschlag nach der WRRL und Empfehlungen zum Monitoring. 2004.
65. Bonnici L, Borg JA, Evans J, Lanfranco S, Schembri PJ. Of rocks and hard places: comparing biotic assemblages on concrete jetties versus natural rock along a microtidal mediterranean shore. J Coast Res. 2018;345:1136–48.
66. Perkol-Finkel S, Zilman G, Sella I, Miloh T, Benayahu Y. Floating and fixed artificial habitats: effects of substratum motion on benthic communities in a coral reef environment. Mar Ecol Prog Ser. 2006;317 July:9–20.
67. Perkol-Finkel S, Zilman G, Sella I, Miloh T, Benayahu Y. Floating and fixed artificial habitats: spatial and temporal patterns of benthic communities in a coral reef environment. Estuar Coast Shelf Sci. 2008;77:491–500.
68. Glasby TM. Development of sessile marine assemblages on fixed versus moving substrata. Mar Ecol Prog Ser. 2001;215 May:37–47.
69. Holloway MG, Connell SD. Why do floating structures create novel habitats for subtidal epibiota? Mar Ecol Prog Ser. 2002;235 September:43–52.
70. Gutperlet R. Habitat dynamics in response to constructional impacts (JadeWeserPort): a biological approach. Dissertation, Bremen; 2016.
71. Gutperlet R, Capperucci RM, Bartholomä A, Kröncke I. Relationships between spatial patterns of macrofauna communities, sediments and hydroacoustic backscatter data in a highly heterogeneous and anthropogenic altered environment. J Sea Res. 2017;121:33–46. https://doi.org/10.1016/j.seares.2017.01.005.
72. Schückel U, Beck M, Kröncke I. Macrofauna communities of tidal channels in Jade Bay (German Wadden Sea): spatial patterns, relationships with environmental characteristics, and comparative aspects. Mar Biodivers. 2015;45:841–55.
73. Singer A, Schückel U, Beck M, Bleich O, Brumsack HJ, Freund H, et al. Small-scale benthos distribution modelling in a North Sea tidal basin in

response to climatic and environmental changes (1970s–2009). Mar Ecol Prog Ser. 2016;551:13–30.
74. Dupont N, Aksnes DL. Centennial changes in water clarity of the baltic sea and the north sea. Estuar Coast Shelf Sci. 2013;131:282–9. https://doi.org/10.1016/j.ecss.2013.08.010.
75. Bartsch I, Tittley I. The rocky intertidal biotopes of Helgoland: present and past. Helgol Mar Res. 2004;58:289–302.
76. Aarup T. Transparency of the North Sea and Baltic Sea—a Secchi depth data mining study. Oceanologia. 2002;44:323–37.
77. El-Sorogy A, Abdel-Wahab M, Ziko A, Shehata W. Impact of some trace metals on bryozoan occurrences, Red Sea coast, Egypt. Indian J Geo-Mar Sci. 2016;45:86–99.
78. Lin H, Wang J, Liu W, Liu K, Zhang S, He X, et al. Fouling community characteristics in subtropical coastal waters of the southwestern East China Sea. Acta Oceanol Sin. 2017;36:70–8.
79. Siddik AA, Al-Sofyani AA, Ba-Akdah MA, Satheesh S. Invertebrate recruitment on artificial substrates in the Red Sea: role of substrate type and orientation. J Mar Biol Assoc UK. 2019;99:741–50.
80. Glasby TM, Connell SD, Holloway MG, Hewitt CL. Nonindigenous biota on artificial structures: could habitat creation facilitate biological invasions? Mar Biol. 2007;151:887–95. https://doi.org/10.1007/s00227-006-0552-5.
81. Witte S, Buschbaum C, van Beusekom JEE, Reise K. Does climatic warming explain why an introduced barnacle finally takes over after a lag of more than 50 years? Biol Invasions. 2010;12:3579–89.
82. Gallagher MC, Arnold M, Kadaub E, Culloty S, O'Riordan RM, McAllen R, et al. Competing barnacle species with a time dependent reproduction rate. Theor Popul Biol. 2020;131:12–24. https://doi.org/10.1016/j.tpb.2019.11.001.
83. Hellmann JJ, Byers JE, Bierwagen BG, Dukes JS. Five potential consequences of climate change for invasive species. Conserv Biol. 2008;22:534–43.
84. Buckeridge JS. Opportunism and the resilience of barnacles (Cirripedia: Thoracica) to environmental change. Integr Zool. 2012;7:137–46.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

CHAPTER 6
Synoptic discussion

CHAPTER 6 - Synoptic discussion

Substrate characteristics in natural and artificial marine environments play an important role as facilitators for settlement and community stability. Understanding of settlement processes, especially in marine artificial environments, is and will remain one of the most challenging tasks to forecast future impacts of climate change such as rising temperature, sea level rise or ocean acidification (Firth et al. 2020; O'Shaughnessy et al. 2020; Airoldi et al. 2021; Strain et al. 2021).

With more than 3 billion people worldwide living in coastal areas, urbanization already has profound impacts on ocean ecosystems (Airoldi and Beck 2007; Bulleri and Chapman 2010; Todd et al. 2019; Airoldi et al. 2021). Regarding a sustainable development in coastal environments worldwide, demands of economy, society and environment need to be taken into account (Airoldi et al. 2021).

Studies conducted within this PhD project can help to improve conservation and protection of natural hard bottom systems and underline the importance to study alternative concrete mixtures and properties for marine artificial constructions. Results will be discussed regarding ecosystem services, settlement processes, material properties, and risk assessments of natural and artificial grounds.

6.1. What kind of ecosystem services are provided by natural coastal systems and how can they be implemented to marine artificial environments?

Nature has an irreplaceable value to humanity, yet it is difficult to define. The concept to grade ecosystems by their services is disputed (Loft and Lux 2010). Services are defined as the ecological characteristics, functions, or processes that directly or indirectly contribute to human wellbeing, that is, the benefits that people derive from functioning ecosystems (Costanza et al. 1998, 2017; MilleniumEcosystemAssesment 2005). Still, the concept of "ecosystem services" contributes to a comprehensive understanding and view of society, economy, ecology, and policy makers on the necessity of the protection of ecosystems.

Costanza et al. (1998) firstly defined ecosystem services as a global perspective. They include gas regulation, climate regulation, disturbance regulation, water regulation, water supply, erosion control and sediment retention, soil formation, nutrient cycling, waste treatment, pollination, biological control, refugia, food production, raw materials, genetic resources, recreation, and cultural services. Coastal ecosystems here contribute to 77% of all global ecosystem services (Costanza et al. 1998).

Human pressures on coastal ecosystems are high; 41% of world global population live within the coastal limit of 100 km of the coastline. Twenty-one of the 33 megacities are found on the coast (Martínez et al. 2007). With the main focus on economic profit environmental consequences on coastal environments have long time been ignored (Lakshmi and Rajagopalan 2000; Obura 2001; Airoldi et al. 2016). Natural habitat loss by a replacement with artificial infrastructure, e.g. concrete armoring has led to chemical, physical, and biotic pollution, as well as extraction of biotic and abiotic functioning (reviewed in: Bulleri and Chapman 2010; Heery et al. 2017; Todd et al. 2019). Studies on the ecological functioning, and impacts of artificial systems have been of minor interest and have received relatively little attention (Southward and Orton 1954; Glasby and Connell 1999; Hawkins et al. 2002; Chapman 2003; Bulleri 2006; Bulleri and Chapman 2010; Assi et al. 2018; Bonnici et al. 2018). However, the present development and degradation of coastal environments, as well as the increased pressures on coastal systems by ongoing climate change (e.g. sea-level rise, ocean acidification) raise the demand for sustainable developments of coastal environments (Firth et al. 2020; O'Shaughnessy et al. 2020; Airoldi et al. 2021; Strain et al. 2021). The awareness of the necessity to protect natural coastal habitats to maintain natural ecosystem services, such as nutrient cycling, water purification and benthic-pelagic coupling (Little and Kitching 1996; Wahl 2009) is increasing. Simultaneously, the idea to copy natural ecosystem services by modifying artificial grounds to "environmentally friendly" habitats can be found in projects worldwide.

One example here is the "billion oyster project". The overall goal of this project is to restore oyster reefs to New York Harbor through public education initiatives (McCann 2019). Oyster reefs provide habitat for hundreds of species, and can to a certain extent protect the city from storm damage by dampening large waves, reducing flooding, and preventing erosion along the shorelines (Burmester and McCann 2019; McCann 2019). This phenomenon is known for intertidal and shallow subtidal habitats e.g. coral reefs that attenuate local currents, dampen wave energy, and accrete and stabilize sediments (Ferrario et al. 2014; Beck et al. 2018).

Nature-based protection projects have many advantages, especially regarding the multi-use of natural habitats services. One habitat can provide for several ecosystem services including nursery grounds for commercial and recreationally valued species, filtration of sediment and pollutants, and carbon storage and sequestration (Airoldi et al. 2021). The social values of these

services are broad and include those reflected in markets, avoided damage costs, maintenance of human health and livelihoods, and cultural and aesthetic sustenance (Airoldi et al. 2021).
In Australia (Sydney Harbor, George River and Sydney coastline, New South Wales) urban waterfront regeneration projects have led to restauration of 1.4 km of intertidal habitats. They were restored by using natural sandstone substrates, rock pool microhabitats, large scale sediment remediation, and establishment of self-sustaining populations of restored crayweed with spread of up to 300 m of linear coastline at various sites (Rhodes and Brinckerhoff 2002; Campbell et al. 2014; Grobman et al. 2017; Strain et al. 2018; Layton et al. 2020).
The potential of implementing natural ecosystem services in artificial grounds is and will be one of the most critical challenges of this century (Airoldi et al. 2021).

6.2. What are the main drivers in benthic community establishment of natural and artificial habitats?

Within this dissertation, two studies (chapter 2, 3) were conducted in the natural protected hard ground environment of the “Helgoländer Steingrund”. They show how non-destructive video sampling methods can help to model the status quo of heterogeneous natural hard ground habitats with low visibility, which is important for the protection of natural grounds. Such models are fundamental for recognizing changes and forecasting the same in future scenarios, especially with regard to environmental or climate change (Guisan and Thuiller 2005; Reiss et al. 2011).
As described, several aspects influence the establishment of benthic communities in natural hard bottom systems. These can be abiotic factors like for instance light conditions, nutrient availability, substrate characteristics, availability of open space, and habitat structure (Little and Kitching 1996; Witman and Dayton 2001; Pehlke and Bartsch 2008; Wahl 2009), but also biotic factors like inter- and intraspecific interaction, larval dispersal and the release of propagules (Benedetti-Cecchi and Cinelli 1996; Bulleri 2005a; Wahl 2009). This already implies that settlement within hard ground habitats is highly dependent on local conditions.
We found that benthic species of the “Helgoländer Steingrund” react especially sensitive to sediment distribution and depth (chapter 2). However, a consideration of environmental parameters by hydrodynamic and hydroacoustic mapping of the “Helgoländer Steindgrund” showed that bryozoan species of *Flustra foliacea* and *Alcyonidium diaphanum* in addition to the sediments also react strongly to current directions (chapter 3). Both chapters show the importance of the interaction between all factors. Depth for instance can also represent a proxy

for light availability (Häder et al. 1998). Sediment distributions can reflect the influence of currents (Bartholomä et al. 2019), which, in turn, are important regarding transport of e.g. nutrients but also larvae within the system and in- and export processes (Benedetti-Cecchi and Cinelli 1996; Bulleri 2005a; Wahl 2009).

A comprehensive understanding of all these factors is a basic requirement concerning differences in artificially influenced environments and habitats. The global increase of coastal infrastructure stands in strong contrast to the protection of natural grounds. This is mainly for the reason that the ecological value of artificial structures have been ignored for long time (Southward and Orton 1954; Glasby and Connell 1999; Hawkins et al. 2002; Chapman 2003; Bulleri 2006; Bulleri and Chapman 2010; Assi et al. 2018; Bonnici et al. 2018). However, there is a growing consensus that artificial systems are different to natural systems in a lot of aspects (Glasby and Connell 1999; Chapman and Bulleri 2003; Gacia et al. 2007; Vaselli et al. 2008; Firth et al. 2014). Nowadays, there is a raise of interest on effects of ocean sprawl as well as on engineering solutions in the marine coastal environment (Perkol-Finkel and Sella 2019; O'Shaughnessy et al. 2020). The question if, and how artificial building material can take influence on settlement and community stability and support local species is still in its infancy. However, settlement of species in artificial grounds is significantly influenced by two main factors, which are also known from settlement in natural grounds: Habitat structure and the chemical composition of the substrate (Firth et al. 2014).

Habitat structure, such as crevices, pits and rock pools not only increase diversity in natural grounds but also urbanized areas can profit from an increase in habitat structure (Cartwright and Williams 2012; Bracewell et al. 2013; Firth et al. 2016; Strain et al. 2021). New approaches that integrate ecological research into the design of consolidated infrastructure provide opportunities to mitigate the environmental impacts of urbanization and recover ecosystem function in waterfronts (Perkol-Finkel and Benayahu 2004; Firth et al. 2014; Dyson and Yocom 2015; Perkol-Finkel and Sella 2015, 2019). Interventions to support local biodiversity can include creating artificial rock pools, pits, and crevices on breakwaters. Projects with so called "habitat enhancement units" in coastal defense schemes, mixtures of stone sizes in gabion baskets, and active gardening of native habitat-forming species, such as threatened canopy-forming algae on coastal defense structures are just some examples of approaches to ecological enhancement in artificial infrastructure (described in Firth et al. 2014).

Results of such experiments are not always clear. The outcome of a current experiment by Strain et al. (2021) challenge the paradigm from Huston (1979) that environmental complexity has universally positive effects on biodiversity. Strain et al. (2021) did a global analysis of complex biodiversity relationships on marine artificial structures. They therefore compared the results of deployment experiments with concrete tiles of different complexity on coastal defense structures at 27 locations all over the globe. Results showed that after 12 months, patch-scale relationships between biodiversity and habitat complexity were not universally positive. Instead, the relationship varied among functional groups and according to local abiotic and biotic conditions. This is just one example, but it shows that the new trend for eco-engineering solutions has many gaps in knowledge and other limitations. Still, the rapid growth of marine infrastructure increases the pressure for quick solutions in marine engineering which results in a high risk of misinterpretation and misuse of the findings of ongoing studies (Firth et al. 2020). Without in-depth studies on the implementation of marine infrastructure such as “habitat enhancement units” and newly built structures, interactions and consequences for adjacent habitats can hardly be foreseen (Firth et al. 2020; Vozzo et al. 2021).

The influence of the chemical composition of building materials is even more difficult to study than artificial habitat complexity and is an additional challenge to the already complex interactions in settlement processes of artificial structures (Coombes et al. 2011; Green et al. 2012). Species settlement and survival differ when the material ingredients differ from their natural habitat origin (Davis et al. 2002; Moreira et al. 2006; Coombes et al. 2011; Green et al. 2012). Local species seem to prefer materials which are similar to their naturally occurring substrate (Perkol-Finkel and Benayahu 2004; Perkol-Finkel and Sella 2014; McCann 2019). To support local species richness, it seems obvious to go for materials, which are closer to natural substrates. However, natural resources are often limited. On top, it takes years to study if static requirements in coastal constructions are still guaranteed with such “natural materials”. With concrete, it is a known fact that it might perform differently than expected when exposed to ocean environments, even if static requirements are calculated in advance (Kosmatka et al. 2008). With respect to the operational life of concrete, which can be 50 to 100 years, reliable exposition experiments take up to ten years (Crow 2008; Kosmatka et al. 2008).

It makes sense, from an ecological perspective, to promote a high biodiversity and support native species in artificially influenced environments. However, a higher biodiversity and settlement also brings higher costs in the prevention and elimination of unwanted succession, or so called biofouling, in areas with a high need of operational infrastructure, i.e. port facilities. Away from marine buildings, problems of biofouling are especially known from the global shipping industry (Howell and Behrends 2006) and from underwater technical devices (Hole 1952; Morales Cruz et al. 2019).

6.3. What is an "environmentally friendly" artificial material?

In the context of a sustainable development in the sea, first attempts were made to create "environmentally friendly" building materials. On the one hand, the term "environmentally friendly", refers to the production process of the material, on the other hand side it implies a positive or at least no negative impact on nature.

One of the most important building material in marine constructions worldwide is concrete (Bijen 1996; Jensen and Glavind 2002; Airoldi and Beck 2007; Kosmatka et al. 2008; Perkol-Finkel and Sella 2019). Concrete accounts for about 70% of coastal and marine construction (Sharma 2009). European coastlines are covered by concrete or asphalt by 22.000 km^2 and artificial surfaces have increased by nearly 1.900 km^2 between 1990 and 2000 alone (Bijen 1996; Airoldi and Beck 2007; Kosmatka et al. 2008; Airoldi et al. 2009). Similar examples exist in other parts of the world – e.g. California (Davis et al. 2002), Australia (Chapman and Bulleri 2003) and Japan (Koike 1996) where hundreds of kilometers have been covered in concrete to variable extents (Airoldi et al. 2009). Concrete coastlines provide poor substrate for marine flora and fauna due to its chemical properties, thus were often referred to as grey environments (Perkol-Finkel and Sella 2019; Airoldi et al. 2021). Ecological enhancement of coastal infrastructure is gaining importance during the last decade (Perkol-Finkel and Sella 2019), especially with regard to consequences of climate change. The phrase "Greening or rather bluing the grey" describes the need of bringing back nature into strongly artificially influenced environments (Perkol-Finkel and Sella 2019; Airoldi et al. 2021). There are several solutions to this task. One is the use of bio-improved materials. Commercial solutions offer "low pH" concrete that potentially support the development of improved marine life (Perkol-Finkel and Sella 2019). However, to date most bio-improved concrete mixes do not comply or fulfill the strict requirements for marine and coastal constructions by the construction industry and policies (Perkol-Finkel and Sella 2019).

A solution for an ecological uplift in urban waterfronts can only be achieved by implantations on marine constructions, that are simple and cost-effective without affecting the operational need of the infrastructure (Perkol-Finkel and Sella 2019). Implementations can be high-performance bio-enhancing concrete elements that significantly enhance the biodiversity, species richness, and life cover (Perkol-Finkel and Sella 2014, 2015; Sella and Perkol Finkel

2015). In this context, the Seattle seawall project needs to be mentioned as the largest eco-engineering project installed to date. It has the goal to yield an improved passage for juvenile salmon and an overall ecological enhancement of the waterfront (Cordell et al. 2017). Microhabitats by textured seawall panels, increased natural daylight illumination by light-penetrating features at the upper boardwalk, and provided additional habitat by marine mattresses at the base of the wall were integrated into the seawall structure (Cordell et al. 2017; Perkol-Finkel and Sella 2019).

However, there is one crucial point missing in almost all studies on bio-enhancing concrete, which is its production process. As already intensively described and discussed in Chapter 3 and 4 concrete production has a high carbon footprint, which results from the calcination process of limestone and the thermal energy demand for Portland cement clinker production (Humphreys and Mahasenan 2002; Crow 2008; Assi et al. 2018). Concrete production is additionally limited by the availability of natural resources commonly used for its aggregates (i.e. sand, gravel, and crushed stones; Crow 2008; bbs 2016; Assi et al. 2018). Chapter 4 and 5 of this dissertation evaluated the use of waste material from steel and copper production, so called iron-slags, in concrete for marine coastal constructions (Schneider et al. 2011; Ehrenberg 2015; bbs 2016). The use of such slags is to date discussed with controversy, as there might be unforeseen problems due to uncontrolled leaching of heavy metals out of pure slag stone (BfG 2008). However, the leaching of heavy metals should be negligible due to the binding capacity of calcium-silicate-hydrates and the very dense pore structure of concrete. Such concrete mixtures do not enhance local biodiversity, but they can be used as alternative building materials in areas with a high need in operational infrastructure.

Within our studies, differences concerning settlement on concrete mixtures with iron-slags were only present at the natural deployment site (chapter 4). Differences in concrete materials showed no negative impact on settlement communities. For the deployment at the anthropogenically influenced harbor site, no such differences were found (chapter 5). Leading to the conclusion that new mixtures should be used in marine artificial constructions. However, there should be no significant difference in succession patterns and establishment of benthic communities between the new concrete mixtures and those which are commonly provided, and notable leakage of environmental pollutants must be excluded. Such alternative concrete mixtures should not negatively influence especially port sites, with an already high impact of environmental pollutants (Hall et al. 1998; Piola and Johnston 2009; Canning-Clode et al. 2011;

Ferrario et al. 2020). This way, at least a more environmentally friendly production would be guaranteed.

6.4. What are the risks of natural and artificial structures regarding invasion by neobiota and which steps can be taken to protect natural and artificial grounds?

Another aspect that has been left out of the discussion so far are the risks of natural and artificial structures regarding biological invasion e.g. by neobiota. Biological invasion occurs when a species enters and spreads into areas beyond its natural range of distribution (Vermeij 1996). The species needs to be transferred to a new region. Invasion can result from natural dispersal, but human-mediated transfers appear to be the prevalent pathway (Ruiz et al. 1997); e.g. shipping, aquaculture, aquarium trade and scientific research are main dispersal mechanisms (Ruiz et al. 2000; Streftaris et al. 2005; Minchin 2007). A literature review on 372 introductions of 271 hard ground species found a prevalence of aquaculture-related introduction in the case of macroalgae, while shipping was the major introduction vector for animals (McQuaid and Arenas 2009). The ecological effects of invasion range from local to global impacts. However, there is no clear link between the invasiveness of a species and its impact (McQuaid and Arenas 2009). The most extreme effects are the extinction of indigenous species leading to a loss of biodiversity, and the reverse, the facilitation of indigenous species, especially through habitat engineering (Ricciardi and Cohen 2007).

Benthic communities in natural hard ground habitats often host large, long-lived sessile species that create stable biogenic habitats for other organisms. Together with stable environmental conditions like in the “Helgoländer Steingrund”, benthic communities of natural hard ground environments establish their own environmental niches over years (de Kluijver 1991; Kühne and Rachor 1996). This can increase the tolerance against invasive competitors. The biotic resistance of natural divers and healthy hard ground communities is usually higher and less susceptible to invasion (Elton 1958). This is an argument for the more complete utilization of available resources, i.e. complementary use of resources by different species (Levine and D’Antonio 1999), referring to the ecological niche concept, especially the resource utilization niche (MacArthur and Levins 1967; Schoener 2009). The resource utilization niche is a precisely formulated description of the natural history of a species: e.g. its habitat, food type, and activity time. Other concepts argue that diverse communities host a higher proportion of suppressive or facilitative species against invasion (Wardle 2001). Meanwhile, the so-called invasion paradox (Fridley et al. 2007) refers to conflicting results in observational surveys and experimental manipulations to both concepts: Large-scale observational studies have reported a positive relationship between native diversity and invader diversity (Stohlgren et al. 1999); in contrast, most of the smaller-scale experimental work support the biotic resistance hypotheses (McQuaid and Arenas 2009). The "Helgoländer Steingrund" does not show any present impairment by neobiota on the natural established communities (Dederer et al. 2015). Neobiota occurring in the "Helgoländer Steingrund" are currently of minor ecological importance.

Natural and artificial disturbances affect to the natural resistance of communities in natural grounds (Mack et al. 2000). Classical ecological theory predict the highest levels of diversity for intermediate frequencies and intensities of disturbance on competing species (intermediate disturbance hypotheses; Connell 1978). However, theoretical as well as empirical studies challenge the predicted diversity disturbance relationship (Fox 2013). Nonetheless, individuals which are removed or distinguished by a disturbance free resources and decrease competition from resident species, which is beneficial for invaders (Shea and Chesson 2002). High levels of disturbance lead to impoverished systems comprising relatively few early successional or opportunistic taxa (Pulsford et al. 2014).

Artificial marine infrastructure are particularly vulnerable to invasion (Glasby et al. 2007). Indications for this are a low diversity of native species, as well as reduced competitive interaction and predation risk on newly raised structures (biotic resistance theory: Elton 1958; enemy release hypotheses: Keane and Crawley 2002). Neobiota often show a higher tolerance to environmental stressors (Dafforn et al. 2009). Filter-feeding invaders, which are often transported on ship hulls, take advantage of being adapted to high shear stress by colonizing open space on moving substrata, for instance floating docks (Dafforn et al. 2009). The raise and rapid growth in coastal infrastructure not only cause drastic changes to natural environments but also provide additional dispersal routes for invasive species, a risk which is hard to calculate. Presently, neobiota can not be excluded from the introduction on artificially raised marine infrastructure, but studies on the biotic resistance of natural habitats against invasion might help to solve this problem. In natural hard ground environments, a healthy habitat seems to be the best protection against invasion. The complete utilization of available resources by a diverse community leads to a natural biotic resistance against invasion of these grounds (Levine and D'Antonio 1999). Local marine hard bottom systems thus need to be protected as a first step. This is important for the preservation of their natural characteristics and biodiversity as well as their biotic resistance. Furthermore, a protection facilitates the opportunity to study these grounds to improve solutions for artificially influenced coastal environments.

Artificial structures, wherever possible should at best mimic local natural habitats. Seawalls, causeways, dikes, piers, locks and breakwaters should be modified with habitat enhancement units, which support native over invasive species, but still maintain the functioning of these structures. “Designing with nature”, a concept known from terrestrial bias, originally coined by Ian McHarg (1992), describes that the way the nature is occupied and modified is best when it is planned and designed with careful regard to both the ecology and the character of the landscape (McHarg 1992, 2017). This concept needs to be adopted into coastal environments by innovative projects, especially in marine coastal infrastructure (Morris et al. 2019; Perkol-Finkel and Sella 2019; Schoonees et al. 2019).

Habitat restoration is an emerging field. Climate-related risks as well as the rising demand for ocean resources enhance pressure on all sectors: ecology, economy and society. Solutions and examples on infrastructural approaches with the goal to actively reverse the degradation and loss of natural ecosystems to reduce pressure are gaining further importance (Airoldi et al. 2021).

6.5. Conclusions and future perspectives

Coastlines globally have already been transformed to sustain human activity for centuries, with consequence of irreversible modification of natural ecosystems and services (Halpern et al. 2008; Knights et al. 2016; O’Shaughnessy et al. 2020). From this perspective, the modification of natural coastlines and hard bottom habitats have existed for decades.

However, a sustainable development in coastal environments, takes into account the growing challenges of climate change, demands for interdisciplinary cooperation. It is high time to rethink the basic understanding of anthropogenic environments not only by ecologists but also by economists and social scientists.

Concluding, the main implications resulting from this PhD-project are

- that natural hard bottom ecosystems need to be protected to conserve their natural ecosystem services wherever possible
- that the design of newly build artificial structures should ideally mimic natural habitats
- that nature-based protection projects on existing structures should be supported if they do not affect the functionality of the structure

- and that aggregates (e.g. iron ore or metallurgical slags) that can be used to lower CO^2-emissons during the production process of concrete and save natural resources should be considered as alternative building materials in marine coastal constructions.

The idea to shape marine constructions and infrastructure by implementing natural ecosystem services to artificial grounds and thereby improve them in an ecological and economic sense is essential to a sustainable development of the coasts. Sustainable management of urban marine environments across the world is becoming an increasingly important issue (Perkol-Finkel and Sella 2019; Todd et al. 2019; Firth et al. 2020; O'Shaughnessy et al. 2020; Airoldi et al. 2021). The preservation and protection of natural habitats is inevitable. However, a changed perspective on artificial structures to see their potential in restoring ecosystem services as well as remaining their functionality is an exciting and interesting view to future research. In addition to research on the impact of complexity on settlement processes in anthropogenic environments, the improvement of material mixtures towards an "environmentally friendly" production process should be the focus of future research. To make sure that materials fulfill the strict requirements given for coastal buildings, and, that innovative ideas are feasible, a close cooperation with the construction industry is advisable

7. References

Airoldi L, Abbiati M, Beck MW, et al (2005) An ecological perspective on the deployment and design of low-crested and other hard coastal defence structures. Coast Eng 52:1073–1087. doi: 10.1016/j.coastaleng.2005.09.007

Airoldi L, Balata D, Beck MW (2008) The Gray Zone: Relationships between habitat loss and marine diversity and their applications in conservation. J Exp Mar Bio Ecol 366:8–15. doi: 10.1016/j.jembe.2008.07.034

Airoldi L, Beck M (2007) Loss, status and trends for coastal marine habitats of Europe. Oceanogr Mar Biol 45:345–405

Airoldi L, Beck MW, Firth LB, et al (2021) Emerging Solutions to Return Nature to the Urban Ocean. Ann Rev Mar Sci 13:445–477. doi: 10.1146/annurev-marine-032020-020015

Airoldi L, Connell SD, Beck MW (2009) The Loss of Natural Habitats and the Addition of Artificial Substrata. In: M. Wahl (ed) Marine Hard Bottom Communities, Ecological Studies 206. Springer-Verlag, Berlin Heidelberg, pp 269–280

Airoldi L, Ponti M, Abbiati M (2016) Conservation challenges in human dominated seascapes: The harbour and coast of Ravenna. Reg Stud Mar Sci 8:308–318. doi: 10.1016/j.rsma.2015.11.003

Arnold CLJ, Gibbons JC (2007) Impervious Surface Coverage: The Emergence of a Key Environmental Indicator. J Am Plan Asscociation 62:243–258. doi: 10.1080/019443696 08975688

Assi L, Carter K, Deaver E (Eddie), et al (2018) Sustainable concrete: Building a greener future. J Clean Prod 198:1641–1651. doi: 10.1016/j.jclepro.2018.07.123

Bacchiocchi F, Airoldi L (2003) Distribution and dynamics of epibiota on hard structures for coastal protection. Estuar Coast Shelf Sci 56:1157–1166. doi: 10.1016/S0272-7714(02) 00322-0

Barnes KB, Morgan JM, Roberge MC (2002) Impervious surfaces and the quality of natural and built environments

Bartholomä A, Capperucci RM, Becker LR, et al (2019) Hydrodynamics and hydroacoustic mapping of a benthic seafloor in a coarse grain habitat of the German Bight. Geo-Marine Lett. doi: 10.1007/s00367-019-00599-7

Bartsch I, Tittley I (2004) The rocky intertidal biotopes of Helgoland: Present and past. Helgol Mar Res 58:289–302. doi: 10.1007/s10152-004-0194-2 bbs (2016) The Demand for Primary and Secondary Raw Materials in the Mineral and Building Materials Industry in Germany up to 2030. 1–5

Beck MW, Losada IJ, Menéndez P, et al (2018) The global flood protection savings provided by coral reefs. Nat Commun 9:. doi: 10.1038/s41467-018-04568-z

Becker LR, Bartholomä A, Singer A, et al (2019) Small-scale distribution modeling of benthic species in a protected natural hard ground area in the German North Sea (Helgoländer Steingrund). Geo-Marine Lett. doi: 10.1007/s00367-019-00598-8

Benedetti-Cecchi L (2000a) Priority effects, taxonomic resolution, and the prediction of variable patterns of colonisation of algae in littoral rock pools. Oecologia 123:265–274. doi: 10.1007/s004420051013

Benedetti-Cecchi L (2000b) Predicting Direct and Indirect Interactions during Succession in a Mid-Littoral Rocky Shore Assemblage. Ecol Monogr 70:45–72

Benedetti-Cecchi L, Cinelli F (1996) Patterns of disturbance and recovery in littoral rock pools: nonhierarchical competition and spatial variability in secondary succession . Mar Ecol Prog Ser 135:145–161

BfG (2008) Umweltaspekte des Einsatzes von industriell hergestellten Wasserbausteinen in Bundeswasserstraßen. Koblenz

BFNReport477 (2018) Die Meeresschutzgebiete in der deutschen ausschließlichen Wirtschaftszone der Nordsee – Beschreibung und Zustandsbewertung – Die Meeres-schutzgebiete in der deutschen ausschließlichen Wirtschaftszone der Nordsee

Bijen J (1996) Blast furnace slag cement for durable marine structures. The Netherlands

Bishop MJ, Mayer-Pinto M, Airoldi L, et al (2017) Effects of ocean sprawl on ecological connectivity: impacts and solutions. J Exp Mar Bio Ecol 492:7–30. doi: 10.1016/j.jembe .2017.01.021

Bonnici L, Borg JA, Evans J, et al (2018) Of Rocks and Hard Places: Comparing Biotic Assemblages on Concrete Jetties versus Natural Rock along a Microtidal Mediterranean Shore. J Coast Res 345:1136–1148. doi: 10.2112/jcoastres-d-17-00046.1

Boos K, Buchholz C, Buchholz F, Gutow L (2004) Bericht über die Zusammensetzung des Helgoländer Makrozoobenthos im Vergleich historischer und aktueller Quellen Klassifizierungsvorschlag nach der WRRL und Empfehlungen zum Monitoring

Bracewell SA, Robinson LA, Firth LB, Knights AM (2013) Predicting Free-Space Occupancy on Novel Artificial Structures by an Invasive Intertidal Barnacle Using a Removal Experiment. PLoS One 8:1–7. doi: 10.1371/journal.pone.0074457

Branch GM, Thompson RC, Crowe TP, et al (2008) Rocky intertidal shores: Prognosis for the future. Aquat Ecosyst Trends Glob Prospect 209–225. doi: 10.1017/CBO978051175179 0.020

Bulleri F (2006) Is it time for urban ecology to include the marine realm? Trends Ecol Evol 21:656–658. doi: 10.1016/j.tree.2006.10.006

Bulleri F (2005a) Role of recruitment in causing differences between intertidal assemblages on seawalls and rocky shores. Mar Ecol Prog Ser 287:53–64. doi: 10.3354/meps287053

Bulleri F (2005b) The introduction of artificial structures on marine soft- and hard-bottoms: Ecological implications of epibiota. Environ Conserv 32:101–102. doi: 10.1017/S0376892 905002183

Bulleri F, Airoldi L (2005) Artificial marine structures facilitate the spread of a non-indigenous green alga, Codium fragile ssp. tomentosoides, in the north Adriatic Sea. J Appl Ecol 42:1063–1072. doi: 10.1111/j.1365-2664.2005.01096.x

Bulleri F, Chapman MG (2010) The introduction of coastal infrastructure as a driver of change in marine environments. J Appl Ecol 47:26–35. doi: 10.1111/j.1365-2664.2009.01751.x

Burmester E, McCann M (2019) New York City oyster monitoring report: 2018

Campbell AH, Marzinelli EM, Vergés A, et al (2014) Towards restoration of missing underwater forests. PLoS One 9:. doi: 10.1371/journal.pone.0084106

Canning-Clode J, Fofonoff P, Riedel GF, et al (2011) The effects of copper pollution on fouling assemblage diversity: A tropical-temperate comparison. PLoS One 6:. doi: 10.1371/jou rnal.pone.0018026

Cartwright SR, Williams GA (2012) Seasonal variation in utilization of biogenic microhabitats by littorinid snails on tropical rocky shores. Mar Biol 159:2323–2332. doi: 10.1007/s 00227-012-2017-3

Chapman MG (2003) Paucity of mobile species on constructed seawalls: Effects of urbanization on biodiversity. Mar Ecol Prog Ser 264:21–29. doi: 10.3354/meps264021

Chapman MG, Bulleri F (2003) Intertidal seawalls - New features of landscape in intertidal environments. Landsc Urban Plan 62:159–172. doi: 10.1016/S0169-2046(02)00148-2

Chapman MG, Clynick BG (2006) Experiments testing the use of waste material in estuaries as habitat for subtidal organisms. J Exp Mar Bio Ecol 338:164–178. doi: 10.1016/j.je mbe.2006.06.018

Clynick BG, Blockley D, Chapman MG (2009) Anthropogenic Changes in Patterns of Diversity on Hard Substrata: an Overview. In: M. Wahl (ed) Marine Hard Bottom Communities, Ecological Studies 206. Springer-Verlag, Berlin Heidelberg, pp 247–256

Connell JH (1978) Diversity in Tropical Rain Forests and Coral Reefs. Science (80-)

199:1203–1310

Connell JH, Slatyer RO (1977) Mechanisms of Succession in Natural Communities and Their Role in Community Stability and Organization. Am Nat 111:1119–1144

Coolen JWP, Bos OG, Glorius S, et al (2015) Reefs, sand and reef-like sand: A comparison of the benthic biodiversity of habitats in the Dutch Borkum Reef Grounds. J Sea Res 103:84–92. doi: 10.1016/j.seares.2015.06.010

Coombes MA, Naylor LA, Thompson RC, et al (2011) Colonization and weathering of engineering materials by marine microorganisms: An SEM study. Earth Surf Process Landforms 36:582–593. doi: 10.1002/esp.2076

Cordell JR, Toft JD, Munsch SH, Goff M (2017) Benches, beaches, and bumps: how habitat monitoring and experimental science can inform urban seawall design. Living Shorelines Sci Manag Nature-Based Coast Prot 419–436

Costanza R, d'Arge R, de Groot R, et al (1998) The value of the world's ecosystem services and natural capital. Ecol Econ 25:3–15. doi: 10.1016/s0921-8009(98)00020-2

Costanza R, de Groot R, Braat L, et al (2017) Twenty years of ecosystem services: How far have we come and how far do we still need to go? Ecosyst Serv 28:1–16. doi: 10.1016/j.ecoser.2017.09.008

Crow MJ (2008) The concrete conundrum. Chem World 62–66

Crowe TP, Thompson RC, Bray S, Hawkins SJ (2000) Impacts of anthropogenic stress on rocky. J Aquat Ecosyst Stress Recover 7:273–297. doi: 10.1023/A

Dafforn KA, Johnston EL, Glasby TM (2009) Shallow moving structures promote marine invader dominance. Biofouling 25:277–287. doi: 10.1080/08927010802710618

Davis AR (2009) The role of mineral, living and artificial substrata in the development of subtidal assamblages. In: Wahl M (ed) Marine Hard Bottom Communities, Ecological Studies 206. Springer Berlin Heidelberg, pp 19–37

Davis JLD, Levin LA, Walther SM (2002) Artificial armored shorelines: Sites for open-coast species in a southern California bay. Mar Biol 140:1249–1262. doi: 10.1007/s00227-002-0779-8

de Kluijver MJ (1991) Sublittoral hard substrate communities off Helgoland. Helgoländer Meeresuntersuchungen 45:317–344. doi: 10.1007/BF02365523

Dederer G, Boos K, Kanstinger P, et al (2015) Tauch-Untersuchung des "Steingrund" bei Helgoland (FFH DE 1714-391) und Konzeptentwicklung eines Tauch-Monitorings für den FFH Lebensraumtyp Riff. Abschlussbericht

Dederer G, Schneider C (2015) Der Helgoländer Steingrund

Diesing M, Coggan R, Vanstaen K (2009) Widespread rocky reef occurrence in the central English Channel and the implications for predictive habitat mapping. Estuar Coast Shelf Sci 83:647–658. doi: 10.1016/j.ecss.2009.05.018

Dijkstra JJ, van der Sloot HA (2013) Dossier of information justifying that concrete qualifies for the potential release of regulated dangerous substances without-further-testing (WFT) by the producer. Petten (The Netherlands)

Duarte CM, Pitt KA, Lucas CH, et al (2013) Is global ocean sprawl a cause of jellyfish blooms? Front Ecol Env 11:91–97. doi: 10.1017/CBO9781107415324.004

Dugan JE, Hubbard DM, Rodil IF, et al (2008) Ecological effects of coastal armoring on sandy beaches. Mar Ecol 29:160–170. doi: 10.1111/j.1439-0485.2008.00231.x

Dyson K, Yocom K (2015) Ecological design for urban waterfronts. Urban Ecosyst 18:189–208. doi: 10.1007/s11252-014-0385-9

EC (1988) Information day on utilization of blast furnace and steelmaking slags. Commission of the European Communities, Liège Belgium

Ehrenberg A (2015) Granulated blast furnace slag - From laboratory into practice. 14th Int Congr Chem Cem

Elton CS (1958) The Ecology of invasion by Animals and Plants. Methuen, London

Feldens P, Schulze I, Papenmeier S, et al (2018) Improved interpretation of marine sedimentary environments using multi-frequency multibeam backscatter data. Geosci 8:. doi: 10.3390/geosciences8060214

Ferrario F, Beck MW, Storlazzi CD, et al (2014) The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nat Commun 5:1–9. doi: 10.1038/ncomms4794

Ferrario J, Gestoso I, Ramalhosa P, et al (2020) Marine fouling communities from artificial and natural habitats: Comparison of resistance to chemical and physical disturbances. Aquat Invasions 15:196–216. doi: 10.3391/AI.2020.15.2.01

Firth LB, Airoldi L, Bulleri F, et al (2020) Greening of grey infrastructure should not be used as a Trojan horse to facilitate coastal development. J Appl Ecol 57:1762–1768. doi: 10.1111/1365-2664.13683

Firth LB, Knights AM, Bridger D, et al (2016) Ocean sprawl: Challenges and opportunities for biodiversity management in a changing world. Oceanogr Mar Biol An Annu Rev 54:193–269. doi: 10.1201/9781315368597

Firth LB, Thompson RC, Bohn K, et al (2014) Between a rock and a hard place: Environmental and engineering considerations when designing coastal defence structures. Coast Eng 87:122–135. doi: 10.1016/j.coastaleng.2013.10.015

Foekema AEM, Sonneveld C, Hoornsman G, Blanco A (2016) Uitloging en effecten van metalen uit staalslakken beoordeeld in mesocosms. Lelystad

Fox JW (2013) The intermediate disturbance hypothesis should be abandoned. Trends Ecol Evol 28:86–92. doi: 10.1016/j.tree.2012.08.014

Franke H-D, Gutow L (2004) Long-term changes in the macrozoobenthos around the rocky island of Helgoland (German Bight, North Sea). Helgol Mar Res 58:303–310. doi: 10.1007/s10152-004-0193-3

Fridley JD, Stachowicz JJ, Naeem DF, et al (2007) The invasion paradox: reconciling pattern and process in species invasion. Ecology 88:3–17

Gacia E, Satta MP, Martin D (2007) Low crested coastal defence structures on the Catalan coast of the Mediterranean Sea: How they compare with natural rocky shores. Sci Mar 71:259–267. doi: 10.3989/scimar.2007.71n2259

Glasby TM, Connell SD (1999) Urban structures as marine habitats. Ambio 28:595–598. doi: 10.2307/4314964

Glasby TM, Connell SD, Holloway MG, Hewitt CL (2007) Nonindigenous biota on artificial structures: Could habitat creation facilitate biological invasions? Mar Biol 151:887–895. doi: 10.1007/s00227-006-0552-5

Gray JS (1997) Marine biodiversity: pattterns, threats and conservation needs. Biodivers Conserv 6:153–175

Green DS, Chapman MG, Blockley DJ (2012) Ecological consequences of the type of rock used in the construction of artificial boulder-fields. Ecol Eng 46:1–10. doi: 10.1016/j.ecoleng.2012.04.030

Grobman YJ, Kozlovsky R, Levy H (2017) A multifunctional computational approach to waterfront design. Archit Sci Rev 60:446–459. doi: 10.1080/00038628.2017.1383229

Guisan A, Thuiller W (2005) Predicting species distribution: offering more than simple habitat models. Ecol Lett 8:993–1009. doi: 10.1111/j.1461-0248.2005.00792.x

Häder D-P, Kumar HD, Smith RC, Worrest RC (1998) Effects on aquatic ecosystems. J Photochem Photobiol 1344:53–68. doi: 10.1111/j.1365-2761.1990.tb00803.x

Hall LW, Scott MC, Killen WD (1998) Ecological risk assessment of copper and cadmium in surface waters of Chesapeake Bay watershed. Environ Toxicol Chem 17:1172–1189.

Halpern BS, Walbridge S, Selkoe KA, et al (2008) A global map of human impact on marine ecosystems. Science (80-) 319:948–952. doi: 10.1126/science.1149345

Hass HC, Mielck F, Fiorentino D, et al (2016) Seafloor monitoring west of Helgoland (German Bight, North Sea) using the acoustic ground discrimination system RoxAnn. Geo-Marine

Lett. doi: 10.1007/s00367-016-0483-1

Hawkins SJ, Allen JR, Ross PM, Genner MJ (2002) Marine and coastal ecosystems. In: Perrow MR, Davy AJ (eds) Handbook of Ecological restoration in Practice. Cambridge University Press, Cambridge, pp 121–148

Hawkins SJ, Southward AJ, Barrett RL (1983) Population structure of Patella vulgata L. during succession on rocky shores in Southwest England. Oceanol Acta 103–107

Heery EC, Bishop MJ, Critchley LP, et al (2017) Identifying the consequences of ocean sprawl for sedimentary habitats. J Exp Mar Bio Ecol 492:31–48. doi: 10.1016/j.jembe.2017.01.020

Hole W (1952) Marine Fouling and its prevention. Annapolis, Maryland

Holler P, Markert E, Bartholomä A, et al (2017) Tools to evaluate seafloor integrity : comparison of multi-device acoustic seafloor classifications for benthic macrofauna-driven patterns in the German Bight , southern North Sea. 93–109. doi: 10.1007/s00367-016-0488-9

Howell D, Behrends B (2006) A review of surface roughness in antifouling coatings illustrating the importance of cutoff length. Biofouling 22:401–410. doi: 10.1080/08927010601035738

Humphreys K, Mahasenan M (2002) Towards a sustainable cement industry. Substudy 8 Climate change. Conches-Geneva (Switzerland)

Huston M (1979) A General Hypothesis of Species Diversity. Am Nat 113:81–101

Jahrespressekonferenz Niedersächsiche Seehäfen (2020) Niedersachsens Seehäfen erzielen mit 53,5 Mio. Tonnen das beste Ergebnis der letzten 10 Jahre. In: by JadeWeserPort. https://www.jadeweserport.de/presse-media/news/4764/. Accessed 19 Mar 2020

Jensen BL, Glavind M (2002) Consider the environment - Why and how. Sustainable concrete production - Proceedings of the Int. Conf. held at the univerity of Dundee, UK, on 9-11 September 2002. p.14

JWP (2020a) Basis-Information JadeWeserPort. Wilhelmshaven

JWP (2020b) Imagebroschüre JadeWeserPort - Das GVZ JadeWeserPort. Wilhelmshaven

Karbe L, Ringelband U (1995) Auswirkungen von in der Elbe im Wasserbau eingesetzter Elektroofenschlacke(sEOS) der Hamburger Stahlwerke auf aquatische Lebensgemeinschaften. Hamburg

Keane RM, Crawley MJ (2002) Exotic plant invasions and the enemy release hypothesis. Trends Ecol Evol 17:164–170. doi: 10.1016/S0169-5347(02)02499-0

Knights AM, Firth LB, Thompson RC, et al (2016) Plymouth — A World Harbour through the ages. Reg Stud Mar Sci 8:297–307. doi: 10.1016/j.rsma.2016.02.002

Koike K (1996) The countermeasures against coastal hazards in Japan. GeoJournal 38:301–312. doi: 10.1007/BF00204722

Kosmatka SH, Kerkhoff B, Panarese WC (2008) Design and Control of Concrete Mixtures, 14th edn.

Kostylev VE, Erlandsson J, Yiu M, Williams GA (2005) The relative importance of habitat complexity and surface area in assessing biodiversity : Fractal application on rocky shores. 2:272–286. doi: 10.1016/j.ecocom.2005.04.002

Krauss J, Bommarco R, Guardiola M, et al (2010) Habitat fragmentation causes immediate and time-delayed biodiversity loss at different trophic levels. Ecol Lett 13:597–605. doi: 10.1111/j.1461-0248.2010.01457.x

Kühne S (1992) Die Fauna des Steingrundes in der Deutschen Bucht - unter besonderer Berücksichtigung der Epifauna. Bonn

Kühne S, Rachor E (1996) The macrofauna of a stony sand area in the German Bight (North Sea). Helgol Mar Res 50:433–452. doi: 10.1007/bf02367159

Lakshmi A, Rajagopalan R (2000) Socio-economic implications of coastal zone degradation and their mitigation: A case study from coastal villages in India. Ocean Coast Manag 43:749–762. doi: 10.1016/S0964-5691(00)00057-0

Lam NWY, Huang R, Chan BKK (2009) Variations in intertidal assemblages and zonation patterns between vertical artificial seawalls and natural rocky shores: A case study from Victoria Harbour, Hong Kong. Zool Stud 48:184–195

Layton C, Coleman MA, Marzinelli EM, et al (2020) Kelp Forest Restoration in Australia. Front Mar Sci 7:. doi: 10.3389/fmars.2020.00074

Levine JM, D'Antonio CM (1999) Nordic Society Oikos Elton Revisited : A Review of Evidence Linking Diversity and Invasibility. Oikos 87:15–26

Little C, Kitching J (1996) The biology of the rocky shores. Oxford University Press, New York

Locher FW (2006) Cement. Düsseldorf

Loft L, Lux A (2010) Ecosystem Services – Eine Einführung

Lukens RR, Selberg C (2004) Guidelines for marine artificial reef materials

MacArthur R, Levins R (1967) The Limiting Similarity , Convergence , and Divergence of Coexisting Species. Am Soc Nat 101:377–385

Mack RN, Simberloff D, Lonsdale MW, et al (2000) Biotic invasions: causes, epodemiology, global consequenses, and control. Ecol Appl 10:689–710. doi: 10.1890/0012-9623(2008) 89[341:iie]2.0.co;2

Martens P (1978) Contribution to the hydrographical structure of the eastern German Bight. Helgoländer Meeresuntersuchungen 31:414–424

Martínez ML, Intralawan A, Vázquez G, et al (2007) The coasts of our world: Ecological, economic and social importance. Ecol Econ 63:254–272. doi: 10.1016/j.ecolecon. 2006.10.022

McCann M (2019) Restoring Oysters to urban waters - Lessons learned and future Opportunities in NY/NJ Harbor. The Nature Conservancy, New York, USA

McGranahan G, Balk D, Anderson B (2007) The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. Environ Urban 19:17–37. doi: 10.1177/0956247807076960

McHarg I (1992) Design with Nature. Jonh Wiley & Sons, New

McHarg I (2017) The Place of Nature in the City of Man. Am Acad Polit Soc Sci 352:1–12

McQuaid CD, Arenas F (2009) Biological Invasions: Insights from Marine Benthic Communities. In: Wahl M (ed) Marine Hard Bottom Communities, Ecological Studies 206. Springer-Verlag, Berlin Heidelberg, pp 309–320

Michaelis R, Hass HC, Mielck F, et al (2019a) Epibenthic assemblages of hard-substrate habitats in the German Bight (south-eastern North Sea) described using drift videos Continental Shelf Research Epibenthic assemblages of hard-substrate habitats in the German Bight (south-eastern North Sea) des. Cont Shelf Res 175:30–41. doi: 10.1016/j.csr.2019.01.011

Michaelis R, Hass HC, Mielck F, et al (2019b) Hard-substrate habitats in the German Bight (South-Eastern North Sea) observed using drift videos. J Sea Res 144:78–84. doi: 10.1016/j.seares.2018.11.009

Mielck F, Bartsch I, Hass HC, et al (2014) Estuarine , Coastal and Shelf Science Predicting spatial kelp abundance in shallow coastal waters using the acoustic ground discrimination system RoxAnn. 143:1–11. doi: 10.1016/j.ecss.2014.03.016

MilleniumEcosystemAssesment (2005) Ecosystems and human well-being: Synthesis. Island Press, Washington, DC

Minchin D (2007) Aquaculture and transport in a changing environment: Overlap and links in the spread of alien biota. Mar Pollut Bull 55:302–313. doi: 10.1016/j.marpolbul.2006.11.017

Morales Cruz C, Weichold O, Kocks H-J (2019) FOULPROTECT zur Problematik des Bewuchses in Meerwasserbauwerken. Beton 162–167

Moreira J, Chapman MG, Underwood AJ (2006) Seawalls do not sustain viable populations of limpets. Mar Ecol Prog Ser 322:179–188. doi: 10.3354/meps322179

Morris R, Heery E, Strain EMA, Alexander KA (2019) Design options, implementation issues and evaluating success of ecologically-engineered shorelines. Oceanogr Mar Biol An Annu Rev 57:169–228

Moschella PS, Abbiati M, Åberg P, et al (2005) Low-crested coastal defence structures as artificial habitats for marine life: Using ecological criteria in design. Coast Eng 52:1053–1071. doi: 10.1016/j.coastaleng.2005.09.014

Mostert E (2003) The European Water Framework Directive and water management research. Phys Chem Earth 28:523–527. doi: 10.1016/S1474-7065(03)00089-5

Nakagawa M, Tsutsumi N, Kato T, Kiso E (2010) Technology of constructing seaweed beds by steel-making slag. Madrid

Neves CS, Rocha RM, Pitombo FB, Roper JJ (2007) Use of artificial substrata by introduced and cryptogenic marine species in Paranaguá Bay, southern Brazil. Biofouling 23:319–330. doi: 10.1080/08927010701399174

Noël LM-LJ, Griffin JN, Moschella PS, et al (2009) Changes in Diversity and Ecosystem Functioning During Succession. In: Wahl M (ed) Marine Hard Bottom Communities, Ecological Studies 206. Springer-Verlag, Berlin Heidelberg, pp 213–223

Nordstrom KF (2014) Living with shore protection structures: A review. Estuar Coast Shelf Sci 150:11–23. doi: 10.1016/j.ecss.2013.11.003

O'Shaughnessy KA, Hawkins SJ, Evans AJ, et al (2020) Design catalogue for eco-engineering of coastal artificial structures: a multifunctional approach for stakeholders and end-users. Urban Ecosyst 23:431–443. doi: 10.1007/s11252-019-00924-z

Obura DO (2001) Kenya. Mar Pollut Bull 42:1264–1278. doi: 10.1016/S0025-326X(01)00241-7

Olenin S, Alemany F, Cardoso AC, et al (2010) Marine Strategy Framework Directive – Task Group 2 Report Non-indigenous species

Papenmeier S, Hass HC (2018) Detection of stones in marine habitats combining simultaneous hydroacoustic surveys. Geosci 8:. doi: 10.3390/geosciences8080279

Pehlke C, Bartsch I (2008) Changes in depth distribution and biomass of sublittoral seaweeds at Helgoland (North Sea) between 1970 and 2005. Clim Res 37:135–147. doi: 10.3354/cr00767

Perkol-Finkel S, Benayahu Y (2004) Community structure of stony and soft corals on vertical unplanned artificial reefs in Eilat (Red Sea): Comparison to natural reefs. Coral Reefs 23:195–205. doi: 10.1007/s00338-004-0384-z

Perkol-Finkel S, Sella I (2015) Harnessing urban coastal infrastructure for ecological enhancement. Proc Inst Civ Eng Marit Eng 168:102–110. doi: 10.1680/jmaen.15.00017

Perkol-Finkel S, Sella I (2014) Ecologically active concrete for coastal and marine infrastructure: innovative matrices and designs. From Sea to Shore - Meet Challenges Sea 1139–1149. doi: 10.1680/fsts597571139

Perkol-Finkel S, Sella I (2019) Blue is the new green: Eco-engineering for climate change. Mar Technol Soc J 53:7–10. doi: 10.4031/MTSJ.53.4.13

Perkol-Finkel S, Zilman G, Sella I, et al (2008) Floating and fixed artificial habitats: Spatial and temporal patterns of benthic communities in a coral reef environment. Estuar Coast Shelf Sci 77:491–500. doi: 10.1016/j.ecss.2007.10.005

Piola RF, Johnston EL (2009) Comparing differential tolerance of native and non-indigenous marine species to metal pollution using novel assay techniques. Environ Pollut 157:2853–2864. doi: 10.1016/j.envpol.2009.04.007

Pratje O (1951) Die Deutung der Steingruende der Nordsee als Endmoraenen. Dtsch Hydrogr Zeitschrift 4.3:106–114

Pulsford SA, Lindenmayer DB, Driscoll DA (2014) A succession of theories: Purging redundancy from disturbance theory. Biol Rev 91:148–167. doi: 10.1111/brv.12163

Reichert K, Buchholz F, Giménez L (2008) Community composition of the rocky intertidal at Helgoland (German Bight, North Sea). Helgol Mar Res 62:357–366. doi: 10.1007/s10152-008-0123-x

Reiss H, Cunze S, König K, et al (2011) Species distribution modelling of marine benthos : a North Sea case study. 442:71–86. doi: 10.3354/meps09391

Rhode S, Schupp P, Markert A, Wehrmann A (2015) Neobiota - Basislinie in niedersächsischen Küstengewässern. Brake-Oldenburg

Rhodes N, Brinckerhoff P (2002) Remediation of Lednez Site, Rhodes and Homebush Bay : environmental impact statement. Australia

Ricciardi A, Cohen J (2007) The invasiveness of an introduced species does not predict its impact. Biol Invasions 9:309–315. doi: 10.1007/s10530-006-9034-4

Rilov G, Benayahu Y (2000) Fish assemblage on natural versus vertical artificial reefs: The rehabilitation perspective. Mar Biol 136:931–942. doi: 10.1007/s002279900250

Ruiz GM, Carlton JT, Grosholz ED, Hines AH (1997) Global invasions of marine and estuarine habitats by non-indigenous species: mechanisms, extent, and consequences. Am Zool 37:621–632. doi: 10.1093/icb/37.6.621

Ruiz GM, Fofonoff P, Carlton JT, et al (2000) Invasion of coastal marine communities in north america: apperent patterns, processes, and biases. Annu Rev Ecol Syst 31:. doi: 10.1002/j.1537-2197.1995.tb11572.x

Russel G, Hawkins SJ, Evans LC, et al (1983) Restoration of a Disused Dock Basin as a Habitat for Marine Benthos and Fish. J Appl Ecol 20:43–58

Santileces B, Bolton J, Meneses I (2009) Marine algal communities. In: Witman J, Roy K (eds) Marine macroecology. University of Chicago Press, Chicago, IL

Schleswig-Holstein Ministerium für Energiewende LU und ländliche R (2016) Managementplan für das Flora-Fauna-Habitat-Gebiet „ DE - 1714-391 Steingrund “. 1–29

Schneider M, Romer M, Tschudin M, Bolio H (2011) Sustainable cement production-present and future. Cem Concr Res 41:642–650. doi: 10.1016/j.cemconres.2011.03.019

Schoener TW (2009) Ecological niche. In: The Princeton Guide to Ecology. pp 72–80

Schoonees T, Gijón Mancheño A, Scheres B, et al (2019) Hard Structures for Coastal Protection, Towards Greener Designs. Estuaries and Coasts 42:1709–1729. doi: 10.1007/s12237-019-00551-z

Schultze K, Janke K, Krüß A, Weidemann W (1990) The macrofauna and macroflora associated with Laminaria digitata and L. hyperborea at the island of Helgoland (German Bight, North Sea). Helgoländer Meeresuntersuchungen 44:39–51. doi: 10.1002/ardp.186818 30330

Schulz HD (1983) Der Steingrund bei Helgoland - Restsediment einer saalezeitlichen Endmoräne. Meyniana 35:43–53

Sella I, Perkol Finkel S (2015) Blue is the new green - Ecological enhancement of concrete based coastal and marine infrastructure. Ecol Eng 84:260–272. doi: 10.1016/j.ecoleng. 2015.09.016

Sharma P (2009) Coastal Zone Management. Global India Publications, New Dehli, India

Shea K, Chesson P (2002) Community ecology theory as a framework for biological invasions. Trends 17:170–176. doi: 10.1109/ICINFA.2010.5512262

Sievers J, Rubel M, Milbradt P (2020) EasyGSH-DB: Bathymetrie (1996-2016). https://doi.org/ 10.48437/02.2020.K2.7000.0002

Sousa W, Connell SD (1992) Grazing and succession in marine algae. In: John D, Hawkins S, Price J (eds) Plant-animal interactions in the marine benthos. Oxford University Press, New York, pp 425–441

Southward AJ, Orton JH (1954) The effects of wave-action on the distribution and numbers of the commoner plants and animals living on the Plymouth breakwater. J Mar Biol Assoc United Kingdom 33:1–19. doi: 10.1017/s0025315400003428

Stocks T (1955) Der Steingrund bei Helgoland. Dtsch Hydrogr Zeitschrift 8:112–118. doi: 10.1007/BF02019797

Stohlgren TJ, Binkley D, Chong GW, et al (1999) Exotic Plant Species Invade Hot Spots of Native Plant Diversity. Ecol Monogr 69:25. doi: 10.2307/2657193

Strain EMA, Heath T, Steinberg PJ, Bishop MJ (2018) Eco-engineering of modified shorelines recovers wrack subsidies. Ecol Engeneering 112:26–33

Strain EMA, Steinberg PD, Vozzo M, et al (2021) A global analysis of complexity–biodiversity relationships on marine artificial structures. Glob Ecol Biogeogr 30:140–153. doi: 10.1111/geb.13202

Streftaris N, Zenetos A, Papathanassiou E (2005) Globalisation in marine ecosystems: The story of non-indigenous marine species across European seas. Oceanogr Mar Biol 43:419–453. doi: 10.1201/9781420037449-10

Svane I, Petersen JK (2001) On the problems of epibioses, fouling and artificial reefs, a review. Mar Ecol 22:169–188. doi: 10.1046/j.1439-0485.2001.01729.x

Taylor RB (1998) Density , biomass and productivity of animals in four subtidal rocky reef habitats : the importance of small mobile invertebrates

Tessler ZD, Vörösmarty CJ, Grossberg M, et al (2015) Profiling risk and sustainability in coastal deltas of the world. Science (80-) 349:638–643

Thompson RC, Crowe TP, Hawkins SJ (2002) Rocky intertidal communities: Past environmental changes, present status and predictions for the next 25 years. Environ Conserv 29:168–191. doi: 10.1017/S0376892902000115

Todd PA, Heery EC, Loke LHL, et al (2019) Towards an urban marine ecology: characterizing the drivers, patterns and processes of marine ecosystems in coastal cities. Oikos 128:1215–1242. doi: 10.1111/oik.05946

Tyrrell MC, Byers JE (2007) Do artificial substrates favor nonindigenous fouling species over native species? J Exp Mar Bio Ecol 342:54–60. doi: 10.1016/j.jembe.2006.10.014

United Nations Envionment Programme (2019) Sand and sustainability: Finding new solutions for environmental governance of global sand resources. Geneva, Switzerland

Vaselli S, Bulleri F, Benedetti-Cecchi L (2008) Hard coastal-defence structures as habitats for native and exotic rocky-bottom species. Mar Environ Res 66:395–403. doi: 10.1016/j.marenvres.2008.06.002

Vermeij GJ (1996) An agenda for invasion biology. Biol Conserv 78:3–9. doi: 10.1016/0006-3207(96)00013-4

Vozzo ML, Mayer-Pinto M, Bishop M j., et al (2021) Making seawalls multifunctional: The positive effects of seeded bivalves and habitat structure on species diversity and filtration rates. Mar Environ Res

Wahl M (1989) Marine epibiosis. I. Fouling and antifouling: some basic aspects. Mar Ecol Prog Ser 58:175–189. doi: 10.3354/meps058175

Wahl M (ed) (2009) Marine Hard Bottom communities. Springer-Verlag, Berlin Heidelberg

Wardle DA (2001) Experimental demonstration that plant diversity reduces invasibility – evidence of a biological mechanism or a consequence of sampling effect ? OIKOS 95:161–170

Wenner EL, Knott DM, Van Dolah RF, Burrell Jr VG (1983) Invertebrate communities associated with hard bottom habitats in the South Atlantic Bight. Estuar Coast Shelf Sci 17:143–158. doi: http://dx.doi.org/10.1016/0272-7714(83)90059-8

Wicke D, Cochrane TA, O’Sullivan AD (2012) Atmospheric deposition and storm induced runoff of heavy metals from different impermeable urban surfaces. J Environ Monit 14:209–216. doi: 10.1039/c1em10643k

Witman J, Dayton P (2001) Rocky subtidal communities. In: Bertness M, Gaines S, Hay M (eds) Marine Community ecology. Sinauer Press, Sunderland, MA, pp 339–366

Acknowledgements

Ich möchte mich an dieser Stelle bei allen Bedanken, die mich bei der Entstehung dieser Arbeit und während meiner Promotionszeit unterstützt haben.

Insbesondere gilt dieser Dank Herrn Prof. Dr. Kai Bischof. Danke für die vielen Stunden, die Geduld und die lehrreichen Gespräche, sowie die moralische Unterstützung nicht nur im Rahmen der Arbeit, sondern auch darüber hinaus. Ich bin froh, einen so tollen und engagierten Doktorvater gefunden zu haben.

Des Weiteren möchte ich mich bei Frau Prof. Dr. Ingrid Kröncke bedanken, die mich seit meiner frühen Studienzeit immer wieder ermutigt hat meinen eigenen Weg zu gehen. Ihre Unterstützung, Ermutigung und Diskussionsbereitschaft ist mir seither eine große Hilfe und ich bin stolz, Sie allzeit unterstützend an meiner Seite zu wissen.

Danke an Herrn Dr. Alexander Bartholomä und Susanne Coers, die mit mir zusammen den Helgoländer Steingrund beprobt und unermüdlich die Auswertung der Daten vorangetrieben haben. Danke auch an Frau Dr. Anja Singer, die mich bei den Modellen unterstützt und beraten hat.

Danke an Herrn Dr. Andreas Ehrenberg und Herrn Dr. Volkert Feldrappe, die meine ausgefallene Idee mit den Betonblöcken seitens des FEhS unterstützt und mir jederzeit mit Rat und Tat zur Seite gestanden haben, um meine Wissenslücken in Ihrem Tätigkeitsfeld zu schließen.

Danke an die Arbeitsgruppe Marine Botanik dafür, dass sie Bremen für mich zu einem so wundervollen Arbeitsplatz gemacht haben. Danke für die unzähligen geselligen Kaffeerunden und all die tollen Aktionen, die über den normalen Arbeitsalltag hinaus gingen. Danke an Frau Dr. Karin Springer für den Crash-Kurs „Algen Bestimmung auf Helgoland“ und für die Unterstützung bei der Auswertung der Blöcke. Danke an Jessica Schiller für den Trip nach Neuseeland. Danke an Frau Britta Meyer-Schlosser für die wundervolle Zeit im Büro und die vielen tollen Gespräche.

Danke auch an die Arbeitsgruppe Meeresbiologie am Senckenberg Institut in Wilhelmshaven, bei der ich mich immer sehr willkommen und aufgehoben fühle und die mich bei meinen Arbeiten immer tatkräftig unterstützt haben. Danke speziell an Maik Wilsenack, Ralf Kuhlmann und Dr. Hermann Neumann.

Danke an die gesamte Intercoast Gruppe. Danke für die einzigartigen Erfahrungen und die vielen schönen Stunden, die ich mit euch verbracht habe.

Ein spezieller Dank geht nach Neuseeland. Ich möchte mich bei Prof. Dr. Conrad Pilditch und Prof. Dr. Christopher Battershill für all die hilfreichen Gespräche und die Unterstützung meiner Arbeit bedanken. Danke an David Culliford für die zahlreichen Tauchgänge. Danke an Bradley Monahan, der mir die schönsten Plätze in seinem Land gezeigt hat und über die Jahre zu einem echten Freund geworden ist.

Danke an Vanessa Köhler, die mir während der ersten Schwangerschaft den Rücken frei gehalten und für mich das regelmäßige Monitoring der Blöcke im JadeWeserPort übernommen hat.

Danke an das Tauchteam des Alfred-Wegener-Instituts auf Helgoland für die Installation und das Monitoring der Blöcke vor Helgoland.

Danke an die Kapitäne und Crew der „Senckenberg“ für alle logistischen Fahrten und für die die Hilfe beim Monitoring im Helgoländer Steingrund.

Danke an die Werkstatt der Uni Bremen, allen voran Herrn Martin Nowak, für das Austüfteln, die Berechnungen und die technische Umsetzung der Rahmengestelle zur Auslagerung der Betonblöcke.

Und zu guter Letzt Danke auch an meine Familie und an all die Freunde, die in den letzten Jahren immer zu mir gestanden und mich unterstützt haben.

Danke an Ester Bertram und Miriam Frank für so manchen sprachlichen Feinschliff und an Lydia Scheschonk für die schönen Teestunden.

Danke an Julia Horn, weil sie einfach immer für mich da ist und mir mit Rat und Tat zur Seite steht. Danke, dass du so oft ohne zu Zögern die Kinderbetreuung für Johann übernommen hast und sogar mit uns zusammen nach Dublin gereist bist.

Danke an meine Schwester Imke. Weil sie für mich die beste Schwester und Tante auf der ganzen Welt ist. Danke an meinen Bruder Hauke und an meine Eltern, die mich ebenfalls immer unterstützt haben.

Vielen Dank an meinen Mann Michael und an meine Kinder Lennard, Johann und Matheo dafür, dass ihr mir jeden Tag ein Lächeln aufs Gesicht zaubert und mir zeigt, wie schön das Leben ist.

Curriculum Vitae

Lydia Ricarda Becker (geb. Kohlmorgen), *22.03.1991 in Hildesheim, Deutschland

Lehrer-Lämpel-Weg 32
28329 Bremen, Germany

lkohlmorgen@marum.de

ORCID iD: 0000-0001-6533-363X

AUSBILDUNG

2/2016 – heute	**Doktorandin des internationalen Nachwuchsforschungsprogramms INTERCOAST** *'Integrated Coastal Zone and Shelf-Sea Research'* *Thesis:* "The ecology of natural vs. artificial hard substrata in marine coastal environments: Substrate characteristics as facilitator of settlement and community stability" *Betreuung:* Prof. Dr. Kai Bischof, University of Bremen, Prof. Dr. Ingrid Kröncke, Senckenberg am Meer, Wilhelmshaven, Prof. Dr. Conrad Pilditch, University of Waikato, Prof. Dr. Chris Battershill, University of Waikato
10/2013 - 11/2015	**Master of Science in Biologie der Carl von Ossietzky Universität Oldenburg** *Abschlussnote*: 1.46 *Thesis*: "Spatial variability of environmental drivers and macrofauna communities in the nearshore area of Spiekeroog island." *Betreuung*: Prof. Dr. Ingrid Kröncke, Senckenberg am Meer, Dr. Ulrike Schückel, lkn Schleswig-Holstein
10/2010 - 08/2013	**Bachelor of Science in Biologie der Julius-Maximilians-Universität Würzburg** *Abschlussnote*: 2.0 *Thesis*: "Temporal changes in the spatial distribution of the macrofauna communities in the sublittoral of the Jade Bay, Germany" *Betreuung*: Prof. Dr. Ingrid Kröncke, Senckenberg am Meer, Dr. Dieter Mahsberg, Julius-Maximilians-Universität Würzburg

PUBLIKATIONEN

Becker L.R., Kröncke I., Ehrenberg A., Feldrappe V., Bischof K., (2021). Benthic community establishment on different concrete mixtures introduced to a German deep-water port. Helgoland Marine Research 75:5
doi.org/10.1186/s10152-021-00550-3

Becker L.R., Ehrenberg A., Feldrappe V., Kröncke I., Bischof K. (2020). The role of artificial material for benthic communities – establishing different concrete materials as hard bottom environments. Marine Environmental Research 161
https://doi.org/10.1016/j.marenvres.2020.105081

Bartholomä A., Capperucci R., **Becker L.R.**, Coers S., Battershill C. (2019) Hydrodynamics and hydroacoustic mapping of a benthic seafloor in a coarse grain habitat of the German Bight. *Geo-Mar Lett.*
https://doi.org/10.1007/s00367-019-00599-7

Becker L.R., Bartholomä A., Singer A., Bischof K., Coers S., Kröncke I. (2019). Small-scale distribution modeling of benthic species in a protected natural hard ground area in the German North Sea (Helgoländer Steingrund). *Geo-Mar Lett.*
https://doi.org/10.1007/s00367-019-00598-8

Kröncke I., **Becker L.R**., Badewien T., Bartholomä A., Schulz A.-C., Zielinski O. (2018). Near- and Offshore Macrofauna Communities and Their Physical Environment in a South-Eastern North Sea Sandy Beach System, *Frontiers in Marine Science* 5:497
DOI:10.3389/fmars.2018.00497