Offshore Wind Power Reef Effects and Reef Fauna Roles

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Publications and patents

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Offshore Wind Power Reef Effects and Reef Fauna Roles

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Publications and patents

Gewidmet meiner Mutter, meinem Vater
und meinen Geschwistern

Before an anchor can be raised it must be let down.
(J. Conrad, The mirror of the sea)

Publications and patents

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ZUSAMMENFASSUNG

Die Deutsche Bucht wird von sandigen und schlickigen Sedimentböden mit ihren typischen Tiergemeinschaften dominiert. Die einzige Felseninsel ist Helgoland. Über die Deutsche Bucht verteilt liegen jedoch mehr als tausend Schiffswracks, deren Tiergemeinschaft bisher unerforscht war. Innerhalb der nächsten dreißig Jahre sollen in der Deutschen Bucht 5000 Windkraftanlagen (WEA) errichtet werden und zur nachhaltigen Energiegewinnung der Bundesrepublik Deutschland beitragen. Bisher sind 12 WEA in Betrieb und 197 befinden sich im Bau. Da bisher keine quantitativen Faunaerfassungen von Wracks und WEA-Fundamenten vorlagen, konnten die Auswirkungen die von den Windkraftfundamenten auf das Ökosystem der Deutschen Bucht ausgehen werden nur vermutet werden.

In der vorliegenden Arbeit wurde die Fauna die an der Forschungsplattform FINO 1 siedeln quantifiziert. Die demersale vagile Megafauna an Schiffswracks wurde ebenfalls quantifiziert und mit der von FINO 1 verglichen. In einem natürlichen Korallenriff wurde das Verhalten eines Fisches untersucht um exemplarisch die Bedeutung einzelner Hartsubstratbewohner für ein komplexes Riffsystem hervorzuheben und um Fragestellungen zur ökologischen Funktion der Bewohner der WEA besser erarbeiten zu können. Gestützt durch die Beobachtungen an FINO 1 und den Schiffswracks wurden technische Geräte konzipiert, mit denen die Besiedlung der Windkraftfundamente verstärkt oder abgeschwächt werden können. Zusätzlich wurde erstmals eine in Korallenriffen zur Riffreparatur verwendete Technik in Nordseewasser erprobt, um damit Offshorefundamente mit zusätzlichen riffartigen Strukturen versehen zu können. Analog zur Besiedlung an FINO 1 wird erwartet, dass sich auf den einzelnen WEA an der Konstruktion haftend 4.300 Kilogramm Biofouling ansammeln werden. Dadurch werden die WEA zu einer Art Hotspots an denen 35-mal mehr Makrozoobenthos-Biomasse vorhanden ist als vor der Errichtung. 5.000 WEA-Fundamente werden den Bestand der Makrozoobenthos-Biomasse der Nordsee um 0,8 % erhöhen. Zusätzlich wird jährlich mindestens etwa die Hälfte dieser Mengen produziert und verlässt die Fundamente. Wie sich diese Biomasseproduktion und -konzentration auf den Energiefluss des Nordseesystems auswirken werden ist noch nicht abzusehen. Sie bedeuten aber, da sich sehr viele Biofouling-Arten filtrierend ernähren, eine gesteigerte Umwandlung organischer Partikel in Makroozoobenthos-Biomasse und somit eine Vergrößerung des Nahrungsangebotes für Beutegreifer wie z. B. Krebse, Fische oder Kegelrobben. Die Windkraftfundamente werden massiv von der Miesmuschel (*Mytilus edulis*) besiedelt werden. In allen Windparks in der Deutschen Bucht zusammen wird so ein Miesmuschelbestand entstehen, der etwa halb so groß sein wird, wie der des gesamten deutschen Wattenmeeres. In dem Miesmuschel-Offshorebestand werden permanent erhebliche Mengen von Muschelschalen produziert, die auf den Meeresboden fallen.

Die daraus resultierende Sedimentveränderung kann dazu führen, dass vermehrt riffartige Strukturen entstehen. Die Miesmuscheln werden eine erhebliche Wassermenge filtrieren, die der Summe der mittleren Abflussmengen aller in die Deutsche Bucht mündenden Flüsse entspricht. Dies kann zu einer deutlichen Verringerung der Schwebstoffmenge in der Nordsee führen - Das Wasser würde dann klarer. Die erhebliche Vergrößerung des Miesmuschelbestandes und die davon ausgehenden Effekte auf das Ökosystem können zusammen als *Mytilusation* der Deutschen Bucht zukünftig beobachtet werden. Mit den Windkraftfundamenten werden erstmals große Mengen felsartiger Flachwasser- und Gezeitenbereiche in die offene Deutsche Bucht eingeführt werden. Dadurch vergrößert sich nicht nur der Bestand der heimischen Arten wie der der Miesmuschel. Auch die Bestandsvergrößerung und Verbreitung exotischer Arten wie die der Pazifischen Auster (*Crassostrea gigas*), die auf Siedlungssubstrat in geringen Wassertiefen angewiesen sind, werden durch diese neuen *Flachwasser-Offshore-Verbreitungszonen* beschleunigt werden. Windkraftfundamente werden von einem ähnlichen Artenspektrum großer Krebse und Fische wie die Schiffswracks besiedelt. Allerdings kommen weniger Tiere an den Windkraftfundamenten vor. 5.000 Windenergieanlagen mit dem Fundamenttyp FINO 1 werden 1 Million Taschenkrebse (*Cancer pagurus*) zu dem Bestand von 2,3 Millionen an den 1.300 Wracks hinzufügen - Auf dem freien Sandboden der Nordsee kommt der Taschenkrebs in sehr geringen Dichten mit rechnerisch weniger als 0,01 Tieren auf Standflächen der Größen von Wracks oder der FINO 1 vor. Der Effekt dieser Bestandsvergrößerung ist schwer abzusehen. Wracks bieten geeignete Habitate für den im Bestand bedrohten Europäischen Hummer (*Homarus gammarus*). Die Windkraftfundamente bieten weniger Verstecke für den höhlenliebenden Europäischen Hummer und es ist noch offen, ob die zukünftigen Windparks zu dessen Verbreitung beitragen werden, da an den bestehenden Fundamenten bisher kein Hummer entdeckt wurde. Freilandbeobachtungen des Borstenzahndoktorfischs (*Ctenochaetus striatus*) in Indo-Pazifischen Korallenriffen zeigten, dass er als *Rifffeger* 18% der kontinuierlichen Sedimentablagerungen entfernt. Dadurch und durch das *Abraspeln von Korallenkalk* erfüllt er zwei wichtige ökologische Funktionen. Zukünftig Untersuchungen sollten zeigen, inwiefern die Tierarten wie z.B. der Taschenkrebs, von den Windkraftfundamenten profitieren, und wie sie die übrige Faunagemeinschaft und die des Fundamentumfeldes beeinflussen. Ähnlich wie im Fall des Borstenzahndoktorfisches empfiehlt es sich hier, vor Ort Verhaltensbeobachtungen durchzuführen, da Bestandserfassungen und Gemeinschaftsanalysen nur begrenzte Rückschlüsse auf die Wechselwirkungen der Arten mit Ihrem Umfeld gestatten. Die zukünftige Untersuchung der Fundamentfauna und die technische Inspektion der Bauwerke können mit einer an einem neu entwickelten *Geräteträger* montierten Kamera von der Wasseroberfläche aus unterstützt werden. Die Windkraftfundamente können mit technischen

Maßnahmen so gestaltet werden, dass sich mehr Hartbodenarten ansiedeln. Zur kommerziellen Nutzung der „Rifftiere“ wurden Fallen entwickelt, die auch als Habitat für die Zielarten dienen. Zur Platzierung dieser *Habitaternter* im direkten Nahbereich der Fundamente kann ebenfalls der *Geräteträger* eingesetzt werden. Mit einer einfachen *Netzsperre* kann der Boden in den Windparks und an den Anlagen vor Grundnetzschleppfischerei geschützt werden. Eine Minimierung der Effekte der Windkraftfundamente auf das bestehende Ökosystem kann am wirkungsvollsten durch die Verhinderung des Biofoulings erreicht werden. Zu dieser ökologischen *Passivierung der Fundamente* kann eine *elektrochemische Antifoulingtechnik* eingesetzt werden. Zusätzlich sollte das Fundament so gestaltet werden, dass möglichst wenige konstruktionsbedingte Höhlen und verstecke für große Fische und Krebse vorhanden sind. Für diese Bedeckung kann ein seminatürliches karbonatisches Riffmaterial eingesetzt werden dessen Herstellung in Nordseewasser erfolgreich getestet wurde. Ob es gewünscht wird Fundamente zu *aktivieren* oder zu *passivieren*, ob die Riffeffekte positiv, negativ oder als unbedeutend zu bewerten werden, hängt von dem Blickwinkel des Betrachters ab.

Die quantitativen Daten zeigen, dass tausende Windenergiefundamente messbare Veränderungen des Ökosystems Nordsee zur Folge haben werden. Das tatsächliche Ausmaß dieser Veränderungen sollte mit der fortschreitenden Errichtung der Windparks langfristig wissenschaftlich weiter begleitet werden, um eine rechtzeitige

Steuerung der Effekte zu erlauben.

SUMMARY

The German Bight is dominated by sandy and muddy sediments whilst rocky terrain is rare. The only rocky intertidal is present on the island of Helgoland. However, thousands of ship wrecks are distributed in the German Bight. Such wrecks have only recently become part of investigations into species settlement and the underwater ecosystem. During the next 30 years 5000 wind power foundations are planned to be built in the German Bight as part of the German renewable energy program. Twelve foundations are completed and 197 in progress. The knowledge of the impact such constructions have on the German Bight underwater ecosystem is poor. Prognoses are the only form of estimation. The present study was conducted at the research platform FINO 1 and different ship wrecks which are located in the German Bight. Consistent with FINO1 it is expected that 4,300 kg biofouling will inhabit the wind power foundations. This means that the foundations can be interpreted as hotspots with 35 times more macrozoobenthos biomass than there was prior to the construction. The 5,000 wind power foundations mean an increased biomass of 0.8% for the entire German Bight. In addition, at least half of this biomasses will be produced at the foundations and leave the foundations on a yearly basis. What impact the increased production and high biomass concentration will have on the energy flow in the North Sea remains unknown. Other scenarios are more obvious. Changes include the increased food supply for species, such as crabs, fish and seals as well as the proliferation of the mussel *Mytilus edulis*. The number of *Mytilus edulis* inhabiting all wind power foundations will be the same as half of the amount of mussels currently living in German Wadden Sea. The mussel shell litter fall may lead to changing sediments and additional reefs. The mussels will also add to the significant increase of the filtration of sea water with the possible result of clearer waters. The mussels are seen as the main contributor to changes taking place in the German Bight following the introduction of wind power foundations. The increased number of mussels as well as the effects such increasing numbers of *Mytilus edulis* on the ecosystem will be titled *Mytilusation*. The introduction of wind power foundations into the German Bight will also mean an increase in rocky shallow waters and intertidal zones in the German Bight. The result will be a proliferation and the development of exotic species, such as the pacific oyster (*Crassostrea gigas*) which relies on low water depths. Whilst wind power foundations will be colonized by a similar range of species, they will be inhabited by a smaller number than ship wrecks. 2.0 Million brown crabs (*Cancer pagurus*) which will inhabit the wind power foundations will be added to the already existing number of 2.3 Million living at the 1,300 ship wrecks. Ship wrecks also provide an ideal environment for the endangered European lobster (*Homarus gammarus*). No lobsters were sighted at the already existing wind power foundations and it is yet to be seen whether the foundations will add to the spread of this species. Behaviour observations of the striped bristletooth surgeonfish (*Ctenochaetus striatus*) in the Indo-Pacific

Coral Reefs revealed that he swept 18% of the sediment. *Reef Sweeping* as well as the bioerosion entail two major ecological functions of that fish. *Ctenochaetus striatus* therefore plays a major role in the preservation of coral reefs. Ongoing studies will show how certain species, such as the edible crab, which inhabit the new wind power foundations, influence the faunal community and surrounding areas. As with the striped bristletooth surgeonfish it is recommended to use behavioural investigations as fauna quantifications and community analyses do not provide satisfying results regarding the relationship between the various species and their environment. As part of the present study, techniques and materials were developed to activate or minimise certain functions of the wind power foundations, i.e., to increase or decrease the development of species at such foundations. Individual techniques are described in detail. Whether to activate wind power foundations or to make them passive, whether the reef effects are positive, negative or neither depends on the interpretation of the individual.

The qualitative data reveals that the thousands of future wind power foundations will indeed transform the German North Sea ecosystem. The on-going scientific research is necessary to analyse the extent of such changes and to lead the pathway of renewable energy into the right direction.

GENERAL INTRODUCTION

The increased demand for renewable energy has stimulated the development of wind turbines at sea on a large scale in many countries. The ecological consequences of the introduction of turbines into the marine environment are not well understood and research is only at its very beginning.

Offshore wind turbines impact the ecosystem beginning with the phase of construction, through the period of operation to their decommission. The present considerations focus on the period of operation which will last up to 25 years per turbine and has a large impact on the ecosystem (Petersen and Malm, 2006). Offshore wind turbines are large, fast rotating objects above the sea surface believed to affect birds (Hüppop et al., 2006; Masden et al., 2009;) and bats (Ahlén et al., 2007). Below the water surface the huge artificial constructions may equally affect marine life. For example, sound emissions of the turbines could deter or even injure marine mammals and fish (Wahlberg and Westerberg, 2005; Madsen et al., 2006; Kikuchi, 2010;) and change topography as well as granulometry (Wilson et al., 2010). In the German Exclusive Economic Zone (EEZ) alone, about 5,000 single wind turbines are planned for construction within the next two decades (BMU, 2010; IEA, 2008) (Fig. 1). To date, 22 wind farms with 1540 turbines have been already permitted (BSH, 2012). The first German North Sea wind farm *alpha ventus* (12 turbines) has been operating since 2009 and three other wind farms with a total of 197 turbines are under construction (RAVE, 2012).

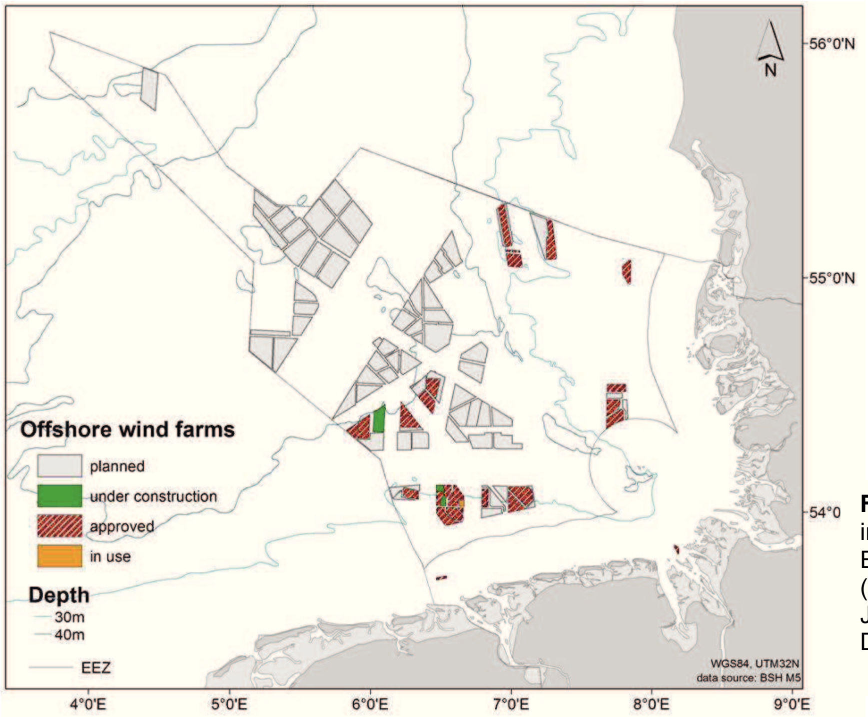

Fig. 1. Wind farm projects inside the German Exclusive Economic Zone (EEZ) of the North Sea. January 2012. Map: BSH/ Dannheim.

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Artificial habitats such as the wind power foundations are being defined as secondary artificial reefs (structures not erected to function as artificial reefs, which deliberately mimic some characteristics of natural reefs (Bohnsack and Sutherland, 1985; Pickering et al., 1998; Thierry, 1988)). The impact of the constructions on the underwater ecosystem is commonly referred to as reef effects and considered to have major impact on the environment (Lindeboom et al., 2011). The foundations will be colonised by an epifauna community and algae (biofouling) as well as by a vagile demersal megafauna (e. g., crabs and fish) whose biomass and species diversity are significantly higher and different to those of the autochthonous soft bottom (Wolfson et al., 1979; Whomersley and Picken, 2003; Lindeboom et al., 2011). In the offshore German Bight, the faunal community of neither wind power foundations nor other artificial habitats have been described quantitatively. Hence it remains difficult to predict the reef effects of wind turbine foundations in this area today.

As part of the present study, a construction named FINO 1 which is similar to wind power foundations and ship wrecks, was used to forecast the biological impact of the future expansion of wind power constructions. The general assumption is that the reef effects of wind power foundations is based on their suitability for biofouling and the biomass quantities produced at these artificial structures (e. g., Kerckhof et al., 2010, Lindeboom et al., 2011).

However, in order to estimate the ecological impact of artificial reefs, behaviour and functions of colonizing species must also be taken into account. For example, calcifying species contribute to secondary hard substrate production whilst gelatinous ones do not. Some benthic fish need hard substrate to rest on, while other demersal species only feed on the epifauna. This means that different species benefit in various ways from the artificial habitats and interact in different ways with the artificial reefs. Offshore *in situ* behaviour investigations are at their very beginning. In contrast, research in highly complex and sensitive tropical coral reef biotopes is much more advanced and may serve as a proxy for species' behaviour and functions in temperate offshore hard substrate habitats. Lessons learned from the highly complex coral reefs may help us to focus on relevant behaviour and functions at less complex artificial reefs. In tropical reefs many species, conspicuous and inconspicuous, interact with the habitat and contribute to its development and resilience (e. g., Schuhmacher, 1988; Bellwood et al., 2004; Green and Bellwood, 2009). Research regularly reveals new functions of reef organisms and provides new inputs into the study of both natural and artificial reefs. As part of my thesis I investigated how a well-studied reef fish contributes in a hitherto unknown way to the sediment balance of a coral reef. I further discuss possible analogies in artificial reefs and identify North Sea species for targeted reef research. A judgement whether the reef effects of wind power foundations are positive or negative for the North Sea ecosystem is not the focus of this scientific ecological investigation. However, there may be particular situations where reef effects need to be decreased to minimise the interaction with the autochthonous faunal community (e. g., reduction of biofouling). In other instances there may be a need to make the foundations more reef-like and attractive for hard bottom organisms (e. g., for endangered species) in order to promote the stocks of certain species (Wilson and Elliot, 2009; Wilson et al., 2010). I introduced a new antifouling technique for marine constructions. Furthermore I tested the production of calcareous reef material which may be used to make artificial North Sea constructions more reef-like. The material in artificial (secondary) North Sea reefs may be considered environmentally benign as it was tested in sensitive tropical coral reefs (Schuhmacher, 1996, 1999; van Treeck and Schuhmacher 1999).

The outlined reef-related topics and hypotheses are addressed in the following chapters in detail.

Reefs, artificial reefs and reef effects

In a biological sense, reefs are self-growing structures which follow sea level fluctuations to a certain degree and withstand breakers. This particularly applies to the highly structured buildings of stone corals and calcareous algae in shallow waters (Schuhmacher, 1988, 1996, 2010) (Fig. 2). Colourful tropical coral reefs are well known as they have been attracting tourists and marine scientist for many decades, but are not fully understood scientifically. Structures similar to these tropical coral reefs were recently detected worldwide outside of shallow tropical waters. Most of these are hidden on deeper sea floors - the so-called cold water reefs (Roberts et al., 2006). The European Council Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora (FFH Directive 92/43/EEC, 1992) characterises reefs in a broader sense as permanently overflowed natural mineral hard-substrates within sandy or gravel sea floor. Biogenic solid substrates such as colonies of tube building Polychaeta (*Sabellaria* spp.) and banks of the blue mussel (*Mytilus edulis*) are also defined as reefs. All reefs have their own characteristic natural community that differs significantly from that of soft bottom (e. g., Caspers, 1950; Roberts et al., 2006). In temperate and tropical waters reefs represent hot spots of species diversity. They fulfil many distinct ecological functions. For example, reefs provide spawning sites and shelter for fish, solid attachment sites for sessile organisms, and food for invertebrates, fish, birds and mammals. Moreover, they function as natural coast protectors and as important food sources for humans. Unfortunately all of these reef types and their functions are endangered due to circumstances created by humans (e. g., fishing, ocean warming and sediment runoff from land) (Bellwood et al., 2004; Wilkilson, 2004; Roberts at al., 2006; Schuhmacher, 2010). For many centuries man-made structures of different size and material (e. g. concrete, steel, bamboo, fibre glass, rubber and coal ash) have been introduced into the marine system (Fig. 3). These artificial reefs are, for example, used to increase fishery yield and production in Japan or for recreational diving in the USA, and to prevent trawling in Europe (Jensen et al., 2000; Baine, 2001; Svane and Petersen, 2001; Bortone et al., 2011). Such artificial habitats usually differ significantly from natural reefs with respect to material, topography, their inability to grow, and thus show different faunal communities. Hence the term reef should be used with caution since such artificial structures do not substitute natural reefs (Schuhmacher, 1994; Perkol- Finkel et al., 2006). Subsequently, Seaman and Jensen (2000) defined artificial reefs as structures composed of one or more objects of natural or human origin deployed purposefully on the seafloor to influence physical, biological, or socio-economic processes related to living marine resources. The European Artificial Reef Research Network (EARRN) and the OSPAR commission define an artificial reef as a submerged structure placed on the seabed deliberately in order to mimic some characteristics of a natural reef (Jackson and Miller, 2009; Jensen, 1998).

However, for any comprehensive evaluation of the use of artificial reefs it should be considered that these “reefs” remain artefacts in the ecosystem and that some waste dumping and industrial constructions could also be masked by the term reef. Nevertheless, all man-made marine structures also act as habitats. Structures employed for other primary purpose such as oil and gas platforms, breakwaters and ship wrecks (Fig. 4) can be considered as secondary artificial reefs (Pickering et al. 1998; Thierry, 1988; Bohnsack and Sutherland, 1985). The biological processes which take place at the constructions as well as their impact on the local ecosystem, such as increased biofouling production, redistribution and production of vagile megafauna, are summarised as reef effects (Langhammer et al., 2009; Petersen and Malm, 2006). Due to the increasing utilization of wind power, thousands of large secondary artificial reefs will be introduced into the North Sea (Fig. 5 and 6). At the rocky island of Helgoland in the German Bight single concrete tetrapods (the same as used for coastal protection) are employed as artificial reefs and have been investigated over the past years. Amongst other outcomes it was found that they attract fish (Fischer, not published). However, there remains a lack of research into the ecological consequences of a large-scale introduction of windmill foundations into marine areas world-wide. Current research into operating wind power farms exists from the first operating years from Denmark, Belgium, The Netherlands and Sweden (Leonhard and Pedersen, 2006; Degraer and Brabant, 2009; Kerckhof et al., 2010; Lindeboom et al., 2011).

In Germany, results exist only for the first two years of settlement at a construction that is comparable to windmill foundations (Joschko et al., 2008; Orejas et al. 2005). In order to understand and manage reef effects, a whole-ecosystem approach on a local scale is necessary and must incorporate studies of all aspects of reef ecology including long term structural and functional variables (Svane and Petersen, 2001). In particular in the German Bight there is a strong demand for more research.

The kind of artificial material used for the secondary reefs also needs to be addressed. The wind turbines currently planned will be built of steel and concrete. For scour protection the employment of bolder fields or synthetic textiles (sandbags and foils) are planned to be placed around the piles on the sea floor. Especially the scour protection materials, once placed in the sea, are difficult to remove. It is assumed that the construction of more reef-like offshore foundations using more natural material is very time and money consuming.

However, there may be an alternative. A semi-natural calcareous reef material could be used to shape scour protections as well as habitat for reef organisms. By the mineral accretion technology (MAT, also called electrochemical accretion technology EAT) three-dimensional structures can be generated (Fig. 7). By electrochemical deposition calcium and magnesium ions precipitate on a cathode. The accreted solid material consists only of marine minerals and is comparable to thalassogenic coral rock. It can be produced on site. The technique has been tested, to some extent, for habitat creation and reef restoration in Mediterranean and Pacific waters (Hilbertz, 1979; Meyer and Schuhmacher, 1992; Eisinger et al., 1998; van Treeck and Schuhmacher, 1999, 1997; Eisinger, 2005; Coleman, 2012). This material could be used for two purposes at offshore windmill foundations. Firstly, environmentally benign scour protections could be created and secondly, structures (e. g., crevices for fish and lobster) could be added in order to increase the reef character of the foundations if designated. As an advantage, the MAT material could spontaneously be dissolved if necessary. However, a previous test in brackish North Sea waters failed (Schuhmacher, pers. communication). It remains to be tested if the production performs in other marine North Sea waters and if the technique is appropriate to shape offshore foundations.

Fig. 2. Natural coral reef structure at 10 m depth, Red Sea, South Sinai (photo: Krone).

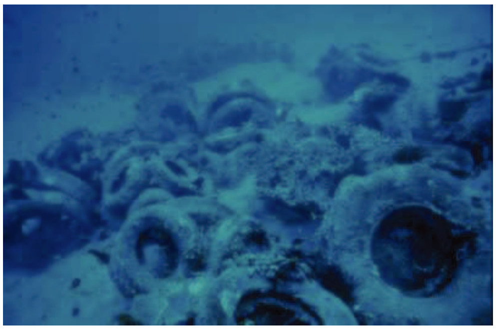

Fig. 3. Artificial “tyre reef” (Dumaquete, Philippines) (photo: Schuhmacher).

Fig. 4. Ship wreck “Umbria” (Red Sea, Port Sudan) (photo: Schuhmacher).

Fig. 5. The operating offshore wind farm *alpha ventus* 20 nautical miles northerly of the island of Borkum (North Sea, German Bight). Jacket constructions: research platform FINO 1 (right side) and wind power foundation (left side). Also other foundations are employed (the piles in the background) (photo: Krone).

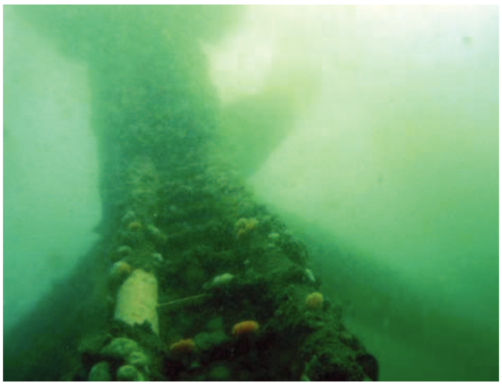

Fig. 6. the upper part of the offshore jacket foundation FINO1 (North Sea), densely colonized by epifauna (biofouling). (photo: Krone).

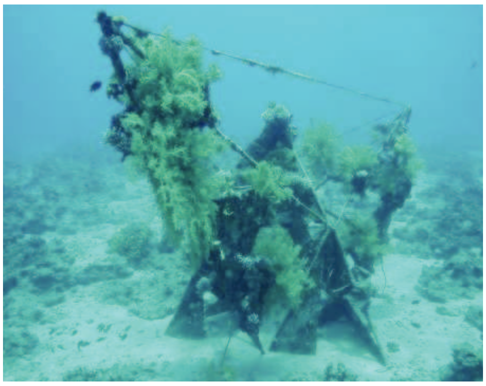

Fig. 7. An artificial coral reef, built with EAT material (Golf of Aqaba, Egypt) (photo: Schuhmacher).

Reef effect - Biofouling

The numerous wind power foundations will significantly add to the limited amount of hard substrate habitat within the soft bottom dominated North Sea and implicate major reef effects on the marine ecosystems (Lindeboom et al. 2011). Many effects will be based on the settlement of macrozoo-epibenthic organisms (also referred to as biofouling when attached to artificial structures) on the allochthonous artificial solid surface (Fig. 8). Epibenthos communities differ between artificial habitats, natural hard substrata (Andersson et al., 2009; People, 2006; Wilhelmsson and Malm, 2008) and soft bottoms (Barros et al., 2001; Fabi et al., 2002; Langlois et al., 2006; Langhammer, 2010). The artificial constructions may favour the settlement and reproduction of certain taxa (e.g. Cnidaria and hard bottom inhabiting mussels; Richardson et al. 2009) which require, to some degree, to be attached to solid substrates during certain phases of their life cycle and which were so far substrate-limited.

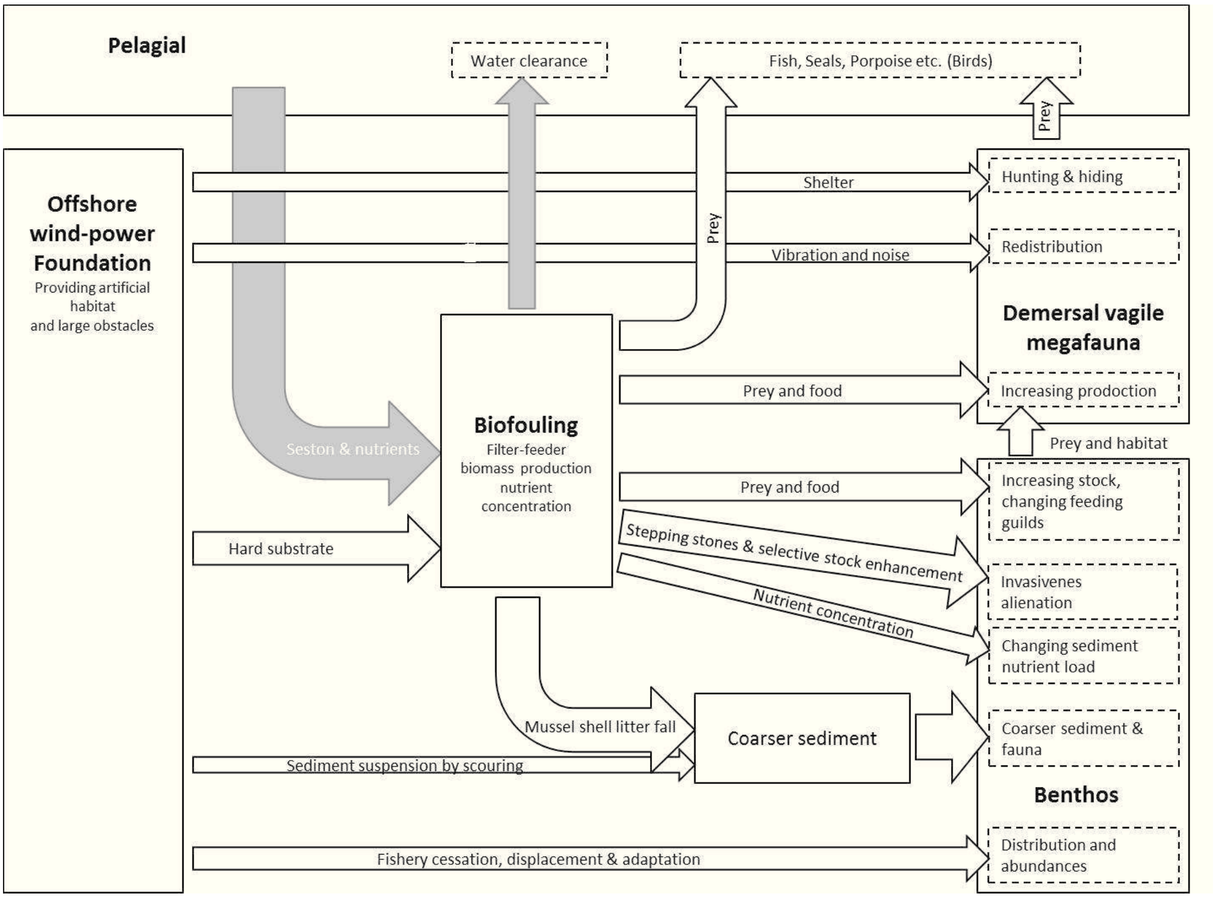

Fig. 8. Offshore wind power reef effects on benthic and demersal fauna and interactions with the pelagial during the operational phase. The width of the arrows indicates the importance as assumed by the author. Biofouling is of major importance.

The increasing number of filter-feeders may affect seston and nutrient fluxes between the pelagial and the benthal, and can alter the biomass of phytoplankton and planktonic larvae (Winter, 1973; Clausen and Riisgård, 1996; Wilhelmsson and Malm, 2008). Mussels also provide secondary hard substrate attractive for additional epifauna (Norling and Kautsky, 2007). Continuous mussel production and litter fall may lead to coarser sediment. Wind park areas are believed to be more suitable for sessile or hemi-sessile reef organisms as these need solid attachment spots such as Anthozoa or prefer solid bottom such as many crabs (Wolfson et al., 1979; Freire and Gonzálesz-Gurriarán, 1995; Riis and Dolmer, 2003).

Biomass aggregations on the foot of the structures cause changes in local benthic biomass, feeding guilds and nutrient sediment character and are an important, highly diverse prey source for a variety of pelagic and benthic predators (Wolfson et al., 1979; Wilhelmsson et al., 2006; Freire and González-Gurriarán, 1995; Page et al., 1999). At the same time the distribution range and abundance of hard substrate species – indigenous and exotic - may be artificially enlarged by the enhanced connectivity of isolated reef sites (Connell, 2001; Bulleri and Airoldi 2005; Glasby et al., 2007; Bulleri and Chapman 2010; Zintzen and Massin, 2010). An alienation or invasiveness is the consequence (Kerkhoff, not published). The potential impacts are of concern and the resulting ecological processes are not well enough understood (Gill, 2005; Inger et al., 2009). So far, biofouling research outcomes are available from oil and gas fields (Kingsbury, 1981; Whomersley and Picken; 2003) in the North Sea and from ship wrecks in Dutch waters (Zintzen; 2006, 2008a, 2008b, Zintzen and Massin, 2010). Young wind power projects inside the Belgian, Dutch and Danish North Sea have also been investigated from the beginning of 2002 with first results emerging (Lindeboom et al., 2011; Degraer and Brabant, 2009; Leonhard and Pedersen, 2006). Outcomes show that species composition, depth and zoning of the biofouling are dependent on the constructions' design and material, the dimension in the water column, distance from shore, the wind regime, time of exposure, as well as on water depth. Therefore the function of wind power foundations as secondary artificial reefs and their reef effects vary with local environmental factors (Kingsbury, 1981; Butler and Connolly, 1999; Whomersley and Picken, 2003; Gill, 2005; People, 2006; Zintzen et al., 2008a; Andersson et al., 2010) and must be investigated for each liocality. In German waters, the only offshore foundation investigated during the first two years after construction is the FINO 1 research platform, built in 2003 next to the wind park *alpha ventus* (built in 2008) (Joschko et al., 2008; Orejas et al., 2005). This means that artificial offshore constructions inside the German Bight have not adequately been studied with respect to biofouling and how it will affect the ecosystem. In light of the extensive future German wind power plans, there is a strong demand for the assessment of ecological impacts and thus explicitly for further biofouling investigation.

Reef effect – Vagile demersal megafauna

Similar to wind power foundations in several other European locations, the ones in the German Bight will provide numerous hard substrate habitats not only suitable for biofouling but also for larger **v**agile **d**emersal **m**egafauna (> 1 cm, further referred to as VDM), such as pout (*Trisopterus luscus*) and brown crab (*Cancer pagurus*) (Langhammer et al., 2009; Reubens et al. 2011;). The species may be attracted by the topography of structure as well as the biofouling food supply (Pickerring and Whitmarsh, 1997). Attraction, production and redistribution of VDM will happen at the same time depending on the species' autecology (Bohnsack, 1989), and this will probably change the faunal community in areas of wind power farms. The redistribution of large VDM, including predators will in turn alter both the local prey community and assemblages of those species that feed on VDM. Today no VDM data are available for German wind farms or other artificial offshore North Sea habitats and therefore all considerations on redistribution and its consequences remain speculative.

However, the bottom of the North Sea was loaded with numerous secondary artificial reefs long before the construction of wind turbines. More than 1,000 ship wrecks have been registered in coastal and offshore waters in the German EEZ. These artificial habitats already interrupt the otherwise homogeneous sandy North Sea bottom (Fig. 9). Massine et al. (2002) provided an overview of the Belgian wreck fauna. Leewis et al. (2000) captured the mobile megafauna at 21 wrecks and the underwater construction of a production platform in Dutch offshore waters. Large, mobile crustaceans and fish often dominate subtidal wreck assemblages in terms of biomass (Leewis et al., 2000; Arena et al., 2007). The VDM represent a functionally important group including numerous predators that potentially control the biofouling (Freire and González-Gurriarán, 1995; Baum and Worm, 2009; McCauley et al., 2010). Furthermore, VDM species are fast and sensitive indicators for habitat quality as they can actively abandon unfavourable habitats (Reiss et al., 2009). There are also certain VDM reef species such as *C. pagurus* and the velvet crab (*Necora puber*) that are commercially important. The wrecks as well as other artificial habitats are expected to increase the moving range and the stocks of certain nomadic VDM reef species (Bennet and Brown, 1983).

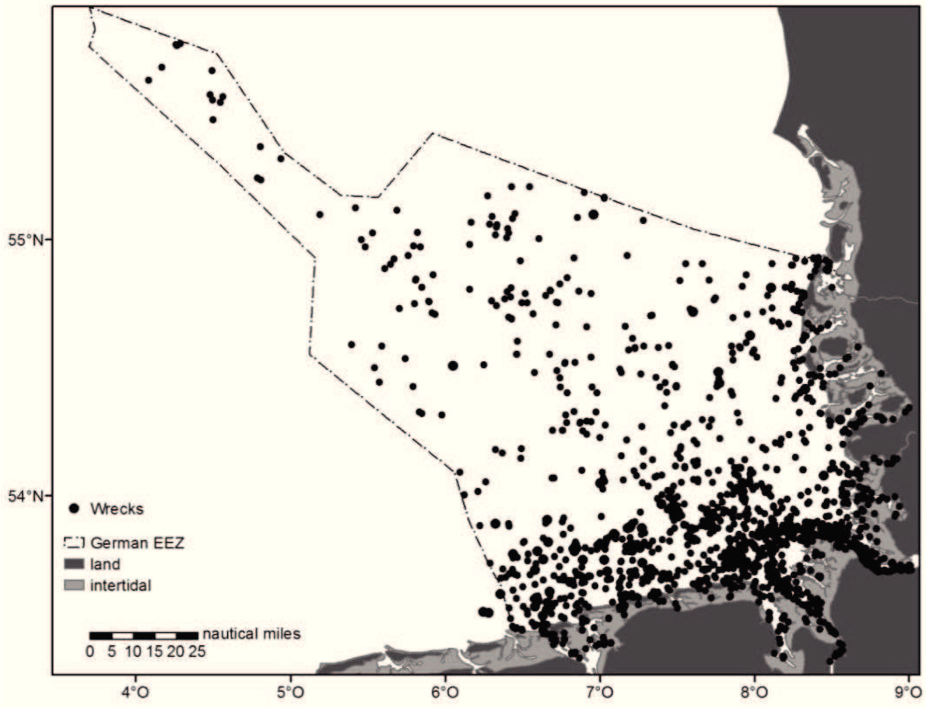

Fig. 9. Wreck locations inside the German part of the North Sea (map: Schröder).

Despite the extensive number of such artificial reefs and the relevant ecological questions, the large mobile fauna associated with wrecks in the South-eastern North Sea is poorly investigated. Whether the faunal community of offshore wind turbine foundations will simply add to the existing pool of wreck community or whether wind turbine foundations will represent different habitats and therefore a new element to the benthic system is still unknown. Wind turbine constructions differ from wrecks in that they reach through the entire water column while wrecks usually extend to only a few meters above the seafloor. Previous studies have shown that water depth and gradients in light intensity as well as wave force are important structural factors for epifaunal assemblages on natural and artificial hard substrates (Whomersly and Picken, 2003; Castric and Chasse, 1991). In particular in deeper offshore waters, wind turbines will therefore provide a more heterogeneous habitat than wrecks and, as a result, may be inhabited by qualitatively and quantitatively different VDM and biofouling communities. For the German Bight megafauna inventories are neither present from wrecks nor from offshore foundations. In the light of the future introduction of thousands of offshore wind power foundations into the North Sea it is important to describe and compare the ecological roles and the reef effects of these two types of secondary artificial reefs and their reef effects concerning the VDM in order to assess whether and how the North Sea ecosystem will be affected.

Ecological functions of reef organisms

According to their ecological roles the inhabitants of aquatic and terrestrial biotopes can be assigned to different functional groups. Bellwood et al. (2004) defines a functional group as a collection of species that perform a similar function in an ecosystem, irrespective of their taxonomic affinities. Furthermore, each inhabitant of a natural or artificial reef plays a role which, for example, serves to preserve the habitat, and has a distinctive position within the food web. The decimation, increase or the appearence of a new ecological role or entire functional group can result in a shift within the food web (favouritism or disadvantage of certain species), or even a complete transformation of a biotope. For instance, the mass mortality of grazing sea urchins in Caribbean coral reefs resulted in an overgrowth of the reef by fleshy algae. Consequently reef rock building corals died (Carpenter, 1990; Hughes et al., 1987). This in turn affected the previous function of the reef as a highly structured nursery of prey organisms for pelagic predators. In tropical coral reefs some parrot fish (Scaridae) feed on coral rock and the symbiotic green algae inside (Bruggemann et al., 1996; Bonaldo and Bellwood, 2009) thus contributing to reef erosion. However, *in situ* observations revealed that the parrot fish defecate grained coral rock on the reef slope or above deep holes beside the shallow growth zone of reefs. This means that they also contribute indirectly to the construction of the reef by avoiding defecation on the living corals. At the same time they shape the reef slope (Schuhmacher, 1988). The functional groups of reef builders (e. g. stone corals, Hydrozoa and incrusting algae) and reef scrapers coexist, fulfilling complementary role for reef development.

In situ observations on behaviour identified important but thus far unknown roles of certain species. The daily, seasonal, and spatial feeding and spawning behaviours of the surgeonfish *Ctenochaetus striatus* are well documented (e. g., Montgomery et al., 1988; Fouda and Zaki, 1988). In their studies on the foraging behaviour of several reef fish, Bellwood (1995) and Krone (2005) observed that the animals used specific sites for defecation. However, the frequency and function of the defecation behaviour was not fully analysed, but it can be assumed that it fulfils an unknown ecological role as it requires energy (Krone, 2005; Krone et al. 2006). Communities of natural and artificial reefs (including secondary reefs) outside tropical waters and inside the North Sea can also be divided into various functional groups.

In light of the introduction of thousands of new artificial wind power reefs, there is a need to study the roles and functions of their faunal community because artificial reef organisms will interact with and alter the surrounding North Sea environment. For instance the waters are inhabited by species which filter suspended seston out of the water column. This group of filter-feeder includes species of different taxa such as Bivalvia and Amphipoda. The filtration results in increased transformation of nutrient and particulate matter into biomass which in turn provides food for other organisms. At the same time this group functions as seston concentrator by aggregating un-consumed matter through the production of pseudofaeces (Widdows et al., 1979, Norling and Kautsky 2007). The identification of more and more functions of reef organisms (both in tropical and temperate artificial reefs) is necessary to get a comprehensive picture of the interactions of reefs with the marine system. Natural coral reefs are endangered worldwide due to threats such as sedimentation, ocean warming and over-fishing (Hughes et al., 2009; Wilkinson, 2004, Schuhmacher, 2010). The study of functional groups has assisted in the management of key species for reef resilience and development. The reefs, in turn, are crucial for other marine biotopes and faunal communities and may serve as a nursery for pelagic fish. However, ecological interactions in reefs are generally very complex and it is difficult to obtain finalised results.

In situ observations

Since the invention of the **s**elf-**c**ontained **u**nder water **b**reathing **a**pparatus (SCUBA) dive technique in the middle of the 20th century, marine organisms can be observed directly within their biotope. Unlike in studies of fished organisms in laboratory aquariums, the behaviour of animals can be investigated nearly undisturbed (Fricke, 1976). Furthermore, diving allows fauna quantifications at complicated habitats (e. g. ship wrecks) where the use of devises such as remotely operating vehicles is very difficult. With the SCUBA dive technique it became also possible to investigate communities of different substrates and reef types by the *in situ* placement of test material. At the very shallow reef crests of tropical coral reefs researchers can get close to the organisms to observe them through snorkeling. For observations at deeper areas (e. g. at the reef slope) a SCUBA is necessary. In this case, German scientists have to follow the German Hazard Prevention Regulation (BGR/GUV, 2011). This regulation entails security relevant requirements to equipment and personnel. It demands of the diver, for example, an exam in scientific diving and a scientific diving crew consisting of at least three people (instructor, diver, safety diver). In less urbanised areas these regulations can at times limit research. Scientific diving research at wind farms and ship wrecks offshore in the North Sea demands additional efforts. Due to the depth, often bad visibility under water and the risk that the divers may entangle at structures, the dive missions must be conducted surface supplied (umbilical with air and telephone). Furthermore, wind farm operators have additional demands for diving and offshore occupational diving equipment must be used. The divers must be especially educated and periodically trained in surface supported deeper diving and seamanship and must be available during the entire project time. Safe diving is only possible in slack water. Therefore, in most instances, only two dives are possible per day (two slack waters a day during day light). A sea-worthy expedition ship is essential and a matter of expense which has to be taken into consideration for project planning. Usually, ship expeditions have to be undertaken at fix dates and the success of a dive mission often depends on suitable sea conditions. All this means that the personal and material efforts have little in common with snorkelling or scientific diving in shallow waters at the coast (Fig. 10).

Fig. 10. Surface supplied diving equipment and diving at a large wind power pile at the wind farm *alpha ventus*, North Sea (photo l: Kanstinger, photo r: Krone).

If all difficulties are mastered and expeditions are run as scheduled, precious, new observations from difficult sites such as wind power foundations and ship wrecks are possible. This will enable researchers to obtain a holistic picture of the North Sea artificial reef ecology by capturing species abundances and distributions which would otherwise remain hidden. The present thesis is based, to some degree, on data gained through offshore scientific diving.

Aims and outline of this thesis

In the decades to come, thousands of large offshore wind power foundations will be introduced into the German Bight. These foundations have the potential to affect the local submarine ecosystem due to the significant differences between the marine fauna communities on such artificial reefs and natural soft and hard bottom communities (Barros et al., 2001; Fabi et al., 2002; People, 2006; Langlois et al., 2006; Wilhelmsson and Malm, 2008; Andersson et al., 2009; Langhammer, 2010). The present thesis focusses on the effects of the expanding offshore wind power industry on the structure and function of the local marine ecosystem. The thesis is divided into two main parts:

- The large scale introduction of secondary artificial reefs and its impact on the ecology of the sand bottom dominated German Bight, and
- the technical concepts developed to control and mitigate the reef effects.

The first part of this thesis aims to better predict how the introduction of wind power foundations will affect the marine ecosystem in the German Bight. The specific objectives of this section of the thesis are:

-To investigate **the function of a reef organism** in the ecology of highly structured hard substrate habitat and to promote the understanding of reef ecology and reef effects.

The **behaviour of the coral reef fish** *Ctenochaetus striatus* was investigated to exemplify the significance of a single species for substrate dynamics in a reef system. After an analysis of the general behaviour of *C. striatus* (Krone et al., 2008 PUBLICATION I), its capacity as a reef sweeper was tested by quantifying the amount of sediment transported from feeding to defecation sites (Krone et al., 2011 PUBLICATION II). Furthermore, it was evaluated whether or not C. *striatus* may contribute actively to reef erosion by studying jaw morphology of *C. striatus* (Krone et al., 2006 PUBLICATION III), reef topography abnormalities and coral rock age (Schuhmacher et al., 2008 PUBLICATION IV).

-To investigate **the biofouling masses and functional groups** which will be generated at the foundations of artificial constructions in the North Sea.

The **epifaunal community** on the offshore research platform FINO1, a construction comparable to wind power foundations was investigated over three years. Ecological functions and reef effects relating to the newly introduced epifauna were identified and extrapolated to future German offshore wind farm projects. The epifaunal community was also compared to those found at wrecks and the island of Helgoland (Krone et al., 2007 PUBLICATION V and Krone et al., submitted PUBLICATION VI).

-To investigate **whether wind power foundations add a new dimension to the vagile demersal megafauna's habitat** and to study if secondary artificial reefs also support the stock and spread of large reef species in the German Bight.

The **vagile demersal megafauna community** was investigated on soft bottom, the research platform FINO1 and at five shipwrecks (Krone et al., submitted PUBLICATION VII). The **presence of the European lobster** (*Homarus gammarus*) found at 65 investigated ship wrecks distributed in the German Bight offers an insight into what may be found at future wind power foundations (Krone and Schröder, 2011 PUBLICATION VIII).

A popular science book chapter illustrates the ecology of natural hard substrates and wind parks (Krone and Brenner, 2009 ILLUSTRATION).

The second part of this thesis deals with the development of techniques to control reef effects identified in the first thesis section, to improve environmental protection measures and to enable the commercial use of the reef organisms which settle at the foundations. The special objectives of this thesis section therefore are:

-In search of a technique that **prevents biofouling induced reef effects,** an **antifouling technique** was designed (Krone and Paster, 2011 PATENT I).

-To examine if **environmentally benign scour protections and artificial reef structures** at wind power foundations can be produced in the North Sea, the **production of the EAT-reef-creation-material** (electrochemical accretion technology material) was examined and a settlement experiment on the produced substrate was conducted (Schröder et al., in press PUBLICATION IX).

-To **develop techniques which enhance the stock of vagile demersal megafauna at wind power foundations** and to enable their commercial use, a **technique for habitat development** was designed to make all construction sections of wind power foundations accessible and attractive to vagile species (Krone et al., 2012 Patent II) . Furthermore, a **combined habitat-harvester** (Krone und Krämer, 2011 PATENT III) and a transportable trap for crabs (Krone und Krämer, 2012 PATENT IV) were developed.

-To **facilitate the ecological monitoring and technical services** at offshore foundations, a **device carrier for multiple uses** at offshore foundations was developed (Krone and Krämer, 2012 PATENT V).

PUBLICATIONS AND PATENTS

The present thesis is based on nine scientific publications, 6 patents and one non-scientific illustration. At the date of thesis submission, seven of the publications (I-V and VIII) are already published in scientific journals and one proceeding. Two publications (VI and VII) are under review and publication IX is in press. Below, the publications and patents are listed by numbers and the author's contributions are specified.

PUBLICATION I

Krone R, Bshary R, Paster M, Eisinger M, van Treeck P, Schuhmacher H (2008) Defecation behaviour of the Lined Bristletooth Surgeonfish *Ctenochaetus striatus* (Acanthuridae). *Coral Reefs* 27: 619 - 622.

The initial idea originates from me. I developed the conceptual approach. Practical field work was performed by me and the third author. I analysed the data together with the second author. I wrote the manuscript together with the sixth author.

PUBLICATION II

Krone R, Paster M, Schuhmacher H (2011) Effect of the surgeonfish *Ctenochaetus striatus* (Acanthuridae) on the processes of sediment transport and deposition on a coral reef in the Red Sea. *Facies* 65: 11-16.

The initial idea originates from me. I developed the conceptual approach. I did the sampling and observations in the field together with the second author. I analysed the samples and the data on my own. I wrote the manuscript together with the third author.

PUBLICATION III

Krone R, van Treeck P, Nebel H, Epple M, Schuhmacher H (2006) A special palate structure of *Ctenochaetus striatus* – a hidden tool for bioerosion. *Coral reefs* 25: 645.

The initial idea originates from me. I developed the conceptual approach. I performed the sampling in the field. I analysed the samples together with the third author. I wrote the manuscript together with the fifth author.

PUBLIKATION IV

Schuhmacher H, **Krone R**, van Treeck P (2008) Enigmatic coral rock pillars – Another look into reef dynamics. *Proceedings of the 11th International Coral Reef Symposium*, Ft. Lauderdale, Florida, 7-11 July 2008 Session number 1.

The initial idea originates from the first and third author. Laboratory work was conducted by me. Sampling was performed by all three authors. I brought samples and documentations from South Sinai. I contributed to the thesis and to the manuscript.

PUBLICATION V

Krone R, Wanke C, Schröder A (2007) A new record of *Styela clava* Herdman, 1882 (Urochordata, Ascidiacea) from the central German Bight. *Aquatic Invasions* 2: 442 – 444.

The initial idea originates from me. I developed the conceptual approach. I undertook the sampling in the field together with the second and third author. I prepared the samples. I wrote the manuscript.

PUBLICATION VI

Krone R, Gutow L, Joschko T, Schröder A (submitted) Epifauna dynamics at an offshore foundation – implications of future wind power farming in the North Sea
Marine Environmental Research.

The initial idea originates from the fourth author. I performed the sampling in the field together with the fourth author. I analysed the samples and the data. I performed ash free dry measures together with the third author. I wrote the manuscript together with the second and fourth author.

PUBLICATION VII

Krone R, Gutow L, Brey T, Schröder A (submitted) Will the spread of offshore wind power alter biodiversity in the North Sea? *Estuarine, Coastal and Shelf Science*.

The initial idea originates from me and the fourth author. I developed the conceptual approach. I and the fourth author undertook the field work. I analysed the data. I wrote the manuscript together with the second, third and fourth author.

PUBLICATION VIII

Krone R, Schröder A (2011) Wrecks as artificial lobster habitats in the German Bight. *Helgoland Marine Research* 65: 11 - 16.

The initial idea originates from me and the co-author. I developed the conceptual approach. I performed the sampling in the field together with the co-author. I analysed the samples and the data. I wrote the manuscript together with the co-author.

IllUSTRATION

Krone R, Brenner M (2009) Muschelzucht, künstliche Substrate & Windparks – In: Mathieu Poulicek. Coquilles coquines - Harte Schale, weicher Kern. *Musée national d'histoire naturelle* Luxembourg. pp 121–137. ISBN: 978-2-919877-15-7.

I wrote the manuscript together with the co-author.

PUBLICATION IX

Schröder A, Gutow L, Joschko T, **Krone R**, Gusky M, Paster M, Potthoff M (in press) Benthosökologische Auswirkungen von Offshore-Windenergieparks in der Nordsee (BeoFINO II). *Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU)*. 170 pp.

The initial idea for the overall project originates from the first and second author. I contributed to field work in soft bottom and hard bottom epifauna sampling, to the sample processing and data analyses as well as to writing of the manuscript.

The initial idea to test a new reef material in North Sea conditions originates from me. I developed the conceptual approach and I performed the laboratory work together with the sixth author. I undertook the field work. I analysed the samples and data together with the sixth author. I wrote the manuscript chapters together with the first, second and sixth author.

PATENT I

Krone R, Paster M (registered) Elektrochemisches Antifoulingsystem für seewasserbenetzte Bauwerke.

German Patent DE102009051768A1; Electrochemical anti-fouling system for structures wetted by sea water. European patent EP000002316584A1; Electrochemical antifouling system for seawater-wetted structures United States patent US020110100804A1.

PATENT II

Krone R, Schröder A, Krämer P (2012) Vorrichtung zur Habitaterschließung im Unterwasserbereich eines Offshore-Bauwerks.

German Patent DE102010021606B4; Device for developing habitats in the underwater area of an offshore construction, international patent WO002011147400A3.

PATENT III

Krone R, Krämer P (2011) Vorrichtung zur Ansiedelung und Erntung von marinen Hartbodentieren.

German Patent DE102009058278B3; Device for colonizing and harvesting marine hardground animals United States patent US020110139083A1.

PATENT IV

Krone R, Krämer P (2012) Transportierbare Vorrichtung zur Ansiedlung und Erntung von wirbellosen Tieren und Anwendung davon.

German Patent DE102009049083B3; Transportable device for colonizing and harvesting invertebrates and its use. Canadian patent CA000002764735A1; Transportable device for establishing a colony of invertebrates and for harvesting same, and use of said devices, international patent WO002011042003A1.

PATENT V

Krone R, Krämer P (2012) Vorrichtung zur Nutzung von technischen Geräten im Unterwasserbereich.

German Patent DE102009058277B4; Device for using technical devices underwater. European patent EP000002336429B1; Device for the use of technical equipment under water. United Sates patent US020110140059A1.

PATENT VI

Krone R (2012) Künstliches Habitat in Polyederform für Krebstiere auf marinen Weichböden und Anwendung.

German Patent DE102010049049B3; submitted to the European patent office.

PUBLICATION I

Defecation behaviour of the Lined Bristletooth Surgeonfish *Ctenochaetus striatus* (Acanthuridae)

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Coral Reefs

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NOTE

Defecation behaviour of the Lined Bristletooth Surgeonfish *Ctenochaetus striatus* (Acanthuridae)

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Abstract The feeding and defecation behaviour of the surgeonfish *Ctenochaetus striatus* was investigated at Ras Mohammed National Park (South Sinai, Red Sea). The fish feed on coral rock mainly by sweeping loose sediment with their flexible broom like teeth into their mouths. Feeding occurred exclusively on coral rock, but defecation took place only outside the grazing area above sand in small, precisely defined areas.

Keywords Red Sea · Defecation behaviour · *Ctenochaetus striatus* · Sediment export

Introduction

Some terrestrial animal species like badgers, ants and geckos use specific places for defecation (Carpenter and Duvall 1995; Neal and Cheesman 1996; Moore 2003; Poulsen and Boomsma 2005). In the marine environment, the herbivorous damselfish *Plectroglyphidodon lacrymatus* uses 1–4 specific sites around the edge of its small territory ($\sim 1\ m^2$, Polunin and Koike 1987). The herbivorous surgeonfish *Acanthurus glaucopareius* and *Acanthurus lineatus* display similar behaviour and defecate mostly during non-feeding time, whilst outside their territories (Robertson 1982). The herbivorous reef-scraping parrotfish *Chlorurus gibbus* also defecates away from its reef crest feeding grounds (Bellwood 1995).

The surgeonfish *Ctenochaetus striatus*, which has been previously reported to defecate at the border of its home range (Bellwood 1995), was the subject of the present study. During surveys on several fringing reefs in the Gulf of Aqaba and on the main Red Sea coast in October 2004 (Fig. 1). *C. striatus* were found to be repeatedly leave the reef flat in search of specific sandy areas in order to defecate. These areas were situated either seawards of the reef crest, in the lagoon or in the deep wells of the reef flat. This article describes and quantifies the spatial defecation pattern.

Materials and methods

The Lined Bristletooth Surgeonfish *C. striatus* (Quoy and Gairmard 1825) is one of the most abundant reef-fish species throughout the Indo-Pacific (Choat 1991). It is a diurnal detritivore (Montgomery et al. 1989; Randall and Clements 2001), which picks at the surface of reef rock using its bristle-like teeth (Purcell and Bellwood 1993) or using the rasping edge of its upper jaw (Krone et al. 2006), consuming sedimentary matter and algal turf.

The study was carried out during October and November 2005 at Marsa Bareika, in the Ras Mohammed National Park on the southern tip of the Sinai Peninsula, Egypt

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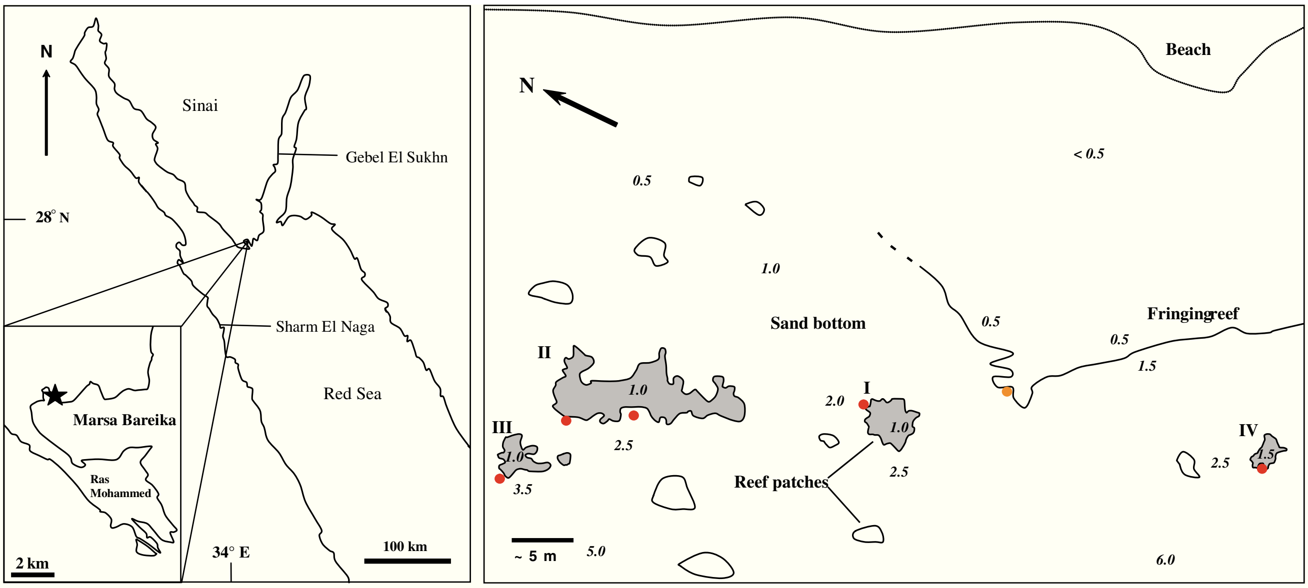

Fig. 1 Research location in the northern Red Sea, at Marsa Bareika (black star). Right-hand diagram: positions of defecation areas (red dots) of *Ctenochaetus striatus* adjacent to four reef patches (I–IV, grey). Individuals living close by on the adjacent fringing reef also used a single site for defecation (orange dot). Numbers = water depth in metres

(Fig. 1). At this site there is a shallow reef which consists a narrow fringe and different sized patches situated 25–80 m from the shore line in depths of 0.5–6 m (Fig. 1) on the sand plain that extends 100 m seawards to a depth of 8 m. Living coral cover on these patches ranged from 5 to 50%. Eleven adult *C. striatus* (standard length 12–14 cm) inhabiting four of the small reef patches (9–27 m^2) were subject to detailed observations.

Reef patches were selected since they were completely surrounded by sand, and it was therefore possible to closely monitor where the fish were defecating. These patches were measured and marked in squares (1.5 × 1.5 m) using small styrofoam balls at the grid intersections (floating 1 m above the bottom). Individual *C. striatus* could be identified from prominent scars or from a distinct white spot on their caudal fin. Swimming tracks, feeding locations, and fish positions were recorded at 2-min interval and recorded on maps. Observation periods were terminated after a minimum of four defecations per fish, resulting in 4–22 observed defecations per individual. The distance between the second last and last foraging spot and between the last foraging spot and the defecation location were compared to show the spatial separation of feeding and defecation. The percentage of observation above hard substrate vs. sandy areas was computed and analysed using non-parametric statistics.

Results and discussion

All 11 *C. striatus* displayed the same feeding and defecation pattern: from 3 h after sunrise until sunset the fish were continuously browsing the reef rock (compare Montgomery et al. 1989). Defecation took place every 5–10 min on the sandy area outside the reef. Typically a fish would cease feeding on the reef rock and immediately swim to a defecation spot beyond the reef edge. It then stopped or reduced speed, whilst about 20 cm above the sand-covered bottom, assumed an oblique head-upward position, spread its pectoral fins and deposited a faecal pellet. It then returned to continue grazing on the reef rock. Throughout, this behaviour, fish were neither disturbed by the presence of the observer nor by swimmers nearby. All 11 individuals visited a single-confined area of a few square decimetres (Fig. 2a, b; Table 1). Each defecation comprise a percentage of the total home range and was not used for other purposes. Neighbours and individuals inhabiting almost the same range usually shared the same area for defecation (Fig. 2b), but the individual areas did not overlap. All defecation sites shared three common features; they were located on the seaward side of the reef, were deeper than the foraging area, and in an area where the current flowed seaward. *C. striatus* individuals that were observed on the continuous reef flat nearby seemed to avoid the shallow backreef area, but defecated on the seaward edge also at distinct spots (Fig. 1).

All observed individuals spent most time above rocky substrate (median 87%), but defecated exclusively over sand (100%), thus defecating significantly more often over sand than predicted by their preferred residence duration (Wilcoxon-test, $n = 11$, $T = 0$, $P = 0.001$). All 11 fish swam greater distances from their rocky foraging area to

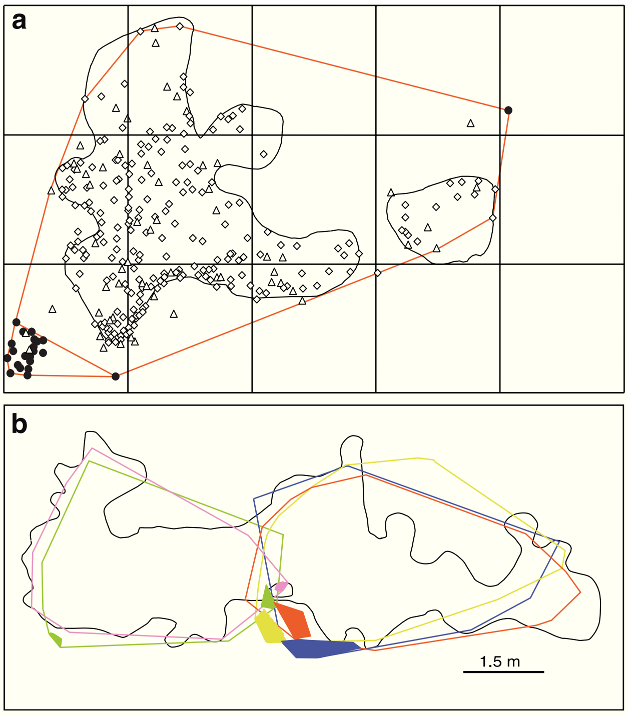

Fig. 2 (**a**) Detailed behaviour of a single *Ctenochaetus striatus* (No. 1 in Table 1) during a period of 118 min on reef patch III (Fig. 1): defecations (black dots), 2 min interval positions (triangles), feeding points (rhombi). This specimen was exceptional for defecating once outside its usual area (compare also No. 4 in Table 2). The red line encloses the entire home range. Grid squares = 1.5 m. (**b**) The home range of five individuals (marked by different coloured lines) including their defecation sites (filled areas) (reef patch II Fig. 1)

the defecation site than between the last two feeding spots (on average 2.3 times further, Wilcoxon-test, $n = 11$, $T = 0$, $P = 0.001$) (Fig. 3, Table 2). The use of a single location to defecate was particularly striking because they could have swum in any direction (including a shorter distance) to defecate on sand.

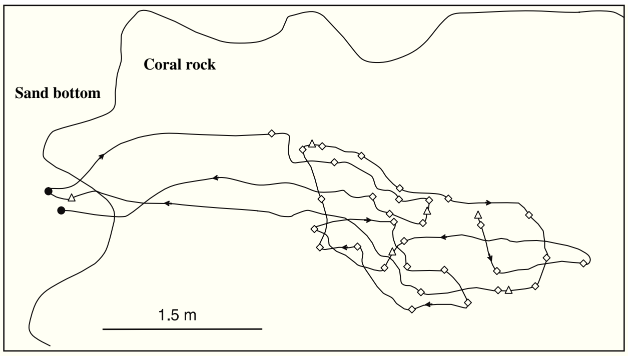

Fig. 3 Example behaviour of an individual *Ctenochaetus striatus* during a 10-min period. The fish feeds (rhombi) in the rocky zone, where it spends most of the time (triangles) (reef patch I Fig. 1) and swims to defecate over the sandy bottom (black dots)

In the case of *C. striatus*, the use of a single-distinct area to defecate rather than a general preference for sand might simply be due to the small size of the home range, where there is only one optimum place. However, this behaviour does not hold for the herbivorous damselfish *Plectroglyphidodon lacrymatus*, which uses 1–4 specific defecation sites around its small (~1 m^2) territory (Polunin and Koike 1987). In a larger home range (e.g., of the parrotfish *Chlorurus gibbus*, Bellwood 1995) fish use any sandy substrate away from the reef. Notwithstanding these differences, there is a similar pattern for all these species of defecating away from the foraging area, which may be a function of removing sediment to improve the growth of the grazer's food sources (*C. striatus* diet includes inorganic matter; Choat 1991; Purcell and Bellwood 1993), and/or by defecating away from foraging areas the risk of re-infection with endoparasites may be reduced (Choat 1991).

Table 1 Home range and the corresponding defecation site of 11 *Ctenochaetus striatus* individuals

Individual no.	Reef patch no.	Home range total (m^2)	Defecation spot (m^2)	Share of defecation spot of the whole home range (%)	Number of defecations (n)
1	III	15.9	0.41	2.6	22
2	III	10.7	0.24	2.2	6
3	II	13.0	0.03	0.2	6
4	II	13.3	0.07 a	0.5 a	4
4	II	13.3	0.03 b	0.2 b	7
5	II	16.4	0.26	1.6	12
6	II	16.0	0.38	2.4	10
7	II	16.0	0.23	1.4	10
8	I	7.7	0.05	0.7	8
9	I	9.4	0.21	2.2	6
10	IV	5.8	0.03	0.5	7
11	IV	8.0	0.01	0.1	4

The individual number four used two spots (a and b) for defecation

Table 2 The ratios of the distance (cm) between the last two feeding events before defecation (way 1) and the last feeding event and defecation (way 2) of *Ctenochaetus striatus*

Individual no.	Reef patch no.	Defecations (*n*)	Way 1 (cm)	Way 2 (cm)	Ratio way 1/way 2
1	III	21	57 ± 46	233 ± 111	0.2
2	III	5	50 ± 20	303 ± 99	0.2
3	II	6	123 ± 65	239 ± 115	0.5
4	II	10	45 ± 45	216 ± 216	0.2
5	II	10	115 ± 115	242 ± 149	0.5
6	II	9	113 ± 57	227 ± 125	0.5
7	II	8	79 ± 33	333 ± 155	0.2
8	I	7	162 ± 120	257 ± 97	0.6
9	I	8	114 ± 73	146 ± 59	0.8
10	IV	5	247 ± 117	329 ± 236	0.8
11	IV	3	151 ± 114	347 ± 98	0.4

Mean ± SD. The average ratio way 1/way 2 was 0.4 (±0.2 SD)

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PUBLICATION II

Effect of the surgeonfish *Ctenochaetus striatus* (Acanthuridae) on the processes of sediment transport and deposition on a coral reef in the Red Sea

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ORIGINAL ARTICLE

Effect of the surgeonfish *Ctenochaetus striatus* (Acanthuridae) on the processes of sediment transport and deposition on a coral reef in the Red Sea

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Abstract Excessive sedimentation is a major threat to coral reefs. It can damage or kill reef-building corals and can prevent the successful settlement of their planktonic larvae. The surgeonfish *Ctenochaetus striatus* feeds on rocky surfaces by sweeping loose material into its mouth with its flexible, broom-like teeth. In addition, it grasps and removes hard substrates with the aid of its special palate structure. It then transports sediment matter off the reef by defecating the ingested material outside the rocky zone of the reef. We analyzed 150 feces samples of six individuals, differentiating between (1) ingested by sweeping and (2) ingested by scraping, and compared their content with inorganic land-derived and marine sediments trapped at the feeding area. Projections based on fish densities, defecation rates, and quantities as well as composition of sediments collected by traps on the same reef site suggest that *C. striatus* removes at least 18% of the inorganic sediment sinking onto the reef crest. The eroded share in the exported matter is about 13%. This finding points to a hitherto not verified role of *C. striatus* as a reef sweeper and reef scraper, whereby the first function is by far dominating.

Keywords Coral reefs · Red Sea · Sedimentation · Feeding and defecation behavior · Reef sweeper

Introduction

Sediment fluxes are one of the major forces influencing the growth of coral reefs (Gilmour 1999). Hard substrates covered by sediments are less attractive to the settlement of coral larvae than bare ones (e.g., Hodgson 1990; Rogers 1990; Babcock and Davies 1991). Crustose coralline algae, which bind the reef framework and thus may enhance conditions for the settlement of coral larvae (Harrington et al. 2004), are also endangered by excessive sedimentation (Fabricius 2005).

Carbonate sands and silts permanently produced (and shifted) in the reef system itself constitute the endogenous sediments; terrigenous sediments may be added by rivers and wind. The removal of sediments off the reef previously deposited on the reef surface is considered to result primarily from abiotic factors like wave action and currents (Hubbard 1990; Fabricius 2005). If reefs occur in protected bays with low hydrodynamic conditions, these factors alone may probably not be sufficient to prevent the over-accumulation of sediments, which in turn would result in the damage or even death of reefs. The idea that certain biological components of the reef can act as a kind of "cleaning agent" is obvious, and becomes more and more interesting in the light of increasing sediment stress and simultaneous overexploitation of reef fish populations.

We studied the feeding behavior of the Lined bristletooth surgeonfish *Ctenochaetus striatus* (Krone et al. 2006, 2008, Fig. 1 and SOM), known as a common detritivorous species throughout Indo-Pacific reefs (Choat 1991; Randall and Clements 2001). With its feeding habits, it also

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Fig. 1 Adult specimen of *C. striatus*, at a fringing reef, northern Red Sea (photo P. Kanstinger)

removes loose sediment matter from the rocky reef substratum (Purcell and Bellwood 1993; Fouda and El-Sayed 1994).

Our field observations and laboratory studies had recently shown that these fish also act as bio-eroders (Schuhmacher et al. 2008) by grasping knobs of hard substrate and removing them with the aid of a special palate structure (Krone et al. 2006). The fish were observed picking the surface of reef rock throughout the day, hereby ingesting sediments trapped in the thin algal turfs colonizing the reefal substrate (Montgomery et al. 1989). Erosive grasping bites were less frequently recorded.

Additionally, our extensive field observations confirmed the unique defecation behavior already mentioned by Bellwood (1995): the fish exclusively feed on rocky surfaces, and defecate only on a distinct small spot located on a sandy area outside the reef (Krone et al. 2008).

This peculiar behavior prompted us to try to answer the following questions on sediment export: (1) what is the amount of material exported off the reef crest through the distinct defecation pattern, and (2) how large is the possible export in relation to the sedimentation there?

To tackle the latter question, we had to distinguish between inorganic material generated by the erosive feeding action and that by intake of loose particles from the reef surface. For this purpose, we differentiated between carbonate and non-carbonate (siliceous) matter. The latter is considered allochthonous (land-derived) material, previously deposited on the reef and as such a tracer of ingestion by browsing. Comparisons with concurrent sediment samples at that site allowed estimating the extent of the fish's peculiar behavior on the sediment regime of its territory.

Materials and methods

Study area

The investigation site Kashaba Bay is located in Marsa Bareika in the Ras Mohammed National Park, Egypt, at the southern tip of the Sinai Peninsula (Fig. 2). At this site, a 150-m-wide "wadi" (a river valley that is dry except in the event of rare heavy rain falls) enters the sea and continues as a submarine canyon. A shallow fringing reef has developed at depths of approx. 0.2–2 m, 25 m off the shoreline. Some isolated patch reefs of different sizes are located in front of the fringing reef. The fringing reef crest has a live coral coverage between 5 and 50% (Krone et al. 2008). The opposite tongue of land, which separates the bay from the open Red Sea, keeps the height of the waves below 50 cm, even during occasionally strong onshore winds. Tides range between 30 and 50 cm. Typical winds are diurnal land-/sea-breezes with an average speed of 3–4 Bft (checked with a cup anemometer and a vane throughout the entire investigation time). Slow currents, causing detritus particles and

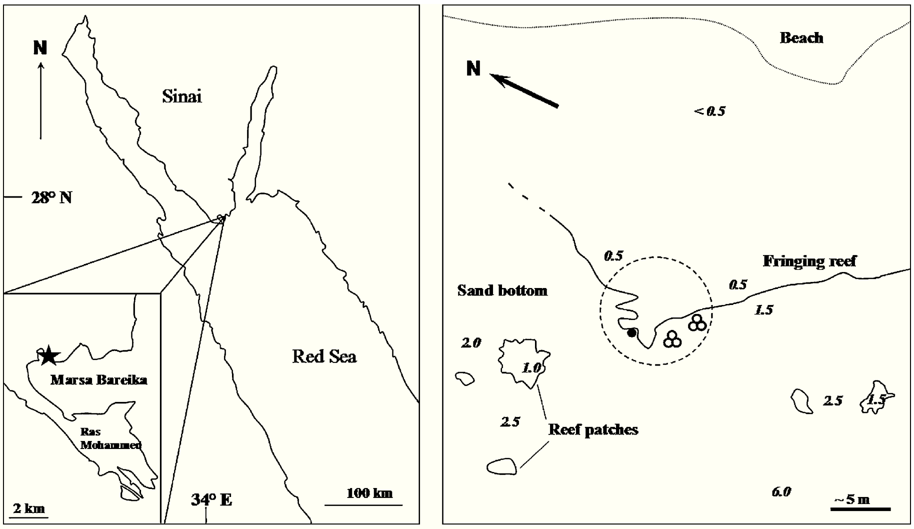


Fig. 2 Research location in the northern Red Sea. *Right*: details of the study site in Marsa Bareika. The *dotted line* shows the approximate home range of six observed *C. striatus* specimens. The *black dot* marks the sampled defecation site. Fish censuses were performed on the fringing reef. Six sediment tube traps beside the reef (*triple rings*). (*Water depth = numbers in italics*). Modified from Krone et al. 2008

small pieces of algae drifting less than 10 cm s^{-1}, were observed along the shore, dominantly from east to west.

Fish feces sampling

The feeding and defecation behavior of *C. striatus* is described in detail by Krone et al. (2008). Defecation sites can be identified as accumulations of approx. 2-cm-long, 0.5-cm-wide drop-shaped pellets on the sand. These feces pellets stay compact for at least 20 min. Fecal samples were collected in order to analyze their mineral content. They were sampled at a defecation site next to the above-mentioned fringing reef (Fig. 2) between the 4th and 18th of November, 2005. This defecation site was frequented by six individuals (standard length 12–14 cm). The fish were observed to be most actively feeding and defecating between 11:00 and 16:00 (see also Montgomery et al. 1989). The fecal pellets were transferred into small plastic bags by hand. Special care was taken to avoid collecting other sediments. In the laboratory, the feces–water mixture was processed through a sieve (50-µm-mesh diameter) and dried for conservation. Over a period of 15 days, we randomly collected ten pellets per day during the main defecation time. The pellets of 1 day were pooled for further analysis.

Mineral content of feces and sediment

To quantify the low masses of carbonate and non-carbonate fractions in the feces, the following analyses were performed: (a) X-ray diffractometric analyses were carried out on the feces samples to quantitatively distinguish carbonates (aragonite, calcite, and magnesium calcite), silicates (quartz, feldspar, and plagioclase), and halite as the main components; (b) The desalted and dried (60 h, 60°C) samples were homogenized with a mortar. They were weighed to the nearest 0.0001 g dry weight. Subsamples <0.06 g were taken and solubilized for 3 h in a 10% HCl solution. Ca and Mg concentrations were identified by means of inductively coupled plasma atomic-emission spectroscopy (ICP/AES). The respective carbonate masses were calculated according to the 1-to-1 ratio of Ca to CO_3 and Mg to CO_3 of the carbonates; (c) Total N and C contents were determined with gas chromatography in order to obtain the solely organic portion of C in the samples, and previously identified C shares from the carbonates were subtracted. The total mass of organic C and N together was considered as the organic dry matter of the sample; (d) The non-carbonate mineral portion was obtained by subtracting the organic and carbonate masses from the sample mass. Organic matter was measured as well, but it is of no relevance in this context.

Sediments

At the Marsa Bareika study site, we examined the sedimentation rate by placing six tube traps (diameter 9.0 cm, height 11.0 cm) alongside the vertical level of the fringing reef edge, at a distance of 1 m (Fig. 2). In order to minimize any possible resuspension and disturbance caused by fish, we installed a baffling grid at the mouth of the trap (height 1.5 cm, mesh size 1 cm, according to English et al. 1997). The traps were emptied every other day. We chose a 2-day interval to be able to collect detectable sediment masses.

Statistical treatments

The portions of carbonate and non-carbonate inorganic fecal matter and the trapped particles were compared using the *t* test. Average masses of sediments and feces contents are displayed with standard deviation (±).

Fish census and calculations

In order to determine the abundance of adult *C. striatus* on the fringing reef in the Marsa Bareika, six 50-m belt transects (on six different days) with a width of 5 m (English et al. 1997) were laid out and observed between 11:00 and 16:00, during the same time of day the feces were sampled. At this time, the fish are very active. Only adult specimens (12–14 cm of standard length) were counted.

The transect lines were laid out on the reef crest of the fringing reef at a distance of 2.5 m to the reef edge, in the same reef section where the traps were deployed and the feces were sampled. To estimate the effect of *C. striatus* on the reef's sediments, the average mineral masses per fecal pellet sampled at the fringing reef were multiplied by the number of fish per m^2 and the minimal daily defecation rate per individual.

Results

The fish started feeding on the reef patches and crest soon after sunrise, and started defecating usually after 10:00 or 11:00 am in the morning. Throughout the observations, individual fish hurried approx. every 10–15 min from its actual feeding area to its "toilet"—a distinct spot outside the reef on sandy ground. Several fish may share the same defecation area; no defecation on hard ground was observed as already shown by Krone et al. (2008).

Mineral contents of feces and material export from the reef

Single fecal pellets contained, on average, 290 ± 80 mg of inorganic matter, composed of 150 ± 40 mg non-carbonates and 140 ± 40 mg carbonates.

The portion of carbonates, amounting to 48%, within the inorganic content of feces differ significantly (*t* test, $p < 0.0001$) from the 35% carbonates within the trapped sediments. Repeated counts of the fresh fecal pellets and video recordings of the defecation site showed that at least 45 pellets per individual per day were transported away from the reef's hard substrate zone. Thus, one individual fish in the studied size-range removed about 195,750 ± 54,000 mg inorganic material from the reef within a period of 15 days—extrapolated to 1 year this amounts to about 4.76 ± 1.31 kg ($290 \times 45 \times 365 \times 10^{-6}$) of inorganic matter (2.46 ± 0.66 kg terrestrial siliceous sediment such as feldspar and quartz, and 2.30 ± 0.66 kg marine carbonates) from the reef rock.

The fish census yielded the density of 0.12 ± 0.04 *C. striatus* individuals m^{-2} reef crest. Within the transect, only fish sized comparable to those specimens visiting the defecation site (12–14 cm SL) were observed. Juveniles usually stay hidden. Combining fish density, feces content, and defecation rate, the calculated bulk transport of mineral sediment during the period of observation was about 1,566 ($290 \times 45 \times 0.12$) mg m^{-2} day^{-1} ± 432 mg m^{-2} day^{-1}.

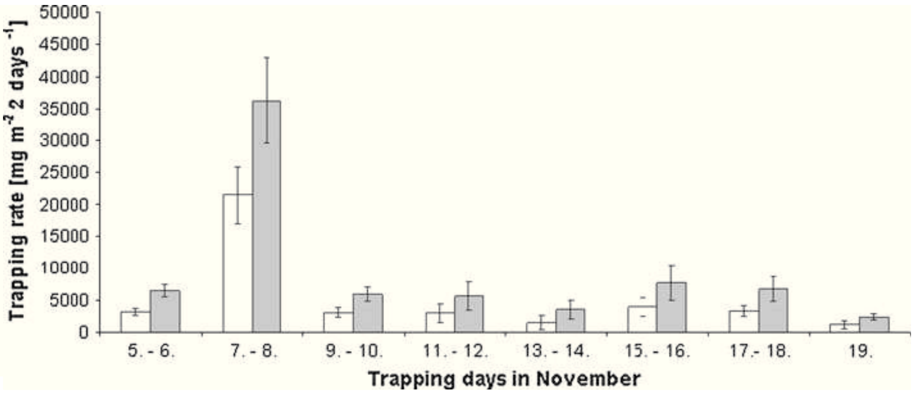
Sedimentation

The trapping rates are given in Fig. 3—on average 7,698 ± 8,114 mg m^{-2} day$^{-\ 1}$. The measurements per day varied by the factor 11 (2,551 mg m^{-2} day^{-1} and max. 28,855 mg m^{-2} day^{-1}). Both silicates and carbonates were found in every single sample: on average 64.7% non-carbonates = 4,981 ± 5,044 mg m^{-2} day^{-1} and 35.3% carbonates = 2,717 ± 3,069 mg m^{-2} day^{-1}). The 7th/8th November collection experienced a strong northerly wind (i.e., from land). In total, a sediment load of 115,480 mg m^{-2} ± 28,876 was trapped within 15 days.

Discussion

The sediment budget of a coral reef is controlled by several factors: hydrodynamic regime, terrigenous inputs, activity of inhabiting fish, and invertebrates. At the Marsa Bareika, fine autochthonous sediments are produced by shell-secreting

Fig. 3 Sedimentation masses measured between November 5th and 19th, 2005, on the observed reef (sediment traps *n* = 6 were collected every 48 h, respectively, the last day after 24 h, carbonates are in *white*; non-carbonates are in *grey*). The high rate measured between November 7th and 8th occurred during strong off-shore winds



organisms (e.g., some calcareous algae, foraminifers, tiny molluscs) and bio-eroders (e.g., boring sponges, scraping sea urchins, parrotfish). Allochthonous material is blown in by the wind. From time to time, both kinds of sediment may be suspended in the water column. The tube traps collected both fractions of sediments. In contrast to the open reef surface, these fractions were hardly resuspended once trapped. Hence, the trapping data represent the gross amount (import) of loose material settling down from the water column.

The export by *C. striatus* also comprises both autochthonous and allochthonous material. The carbonate portion of feces contains loose material that was swept in with the bristle-like teeth—e.g., tiny shell fragments of shells, sea urchins, foraminiferans (Fouda and El-Sayed 1994) as well as small solid rock edges bitten off the reef surface (Krone et al. 2006; Schuhmacher et al. 2008) and further processed during digestion (Nelson and Wilkins 1988). The siliceous portion of the feces is undoubtedly sediment material that had settled down on the reef. Hence, the siliceous fraction can be considered as a “tracer” of loose particles, deposited on the reef, consumed, and subsequently exported from the reef.

The fact that both the *C. striatus’* feces and the collected sediments contain non-carbonate minerals in relatively high quantities shows that the investigated reef receives considerable amounts of terrigenous sediments. Eisinger (2005) measured 37–50,000 mg m^{-2} 15 $days^{-1}$ during Dec–Feb 1999/2000 at the same site in 5-m depth.

To give a quick overview on the export efficiency of *C. striatus*, we found that with an estimated sediment removal rate of 1,367 mg m^{-2} day^{-1}, and ignoring the small resuspension possibility at the sheltered site, *C. striatus* exported approx. 18% of particulate matter off the reef, as was found accumulated in traps during the study period of 15 days, and 87% of the exported material was loose sediments and 13% was eroded matter.

In detail, this means that in order to figure out the sedimentary share (apart from the eroded one) in the fecal carbonate fraction, traces of the non-carbonate material were followed. To do this, we compared the percentage of non-carbonate particles in sediment traps and feces. The average quantity of trapped sediment amounts to 7,698 mg m^{-2} day^{-1}; 64.7% of this amount is non-carbonate matter, totaling 4,981 mg m^{-2} day^{-1}. The mineral content of feces transported off the reef surface totals 1,566 mg m^{-2} day^{-1}, of which 52%—equaling 814 mg m^{-2} day^{-1}—are non-carbonates. This amount corresponds to 64.7% of non-carbonates in the sediment traps; hence, the remaining 35.3% carbonate share equals 553 mg m^{-2} day^{-1}.

Judging from these observations, we can conclude that *C. striatus* ingested and exported 1,367 mg m^{-2} day^{-1} (= 17.76%) of the total examined sediment amount of 7,698 mg m^{-2} day^{-1} from the reef, which is the sum of the above stated figures of 814 mg m^{-2} day^{-1} non-carbonates and 553 mg m^{-2} day^{-1} carbonates. By deducting the amount of settled sediment exported by *C. striatus* from the total amount of fecal mineral content transported off the reef (1,566 mg m^{-2} day^{-1} − 1,367 mg m^{-2} day^{-1} = 199 mg m^{-2} day^{-1}), we conclude that this remaining portion—approx. 13% of the exported material—can be attributed to fish erosion. This conclusion does not, however, account for benthic organisms such as foraminifers, bryozoans, and others that live attached to turf algae and are not captured by the traps.

Our analysis principally elucidates the role of *C. striatus* as questioned in the introduction. *C. striatus* is a reef sweeper, i.e., it cleans the reef surface by collecting and exporting parts of the sedimentary cover. It is also a bio-eroder. Earlier gut analyses (Choat 1991; Fouda and El-Sayed 1994) had identified considerable amounts of carbonate matter, however, without information on its origin. The intake of carbonate matter varies during the year with minima during summer and autumn and maxima during spring (Fouda and El-Sayed 1994); hence our data gathered in November can be considered as conservative when extrapolated to an annual mean. The experimentally collected data of eroded carbonate matter (Schuhmacher et al. 2008)—449 g $ind.^{-1}$ $year^{-1}$—are definitely conservative, since they were obtained from subadult fishes scraping on coral plates not yet weakened by endolithic borers. Nevertheless, the erosive impact is low compared to that of some parrotfishes close to our study area: Alwany et al. (2009) measured 42.3 kg $year^{-1}$ for *Chlorurus sordidus* and even 290.3 kg $year^{-1}$ for *C. gibbus*.

Even though this study is based on a limited time span and number of fish, some theoretical approximations of the fish’s role in the sediment dynamics of the studied coral reef can be done. The reef in the sheltered Kashaba Bay is very rarely exposed to strong water movement. The current velocity, usually below 20 cm s^{-1}, does not significantly resuspend settled sediments (Ogston et al. 2004). However, terrestrial carbonate and non-carbonate dust is blown in from the hills and fossil reefs surrounding the bay. This situation is different from localities where the dynamics of sedimentation and resuspension as well as transport on and off the reef were studied (e.g., Bothner et al. 2006; Ogston et al. 2004; Gibbs 2001). Hard substrates covered by sediments are less attractive to coral larvae than bare ones. Experiments have shown that a 50% sediment cover (only inorganic particles) reduces larvae settlement on glass by a factor 6 (Hodgson 1990). Babcock and Davies (1991) tested the influence of different sedimentation regimes on coral larvae (*Acropora millepora*). Even their lowest sediment treatment of approx. 31,000 mg m^{-2} day^{-1} was found to significantly reduce the number of larvae settling on the upper sides of settlement plates (from ~30 to 5). The average trapping rate of carbonates and non-carbonates found in the Marsa Bareika (7,698 mg m^{-2} day^{-1}) probably do not present a critical sediment load for coral recruitment, but during calm weather periods with low resuspension by currents (Hubbard 1990; Chazottes et al. 2008), sediments could accumulate beyond a critical level. Hence, the export activity of *C. striatus* amounting to 18% sediment removal per day may play an important role in keeping the reef habitable for coral larvae. Cleaning the algal turf from sediments may also be beneficial to the co-occurring herbivorous species as *Acanthurus sohal* (Red Sea) and *Acanthurus lineatus* (Indo-West-Pacific). These fish defend their territory against other fish—except *C. striatus* (Choat 1991).

Values of sedimentation vary strongly between sites, depending on coastal topography and wind regimes (Wilson et al. 2003), wave action, and human impact. Nevertheless, our results not only corroborate the findings of sediment transport by fish (Bardach 1961; Bellwood 1995) but they also show that reef sweepers actively transport loose sediments away from the reef. They are distinguished from the reef scrapers (Steneck 1988)—e.g., the parrotfish *Chlorurus gibbus*—which export matter eroded mainly by themselves off the reef crest and disperse it on the sediment apron (Bellwood et al. 2003).

The assignment to the group of scrapers or sweepers depends on the percentage of loose sediment that is transported away from the hard reef surface. These proportions may vary depending on the site. In our case, *C. striatus* clearly has to be classified as a reef sweeper, and only to a much lower degree as a reef scraper. It might be intriguing to investigate the variations within the sweeper/scraper ratio at different reefs in the vast distribution area of *C. striatus.*

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PUBLICATION III

A special palate structure of *Ctenochaetus striatus* – a hidden tool for bioerosion

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Coral Reefs

A special palate structure of *Ctenochaetus striatus*—a hidden tool for bioerosion

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The genus *Ctenochaetus* (Acanthuridae, surgeonfish) is present on most reefs in the Indo-Pacific, sometimes in large abundance. A particular characteristic of this genus is the bristle teeth (Randall 1955; Purcell and Bellwood 1993). During aquarium experiments a second dentiform structure was detected. As the fish swam with slightly opened mouths, a compact structure pointing downwards, appeared behind the folded upwards bristle teeth of the upper jaw. In specimens of various sizes caught in the Gulf of Aqaba, Red Sea in April 2004, a knobby stripe was detected next to the bristle teeth (Fig. 1a). This structure exists only on the palate. It runs curvewise with a distance of ~1 mm parallel to the row of bristle teeth. The bulk of the structure increases up to the vertex of the curve (max. height ~0.7 mm). The width of the stripe is approximately 1 mm. It can be seen in the sagittal section (Fig. 1b) that this knobby stripe extends over the edge of the premaxilla, in which the flexible bristle teeth are embedded. It is assumed that this structure contacts the substrate while grazing when the mouth is opened at an angle of 180° (Purcell and Bellwood 1993). The stripe is rigid and consists of numerous single hard knobs which do not rest in the upper jaw bones, but are embedded in elastic tissue. The elementary composition of the single knobs (by energy-dispersive X-ray analysis; EDX) suggests robust horny substance (α-keratin). Thorough close-up observations in the field (Ras Mohammed National Park, Sinai-Peninsula) and during aquarium experiments revealed two different grazing techniques in this species: firstly, brushing the surface of reef rock and coral slabs with the bristle teeth, exerting only slight pressure, to ingest detritus and fine algae (as described by Purcell and Bellwood 1993), and secondly, chafing the substrate with energetic grasping bites with contact pressure being generated by a shaking of the whole body. During the second feeding mode the jaws are wide open, allowing the palate dentation to rasp and erode the reef substrate.

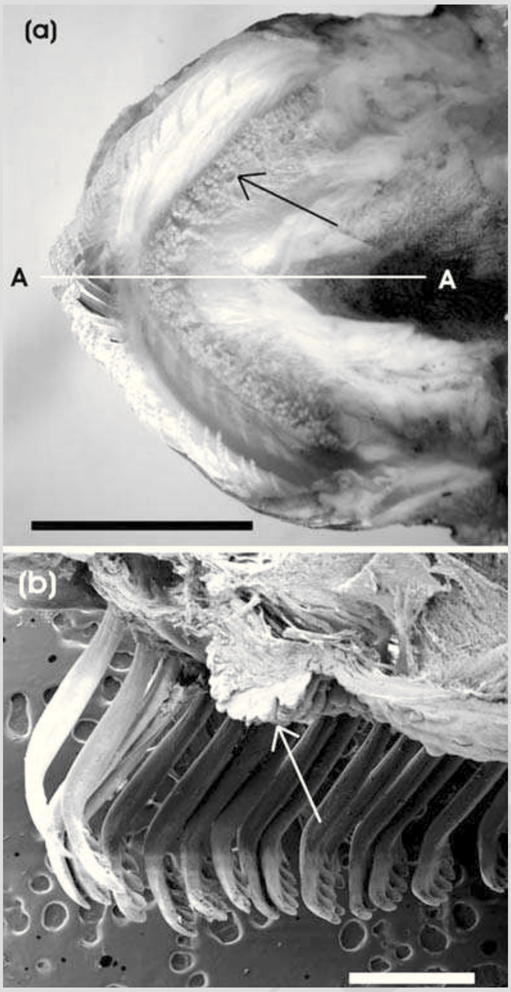

Fig. 1 **a** Knobby structure of the palate of *Ctenochaetus striatus* (*black arrow*) and the position of the sagittal section (A-A), Scale bar = 0.5 cm (total length of the fish: 18 cm). **b** Sectional view (SEM image) of the knobby structure (*white arrow*) and the typical bristle teeth, Scale bar = 1.0 mm

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Reef sites

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PUBLIKATION IV

Enigmatic Coral Rock Pillars – Another Look into Reef Dynamics

Helmut Schuhmacher, Roland Krone & Peter van Treeck

Proceedings of the 11th International Coral Reef Symposium

Proceedings of the 11th International Coral Reef Symposium, Ft. Lauderdale, Florida, 7-11 July 2008
Session number 1

Enigmatic Coral Rock Pillars – Another Look into Reef Dynamics

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Abstract. Stone capped calcareous pillars, rising 10-70 cm above the surrounding reef surface are to be found at Aqaba (Jordan) and on several other fringing reefs of the Northern Red Sea from intertidal down to 3 m depth. Terrigenous (non-calcareous) cobbles and boulders are fixed on top of coral limestone. At Aqaba it is assumed that the stones were once introduced by fishermen and came to rest in depressions of the reef. Afterwards the surrounding reef limestone was eroded so that only the substrate underlying the granite stones has been left as singular towers. ^{14}C-dating of a column sample provided an age of 345-560 years. Several interpretations are possible: the respective reef part did not grow since then, or younger layers were removed by bioerosion. Some suggestions are provided based on erosion data of sea urchins (*Diadema setosum*) and fish, gathered at that site. Two more examples of partial reef decline are presented from a reefflat at the Sinai coast north of Dahab indicating uplift along the margin of the Gulf of Aqaba and from the bay Marsa Bareika at the southern tip of Sinai where big boulders are interpreted as ballast stones discharged in an antique harbour.

Key words: Long-term reef shaping, bioerosion, Gulf of Aqaba (Red Sea)

Introduction

Some reefs at Aqaba (Jordan, Northern Red Sea) are under observation since 1972 (Mergner and Schuhmacher, 1974). They exhibit contrasting aspects from thriving coral communities with up to 60% living cover to barren limestone rock. The latter one is cleared by grazing fish and sea-urchins, especially *Diadema setosum.* Stone capped limestone pillars which rise 10-70 cm above the surrounding reef surface caused us to take a closer look at these structures and their history.

Similar structures found in other parts of the Red Sea are also shown.

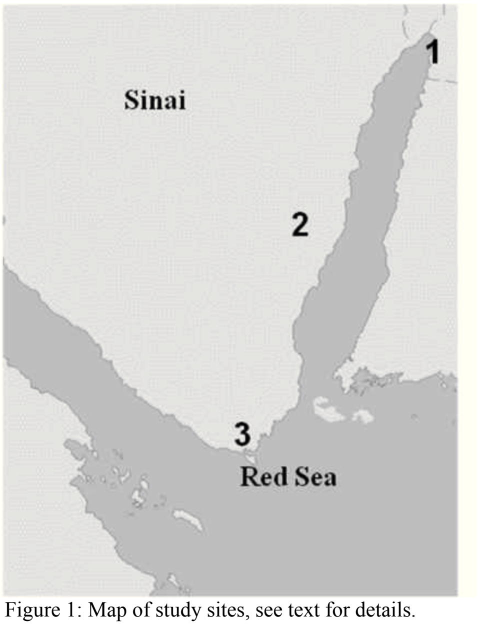

Figure 1: Map of study sites, see text for details.

Results and discussion

Findings from three sites of the Northern Red Sea are presented (Fig. 1):

1. Aqaba (northern end of the Gulf of Aqaba),
2. East coast of Sinai Peninsula between Dahab and Abu Galum,
3. Marsa Bareika, Ras Mohamed National Park, southern tip of Sinai.

In each case terrigenous cobbles and boulders are fixed on top of columnar elevations carved out from coral limestone.

Case study Aqaba:

Fig. 2 shows the top of a forereef mound at approx. 10 m depth off the Marine Science Station Aqaba. The arrow points to one of the cobblestones. The underlying pillar was identified as remnant of a *Porites* colony (Fig. 3). Its ^{14}C-dating revealed an age of 453 +/- 107 years. A neighbouring column made of a faviid skeleton was dated as to a maximum of 50 years.

It is assumed that the stones were once introduced by fishermen and came to rest in depressions of the reef. Afterwards, the surrounding reef limestone was eroded so that only the substrate underlying the granitic stones was left as singular towers. It is unknown when the stones were introduced, therefore several interpretations are possible: The respective reef part did not grow since decades/ages, or younger layers were removed by bioerosion, before the stone fell down. There is considerable bioerosion at that site: The density of *Diadema setosum* is 1.2 ind m^{-2}; the removal of carbonate substrate was calculated from gut contents and faeces analyses (considering reworked material) as 1.023 kg m-²yr^{-1} (Kroll 1995, Reinicke and Schuhmacher 2008). Grazing fish, especially the acanthurid *Ctenochaetus striatus*, removed 1-3 mm yr^{-1} from *Favia* skeleton tiles which were exposed as colonization plates (v.Treeck et al. 1996 - regarding the impact of *C.striatus* see also Schuhmacher et al., session 10, this volume).

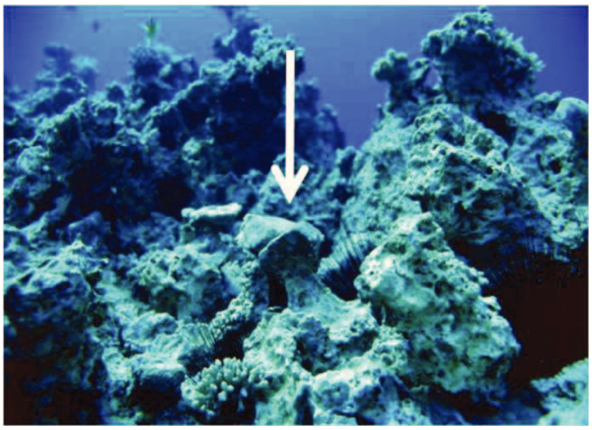
Figure 2: Granite stone on top of a forereef mound, Aqaba.


Figure 3: Stone capped *Porites* column; scale bar 7.5 cm.

Example case Sinai coast:
The mountains between Dahab and Ras Abu Galum steeply slope into the Gulf allowing development of only a narrow fringing reef. The reef flat continuously receives rubble tumbling down from the adjacent mountains. Fig. 4 shows the reef flat at low tide. At high tide the boulders are immersed except those on the tallest sockets. From the height of the calcareous columns it can be concluded that a 30-50cm thick layer was removed from the reef flat. The fact that the recent reef surface reaches to low tide level indicates a still considerable uplift of the western margin of the Gulf of Aqaba graben. Specific agents of bioerosion and time scales were not investigated.


Figure 4: Reef flat at low tide with terrigenous debris.

Example case Marsa Bareika:
Marsa Bareika is a large bay at the southern end of Sinai. A slightly inclined sandy wadi (river bed) enters the inner bay from the north. A poorly developed reef is interrupted by sandy areas. Several limestone outcrops, crowned by heavy boulders represent hardbottom islets that are sparsely colonized by corals (Fig. 5-6). The present topography does not provide an indication how the big boulders got to the site; anthropogenic transport, however, is likely. The bay is a natural harbour (today small vessels of the Ras Mohamed National Park are moored here). It is assumed that in ancient times (perhaps 2-4000 years ago) ships anchored at this site and dropped ballast stones – probably in exchange for copper or other minerals which were mined on Sinai and shipped to Egypt and further south. For a hypothetical bottom profile of that time see Fig.6. Archaeological studies have yet to be conducted. It would be intriguing to investigate ecological conditions and time periods, when this reef body formed and faded.


Figure 5: Boulder on top of a 70 cm high socket of reef rock.

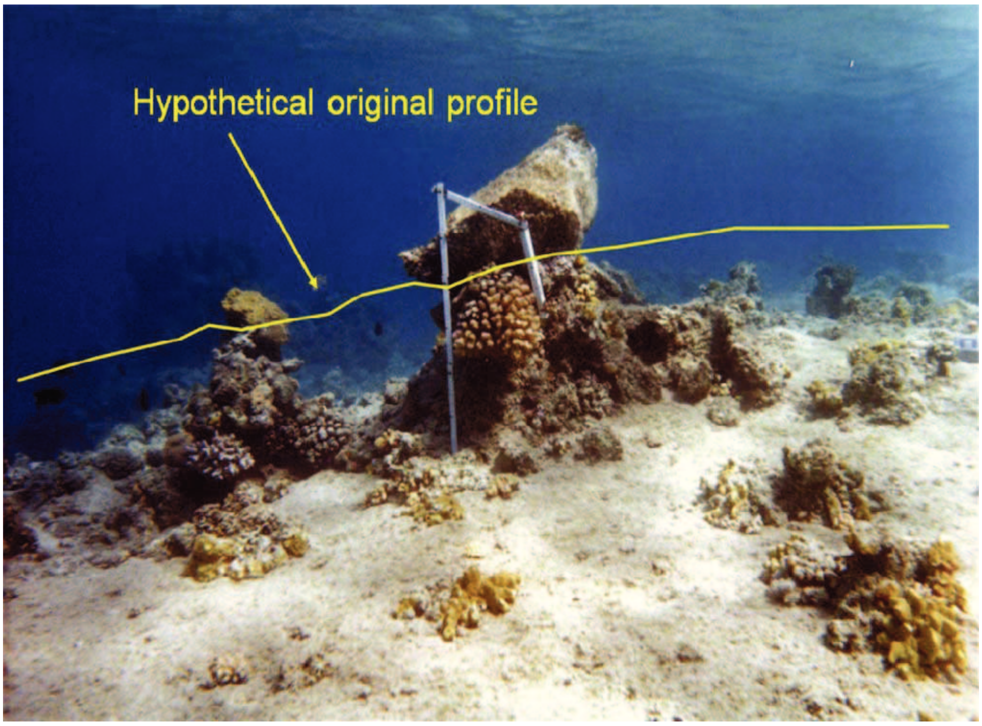

Figure 6: Boulder capped remnants of a former reef.

Conclusion

All three examples show reef areas, where the reef framework is eroding. The stone capped towers are remnants wittnessing of former reef developments. Anthropogenic reasons for the decline of these reef parts can be excluded. This presentation is thought to sensitize for this phenomenon at other places and to generate discussion about circumstances and modes of bioerosional reef shaping.

Acknowledgement
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PUBLICATION V

A new record of *Styela clava* Herdman, 1882 (Urochordata, Ascidiacea) from the central German Bight.

Roland Krone, Carsten Wanke & Alexander Schröder

Aquatic Invasions

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Special issue "*Alien species in European coastal waters*", Geoff Boxshall, Ferdinando Boero and Sergej Olenin (eds)

Short communication

A new record of *Styela clava* Herdman, 1882 (Urochordata, Ascidiacea) from the central German Bight

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Abstract

The Asian ascidian *Styela clava* was recorded for the first time from the island of Helgoland-Düne, Germany, in July 2007. This is the first record of this species from the only two offshore islands in the SE North Sea.

Key words: *Styela clava*, Asiatic ascidian, new record, German Bight, Helgoland

Styela clava, indigenous to the NW Pacific, has spread to several world regions (Minchin et al. 2006). This is the first account from Helgoland, (Figure 1) a rocky area with harbours on each of its two islands. This solitary ascidian can attain a maximum tunic length of 20 cm and live up to about two years (Davis and Davis 2007, Davis et al. 2007). It becomes mature at a size of 5.0 to 7.5 cm after about ten months and tolerates temperatures from -2 to +23°C and salinity ranging from 20 to 32 psu. The conditions found at Helgoland lie well within this range. Its pelagic larvae have a life expectancy of up to 28 hours and appear from late July to the end of October (Lützen 1999). This ascidian attaches to various natural solid substrates, such as rocks, oyster shells and other firm surfaces including harbour structures such as sheet pilings, fender beams, and mooring lines. Densities of up to 1000 individuals m^{-2} of *S. clava* have been found in sheltered places between 0.3 m above and 25 m below low water spring tide (Minchin et al. 2006, Lützen 1999).

Due to the short planktonic phase of the larvae, they settle close to areas where it has become established. However, they will also settle on the hulls, or within the sea chests, of vessels. Their planktonic stage may also be carried in ship's ballast water over greater distances. Transfers with oyster movements are possible (Locke et al. 2007) and their spread attached to floating debris may also occur. In the past, *S. clava* was not believed to endanger autochthonous communities (Lützen 1999).

However, on the coast of Prince Edward Island, Canada, the extent of the fouling on mussel lines has resulted in a decline in production (Bourque et al. 2007) and it is an important fouling organism even within its native range (Minchin et al. 2006). European populations of *S. clava* have persisted where they have become established (Davis and Davis 2007) and it is listed in the UK Biodiversity Action Plan (1999) as a potential threat to native species.

After the species' first discovery in Europe (Plymouth, Britain) in 1953 (Carlisle 1954) it spread to several other sites in the British North Sea and Atlantic, to the coasts of Ireland, Belgium, The Netherlands, Germany and Denmark, and southward on to Portugal (Davis and Davis 2007, Davis et al. 2007, Minchin et al. 2006).

It was first recorded in German waters from Sylt island in the Wadden Sea in 1997 and from Wilhelmshaven port in 1998 (Lützen 1999). In 1999 it was found at the Wadden Sea island Norderney (Daehne 2000) (Figure 2). Despite its abundance it has not resulted in any economic impact along German coasts (K. Reise, pers. comm.).

In July 2007 two specimens of *S. clava* were collected while diving in the harbour of the "Düne", Helgoland ("Dünenhafen"; 54°11.117'N, 07°54.120'E; 32 psu; 18°C). These were photographed then preserved in a 4% formalin solution. Specimens were found attached to an iron bulkhead 2 m below the low water line in an area where six horizontal transects (each 2.0 m x 15.0 m) were made on the harbour wall. No further specimens were detected in six similar transects on concrete pilings in the sheltered Südhafen or during underwater surveys in the Nord-Osthafen. Helgoland quay walls have been surveyed to the depth of 7m each year for the last ten years and this account reports the first specimens to be found (H.-D. Franke, pers. comm.).

The larger specimen is likely to have been in reproductive condition and both were probably less than one year of age based on information from Lützen (1999).

Figure 1. Styela clava specimens from Helgoland (scale bare 10 cm) (R. Krone)

Figure 2. Styela clava in the SE North Sea (● record, ○ no record, scale bar 10 km) (K. Jerosch)

Helgoland is the only offshore island in the SE North Sea and is situated in the centre of cyclonic water currents (Giménez and Dick 2007). It is difficult to see how *S. clava* could have reached Helgoland by natural means (Davis et al. 2007). However, there are up to five visits daily by ferryboats and many visits from recreational vessels, which sail from "*S. clava* ports" around the North Sea in the summer. It is likely that ferryboats or other craft were responsible for the arrival some eight to ten years after its first discovery from the German inshore coast. It is possible that other specimens were present and it is unclear whether all of these would normally survive as it is unlikely there are sufficient numbers present to form a viable population and any small individuals present may be compromised by predation by snails or fish, as has been observed elsewhere (Osman and Whitlach 1999). In north-western Europe adults have no known predators (Lützen 1999).

Further surveys for this species in Helgoland could form a useful basis for the study of the colonisation process and of the alien's interactions with the native fauna.

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PUBLICATION VI

Epifauna dynamics at an offshore foundation – implications of future wind power farming in the North Sea

Roland Krone, Lars Gutow, Tanja Joschko & Alexander Schröder

Marine environmental Research submitted manuscript

Epifauna dynamics at an offshore foundation - implications of future wind power farming in the North Sea

R. Krone, L. Gutow, T. J. Joschko, A. Schröder

Abstract In the light of the introduction of thousands of large offshore wind power foundations into the North Sea within the next decades, this manuscript focuses on the biofouling processes and likely reef effects. The study explores the macrozoobenthos (biofouling) colonization at an offshore platform which is comparable to offshore wind turbine foundations. A total of 183 single samples were taken and the parameters water depth and time were considered comparing biofouling masses and communities. The blue mussel *Mytilus edulis*, Anthozoa and the Amphipoda *Jassa* spp. were the dominant species. The community from the 1m zone and those from the 5 and 20-28m zones can clearly be differentiated. The 10m zone community represents the transition between the *M. edulis* dominated 1m and 5m zones and the Anthozoa dominated 20-28m zone. The construction was covered by an average of 4,300 kg biomass. This foundation concentrates on its foot print area (1024 m²) 35 times more macrozoobenthos biomass than the same area of soft bottom in the German exclusive economic zone (0.12 kg m^{-2}). Concerning the temporal biomass variation, we assume that at least 2,700 kg biomass was exported on a yearly basis. 345 x 10^4 single mussel shells of different sizes were produced during study time. It is anticipated that the *M. edulis* abundance will increase in in the North Sea, due to the expansion of offshore wind farm development. The *Mytilus*ation of the North Sea ecosystem will result in ecological system changes.

Key words: Offshore structures, German Bight, Habitat creation, Artificial habitats, Biofouling, Benthic ecology, Bioaccumulation, *Mytilus*ation, Environmental impact

1. Introduction

In the near future the wind energy industry will expand on a largescale into offshore regions of western European shelf seas. Thousands of large steel turbine foundations will function as artificial reefs within areas which are naturally characterised by extensive sedimentary soft bottoms. It is expected that the turbine foundations will affect marine life through noise emission (Wahlberg and Westerberg, 2005; Madsen et al, 2006; Lindeboom et al. 2011), changed seafloor topography and sediment regimes (Wilson et al., 2010), and barrier effects (Masden et al., 2009). Additionally, strong implications for the subtidal ecosystem are expected from the settlement of macrozoobenthos on the artificial solid surface of the turbine foundations (Lindeboom et al. 2011). The macrozoobenthos communities on artificial hard substrata (biofouling or fouling) differ from natural macrozoobenthos communities on natural hard substrata (People, 2006; Wilhelmsson and Malm; 2008; Andersson et al., 2010) and on soft bottoms (Barros et al., 2001 Fabi et al., 2002; Langlois et al., 2006; Langhammer, 2010). In particular, in areas were natural hard substrata are rare, high numbers of artificial constructions favour the establishment of taxa such as cnidarians and mussels whose life histories include temporary or permanent attachment to solid substrates (Richardson et al., 2009). Increasing numbers of filtrating mussels (Winter, 1973; Clausen and Riisgård, 1996) may influence particle and nutrient fluxes between the water column and the sediment, thereby potentially affecting the plankton biomass (Wilhelmsson and Malm, 2008). Mussels, in turn, provide secondary hard substrate attractive for other epifaunal organisms (Norling and Kautsky, 2007). Continuous mussel shell litter fall modifies the grain size of the sediment where shells aggregate at the seafloor, providing new habitats for hemi- and holo-sessile organisms such as Anthozoa which require solid attachment sites, and typical hard bottom crabs (Wolfson et al., 1979; Freire and Gonzálesz-Gurriarán 1995; Riis and Dolmer, 2003). Aggregations of marine biota at wind turbines will change the benthic biomass and provide food for a variety of predators (Wolfson et al., 1979; Freire and González-Gurriarán, 1995; Page et al., 1999; Wilhelmsson et al., 2006; Krone et al., submitted). Accordingly, benthic invertebrate communities and the local physico-chemical conditions are expected to change around the structures (Wolfson et al., 1979; Falcão et al., 2007). Finally, artificial reefs such as wind turbine foundations have been found to act as stepping-stones for the dispersal of hard bottom organisms facilitating the spread of both exotic and indigenous species (Connell, 2001; Bulleri and Airoldi 2005; Glasby et al., 2007; Bulleri and Chapman 2010; Zintzen and Massin, 2010).

In the German Exclusive Economic Zone (EEZ) of the North Sea at least 5000 single turbines are envisaged to be built within the next 20 years (IEA, 2008; BMU, 2010). To date, 22 wind farms with 1540 turbines are authorised for construction (BSH, 2012) and one wind farm with 12 turbines is operating. The potential impacts of the massive biofouling associated with the large-scale introduction of numerous turbine foundations into the North Sea are of concern and the resulting ecological processes are not well enough understood (Inger et al., 2009; Gill, 2005). Studies on specific effects of biomass accumulations on artificial structures are costly and often not feasible in offshore waters. Accordingly, ecological implications have to be derived from the qualitative and quantitative composition of fouling communities sampled in the course of baseline monitoring programs. Previous studies indicate that the composition of the fouling assemblage and, thus, the ecological implications of offshore constructions depend on a variety of factors such as the material and the size of the construction, the time of exposure, distance from the shore, the wind and current regime, and the water depth (Kingsbury, 1981; Butler and Connolly 1999; Whomersley and Picken, 2003; Gill, 2005; People 2006; Zintzen et al., 2008a; Andersson et al., 2010).

Most biofouling studies on offshore constructions in the North Sea have been conducted on oil and gas rigs. The biomass and the composition of the epifauna varied between rigs in coastal waters of the North Sea and those under Atlantic influence with growth rates of some species differing by up to 50 % (Kingsbury, 1981). Similarly, the fouling communities varied between scattered ship wrecks in Dutch waters indicating spatial variation depending on the water mass (Zintzen, 2006, 2008a, 2008b, 2010). Fouling on offshore constructions are often completely dominated by either mussels or Anthozoa. On four North Sea oil platforms (45 to 67 m depth) blue mussels, *Mytilus edulis*, dominated the fouling assemblages in the shallow subtidal while Anthozoa occurred mainly in the deeper sections (Whomersley and Picken; 2003). Eleven years after construction, the fouling communities on the rigs were still changing.

The young wind power projects in the southerly North Sea have also been investigated from the beginning in 2002 with first results emerging. In Belgian North Sea waters, six concrete gravity foundations of offshore wind turbines were erected at water depths of 25 m. Within the first two years after implementation, the fouling community displayed strong seasonal variations and lower numbers of taxa than that on older ship wrecks in the same region (Degraer and Brabant, 2009, Kerckhof et al., 2010). On turbine foundations of a Dutch wind farm (water depth: 21 m), 80-100% of the construction surface was covered by mussels down to a depth of 10 m while deeper sections were fully covered by Anthozoa and Hydrozoa (Lindeboom et al., 2011). As for most other North Sea constructions, the Amphipoda *Jassa* spp. (further also referred to as *Jassa*) and its tubes occurred all over the pylons. *Mytilus edulis* dominated the fouling assemblages also on wind turbines in shallow (max. 14 m depth) coastal waters of the Danish North Sea (Leonhard and Pedersen, 2006). However, the mussel abundances varied substantially among the foundations within the wind farm.

The aim of the present study is to investigate the biofouling community on the steely foundation of an offshore research platform in the south-eastern North Sea, to estimate the impacts of largescale offshore wind farming on the North Sea ecology. The underwater construction of the platform is similar in size and shape and thus equivalent to common wind turbine foundations. Depth zone typifying fouling communities were identified and their temporal and spatial development was addressed. Dominant species and the biomass aggregation were compared between the construction, the natural sedimentary bottom at that site and the rocky island of Helgoland. The biomass balance and the production of secondary hard substrate by mussel shell litter fall were calculated.

2. Material and methods

2.1 Study site

The investigation was conducted between April 2005 and October 2007 at the research platform FINO 1 (**F**orschung **i**n **N**ord- und **O**stsee 1) (Fig. 1) that was erected close to the location of future planned wind farms. This steely jacket construction was built in July 2003 in the south-western German Bight, at a water depth of 28 m below low tide level. The total subtidal substrate surface measures 1280 m² and the square area beneath the structure (footprint area) measures 1024 m². The platform allows for research on physical and oceanographic conditions and the possible changes of the marine ecosystem due to the construction of offshore wind turbines. The sea floor around the platform consists of medium fine sand. The salinity ranged from 32.9 to 34.7 psu; the surface water temperature was 3°C in spring, 19°C in summer, and 14°C in autumn. The water body was never stratified with regard to temperature and salinity during the study. Secchi depth varied between 4 and 7 m. The daily maximum tidal current velocity was 0.4 m s^{-1} at 20 m depth and 1 m s^{-1} at the surface. The average tidal range was 1.9 m (Joschko et al., 2008; Schröder et al., in press).

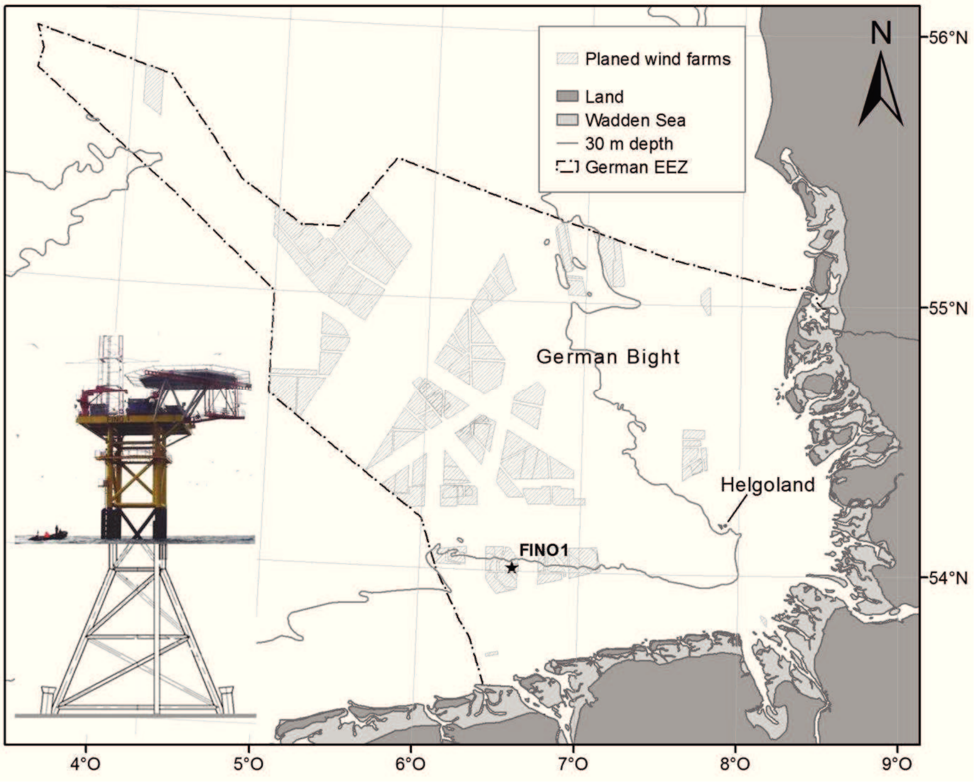

Fig. 1. The jacket construction of the research platform FINO 1 (with diving boat) and planed wind farms in the south-western German Bight. Map J. Dannheim

2.2 Sample collection and processing

The epifauna was sampled from the vertical surfaces of the four main pylons by scientific divers during cruises of the research vessel *Heincke*. Scrape samples were taken in April, July/August, and October 2005 to 2007 at water depths of 1 m (0-2.5 m), 5 m (2.5 – 7.5 m), 10 m (7.5 – 15.0) , 20 m (15.0 – 22.5), 25 m (22.5 – 27.0 m) and 28 m (27.0 – 30.0 m) below low tide level. A total of 183 single samples was taken (Table 1). Due to time constraints and for safety reasons it was not possible to always sample each pylon at all depths.

depth [m]	04.'05	07.'05	10.'05	04.'06	08.'06	10.'06	04.'07	08.'07	10.'07
1	1	5	4	4	4	4	4	4	1
5	2	3	4	4	4	4	4	4	3
10	2	4	4	4	4	4	4	4	4
20	2	0	2	4	4	4	5	5	3
25	2	4	2	4	3	4	4	4	3
28	0	4	2	4	5	3	4	4	1

Table 1. Number of scrape samples of the epifauna taken in 6 depth zones (month.'year) on the foundation of the research platform FINO 1.

At each depth the samples were taken at random positions. 20 x 20 cm samples were scraped off with a putty knife and captured in a mesh-bag (mesh size: 0.5 mm) attached to a metal frame. All samples were preserved in 4% borax-buffered formalin. In the laboratory, the samples were weighed (wet weight), pre-sorted, and the organisms preserved in 75% ethanol for later identification. The organisms were sorted and identified to the lowest taxon possible. Solitary taxa were counted. Large individuals, which were identified with the naked eye (except Amphipoda and Hydrozoa), were separated from the complete samples. Subsequently, sub samples of 1 to 3 g were taken from large samples and sorted. All individuals of *M. edulis* were cleaned from byssus and epifauna, weighed and the shell length measured to the nearest 0.1 mm. After identification, the taxa were weighed. All wet weights were corrected by the factor 1.2 to account for weight changes due to storage in ethanol (Zintzen et al., 2008). Qualitative observations during the dives were documented.

2. 3 Data analysis

Analyses were based on the biomass per taxon to allow an equal representation of colonial and solitary species. For the statistical analysis some species and congeners which could not be identified to the species level had to be combined on higher taxonomic levels to achieve a homogeneous taxonomic resolution among the samples. The biomass of the tubes of *Jassa* spp. and the byssus threads of *M. edulis* were excluded from the analysis of the epifauna community.

2.3.1 Spatial and temporal variation of the epifauna biomass

The biomasses of different depths were compared by a one way ANOVA with a subsequent Newman-Keuls Posthoc-Test. Due to the limited number of samples, the data from all years were pooled for each equal season and the depth specific biomass was compared separately for spring, summer and autumn. Prior to the analysis the biomasses data were fourth root transformed to achieve homogeneity of variance (Bartlett's test for equal variances). To understand temporal development of the biomass from the beginning until the end of the study, all sampling events were compared separately for the depth zones which had been identified by the above analysis of the depth structure of the epifauna community using Kruskal-Wallis followed by Dunne's multiple comparison (software GraphPad Prism™ v 5.04). The total biomass on the entire underwater construction of the platform was calculated by multiplying the average biomass per m^{-2} by surface area of the respective depth zone (obtained from construction plans of the platform) and summing up the values from all depth zones.

2.3.2 Export of biomass and *Mytilus edulis* shells

The potential biomass export from the epifauna on the foundation into the surrounding sediments was roughly estimated as the change in total biomass between two successive sampling events. Due to missing information on recruitment, turnover and growth between sampling events, biomass substitution between sampling events by new specimens and continuous faecal export had to be ignored. The change in the number of blue mussel (*M. edulis*) shells on the underwater construction was calculated for each depth zone to estimate the export of secondary hard substratum into the surrounding sediments. Shell production was quantified on a yearly basis, taking into consideration the changes in mussel numbers, the shell lengths, and the annual mussel biomass. The long term export of shells from the mussel stock in autumn 2007 was calculated using population turnover rates obtained from Wolfson et al. (1979).

2.3.3 Epifauna community

To detect global temporal and spatial variations the epifauna community was analysed by a two-way crossed ANOSIM (factors depth zone and sampling time). Each sample was treated separately. The sample data were root transformed to reduce the influence of dominant species (Clark and Warwick, 2001). Samples taken in spring, summer and autumn were compared by a two-way crossed ANOSIM (factors season and depth zone). This comparison was done for each year separately to identify intra-annual variations. Inter-annual variations were analysed for each season separately by a two-way crossed ANOSIM (factors year and depth zone). Characteristic species of each depth zone were identified by similarity percentage (SIMPER) analysis of root transformed data. Analyses were carried out using PRIMER™ v 6.0 (Clark and Gorley, 2006). Following Clark and Warwick (2001) we defined depth zone characterising species by two conditions: 1. The taxon discriminates the depth zone. With a consistent value it contributes to the dissimilarity ($\overline{\delta_i}$ /SD (δ_i) ≥ 1) and cumulatively with at least 80%, it adds to the dissimilarity to at least one other depth zone. 2. The taxon typifies the depth zone, contributing with a consistent value to the similarity ($\overline{S_i}$ /SD (S_i) ≥ 1) and it contributes cumulative to at least 80% to the similarity within the depth zone. The depth zones were named after the typifying species which together contribute at least 50% to the biomass.

3. Results

A total of 58 taxa was identified to species level. To achieve a homogeneous taxonomic resolution among all samples, some species had to be combined on a higher taxonomic level resulting in a data set for the analysis which consisted of 35 taxa.

3.1 *In situ* observations

Around the high tide water level a thin layer of green algae (cf. Ulvaceae), few pacific oysters (*Crassostrea gigas*), and small numbers of barnacles were found occasionally but not sampled. During all visits, at 1 m depth the surface of the platform structure was permanently covered by a compact layer of *M. edulis* with an estimated thickness of up to 40 cm. At 5 m water depth, *M. edulis* was heterogeneously distributed in lower numbers and biomass than at 1 m depth. Mussels were patchily distributed among Anthozoa and the residential tubes of the Amphipoda *Jassa* spp. Below 5 m depth the substrate was almost completely covered by a brownish layer of *Jassa* tubes and Anthozoa of estimated 2 to 5 cm widths. Millions of *Jassa* inhabited the jacket construction. In each water depth their tubes covered the steely substrate between the mussels and the Anthozoa. From the diver's perspective *Jassa*, *M. edulis* and the Anthozoa (mostly *Metridium senile*) were the characteristic organisms on FINO 1. The diver repeatedly observed hundreds of horse mackerels (*Trachurus trachurus*) swimming around and inside the construction. Close to the seafloor, at a water depth of 28 m, many pouts (*Trisopterus luscus*) were observed. Inside the scour at the base of the platform, which was covered by shell detritus, swimming crabs (e. g., *Necora puber*) and edible crabs (*Cancer pagurus*) were frequently detected close to the pylons. Quantitative data on the vagile demersal megafauna are given in Krone et al. (submitted).

3.2 Epifauna biomass

In spring, summer, and autumn, the biomass at 1 m depth was significantly higher than in all other depths ($p < 0.001$; Fig. 2). It varied between 23.3 kg m^{-2} in spring 2005 (a single sample) and 45.4 ±22.3 kg m^{-2} in summer 2007 with conspicuous seasonal fluctuation. The biomass was highest in summer and lowest in spring.

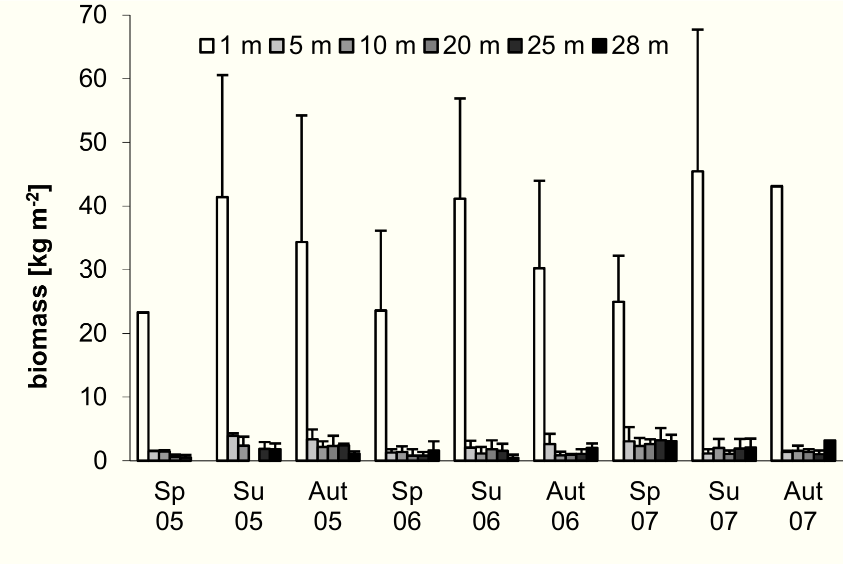

Fig. 2. Average biomass (± SD) of the epifauna on the underwater construction of the offshore platform FINO 1 at different water depths in spring (Sp), summer (Su) and autumn (Aut) up to five years after installation,2005 to 2007. Only one sample was taken in spring 2005 at 1 m depth and in autumn 2007 at 1 and 28 m depth. No sample was taken in spring 2005 at 28 m and in summer 2005 at 20 m.

However, the seasonal differences were statistically not significant ($p > 0.05$). The biomass did not vary significantly among the other depths levels and ranged from 0.5 ± 0.5 to 3.9 ± 0.4 kg m^{-2}. The biomass fluctuations did neither show a clear seasonal pattern nor a consistent trend. Consequently, the 1m depth zone will be differentiated from a 5-28m depth for the comparison of the total biomass. Within the 5-28m depth zone, the biomass varied significantly between the sampling events ($p < 0.0001$), however, no consistent seasonal pattern was apparent. In spring 2007, the biomass was significantly higher than in spring 2005 (factor 2.4) and throughout 2006 (spring factor 2.9, summer factor 2.5, autumn factor 2.3). The only significant seasonal variation existed in 2007 with 1.9 times higher biomass in spring than in autumn ($p < 0.05$).

3.3 Export of biomass and *Mytilus edulis* shells

The total biomass on the platform construction was highest in summer 2005 at 5,690 kg (Fig. 3). The seasonal fluctuations of the total biomass decreased from 2005 to 2007. Accordingly, the biomass was seasonally more stable on a high level of about 5,000 kg throughout the 2007 sampling period. 50% of the biomass occurred in the 1 m depth zone. However, it has to be kept in mind that in autumn 2007 the biomass in the 1 m depth zone was estimated from a single sample. The total biomass in spring increased throughout the investigation period while the biomass in summer and autumn were roughly similar between the years. Averaging the masses of spring, summer and autumn per year a slight increase can be assumed on a yearly basis during the study period.

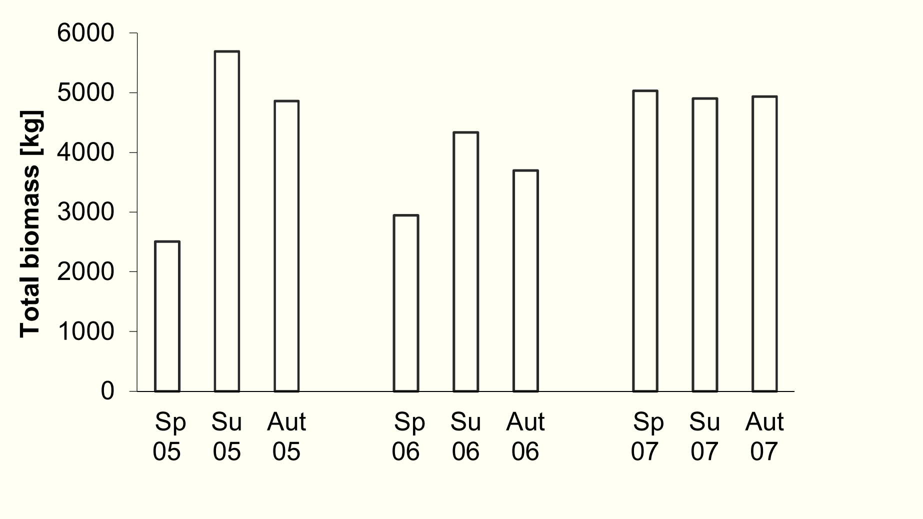

Fig. 3. Total biomass of the epifauna community on the foundation of the offshore platform FINO 1, North Sea, up to five years after construction. Spring (Sp), summer (Su) and autumn (Aut), 2005-2007.

At present, however, the trend of increasing biomasses was only significant between the spring samples from the 5-28m zone (compare section before). Abundance and length of *M. edulis* differed between the 1 m depth zone and all deeper levels. From 2005 to 2007, the abundance decreased from 22,350 ± 15,360 ind. m^{-2} to 4,970 ± 2,470 ind. m^{-2} in the 1m depth zone and from 2,470 ± 2,360 ind.m^{-2} to 130 ± 240 ind.m^{-2} in the 5-28m depth zone. Below the 1 m depth zone the abundance decreased at all depths. In the 1m zone, the average shell length increased from 17.5 ± 14.8 mm in 2005 to 35.4 ± 18.6 mm in 2007. The mussel shells were an order of magnitude shorter in the 5-28 m zone and the shell length remained relatively stable at 2.9 ± 3.8

mm in 2005 and 2.4 ± 5.3 mm in 2007. Calculated for to the entire submarine surface in the 1m depth zone, 882,600 complete shells (i.e. both valves) (17.5 - 29.6 mm) fell off the foundation during 2005 to 2006 (Fig. 4) and 232,600 complete shells (29.9 - 35.4 mm) during 2006 and 2007.

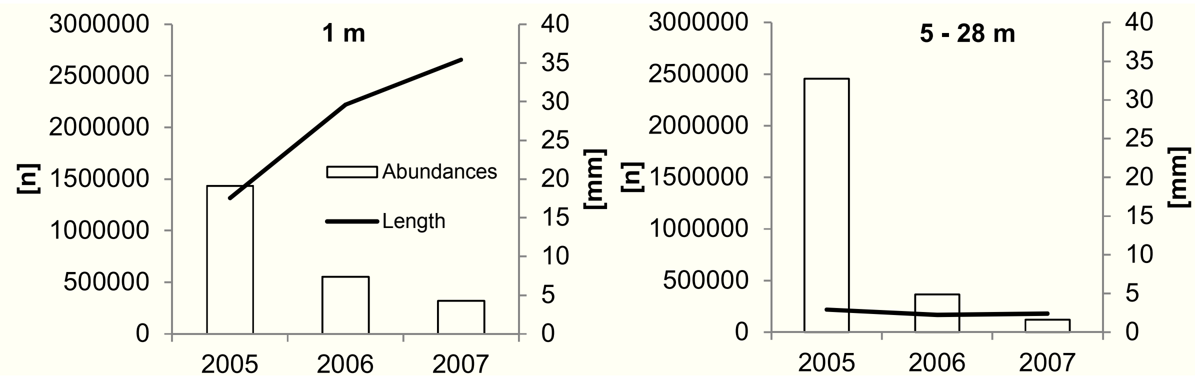

Fig. 4. Abundance and length of *M. edulis* in the 1 m and the 5-28 m zone of to the foundation of the offshore platform FINO 1, North Sea. Abundance and shell length from different seasons (spring, summer, autumn) were pooled for each year.

Calculated for the 5-28 m depth zone, 2,089,400 shells with a length of 3.8- 5.7 mm were released at the platform foundation during 2006 to 2007 and 246,720 complete shells with a length of 5.3-5.7 mm from 2006 to 2007. In 2007, a total of 318,850 live mussels with an average shell length of 35.4 ± 18.6 mm occurred in the 1m depth zone providing a total biomass of 2,130 kg. A total 120,360 specimens with an average shell length of 2.4 ± 5.3 mm colonized the 5-28m depth zone with a total biomass of 105 kg. Due to shell weight (ash weight) being 0.24 ± 2.9 times of the mussel's total biomass (Krone and Joschko, not published), 535 kg pure mussel shells were attached to the entire construction. Calculating with a ratio of 0.011 between volume (m^3) and the tissue biomass (kg) of living *Mytilus* colonies (Wolfson et al., 1979), the total attached mussel volume was 19 m^3 during the final investigation year. The analogous average mussel layer width of 26 cm at 1 m depth (on 64 m^2) and the not detectable < 1 cm between 5 and 28 m (on 1215 m^2) are conform to the divers' observations during sampling. The outer sides of the shells (presuming an elliptic planar surface) of *M. edulis* provided 303 m^2 surfaces in 2007.

3.3 Epifauna community structure

Global differences

The structure of the epifauna community varied significantly between the sampling events ($R = 0.45$, $p < 0.001$) and between the depth zones ($R= 0.56$, $p < 0.001$). The community at 1 m depth could clearly be distinguished from the communities in all other depths while the community at 5 m depth differed from the communities found at 20, 25 and 28 m depth but not from the community at the 10 m depth (Table 2). The 10 and the 20 m depth zones contained similar communities. Finally, the communities in the 20 to 28 m depth zones were indistinguishable. Accordingly, three specific epifauna communities were identified typifying the 1, 5 and 20-28 m depth zones. The community in the 10m depth zone was considered a transition between the 5 and the 20-28m depth zones.

m	1	5	10	20	25
5	0.96*				
10	0.98*	0.14*			
20	1.00*	0.50*	0.16*		
25	1.00*	0.50*	0.24*	0.08	
28	0.96*	0.50*	0.24*	0.29*	0.09

Table 2. R-values from pairwise comparisons of epifauna communities in different depth on the underwater construction of the offshore platform FINO 1 in the North Sea by a two-way crossed ANOSIM based on √ transformed biomass data (factors water depth and sampling event). Asterisks indicate significant differences ($p < 0.05$).

Among the typifying taxa *M. edulis* was the dominant taxon with regard to biomass and constituted 96.2 and 40.7 % of the total biomass in the 1 and 5 m zone, respectively (Fig. 5). Beneath the 1 m depth zone the biomass of the Anthozoa increased while the biomass of *M. edulis* decreased. Within the 20-28 m zone Anthozoa achieved 46.2 % of the total biomass whereas *M. edulis* contributed less than 1% to the total biomass. The Amphipoda *Jassa* spp. were characteristic for all depth zones and from 5 to 28 m they contributed between 22.2 and 27.5 % to the total epifauna biomass.

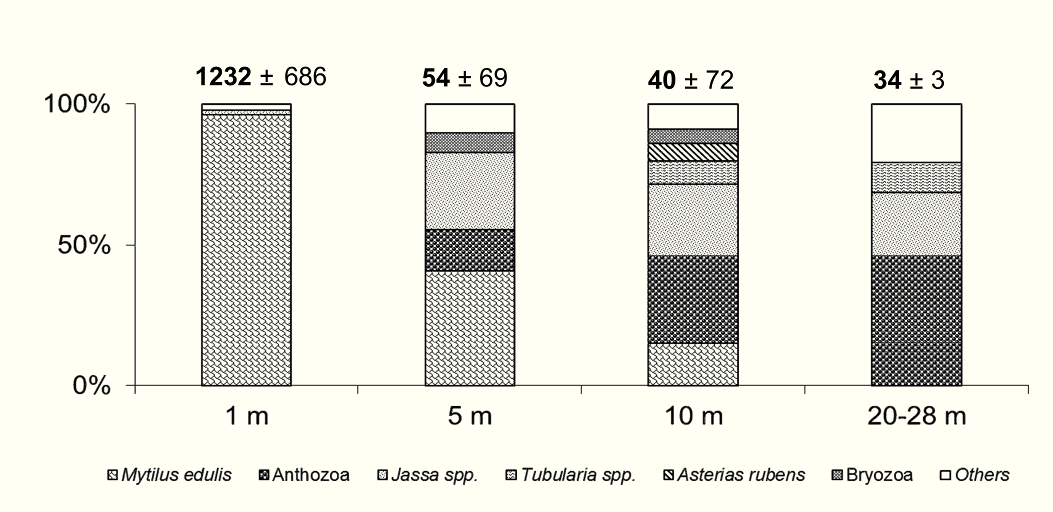

Fig. 5. Average contribution (%) of the depth zones typifying taxa (identified by SIMPER analysis) to the total epifaunal biomass in each depth zone on the underwater construction of the offshore platform FINO 1. Numbers above the bars give the average total biomass (g 0.04 m^{-2} ± SD) of the epifauna in each depth zone.

Accordingly, four depth specific communities were identified

1. The "1m zone ***Mytilus* community** with subordinate co-occurring *Jassa"*
2. The "5 m zone ***Mytilus*-*Jassa* community** with subordinate co-occurring Anthozoa and Bryozoa"
3. The "10m transient zone **Anthozoa-*Jassa* community** with co-occurring *Mytilus*, Hydrozoa, *Asterias rubens* and Bryozoa"
4. The "20-28m zone **Anthozoa community** with co-occurring *Jassa* and Hydrozoa"

Thus, *M. edulis*, Anthozoa and *Jassa* were the dominant species of the epifauna community. Calculated for the entire submarine foundation, the average biomass of these taxa during the study period was 2,060 kg, 430 kg and 306 kg, respectively, while all other taxa together had an average biomass of 337 kg. *Jassa* residential tubes achieved 832 kg and *M. edulis* byssus 72 kg. *M. edulis* achieved 2,849,000, the Anthozoa 2,145,000 and *Jassa* 324,855,000 single specimens at the foundation.

Intra-annual variations

Variations were detected in all three sampling years (√ transformed data two-way crossed ANOSIM and two way SIMPER, factors season and depth). But no obvious pattern could be detected. The community differed between all three seasons in the first and last investigation year but not between. The depth segregation either follows no seasonal trend and its peculiarity varies undirected. But, during all years the depth variations of the community were stronger than the seasonal variations.

Inter-annual variations

During the first and second research year (2005-2006) the communities did not differ (spring-spring R 0.10, p 0.20; summer-summer R 0.04, p 0.25; autumn-autumn R 0.10, p 0.11. (two-way crossed ANOSIM, year and depth zone). However, spring, summer and autumn communities changed between 2006 and 2007 (R 0.48, p 0.001; R 0.44, p 0.001; R 0.30, p 0.001). In spring, summer and autumn the 1m zone differed strongly from all other depth-zones ($R > 0.91$, p 0.001) due to very high *M. edulis* abundances.

The segregation of the greater depths differed between the years and was lowest in 2007 in all three seasons. **Spring:** The differences between the first and the third year in spring are mostly due to the occurrence of *Tubularia* spp. and in relevant masses with 5 times more Anthozoa and 1.5 times more *Jassa*. **Summer:** In summer, the differences between the first and third year were mostly because there were 1.5 times more Anthozoa, 5 times more *Tubularia* spp. 2.5 times fewer *Jassa* in the last study year. **Autumn:** The differences between the first and the third year in autumn were mostly due to 1.3 times more Anthozoa and 1.4 lesser *Jassa* and 7 times lesser Bryozoa in 2007.

The subsequently performed ANOSIM and SIMPER (factor depth zone, √ transformed data) (Fig. 6) showed that the depth zone segregation below the 1m zone varied during the whole study period and disappeared in autumn 2007. As seen in the biomasses of relevant species (Table 3) the Anthozoa became more important towards the final samplings throughout the study during all seasons.

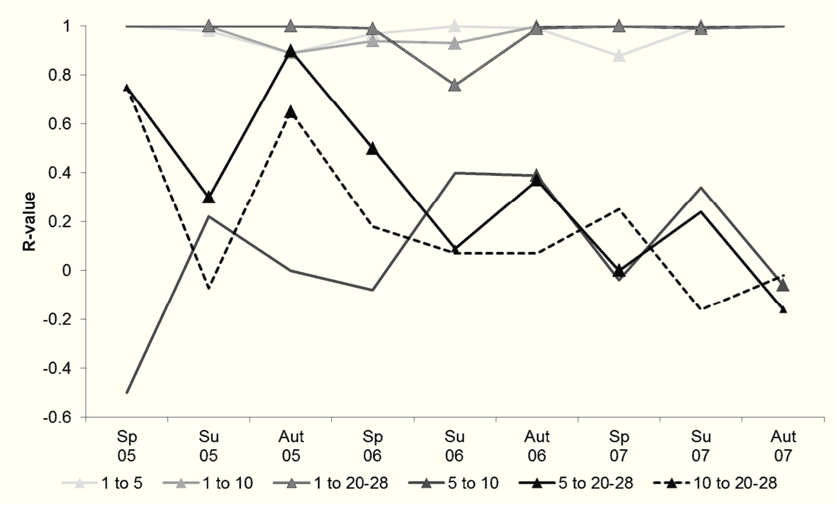

Fig. 6. R-values between depth zones (ANOSIM, ▲ donates for p < 0.05).

Their percentile share increased and achieved high values. At the same time, the *M. edulis* chare below the 1m zone decreased in all seasons and years. At the last sampled data in summer and spring, the community in the depths from 5 to 28 m were dominated by the Anthozoa; *M. edulis* occurred only with negligible shares and was not depth zone typifying. In 2007, the Hydrozoa *Tubularia* spp. achieved depth-zone typifying relevance for the zones deeper than the 1m zone. *Asterias rubens* appeared with relevant abundances but without conspicuously high masses. *Jassa* spp. contributed to all depth zone communities.

Table 3. Average not transformed biomasses and percentile shares of depth zone characterising species (revealed by SIMPER analysis with √ transformed biomasses, see text for definition) at all investigation years and seasons. Less than two samples in groups at 1 m in spring 2005 and autumn 2007. For the characterising species at the 5 and 10m zones in 2005 the preconditions $\overline{\delta_i}$ /SD (δ_i) ≥ 1 and $\overline{S_i}$ /SD (S_i) ≥ 1 were assumed (less than 3 replicates).

			biomass [g 0.04 m^{-2}] and [%]							
		Taxa	1 m		5 m		10 m		20-28 m	
2005	Spring	*Mytilus edulis*	753.8	94.3	**20.2**	48.7	**26.8**	71.8	<0.1	<0.1
		Jassa spp.	17.3	2.2	**10.4**	25.2	**6.9**	18.6	**5.5**	55.5
		Asterias rubens	21.5	2.7	**5.9**	14.3	1.7	4.5	1.5	15.7
		Bryozoa	2.6	0.3	**4.4**	10.7	1.4	3.8	**0.4**	3.9
	Summer	*Mytilus edulis*	**1316.7**	93.4	25.3	31.6	0.6	1.2	2.6	6.7
		Jassa spp.	**46.6**	3.3	**23.7**	29.6	**39.9**	68.0	**13.8**	36.8
		Anthozoa	25.2	1.8	**12.1**	15.2	**7.4**	15.7	**12.9**	34.3
		Bryozoa	2.6	0.2	**8.8**	11.0	**4.7**	10.0	**3.3**	8.8
	Autumn	*Mytilus edulis*	**1093.5**	97.7	**37.7**	48.0	11.0	27.4	0.1	0.3
		Jassa spp.	16.1	1.4	**30.5**	38.8	**9.5**	23.8	1.8	4.6
		Anthozoa	2.9	0.3	**4.5**	5.7	**10.3**	25.6	**31.5**	81.6
		Bryozoa	1.1	0.1	**2.9**	3.7	**1.1**	2.9	**2.6**	6.7
2006	Spring	*Mytilus edulis*	**796.3**	93.6	**19.8**	50.7	18.7	46.9	<0.1	<0.1
		Jassa spp.	11.2	1.3	**9.2**	23.5	**12.1**	30.4	**6.1**	28.6
		Bryozoa	2.2	0.3	**7.1**	18.2	**4.9**	12.4	**0.7**	3.3
		green algae	**24.1**	2.8	0.1	0.2	0.0	0.0	0.0	0.0
	Summer	*Mytilus edulis*	**1504.0**	97.6	**34.0**	52.1	5.7	17.9	0.1	0.3
		Jassa spp.	**17.4**	1.1	**13.9**	21.3	**8.9**	28.0	**13.8**	38.7
		Anthozoa	4.9	0.3	2.7	4.1	0.2	0.5	**4.1**	11.6
		Asterias rubens	0.1	<0.1	**8.5**	13.0	**0.6**	1.8	**0.8**	2.3
		Bryozoa	11.7	0.8	**5.2**	8.0	**4.4**	13.7	**12.1**	34.0
	Autumn	*Mytilus edulis*	**1117.6**	98.5	24.3	39.6	0.01	0.01	<0.1	0.1
		Jassa spp.	7.4	0.6	**14.0**	22.8	**2.3**	10.8	**1.2**	4.9
		Anthozoa	2.6	0.2	**14.3**	23.3	**16.6**	77.0	**17.8**	73.5
		Asterias rubens	0.3	<0.1	**3.0**	4.9	**1.2**	5.7	0.5	1.9
		Porifera	1	0.1	1.1	1.8	0.1	0.6	**0.6**	2.7
		Bryozoa	3.7	0.3	**3.6**	5.9	0.5	2.3	**2.7**	11.0
2007	Spring	*Mytilus edulis*	**899.7**	97.5	29.5	49.5	0.02	0.05	0.03	0.1
		Jassa spp.	14.1	1.5	**19.0**	31.9	**10.8**	22.9	**16.1**	43.0
		Anthozoa	2.4	0.3	4.4	7.5	12.7	26.9	**5.7**	15.3
		Tubularia spp.	1.6	0.2	3.3	5.5	**14.3**	30.4	10.5	28.0
	Summer	*Mytilus edulis*	**1631.5**	96.8	**0.3**	1.5	0.2	0.3	1.9	3.9
		Jassa spp.	**20.9**	1.2	**5.0**	22.9	**2.9**	5.5	**1.6**	3.2
		Anthozoa	**10.9**	0.6	11.1	50.3	**32.3**	62.1	**36.2**	74.1
		Tubularia spp.	2.7	0.2	**3.8**	17.2	**7.9**	15.2	**5.8**	11.8
		Asterias rubens	6.1	0.4	0.2	1.0	**3.6**	6.9	**1.2**	2.5
		Porifera	2.3	0.1	**1.1**	5.2	3.8	7.4	0.1	0.3
	Autumn	*Mytilus edulis*	1549.7	96.0	0.6	1.8	0.1	0.1	-	
		Jassa spp.	51.3	3.2	**4.9**	15.7	**3.9**	10.5	**2.6**	7.4
		Anthozoa	2.3	0.1	**22.1**	71.4	**24.4**	65.6	**26.4**	76.1
		Tubularia spp.	1.2	0.1	**1.3**	4.3	**2.2**	5.9	3.1	8.9
		Asterias rubens	1.2	0.1	2.0	6.6	**3.7**	10.0	1.9	5.6

4.0 Discussion

In future offshore wind farms, thousands of wind turbine foundations will provide habitat for a hard bottom fauna which otherwise restricted to the sparse rocky habitats scattered within extensive sedimentary soft bottoms of the German Bight. For the German Bight it was proofed that an offshore construction functions as a biomass hotspot within extensive soft sediment seafloor terrains. Such constructions also produce secondary artificial hard substrates by mussel shell litter fall and most probably alter the local ecology due to the fact that they are colonized by allochthonous epifauna communities.

4.1 Biomass and substrate production

Biomass production

Approximately half of the total biomass (4,300 kg on average; 5,000 kg during the last year) was attached to the 1m zone. More than 90% of the mass was *Mytilus edulis*. Throughout the investigation, the biomass in the uppermost sections of the underwater construction right below the sea surface fluctuated between 25 and 40 kg m^{-2} but remained high with no consistent interannual development. On oil rigs, the biomass remained stable at this depths 5 years after construction (Kingsbury, 1981). In contrast, the biomass increased in deeper water levels of the platform FINO 1 throughout the study period. In the longterm, this increase might lead to biomass below 20 m depth that is comparable to that found in the 1m depth zone also in the deeper levels of at least 20 m (Kingsbury, 1981).

With 4.9 kg biomass on a footprint area of 1024 m^2, the platform represents a macrozoobenthos hotspot within a sedimentary environment where the average macrozoobenthos biomass is 0.12 kg m^{-2} (Dannheim, not published). When extrapolated to 5,000 wind turbine foundations in the German EEZ, our results predict additional 25,000 tons of biomass in that region which is equivalent to the macrozoobenthos biomass of 208 km^2 sandy soft bottom or an increase of 0.8 % of total macrozoobenthos biomass. This biomass will be continuously exported from the artificial constructions into the surrounding sediments as released metabolic waste products or (dead) individuals that fall off the substratum. The largest biomass difference at FINO 1 was detected between summer 2005 with 5,700 kg and the following spring 2006 with 3,000 kg. The biomass of animals which are substituted by new recruits as well as the growth during this period was ignored and 2,700 kg were expected to be a careful estimation of the potential net export of biomass within ¾ year because for comparable sites biofouling turnover rates of 11-18 months are possible (Wolfsson et al., 1979; Kingsbury, 1981). Therefore, a calculated yearly minimal net export of 13,500 tons from 5,000 turbines is a careful assumption. These masses may represent a secondary net production of biomass in the eutrophic North Sea (Carstens et al., 1990; Radach, 1992; Hickel et al., 1993; van Beusekom et al., 2008). The prospering communities on the artificial structures intensify the transformation of particulate organic matter (POM) into biofouling masses – which will be available for consumers of higher trophic level (Wolfson et al., 1979; Freire and González-Gurriarán, 1995; Page et al., 1999; Reubens et al. 2011; Krone et al., submitted). In turn, substantial increases of predators may lead to an alteration of the predatory pressure on certain prey organisms (Baum and Worms, 2009).

*Mytilus*ation

M. edulis are common in the Wadden Sea and on natural hard substrates in the North Sea, but also on man-made constructions (Kingsbury, 1981; Riesen and Reise, 1982; Whomersly and Picken, 2003; Reise, 2005; Buschbaum et al., 2009; Kerkhoff et al. 2010). At FINO 1, mussels accounted for about 75% of the whole epifaunal biomass. During this investigation, *M. edulis* occurred almost exclusively in the uppermost depth zone where the numbers decreased during the course of the investigation while shell size increased. Thereby, the biomass remained on a high constant level in the 1m depth zone. At deeper levels, mussel biomass and abundance decreased. The massive colonization of thousands of offshore wind turbine foundations by *M. edulis* will lead to a *Mytilus*ation of offshore regions which will be accompanied by effects on the local ecosystem through the production of secondary hard substrates, the massive release of planktonic larvae, and an intensified filtration of the North Sea water. The substrate export due to mussel shell litter fall changed qualitatively throughout the study time. The last detected standing stock contained 319,000 double shells at the 1m zone and 120,000 at all deeper zones; totalling 2,000 kg mussel shells. Assuming a yearly turnover (Wolfson et al. 1979), this amount of shells would also be exported every year. The revealed annual hard substrate production (303 m^2 mussel shell surface) may alter the substrate characteristic of the surrounding sea bottom to some degree. Yearly, 878,000 single shell halves sink onto the bottom. Therefore the reef effect exceeds by far the habitat creation by the construction of ~1300 m^2 steel surface. Within 15 years, calculated 4,545 m^2 mussel shells, 3.5 times of the construction surface, will be added to the sea floor. Many of the shells will be ground to sand and covered by sediment, however, as found beneath mussel aquacultures (Freire and González-Gurriarán, 1995) and offshore rigs (Wolfson et al., 1979) the production of long lasting shell debris may lead to coarser, shell-dominated sediment and enriched structure diversity. Aggregated as well as dispersed shells potentially serve as attachment sites for sessile reef forming organisms such as *Sabellaria* spp. (Holt et al., 1998) and *Ostrea edulis* (Schmidt, 2009). This additional stock in offshore locations will be a permanent larvae source for settlement in artificial and natural offshore and coastal habitats. Another 10^4 tons or 1.6 x 10^9 individuals of *M. edulis* (calculated for 5000 wind turbines) would add an additional 60% and 33% (calculated with FINO 1 data from 2005 and 2007) of the already existing German Wadden Sea mussel population to the ecosystem (Nehls et al., 2009). The mussels must be expected to influence the water clearance through their filtering activity at least on a local scale. With an average filtration rate of 1.5 to 3.0 L h^{-1} $individual^{-1}$ (Mølenberg and Riisgård, 1979; Famme et al., 1986; Clausen and Riijsgård, 1996) this offshore mussel population will filtrate an amount of seawater which is within the range of the combined effluent of the rivers Elbe, Weser, Ems, and Eider (4.56 x 10^9 l h^{-1}) into the German Bight. These calculations are based on the abundance, biomass and the specific distribution pattern of *M. edulis* on FINO 1 in the years 2005-2007. Previous studies have shown that *M. edulis* populations on offshore construction can extent into much deeper waters (Kingsbury, 1981; Whomersly and Picken, 2003). A recent inspection of the platform construction revealed that *M. edulis* is expanding into deeper water levels (Winter, unpublished results) indicating that the mussel biomass will further increase even after longer periods of time after the construction of the platform. To what extend the expected *Mytilus*ation will influence the North Sea ecosystem will also depend on the size, shape and material of the future wind turbine foundations.

4.2 Epifauna communities on the artificial structure

The biomass of the epifauna community remained relatively stable on a yearly basis with a tendency towards higher values in summer while the structure of the community changed during the investigation. On other offshore constructions, substantial changes in the epifauna community still occurred nine years after construction (Whomersley and Picken, 2003; Butler and Conolly, 1999). The epifauna on the underwater construction of FINO 1 was vertically structured into three distinct communities. In the 1 m zone the community was dominated by *M. edulis*. In the 5 m depth zone, the *M. edulis* cover became interspersed by tubes of the Amphipoda *Jassa* spp. Below the 5 m zone down to the seafloor the community was dominated by Anthozoa. In some seasons, the distinction of these three communities was less pronounced and was not evident in summer 2005 and in autumn 2007. Whether a uniform community will develop below the *M. edulis* belt in the long term, as it has been described for steely foundations in Danish and Dutch coastal waters (Leonhard and Pedersen, 2006; Lindeboom et al., 2011), remains to be seen. The composition of the epifauna community varied seasonally, however regular seasonal cycles with typical spring, summer or autumn communities were not evident, even though some species showed consistent biomass cycles each year. For example, biomass of *M. edulis* was lowest in spring and highest (approximately double) in summer. Biomass of the Anthozoa was lowest in spring. Similar pronounced seasonal biomass fluctuations have been reported from soft bottom epibenthos (Reiss and Kröncke, 2004).

Macroalgae were almost entirely absent from the platform construction. Water turbidity would allow macroalgae to proliferate in the German Bight into water depths of at least 7 (green algae), 10 (red algae) and 5 m (brown algae), respectively (Lüning, 1970; Pehlke and Bartsch, 2008) at FINO 1. Dense brown algae stocks have been reported from platforms in the central North Sea (Kingsbury, 1981). The lack of algae may be a result of the young age of FINO 1 community where changing biofouling layers may not allow enough time for an algal community to develop. Other reasons may be the variability between individual offshore constructions in general, where succession depends on the date of exposure or the presence of browsers (Kingsbury, 1981).

The community below the 1m zone was dominated by Anthozoa. The many juvenile *M. edulis*, which were observed in deeper sections of the foundation at the beginning of the investigation period, vanished over time and the Anthozoa started to take over in addition to *Jassa.* The Hydrozoa *Tubularia* spp. started to contribute significantly to the deep community during the 5th year after construction. Increasing amounts of *Tubularia* spp. agree with observations by Zintzen et al. (2008) and Krone (not published) who found that most ship wrecks in deeper waters were dominated by Anthozoa or Hydrozoa.

The subtidal zonation pattern on FINO1 differs from those on offshore platforms in deep waters of the central and the northern North Sea where *M. edulis* dominated since the third year after construction down to a water depth of 20 m. In deeper levels from 20 to 140 m, Hydrozoa and Anthozoa (on a single platform) dominated the communities while the tubes of *Jassa* did not seem to contribute conspicuously to the surface coverage (Whomersley and Picken, 2003). At concrete foundations of offshore wind turbines in Belgian waters, *M. edulis* dominated stocks were reported from the shallow subtidal down to 20 m during the first two years after construction (Kerckhof et al., 2010). At FINO1, *Jassa* rather than *M. edulis* dominated the surface cover in the 15-20 m water depths. Perhaps in the Belgium case the juvenile cover will also decrease due to crabs and *Asterias rubens* as their main predators (Wolfson et al. 1979; Reise pers. comm.). The different zoning of concrete gravity foundations and the steely FINO 1 as well as general differences between the communities on these two substrates (Conell, 2001; Andersson et al., 2010) need to be considered in future in-depth epifauna research and impact assessments.

The dominant epifauna species on FINO 1, *M .edulis*, Anthozoa (mostly *Metridium senile*) and *Jassa* also occur in the littoral of the island of Helgoland (Anger, 1978; de Kluijver, 1991 Reichert and Buchholz, 2006; Reichert et al., 2009) which is the only significant comparable natural rocky littoral site in the south eastern North Sea. At Helgoland, *M. edulis* is restricted to the lower intertidal where the species reaches a surface coverage of only 0-5.7 % (Reichert et al., 2008). Deeper, down to 17 m water depth, *M. edulis* is not abundant either with a maximum surface coverage of 2.6 % (de Kluijver, 1997) These mussels densities appear negligible as compared to the dense *M. edulis* belt on FINO 1. *Metridium senile* as well as Anthozoa are patchily distributed. Within the patches these species might occur with densities comparable to those on the FINO 1 underwater construction. However, large areas of the Helgoland rocky subtidal are almost entirely free of these species. *Jassa*, which is very abundant on FINO1, occurs also in the natural intertidal of Helgoland albeit in, lower densities than on the offshore platform (Reichert et al., 2008; Reichert and Buchholz, 2006). Only on the artificial hard substrata of Helgoland, such as pontoons and jetties, these Amphipoda achieved densities of up to about 20,000 individuals m^{-2} (Nair and Anger, 1979; Beermann and Franke, 2012). In comparison FINO 1 provides ten times more *Jassa* per m^2 than Helgoland's artificial habitats. The permanent presence of *Jassa* with its lifespan of 149 to 252 days (Nair and Anger, 1979) may yield 1.5 to 2.5 times per year of the 306 kg (plus 830 kg tubes) and 3.3×10^8individuals are being produced at FINO 1. They may serve as a rich and easily accessible food resource for e.g., large pouting coveys (*Trisopterus luscus*) which feed in the vicinity from artificial hard substrata on *Jassa herdmani* (Reubens et al., 2011).

Our results showe that offshore constructions such as platforms and wind turbines not only increase the amount of habitat available for hard bottom communities in the North Sea. They also allow for a massive population increase of certain species, which might, for example, result in a *Mytilus*ation of the ecosystem. Furthermore, artificial hard substrata might add a benthic component to the process of "jellification" of coastal seas (Richardson et al., 2009) as they allow for the colonization by abundant Anthozoa. Finally, high densities of Amphipoda will provide a valuable food source for fish and other predators. Wind turbine foundations will likely provide stepping stones for the spread of hard bottom species. In this context, Lindeboom et al. (2011) suggest that the function of wind turbine foundations will hardly exceed those of the thousands of ship wrecks, which have been present in the North Sea for a long period of time. However, among 64 investigated ship wrecks in the German Bight not a single one (Krone and Schröder, 2011) has been visibly colonized by *M. edulis* (Krone and Schröder, not published). Additionally, the pacific oyster *Crassostrea gigas,* which is restricted to a maximum water depth of 15 m (Miossec et al., 2009), has not been detected on ship wrecks or in the deeper sections of FINO 1 while the intertidal of the platform has been successfully colonized by *M. edulis* and the invasive oyster. These examples clearly demonstrate that wind turbine foundations will add an extensive qualitatively new intertidal and shallow subtidal habitat in the North Sea and, thus, also numerous stepping stones for the spread of species which are able to colonize this habitat.

Conclusion

The present study provides the most comprehensive biofouling data on offshore artificial construction for the south easterly North Sea. It is a basis for impact scenarios related to the large-scale introduction of the artificial reefs and for long-term studies in this context. As a tribute to project extent and diver safety, methodological constraints need to be taken into consideration and must be recognised when interpreting the results and predicted scenarios. Since weather conditions hardly allow an offshore sampling in winter, this season was not included. The present data allows, for example, more in-depth analysis on biodiversity. Offshore constructions will accumulate epifaunal biomass as a kind of hotspot and alter surrounding sediments. The high numbers of suspension feeders on the surfaces of the constructions will remove large amounts of suspended particles from the water column and provide valuable food for intermediate and top predators, potentially altering the local food net. Although the cumulative effects of numerous wind turbines in future wind farms cannot be appropriately estimated yet the predicted *Mytilus*ation and better food availability for vertebrates and invertebrates are suggested to be major effects on the ecosystem. Further research is required to assess whether the epifauna community structure and its depth distribution at FINO 1 remain stable over time and whether other foundation types support different communities. The process of *Mytilus*ation and its effects on the cycling of matter and energy as well as the associated generation of biogenic reefs are still at the very beginning as only a small percentage of the thousands of planned wind turbines have been built so far.

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PUBLICATION VII

Will the spread of offshore wind power alter biodiversity in the North Sea?

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Estuarine, Coastal and Shelf Science submitted manuscript

Will the spread of offshore wind farms alter biodiversity in the German Bight?

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Abstract Within the next decades large offshore wind farms will be constructed in offshore waters of the German Bight (North Sea). The underwater structures of thousands of wind turbines will substantially increase the amount of habitat available for a diverse hard bottom fauna which has formerly been restricted to only few natural hard substrates and numerous wrecks. In contrast to wrecks the underwater structures of wind turbines will extend throughout the entire water column and might, therefore, provide a new type of hard bottom habitat with respect to water depth. To estimate the potential impact of these new structures on the regional biodiversity we compared the mobile mega-epifauna (decapods and fish) associated with five wrecks, the underwater construction of an offshore research platform (a wind turbine equivalent) and open soft bottoms in the southern German Bight. The mobile epifauna assemblages on the near bottom sections of the platform construction and on the wrecks were similar. However, the upper sections (5 and 15 m depth) of the platform construction were only sparsely colonized by mobile epifauna. The epifauna assemblages of the artificial hard substrates and the open soft sediments differed clearly from each other. On a regional scale the additional hard substrates will allow for a doubling of the abundance of typical hard bottom species. We expect that the addition of numerous underwater constructions in future offshore wind farms will alter the biodiversity of the German Bight by supporting an increase in abundance of predatory hard bottom species.

Key words: artificial reef, crustaceans, fish, mobile epifauna, offshore platform, wrecks, North Sea

1. Introduction

The offshore wind energy industry is expanding towards the open North Sea. A total of about 5,000 single wind turbines are planned for construction in the German Exclusive Economic Zone (EEZ) within the next two decades (BMU, 2010; IEA, 2008). Offshore wind turbines are large, fast rotating objects above the sea surface which are expected to affect birds (Masden et al., 2009; Hüppop et al., 2006) and bats (Ahlén et al., 2007). Below the surface the huge artificial constructions may equally affect marine life. For example, sound emissions during construction and operation of the turbines can deter or even injure marine mammals and fish (Madsen et al., 2006; Kikuchi, 2010; Wahlberg and Westerberg, 2005).

Wind farms in the German Bight provide numerous artificial hard substrates in areas which are naturally dominated by soft bottoms. In the southeastern North Sea the island of Helgoland and few glacial bolder reefs provide the only natural subtidal hard substrates. However, the bottom of the North Sea has been loaded with numerous artificial structures long before the construction of wind turbines. More than 1,000 wrecks have been registered in coastal and offshore waters of the German EEZ (Krone and Schröder, 2011). These artificial, reef-like structures punctuate the otherwise homogenous sandy North Sea bottom.

The large mobile wreck fauna of the southeastern North Sea is as yet only poorly investigated. Massine et al. (2002) gave an overview over the Belgian wreck fauna. Zintzen et al. (2008, 2008a) and Zintzen and Massin (2010) compared the epifauna of nine respective ten ship wrecks in Belgian waters. Leewis et al. (2000) inventoried the mobile megafauna (fishes and large decapod crustaceans) at 21 wrecks and on the underwater construction of a production platform in offshore waters of the Netherlands. The latter study revealed clear variations in the faunal composition among wrecks from different water masses. However, all studies concluded that the epifaunal assemblages on wrecks differed substantially from the biota of the surrounding soft bottoms by a high degree of sessile organisms.

The foundations of wind turbines will provide ample habitat for fouling organisms (Whomersley and Picken, 2003; Joschko, 2008), large mobile epibenthos and fish (Picken et al., 2000; Jørgensen et al, 2002; Løkkeborg et al., 2002; Andersson et al., 2009; Langhamer et al., 2009). Furthermore, artificial hard substrates in the marine environment are expected to facilitate the invasion and establishment of non-indigenous species (Bulleri and Chapman, 2010; Zintzen and Massin, 2010). Whether offshore wind turbine foundations will simply add to the existing pool of artificial structures or whether they will represent qualitatively different habitats and, thus, a new element to the benthic system is as yet unknown. Wind turbine constructions differ from wrecks in that they reach through the entire water column while wrecks usually extend only a few meters above the seafloor. Previous studies have shown that water depth and gradients in light intensity and wave force are important structuring factors for epifaunal assemblages on natural and artificial hard substrates (Whomersly and Picken, 2003; Castric and Chasse, 1991). Particularly in deeper offshore waters wind turbines will, thus, provide a more heterogeneous habitat with regard to water depth and light intensity distribution than wrecks and might, therefore, be inhabited by a qualitatively and quantitatively different biota.

Most studies on the biota on artificial structures in the North Sea focused on fouling communities (Wilhelmsson and Malm, 2008; Zintzen and Massin, 2010; Zintzen et al., 2006; Joschko et al., 2008). However, large, mobile crustaceans and fishes often dominate subtidal wreck assemblages in terms of biomass (Leewis et al., 2000; Arena et al., 2007). The mobile megafauna is a functionally important group including numerous predators that potentially control the wreck fauna (Freire and González-Gurriarán, 1995; Relini et al., 2002; Baum and Worm, 2009; McCauley et al., 2010). Furthermore, large and mobile macrozoobenthic species are rapid and sensitive indicators for habitat quality because they can actively abandon unfavorable habitats (Reiss et al., 2009). Finally, some megafaunal species such as edible and velvet crab are commercially important.

In this study, we will test the following hypotheses: (1) The mobile mega-epifauna differs substantially between the underwater constructions of offshore wind turbines and the surrounding soft sediments. (2) The underwater constructions of offshore wind turbines will harbor different mobile mega-epifauna assemblages than wrecks because they provide additional habitat in higher sections of the water column.

We inventoried the mobile mega-epifauna (> 1 cm) on the underwater construction of the offshore research platform FINO1, five wrecks and sandy bottoms in the southern German Bight (North Sea). FINO1 was built to measure biological and physical parameters relevant for the operation of offshore wind farms.The underwater construction of the platform is similar in size and shape to the common jacket type foundations of wind turbines in the German Bight. It is, therefore, considered a “dummy wind turbine” which allows for drawing direct conclusions on the implications of the underwater constructions of offshore wind turbines on marine biota.

2. Materials and methods

2.1. Study sites

From summer 2007 until spring 2009 visual censuses were performed on the mobile mega-epifauna on four ship wrecks and a sunken floating dock, the underwater construction of the offshore research platform FINO1 and on sandy soft bottoms (Fig. 1, Table 1). The four-legged steely underwater construction of FINO1 rests on the seafloor and is anchored by four piles driven through sleeves (anchorings) in each corner of the foundation (for details see Joschko et al. 2008). The soft bottom megafauna was surveyed at 21 sites scattered around the wrecks and the platform.

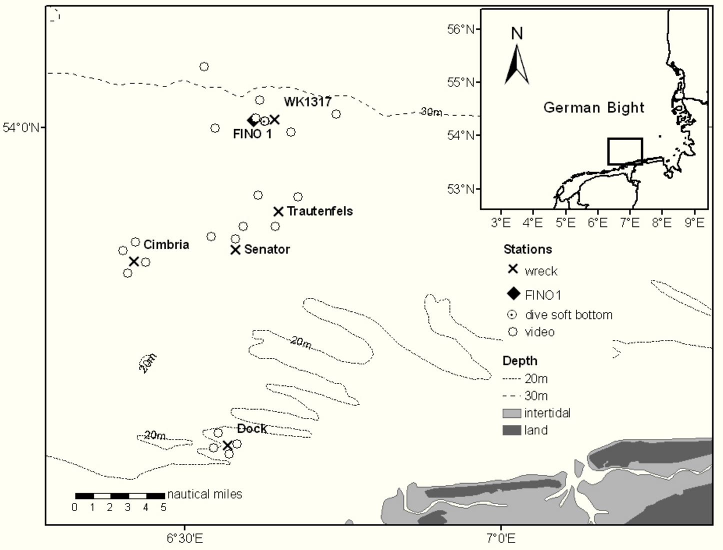

Fig. 1. Geographic position of the investigated wrecks, the research platform FINO1, and soft bottom stations in the south-western German Bight.

Table 1. Characteristics of the investigated wrecks, the research platform FINO1 and soft bottom sites.

	Cimbria	Trautenfels	Senator	Dock	WK 1317	FINO 1	Soft bottom
Founding resp. sinking [year]	1883	1942	1979	1991	Before 1982	2003	-
Type	Steam sailor	Cargo ship	Fishing boat	Floating dock	Fishing boat	Jacket construction, nearby seafloor	-
Material	Wood and Steel	Steel	Wood and glass fibre	Steel	Steel	Jacket: steel; Seafloor: massive shell top layer	Fine to coarse sand
Depth [m]	24,5	25,5	24,4	18,5	33,5	28	32.4 -20.5
Max. wreck height [m]	4,9	7	5,5	1,8	5,8	Up to sea level	-
Length [m]	101	140	24	70	40	32 on ground	-
With [m]	12	50	6	35	6	32 on ground	-
Investigation periods [month/year]	04/08 and 08/08	08/07	08/07	10/07	04/09	08/07 and 04/09	08/07 and 10/07
Orientation	E/W	N/S	SSE/NNW	N/S	NNE/SSW	-	-
Condition	Expanse of ruins	Expanse of ruins	Massive, broken in two parts	Walls toppled over	Expanse of ruins	-	-

2.2. Diving censuses

To quantify the mobile mega-epifauna on the wrecks and FINO1 visual censuses were conducted by air line supported scientific diving around slack water. The mobile mega-epifauna on each wreck was recorded on three to four 15 x 1 x 1 m transects. Transect length was controlled by a 15 m transect line. Transect width and height were controlled by a 1 m-spacer clipped to the line reel. The transects stretched linearly above the wreck in haphazard direction, thereby ignoring minor three dimensional structures of the wreck surface. The diver stopped every marked meter along the transect to search the 1 m^3 ahead for fishes and mobile decapod crustaceans (Wilhelmsson et al., 2006). If a transect extended beyond the wreck area, the diver changed the direction at the edge of the wreck to complete the transect within the wreck area (Fig. 2A). Small interspersed patches (approx. 0.25 - 2.25 m^2) of sediment among wreck fragments were not excluded from the transects. The insides of the ship hulls were not surveyed for safety reasons. The minimum threshold body size for organisms to be reliably detected by this method was ~1 cm. All individuals were counted and identified *in situ* to the lowest taxonomic level possible. Each record was reported to a co-worker at the surface via underwater telephone. All organisms counted within a 15 m^3 transect were assigned to a projection area of 15 m^2.

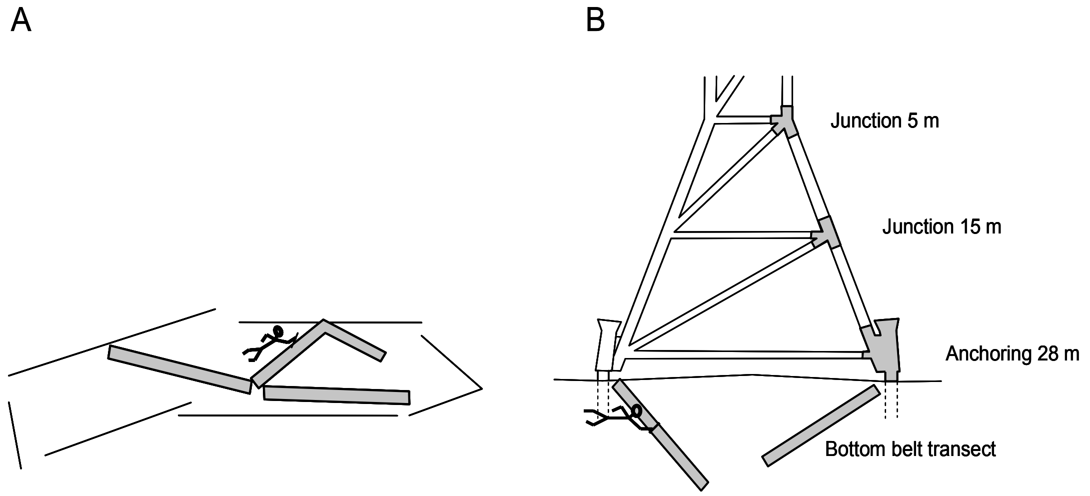

Fig. 2. Schematic drawing of dive transects at ship wrecks (A) and the jacket structure of the research platform FINO1 (B). The diver was connected to the surface via telephone cable and air support. Wrecks and the bottom around FINO1 were searched by belt transects (1m width, 15 m length, 1m height). Anchorings and junctions of the research platform FINO1 were searched completely. Abundances of the megafauna were referred to the projection areas of the platform sections and the 15 m^2 projection area of the line transects.

The mobile mega-epifauna on the research platform FINO1 was studied in summer 2007 and spring 2009. The search technique was adapted to the specific architecture of the jacket structure. Four different sections of the jacket were identified: tube junctions in 5 and 15 m water depth (joining a near vertical main tube, two horizontal and one diagonal tube), bottom anchorings (at this section two horizontal one diagonal tube join; a broad but short vertical tube is attached, through which a pile is driven into the sea floor), and the nearby seafloor (Fig. 2B). Junctions and anchorings including 1 m of each joining tube were searched completely together with the adjacent water body to a distance of 1 m. The diagonal and vertical tubes of the jacket structure were not surveyed as previous inspections revealed that these structures are virtually free of large decapods and fish. As done for the wrecks, abundances of the megafauna were referred to the projected surface area of the platform sections. Thereby, we neglected structural peculiarities such as the bulged surface of cylindrical tubes or ladders mounted to the main piles for maintenance purposes. The vertical projection area of each platform section was calculated from architectural drawings and was 32 m² for each anchoring and 11 m² for each junction. For nearby bottom transects we applied the same 15 m^3 line transect method as for the wrecks. Each transect started in 1 m distance from a bottom anchoring to avoid spatial overlap with the 1 m search space around the anchorings and stretched from there into haphazard directions away from the jacket. For safety reasons, the area beneath the jacket structure was not surveyed. 26 W halogen underwater torches were used for searching the anchorings, the 15 m-junctions and the bottom transects but not for the 5 m-junctions. Three 5 m-junctions, three 15 m-junctions, three anchorings and four bottom transects were investigated in August 2007. In April 2009 we sampled four 5 m-junctions, three 15 m-junctions, three anchorings and three bottom transects.

2.3. Soft bottom video transects

The mobile mega-epifauna on natural soft bottoms was surveyed by a ship-based underwater video camera system (CMOS video TV resolution with 9 W high power LED light) towed over ground at a drift speed of 0.2 to 0.5 knots. On drift transects of 500 m length the camera was positioned a few centimeters above the seafloor. The camera was equipped with parallel lasers 7 cm apart from each other to allow quantitative analysis of the videos. For the analysis we counted animals on ~21 cm wide strips. To obtain transects of 15 m², sections of about 71 m length were randomly selected from each video. To evaluate the comparability of dive transects and video transects we sampled two dive transects (15 m² each) in August 2007 on soft bottom areas that were previously surveyed by the underwater camera.

2.4. Data analysis

The video transects from the soft bottoms had a lower taxonomic resolution than the *in situ* observations by divers. The taxonomic resolution of the data sets from all dive transects were adjusted accordingly. Species of the taxa Gobiidae, Syngnathidae, Triglidae, flat fishes (Pleuronectiformes except for *Pleuronectes platessa*) and swimming crabs (except for the velvet crab *Necora puber*) were not fully distinguishable by both *in situ* and video records and were summarized on higher taxonomic levels.

Species assemblages from different structures and habitats were compared by multivariate statistics using Primer Software Version 6 (Clarke and Warwick, 2006). Similarities between assemblages were visualized by non-metric multi-dimensional scaling (nMDS) based on Bray-Curtis similarities after square root transformation of abundance data. Differences between assemblages were analysed by ANalysis Of SIMilarity (ANOSIM). Taxa which contributed most to the dissimilarities between assemblages were identified by the SIMilarity PERcentage procedure (SIMPER). No megafauna was found on four out of seven 5 m-junctions and on three out of six 15 m-junctions of the platform FINO1. These empty samples were excluded from the multivariate analysis.

We calculated the total number of individuals on the bottom area which is covered by the artificial structures ("footprint"). For the wrecks, the average density (ind. m^{-3}) of each taxon was multiplied by an average North Sea wreck area of approximately 1200 m^2 (Krone and Schröder, 2011). The average abundance of each taxon on each jacket section was multiplied by the number the respective section appears in the construction, summed up and projected on the bottom area (1024 m^2 between the piles). The number of specimens living on the seafloor between the jacket piles was adopted from the bottom transects adjacent to FINO1. These calculations were done only for species which occurred on the artificial structures with > 0.3 ind. m^{-2} but not on the soft sediment.

3. Results

A total of 24 taxa (6 crustaceans, 18 fishes) were identified in this study (Table 2). We found 20 taxa on the hard substrates (wrecks and FINO1 sections). 15 taxa were recorded on the soft sediments around FINO1 and the open soft bottom. 9 taxa occurred exclusively on the artificial structures while 5 taxa occurred on soft bottoms only. The number of taxa on FINO1 including anchorings (14 taxa), 5 m-junctions (3 taxa) and 15 m-junctions (3 taxa) was 15. A total of 16 taxa were found on the wrecks and 11 taxa were found on the soft bottom video transects.

Table 2. List of species and densities (mean ± SD no. of ind. m^{-2} and total calculated numbers inside the foot print area) of the megafauna on dive and video transects on wrecks, junctions and anchorings of the research platform FINO1, and soft bottom areas in the German Bight.

	Densities [n m^{-2}]						Calculated absolute numbers		
	Wrecks	Anchorings	Junction 15 m	Junction 5 m	FINO ground	Soft bottom	Wreck ($1200\ m^2$)	FINO1 ($1024\ m^2$)	Soft bottom ($1200\ m^2$)
Crustacean									
Pagurus bernhardus	0.13 ± 0.26	0.43 ± 0.56			0.68 ± 0.48	0.06 ± 0.06	156	751	72
Homarus gammarus	0.003 ± 0.01						4		
Corystes cassivelaunus						0.003 ± 0.01			4
Necora puper	0.49 ± 0.37	0.58 ± 0.25	0.13 ± 0.21		0.11 ± 0.09		588	193	
Liocarcinus spp.	0.01 ± 0.02	0.35 ± 0.37		0.03 ± 0.06	1.17 ± 0.88	0.29 ± 0.34	12	1244	348
Cancer pagurus	1.52 ± 0.92	0.34 ± 0.14	0.01 ± 0.04	0.01 ± 0.03	0.17 ± 0.14		1824	218	
Fish									
Trisopterus luscus	2.20 ± 3.86	0.17 ± 0.37				0.003 ± 0.01	2640	22	4
Gadus morhua	0.06 ± 0.09						72		
Merlangius merlangus	0.12 ± 0.39	0.04 ± 0.09					144	5	
Ciliata mustela		0.01 ± 0.01						1	
Pholis gunellus	0.01 ± 0.03	0.03 ± 0.01			0.01 ± 0.03		12	14	
Parablennius gattorugine	0.01 ± 0.03			0.01 ± 0.03			12	0.4	
Gobiidae indet.	0.06 ± 0.14				0.30 ± 0.29	0.48 ± 0.41	72	307	576
Ctenolabrus rupestris	0.54 ± 0.88	0.01 ± 0.03					648	1	
Callionymus spp.	0.01 ± 0.02				0.33 ± 0.24	0.09 ± 0.15	12	338	108
Trachurus trachurus						0.01 ± 0.02			12
Mullus surmuletus						0.003 ± 0.02			4
Pleuronectes plattessa						0.03 ± 0.04			36
other flat fishes		0.02 ± 0.03			0.15 ± 0.20	0.09 ± 0.16		156	108
Triglidae indet.					0.01 ± 0.03			10	
Taurulus bubalis	0.14 ± 0.16	0.30 ± 0.20	0.03 ± 0.07				168	40	
Myoxocephalus scorpius	0.003 ± 0.01	0.02 ± 0.04					4	3	
Agonus cataphractus	0.003 ± 0.01	0.01 ± 0.03					4	1	
Syngnathidae indet.		0.01 ± 0.01				0.01 ± 0.03		1	12
Total taxon number	16	14	3	3	9	11			
Average taxa per sample	4.9 ± 1.1	7.2 ± 1.7	0.8 ± 1.0	0.5 ± 0.8	6.0 ± 1.4	4.3 ± 1.5			
Number of samples	23	6	6	7	7	21			

The dominant taxa on the hard substrates were the edible crab *Cancer pagurus* and pout *Trisopterus luscus*. Large *C. pagurus* of up to 25 cm carapax width aggregated only on wrecks and at the anchorings of the FINO1. At higher water levels (5 and 15 m depth) only small individuals (max. ~5 cm carapax width) were found resting within the fouling assemblage (mostly dominated by *Metridium senile*). A single European lobster (*Homarus gammarus*) was found on the wreck of the "Cimbria". Few tompot blennies (*Parablennius gattorugine*) occurred on the research platform and on a single wreck. Portunid crabs (*Liocarcinus* spp.) were the most common taxon on soft bottoms with higher abundances close to the platform than on open sediments.

Three major megafaunal clusters were evident on the nMDS-plot (Fig. 3). The first cluster comprises the samples from open soft bottoms. Soft bottom samples obtained from underwater videos and from *in situ* diving censuses on soft bottom were indistinguishable from each other confirming that the separation of the open sediment cluster from all other clusters was not a methodical artifact but reflects real structural differences. *Callionymus* spp., *Pagurus bernhardus*, *Liocarcinus* spp. and Gobiidae contributed together almost 100 % to the similarity between the soft bottom samples. The Gobiidae alone accounted for approx. 50 %

of the similarity. Together with *Liocarcinus* spp. (~30 % contribution) they dominated the open soft bottom numerically.

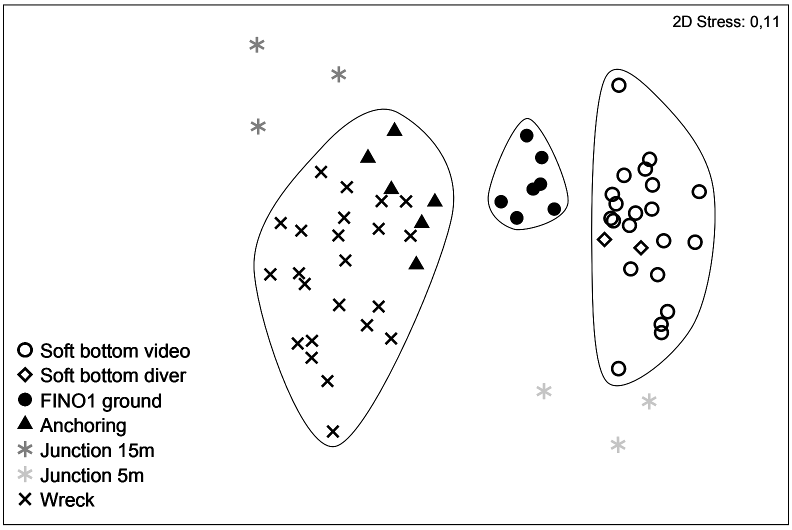

Fig. 3. 2D-nMDS-plot showing Bray-Curtis dissimilarities among megafauna communities from wrecks, junctions and anchorings of the research platform FINO1, and soft bottom areas in the German Bight. Abundance data were square root transformed.

The second cluster was represented by hard bottom samples from the wrecks and the platform anchorings. The wreck and anchoring samples showed a strong compositional overlap with a small yet significant difference (Table 3). *C. pagurus* and *N. puber* accounted for 67 % of the similarity between the samples from these two artificial habitats. The separation from the open soft bottom samples was due to the higher abundance of *C. pagurus*, *N. puber* and the gadoid *T. luscus* on the hard substrates and higher abundances of gobies on the soft bottoms. The SIMPER routine revealed that each of these taxa contributed more than 10 % to the total dissimilarity between the samples from open soft bottom and the hard substrates.

	Wreck	FINO ground	Anchoring	Junction 15m	Junction 5m
FINO ground	0.84*				
Anchoring	0.30*	0.90*			
Junction 15m	0.80*	1.00*	0.81*		
Junction 5m	0.99*	1.00*	1.00*	0.94	
Soft bottom	1.00*	0.49*	0.98*	1.00*	0.83*

Table 3. Results of the ANOSIM (*R* values; 0 and around = no differences between groups, 1 = groups totally separated) comparing megafauna communities from wrecks, junctions and anchorings of the research platform FINO1, and soft bottom areas in the German Bight. Abundance data were square root transformed. Asterisks denote for statistically significance at $\alpha = 0.05$.

The third cluster has an intermediate position in the nMDS-plot and covers the samples from the bottom transects adjacent to the platform (FINO1 ground). Around the platform foundation a scour extended at least 15 m away from the platform (RK pers. obs.). The maximum depth of the scour was about 2 m and levelled out towards the edges. Close to the jacket anchorings, the bottom was covered by a thick shell layer. Scours around the wrecks were also covered by shell layers but were less deep than at FINO1. The bottom samples were distinguishable from the hard substrate samples of the wrecks and the platform by the occurrence of typical soft bottom species such as flat fish, gobiids and callionymids, as well as by higher densities of *Liocarcinus* spp. and the hermit crab *Pagurus bernhardus*. They differed from the hard bottom samples by lower densities of *C. pagurus* and *T. luscus*. Each of these taxa contributed more than 10 % of the dissimilarity between the clusters. The third cluster showed small but significant differences to the open soft bottom cluster. Typical soft bottom species were common on both the bottom around FINO1 and the open soft bottom. However, densities of Portunidae were four times higher around the jacket structure while on the open soft bottom 1.6 times more Gobiidae were detected.

The samples from the 15 m-junctions and from the 5 m-junctions of the platform could not be assigned to any of the three clusters because of the overall low megafauna abundance at the junctions. The samples from the 15 m-junctions were more similar to the hard substrate samples of the wrecks and the anchorings. The only three species (*C. pagurus*, *N. puber* and *T. bubalis*) from the 15 m-junctions were also found on the wrecks and at the platform anchorings but not on the soft bottom. On the 5 m-junctions we found a single *Parablennius gattorugine*, one small *C. pagurus* and a single *Liocarcinus* spp.

Calculated abundances of *T. bubalis* were four times higher on the average footprint area of a wreck than on the footprint area of the FINO1 structure (Fig. 4). Numbers of *N. puber* and *C. pagurus* were three and eight times, respectively, higher on wrecks than on the platform. More than 1,000 wrecks inside the German EEZ add about 1.2 x 10^6 m² footprint area of hard substrate to the North Sea. They provide habitat for extrapolated numbers of 1.8 x 10^6 *C. pagurus* and 5.9 x 10^5 *N. puber*. 5000 jacket foundations of the FINO1 type would add a food print area of artificial hard substrate of 5.1 x 10^6 m^2 to the German EEZ providing habitat for 1.1 x 10^6 *C. pagurus* and 9.7 x 10^5 *N. puber*.

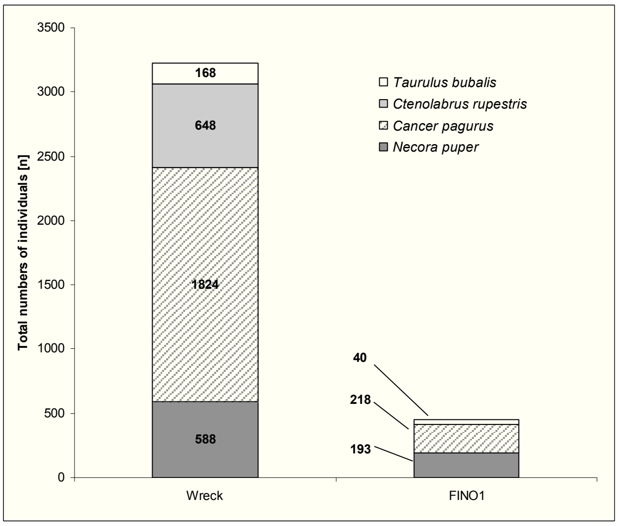

Fig. 4. Extrapolated total abundances of dominant megafauna species at a standardized wreck (area: 1200 m²) and the projected area of the research platform FINO1 (area: 1024 m²). (only those species with > 0.3 ind. m^{-2}, which did not occur on soft bottom).

3. Discussion

Numerous wind turbines with underwater structures comparable to the investigated jacket construction will be established in future North Sea wind farms. Their number will exceed that of the more than 1,000 wrecks which already exist in this region. Both types of artificial structures provide habitat for a hard bottom fauna which is otherwise restricted to the sparse rocky habitats scattered within the extensive soft bottoms of the German Bight. The megafauna assemblages from the soft bottoms, the wrecks and from various sections of the research platform can be distinguished into two major groups: the fauna of solid structures and the fauna of soft bottoms. The assemblage on the platform construction was clearly different from the assemblage of the soft bottoms confirming our first hypothesis that offshore wind turbines will provide habitats for species assemblages which differ substantially from the assemblages of soft sediments. Similar assemblages occurred on the wrecks and on the anchorings of the platform while the upper sections of the platform constructions were virtually free of mobile mega-epifauna. We, therefore, reject our second hypothesis that the underwater constructions of offshore wind turbines will provide a new habitat for epifauna assemblages which are not found on wrecks.

3.1. Wrecks

Similar to wrecks from the Atlantic coast of North America (Stephan and Lindquist, 1989; Arena et al., 2007) and from waters of the Netherlands and Belgium (Leewis et al., 2000; Massin et al., 2002; Zintzen, 2008a), the wrecks in the southeastern German Bight serve as habitat for an abundant and diverse fauna. Some of the taxa are obligatorily associated with hard substrates (e.g. *N. puber*) or are clearly less abundant on soft bottoms such as *C. pagurus*.

C. pagurus is a facultative resident on hard substrates. Especially large adult individuals migrate among soft and rocky substrates in search for food and mates. The omnivorous crabs feed on other decapod crustaceans on rocky substrates such as *Pilummnus hirtellus*, *Mytilus edulis*, *Crassostrea gigas* and young conspecifics (Lawton, 1989; Mascaró and Seed, 2001) and invertebrates from soft bottoms (e. g. *Cerastoderma edule*). Breeding females of *C. pagurus* prefer a heterogeneous seabed of sand and bolders or rocks. The velvet crab *N. puber* occurs frequently on the rocky substrates of the island of Helgoland (Harms, 1993; RK pers. obs.). *N. puber* is an aggressive omnivore decapod that can become locally dominant (Freire and Gonzáles-Gurriearán, 1995). The species was found on each hard bottom transect and appears to be a characteristic species on natural and artificial hard substrates. The crabs were encountered on the wrecks and the platform anchorings close to the seafloor. *N. puber* was not reported in comparable regularity and density from wrecks in the Bristol Channel and in Belgian waters (Hiscock 1980; Massin et al. 2002 and Zintzen et. al. 2008a). However, it is unclear whether the species was actually absent from those wrecks. Alternatively, the species might not have been recorded as the studies focused exclusively on the fouling assemblages and, therefore, might have failed to sample the mobile megafauna appropriately.

3.2. FINO1 jacket construction

The mobile megafauna on the jacket construction varied in their composition most probably depending on the structural complexity of the various platform sections and their height above the sea floor. The anchorings are more complex than the junctions in 5 and 15 m depth and were the most densely populated sections. Additionally, organisms are less exposed to hydrodynamic forces in lower than in upper water levels. Accordingly, shelter from predators and abiotic stress are probably responsible for the elevated abundances of mobile megafauna at the anchorings as compared to the junctions.

The megafauna on the anchorings was virtually indistinguishable from the wreck fauna. Both structures are morphologically complex and provide shaded areas, which are important hiding and foraging habitats for fish (Bohnsack, 1989). Both artificial habitats, wrecks and the platform anchorings, are directly connected to the sea floor and form a transition zone between hard and soft bottom habitat. Many mobile crustaceans inhabited the small ecotones at the edges of artificial structures where they can exploit resources from both habitats. Accordingly, the voracious predators *C. pagurus* and *N. puber* accumulated around the platform piles and the ship ruins where they benefit from enhanced food supply provided by both the fouling organisms on the hard substrates (Freire and Gonzáles-Gurriearán, 1995; Page et al., 1999) and the organisms from the surrounding soft bottom (Barros et al., 2001).

The higher sections of the jacket construction were inhabited by a poor megafauna assemblage. Surprisingly, the assemblage from the 5 m-junctions was quite similar to the soft bottom assemblage, although these sections are high up in the water column. This was mainly due to the occurrence of portunid swimming crabs at the 5 m-junctions. Swimming crabs inhabit soft bottoms but display a circadian activity rhythm with most swimming activities at daytime e.g. in search for food (Abelló et al.; 1991). Excursions into the water column might facilitate encounter with the platform structure and might, therefore, explain the occurrence of these soft bottom species on platform sections close to the sea surface. Predatory swimming crabs might have also been attracted by a thick layer of the blue mussel (*Mytilus edulis*) in the inter- and upper subtidal sections of the platform structure (RK pers. obs.). Dense aggregations of mussels provide habitat for diverse assemblages of accompanying fauna (Fausto et al., 2010; Saier, 2002) which provide a valuable food source for predatory decapods (Freire and Gonzáles-Gurriearán, 1995).

3.3. Soft bottoms

The soft bottoms were typically inhabited by flat fishes, gobies, hermit crabs (*P. bernhardus*) and *Liocarcinus* spp. Some of these typical soft bottom taxa also occurred on small sandy patches within the wreck areas. However, densities were much smaller than on open soft bottoms indicating that the proximity of solid structures decreases habitat quality for typical soft bottom species which might suffer from predation e.g. by the aggressive omnivore *N. puber* (Freire and Gonzáles-Gurrieарán, 1995).

The megafauna on the seafloor close to the platform foundation showed some similarity to the open soft bottom megafauna but was clearly distinguishable from the latter by the occurrence of several hard bottom associated species venturing on the surrounding seafloor (especially *N. puber* and *C. pagurus*). Simultaneously, typical soft bottom species such as *P. bernhardus*, *Callionymus* spp. and flat fishes were found in this habitat confirming the transitional character of this habitat.

3.4. Implications of offshore wind farms

The mobile mega-epifauna assemblages from wrecks and from the platform structure were largely identical with regard to the qualitative species composition. However, in terms of abundance of associated individuals the jacket structure varies from a typical wreck. The footprint area of a wreck provides habitat e.g. for four (for *T. bubalis*) to eight (for *C. pagurus*) times as many individuals as a jacket construction. The sections of the jacket which were higher up in the water column were only sparsely colonized by mobile fishes and crustaceans and contributed, thus, only little new habitat for mobile epifauna. However, a future wind farm will probably be more than just the sum of the single turbine structures. Within the planned wind farms, the turbines will be positioned less than 1000 meters apart from each other, a distance which is well within the migratory range of many mobile hard bottom species. This might increase the connectivity between the structures and promote migration of the organisms thereby influencing the use of space and food resources. Moreover, unlike FINO1 operating wind turbines vibrate and thus are emitting low frequency sound into the water (pers. obs. A. S.). How the fishes and decapods will react to this is still unknown. For evaluating if and how offshore wind farms might influence benthic biodiversity on a larger spatial scale it is essential to decide whether the artificial constructions locally enhance productivity or simply attract (redistribute) organisms ("Aggregation vs. Production debate"; Bohnsack, 1989; Page et al., 1999; Pickering and Whitmarsh, 1997; Osenberg et al., 2002; Powers et al., 2003). Although our investigations did not directly address this question assumptions can be made based on the autecology of some species (Bohnsack, 1989). The population size of obligate hard bottom species such as *N. puber* is limited in the German Bight by the availability of hard substrates. Any addition of hard substrate will allow for a population increase and, thus, for additional biomass production. *N. puber* does not occur on soft bottoms and is, thus, unlikely attracted from the nearby seafloor. Colonization occurs through planktonic larvae which are collected by the three dimensional artificial structure and its specific current field (Falcão et al., 2009). This predatory species clearly benefits from the fouling organisms inhabiting the wrecks and jackets (Freire and Gonzáles-Gurriarán, 1995; Page et al., 1999). Further likely examples for production on wrecks and the platform structure are the fish species *Taurulus bubalis* and *Ctenolabrus rupestris* which are also absent from soft bottoms. These species associate with hard substrates or live among subtidal seaweeds attached to solid substrates (Hilldén, 1981; King and Fives, 1983; Sundt and Jørstad, 1998).

Species like *C. pagurus* and *H. gammarus* probably aggregate at artificial hard substrates. These decapods visit rocky habitats in search for shelter and food (Sodal et al., 2002) but perform extensive migrations (Bennet and Brown, 1983, Krone and Schröder, 2011) thereby using artificial hard substrates as stepping stones within extensive sedimentary areas. We encountered numerous *C. pagurus* on the wrecks and the platform anchorings but only rarely on the open soft bottom. Larger crabs may have aggregated at the structures while smaller individuals most likely have settled on the structure as larvae (Bennet and Brown, 1983). Enhanced food supply from the fouling assemblage on the underwater structures will locally enhance biomass production of these animals.

In summary, we expect that the construction of numerous wind farms will lead to an increasing stock of obligatory hard bottom species in shelf regions. Some dominating predatory species, such as *N. puber* will be positively affected and will, in turn, regulate prey populations. Our calculations indicate an increment of the population sizes of *C. pagurus* and *N. puber* by about 50 and 150 %, respectively, within the entire area of the German EEZ by the construction of thousands of turbines. Accordingly, we expect that the planned construction of extensive wind farms will substantially alter the biodiversity of the German Bight.

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PUBLICATION VIII

Wrecks as artificial lobster habitats in the German Bight.

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ORIGINAL ARTICLE

Wrecks as artificial lobster habitats in the German Bight

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Abstract Once, the European lobster could be found in high abundances on rocky substrate around the island of Helgoland. Since the 1960s, the stock has been decreasing dramatically. Until now, it has been assumed that the lobster stock of Helgoland is the only one in the German Bight. Here, we provide first information about lobster distribution inside the German Bight off Helgoland. Diving in situ observations revealed that lobsters inhabit at least 15.6% of all 64 investigated wrecks. Considering the difficulties of detecting lobsters at wrecks, the true percentage is most likely much higher. Their locations are spatially homogenously distributed throughout the inspected area. The study indicates a broad distribution of the European lobster over the German Bight. The habitats provided by a considerable fraction of the more than one thousand wrecks outside the Wadden Sea are potential lobster refuges within the mud and sand dominated sea floor. Besides providing additional habitats, they represent stepping stones enhancing the connectivity of the North Sea lobster population.

Keywords *Homarus gammarus* · Wrecks · Artificial structures · North Sea · German Bight

Introduction

The European lobster, *Homarus gammarus* (L.), is a large, highly mobile decapod crustacean of considerable commercial importance within the north-east Atlantic and the Mediterranean. European lobsters usually inhabit irregularly shaped rocky substrates and boulder fields—rare bottom types and thus a limiting factor within the sand- and mud-dominated south-eastern North Sea. The assumed rareness of lobsters in the German Bight outside Helgoland is generally attributed to the perceived scarcity of suitable habitats. However, many irregularly shaped artificial hard-substrate structures can be found within the German Bight. More than 1,500 wrecks (ships, airplanes, containers, etc.) have been registered by German authorities (BSH 2009), but so far no investigation of their ecological function has been performed.

The European lobster *Homarus gammarus* is the largest decapod crustacean of the southern North Sea, reaching a total length of 60 cm and an age of 60 years (Phillips 2006). This omnivorous top predator is widely distributed throughout European seas—from the east Mediterranean, along the Atlantic coast around the British Isles to northern Norway. It does not, however, inhabit the Baltic Sea. *H. gammarus* can be found from the intertidal down to a water depth of 60 m (Galparsoro et al. 2009) and inhabits fully marine waters as well as low saline coastal waters of only 10 PSU (Linnane et al. 2000). Clawed lobsters live solitarily within crevices between rocks or inside holes which they shape between hard substrate and soft bottom. Unlike the similar American lobster (*H. americanus*), which occurs at the east coast of North America at water depths down to 200 m, *H. gammarus* does not dig own burrows into pure soft bottom. Therefore, its population size depends on the availability of appropriate hard-substrate biotopes suitable for settling. Within the investigation area, up to 26,000 larvae are released annually between May and August by each adult female. The pelagic larval phase lasts up to 4 weeks until the larval stage 4 finally sinks to the sea

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floor in search for a suitable habitat for settlement (Phillips 2006; Schmalenbach 2009).

Up to now, only a small subpopulation was recognised in the German Bight in the vicinity of the rocky island of Helgoland (Schmalenbach and Buchholz 2010; Ulrich et al. 2001). Like most of all North Atlantic and Mediterranean subpopulations it was decimated drastically in the mid-1900s (Browne et al. 2001; Cobb and Castro 2006; Franke and Gutow 2004). During the 1930s, the annual catch from Helgoland reached up to 87,000 lobsters. Today only a few hundred specimens are caught here yearly. Several anthropogenic factors might be the cause of the decline, e.g. overexploitation and pollution of the sea through chemicals (Schmalenbach et al. 2009). Within German waters, the European lobster today is considered a highly endangered species (Rachor et al. 1998).

Neighbouring populations are found at the rocky coasts of Norway (Agnalt et al. 2006; Jørstad et al. 2004), Great Britain (Smith et al. 1998; Jensen et al. 1994) and around the Oosterschelde in the Netherlands (Ulrich et al. 2001). Investigations of Ulrich et al. (2001) suggest that the lobster population of Helgoland is widely separated from those found in other parts of the North Sea. However, more extensive studies by Triantafyllidis et al. (2005) found the North Sea lobster stocks of Germany, southern Norway, East England, and Scotland to be part of one single large population. Only the lobsters of the enclosed Oosterschelde (The Netherlands) and of North Norway were well separated from the North Sea population by mitochondrial DNA comparison. If these sampled lobster groups belong to one population, there must be some genetic exchange between the spatially separated subpopulations.

Adult lobsters have been observed to reside in the same place over several years, but in principle, *H. gammarus* can cover large distances in search, for e.g. food or shelter, at least when there are suitable habitats along the way (Hepper 1978). However, the known lobster habitats of the east coast of England, the Oosterschelde, Helgoland, and the south Norwegian coast are separated by very large distances with only sandy bottom. During their pelagic phase, lobster larvae can cover some distance drifting with the anticlockwise residual current in the North Sea. Nevertheless, they need to find an adequate habitat at metamorphosis, when their benthic live begins. The scarcity of natural reefs providing suitable lobster habitats led to the assumption of separated populations and little is known about their connectivity.

So far, no scientific investigations have been undertaken about the existence of lobsters in the German Bight outside Helgoland. The only evidence that existing came from occasional bycatches in crab-pots (H. D. Franke and I. Schmalenbach, pers. comm.) and anecdotic observations by professional divers at offshore constructions (A. Stutz, pers. comm.).

However, numerous wrecks in the German Bight provide a lot of solid habitats, serving as a kind of secondary artificial reefs (sensu Pickering et al. (1998): structures not placed with the intention to serve as a reef), which could be assumed to be inhabited by European lobsters.

The aim of the present study was to investigate to which degree the numerous wrecks inside the German Bight are inhabited by *H. gammarus*, whether they can be counted as lobster habitats in the German Bight and what role they may play for the connectivity between the local North Sea lobster subpopulations.

Methods

Study area

The German Bight (Fig. 1) sea floor is dominated by loose sediments from coarse sands to mud in the deeper parts (Figge 1981), like most of the North Sea. The large intertidal flats of the Wadden Sea are separated from the open North Sea by chains of sandy barrier islands. Helgoland, inside the south-eastern German Bight, represents the only natural rocky shores between southern England and the southern Norway coast. Apart from this, natural hard substrates exist only at a few stony bolder reefs from glacial relicts, which are scattered on the Borkum Reef Ground and along the eastern side of the glacial Elbe valley.

Within the German Bight outside the national base line, salinity ranges from 35 offshore to 25 PSU close to the

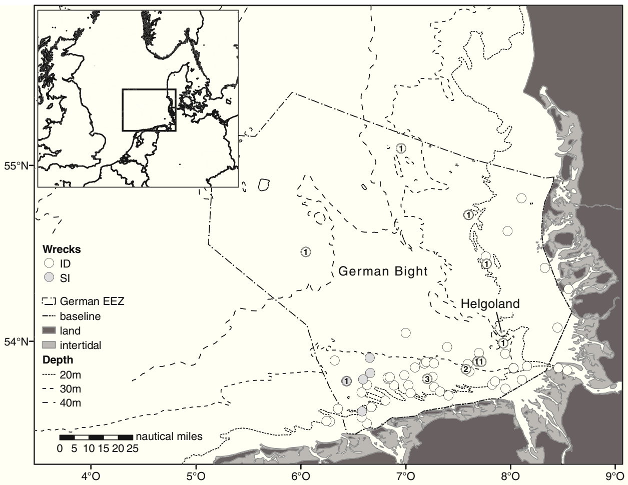

Fig. 1 Distribution of inspected wrecks in the German Bight. The number of lobster detections at wrecks are given by the numbers inside the dots. Wrecks scientifically investigated (SI) and wrecks investigated by inspection divers (ID)

plume of the river Elbe (Jones and Howarth 1995). The maximum depth reaches 45 m in the north-west (compare Fig. 1), except for the small area of the Helgoland Trench, with a maximum of 60 m. The underwater visibility strongly depends on the distance to the coast, the water depth, and the hydrodynamic conditions. They are ranging from only a few centimetres close to the cost or after storms to over 5 m in offshore locations and after the rare periods of calm weather.

Wrecks

Within German waters, more than 1,500 Wrecks are presently known to the authorities (BSH 2009), and new one keep being added. Most of them are ships, but also airplanes, containers, or other bodies are among them.

To assure safe shipping, the German federal maritime agency (BSH) keeps a record of all known wrecks in German waters. All wrecks which present possible hazards to navigation are inspected irregularly by divers to verify their position, depth, and condition. Since 2004, some of these control dives are recorded on video for safety and documentation reasons. The BSH kindly supplied video records of 59 different wrecks (from the years 2004 to 2008, one visit per wreck) for our analysis. These wrecks are situated between 8.6 and 44.5 m (on average 27 m) water depth and are 5–127 years old. The average surface area of the wrecks is 1,200 m^2 (±SD 1,800 m^2). Most of them are made of steel. Wrecks in deeper waters are visited rarely since they do not endanger ship traffic and diving becomes more difficult with increasing water depth (Fig. 1). From an ecological point of view, the order and position of the searched wrecks are rather random depending only on nautical requirements.

To gain a representative number of wreck visits within an adequate time and cost effort, we combined scientific wreck studies with an analysis of video footage taken during routine wreck inspections by the BSH.

Routine wreck inspections

At each location, the BSH divers descend to the wreck and dives alongside it as far as the umbilical cable and maximum dive limits permit. During the dive, they search the deepest depression (scour) and try visiting as many parts of the wreck as possible, as well as locating the highest point. The diver is equipped with a continuously recording helmet camera (water proof housing, 1/4″-Sony-CCD-Colour-Chip, display and recorder inside the dive boat) and a helmet light. As these dives serve only for technical inspection, no ecological parameters are recorded, but underwater visibility, maximum water depth and length of time of the video are noted. The diver gains a broad overview of the wreck, which is recorded on video, allowing a later identification of the fauna on the wreck.

Scientific dives

We investigated five shipwrecks (Fig. 1) in detail applying scientific survey methods; wrecks were chosen in the vicinity of planned offshore wind farms for a comparison of artificial structures. On each wreck, the mobile mega fauna was recorded on 3–4 belt transects laid out into arbitrary directions from where the diver first hit the wreck. Each transect was 15 m long, 1 m wide and 1 m high. Transect width and height were controlled by 1-m spacers clipped to the transect line and a hand held 1 m ruler. Equipped with a 26 W halogen underwater torch, the diver moved slowly along the transect line and stopped at every marker to search the 1 m^3 ahead for fish and mobile decapod crustaceans (Wilhelmsson et al. 2006). If a straight transect extended beyond the wreck area, the diver changed the direction at the edge of the wreck to complete the transect within the wreck area. The inside of the ship hull was not surveyed for safety reasons. The diver reported all organisms found within the transect via telephone to the recording person located in the dive boat. Here, we present the recorded detections of *H. gammarus* only. An analysis of the distribution of other species will be published elsewhere.

All dives were done at slack water between 6 am and 5 pm. For each wreck, the total extent and the percentage covered by the dive surveys were calculated.

This ratio was used to estimate the probability of detecting lobsters at any particular wreck. Possible coherence of the wreck system for moving lobster outside the Wadden Sea is displayed by plotting a 3 nm buffer around each wreck, representing a conservative estimate for adult lobster moving range (Hepper 1978; Jensen et al. 1994).

Results

This investigation includes many types of wreckages, e.g. large hulls, expanses of ruins, a lost anchor with its chain, a ship container, and a car. Most wrecks (n = 50), however, are ship ruins made of steel, although smaller wrecks occasionally consist of wood or plastic. The average projected wreck surface was 1,200 m^2. The recorded visibility ranged from 0.4 to 5.5 m (average 1.75 ± 1.3 m SD). The length of the video records varied from 2 to 36 min (average 11.6 ± 6.6 min SD, total 690 min). Considering video records length and the divers' speed and technique, on average 43% of the 64 wrecks' surface were searched. At 9 of the 59 wrecks on inspection videos, we found a total number of 12 lobsters (on average 33% of the area of these lobster wrecks were inspected). At 7 wrecks, respectively, one individual was detected. At another single wreck, two and at one other three individuals were identified on single video recordings. At one of the five scientifically investigated wrecks, a single lobster was found. Considering all wreck investigations together, lobster were detected at 15.6% of all wrecks.

The highest wreck densities are found along the main traffic lanes in the German Bight south of Helgoland (Fig. 1). Accordingly, most of the investigated wrecks were located in these areas (Fig. 2). Out of the 54 wrecks inspected here, at six wrecks (11.1%) lobsters were observed. In the northern part the density of wrecks is much lower and only few wrecks were inspected. At four of the ten inspected wrecks (36.4%) in the north of Helgoland, lobsters were found—all of them in offshore locations deeper than 20 m.

All of the specimens had an estimated carapax length of more than 6 cm (age > 3 years). One lobster, found during a scientific dive mission, had a carapax length of approx. 14 cm (age > 8 years). Sex was not identified. The occurrences of lobsters over the investigated wrecks are relatively homogenously distributed (Fig. 1) and exhibit no obvious pattern so far. Most lobsters were found at shipwrecks or expanses of ruins (projected expanse of 188–2,000 m^2). One individual was detected at a single large steam boiler (4 m width × 9 m length) lying on the sand ground. Approximatly 90% of all wrecks presented here are located less than 3 nm from the next wreck (Fig. 2).

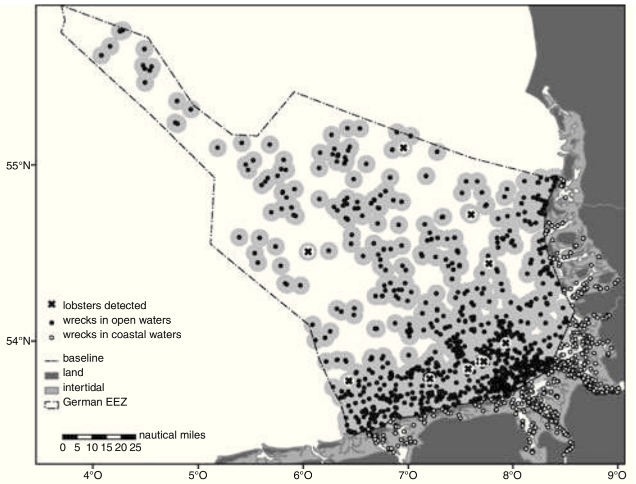

Fig. 2 Distribution of wrecks inside the German exclusive economic zone. Over 1,000 wrecks are found seawards of the baseline, another well over 500 in coastal waters. The *greyish area* represents a buffer of 3 nm around each wreck. In the inner German Bight more than 90% of all wrecks are well connected

Discussion

We used the method of non-ecological transect analysis, which did not reveal absolute abundances since search times and visibility varied strongly between the wreck visits, and small specimens were hardly detectable. However, the videos provide evidence of the occurrence of lobsters at a considerable percentage of the investigated wrecks. These occurrences can be considered as a minimum number and can be tentatively projected by carefully correcting the numbers by the effort. This shortcoming of the method may not allow for concise estimates of actual population size, but adds an enormous coverage of wrecks through the professional diver videos, which could not be investigated scientifically with the given time and money constrains. In addition to this, it provides the rare opportunity to study wrecks and their inhabitants at places were diving is extremely difficult (e.g. inside traffic zones).

The detected specimens were found in crevices as well as in relatively open spaces among solid wreck compartments. As reported by Langhamer et al. (2009) and Spanier (1994), we also found that lobsters tend to prefer places between solid structures and bottom that can be excavated. Since the BSH dives were not intended to compile data about the local fauna, we can assume that by far not all lobsters present at these wrecks were detected, particularly since these crustaceans often stay hiding during the day (Jensen et al. 1994). In fact, we assume that there is a substantially higher number of lobsters at more than the 15% of the observed wrecks. Considering the above-mentioned fractions of the wrecks that were actually inspected (33–43% of their surface), and the fact that the inspection dives were not set up to detect lobsters, the real percentage of lobster-inhabited wrecks may be assumed to be two to three times higher. Assuming that the investigated wrecks are representative for most of the wrecks in the open German Bight, a similar percentage of the over 1,000 wrecks outside the baseline (Fig. 2) might be inhabited by lobsters. Within the baseline, the Wadden Sea and the estuaries represent habitats with considerably different physical conditions. However, as lobsters are reported to also inhabit coastal waters (Linnane et al. 2000), a certain percentage of these wrecks might also be considered as potential habitats and stepping stones.

Although at rocky shores and also at Helgoland lobsters are found up to the intertidal (Linnane et al. 2000), all lobsters were observed at wrecks in more than 20 m depth. The number of inspected wrecks in offshore locations north of Helgoland is rather low, but indeed four of the five inspected wrecks were inhabited by at least one lobster. This might indicate that in these offshore locations the percentage of lobster-inhabited wrecks is very high.

Despite the high number of inspected wrecks in the southern German Bight, the frequency of wrecks with lobster detections was lower than that in the north. Whether this holds true when more wrecks are inspected in the north and what factors could be responsible for such an unequal distribution (e.g. the intensive ship traffic, hydrography) remains uncertain until more inspection data are available.

No lobsters were observed at the wrecks in shallower waters closer to the Wadden Sea. This could be related to various reasons. Methodical influences such as longer dive times at deeper locations (average record length 44.5 min at >20 m depth vs. 31.1 min in shallower areas) could increase the chance of finding lobster through larger coverage of the wrecks. On the other hand, higher sediment loads in the more coastal water, hydrodynamics, a different wreck associated biocoenosis, or other environmental factors could be the responsible parameters determining the suitability of wrecks for lobsters. However, the relative low number of detected lobsters and the low number of inspected wrecks in the northern part of the German Bight precludes statistical analysis on ecological aspects. Nevertheless, the high frequencies of lobster observations are a strong argument in themselves. A higher number of wreck inspections in these areas expected for the coming years will alleviate this problem and allow more detailed analyses of factors determining whether a wreck is inhabited by lobsters or not.

Since lobsters prefer rocky habitats with suitable hideouts and are known to reside in one place over several years (Jensen et al. 1994; Bannister et al. 1994), and were never found in hundreds of German Bight beam trawl catches from pure soft bottom (own unpublished data), it is likely that the observed individuals are not just attracted temporarily from the adjacent muddy and sandy areas or from Helgoland but actually use the wrecks as their habitat.

Homarus gammarus are known to migrate over larger distances of more than 16.0 nm (Hepper 1978). However, it is unclear whether they also cover similar distances over open sandy bottom. From southern England, lobsters were reported to move on average 3.2 nm (males 2.6 nm; females 3.7 nm) from their release point at artificial reef amidst sandy grounds (Jensen et al. 1994). Most of all wrecks presented here, however, are located less than this distance from each other. Therefore, the individuals found at the wrecks could have reached the spots as migrating adults. The fact that also some wrecks located at greater distances from neighbouring wrecks are inhabited by lobsters (see Fig. 2) indicates that some larger distances can be overcome. Within the German Bight the population found around Helgoland may be the main source for emigrating lobsters and their larval instars. Nevertheless, it appears that a part of the lobsters-inhabited wrecks far from Helgoland shelter permanent inhabitants and thus contribute to the overall population in the eastern North Sea.

The large distances between the known occurrences of lobster subpopulations in the North Sea led to the assumption of effectively separated populations. In a conservative estimate, the distance covered by the drift of larvae zoea instar one and two during their predominant pelagic phase of 7 days (in German waters during summer temperature; Schmalenbach and Buchholz 2010; Tully and Ó Céidigh 1987) reaches approximately 33 nm (considering 0.2 nm h^{-1} effective residual current (Hickel 1972)). As this, as well as the distance covered by migrating adults (Jensen et al. 1994), is much smaller than the distance between the different recognised North Sea populations, a genetic exchange between them was considered very unlikely (Ulrich et al. 2001).

However, the distance between most wrecks is much smaller than the possible range of moving lobsters and drifting larvae. The observation that a considerable percentage of the wrecks in the German Bight seem to be inhabited by lobsters allows a different perspective on the availability of potential lobster habitats in this area perceived as largely barren sands. The assumed lack of suitable habitats between known lobster populations in the North Sea left scientists wonder how the apparent genetic similarity between them could be explained (Ulrich et al. 2001; Triantafyllidis et al. 2005). However, these sand and mud areas are actually interspersed by thousands of potential lobster habitats throughout the North Sea. The approximately 1,500 registered wrecks, spread across most of the open German Bight, may not only present permanent suitable habitats for lobsters, but probably also serve as stepping stones. Assuming a similar distribution of wrecks in the Dutch, British, Danish and Norwegian parts of the North Sea, these would effectively connect widely separated locations and permit a genetic exchange between the known hotspots of local European lobster subpopulations explaining their observed genetic similarity.

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IllUSTRATION

Muschelzucht, künstliche Substrate & Windparks

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MUSCHELZUCHT, KÜNSTLICHE SUBSTRATE & WINDPARKS

von ROLAND KRONE & MATTHIAS BRENNER

Das Lehrbuch definiert den Begriff Substrat im ökologischen Kontext, als das Material, auf oder in dem ein Organismus lebt. Spezialisierte Organismen sind oft von bestimmten Substrattypen abhängig. Bestimmte Meeresorganismen sind auf Hartsubstrat, andere auf Weichboden angewiesen. Viele Bereiche der europäisch-atlantischen Küstenmeere haben Weichböden als Substrat und sind dadurch nur für bestimmte Meeresbewohner attraktiv. Natürliche Hartsubstrate wie Felsen oder Riffe sind rar. Seit der Mensch jedoch das Meer für seine Aktivitäten nutzt, verändern sich nicht nur die Küstenbereiche durch den Bau von Dämmen, Buhnen und Hafenanlagen, sondern auch der Meeresboden und die räumliche Struktur ganzer Meeresgebiete. Seit Jahrhunderten bleiben Schiffe als Wracks auf dem Meeresboden zurück und bieten für Jahre und Jahrzehnte Lebensräume für Arten, die unter natürlichen Umständen nur an wenigen Stellen überleben könnten. Im letzten Jahrhundert kamen in vielen Meerebereichen Bohrinseln zur Ausbeutung von Bodenschätzen hinzu, die für einige Jahre bis Jahrzehnte den Lebensraum punktuell neu strukturierten. Falls wie geplant noch mehrere hundert Windanlagen in diesem Jahrhundert hinzukommen, haben Artgemeinschaften, die festen Untergrund zum Überleben benötigen die wohl besten Bedingungen seit Bestehen der europäisch-atlantischen Küstenmeere.

NATÜRLICHE HARTSUBSTRATE

Die weiten Flächen der europäisch-atlantischen Schelfmeere sind vorwiegend von sandigen und schlickigen Sedimenten bedeckt. Dabei handelt es sich zum Großteil um Reste verwitterter Gesteine, die mit den Flüssen und Gletschern vom Land ins Meer transportiert wurden. Besonders zwischen den Kaltzeiten - in den sogenannten Interglazialen - als die Gletscher schmolzen und sich nach Norden und Süden zurückzogen, haben mächtige Ströme aus Schmelzwasser ungeheure Sedimentmengen auf den späteren Schelfmeerflächen abgelagert. Zu dieser Auflage kommen Myriaden herabsinkender Kalk- und Silikat-

schalen kaum sichtbarer, ständig neu entstehender und wieder absterbender tierischer und pflanzlicher Kleinstorganismen und die Panzer und Schalen größerer Tiere wie etwa der Schnecken, Muscheln und Seeigel hinzu. Bis auf wenige Ausnahmen liegen die soliden, felsigen Untergründe vulkanischen Ursprungs bzw. die Tiefen- und Sedimentgesteine der Schelfmeere unter dieser lockeren, mitunter mehrere hundert Meter mächtigen Sedimentdecke verborgen. Sie treten nur dort auf, wo der Fels zu steil ist oder die Sedimente durch Wasserbewegungen kontinuierlich abtransportiert werden. Typische Beispiele sind die teils granitischen, teils aus Gneis aufgebauten Felsküsten Skandinaviens, Schottlands, der Bretagne und die helle karbonatische Kanalküste Englands.

Felsige Untergründe im Gezeitenbereich

Foto : shutterstock

Bodenbeschaffenheit der Nordsee:

Weichboden

Sandboden

Weichboden mit Fels und Tieren

Fotos: Inken Suck

DIE HARTSUBSTRATE DER NORDSEE UND DER KANALKÜSTE

Primäre, natürliche Hartsubstrate treten am Grunde des Ärmelkanals und in der südlichen Nordsee lediglich in Form grober Gerölle auf. Es sind einzelne unregelmäßig verteilte Felsblöcke unterschiedlicher Größe, die sich während der Kaltzeiten aus den Eismassen gelöst haben oder von diesen zusammengeschoben wurden. Viele davon sind, da sie ein Hindernis für die Netzfischerei darstellen, an Land gebracht und dort als Baumaterial verwendet worden. Neben den größeren Felsbrocken gibt es örtlich begrenzte Gebiete eiszeitlicher Reste von Moränen mit dichten oder lockeren Ansammlungen kleinerer Steine.
Die einzige kompakte Felsformation in der südlichen Nordsee ist der Felssockel der Insel Helgoland. Vor etwa 200 Millionen Jahren, wurden die Buntsandstein- und Kreidefelslagen von einem darunter liegenden aufwärts drängenden Salzstock einseitig aufgebogen und durch die Nordseesedimente hindurch gedrückt. Der Felssockel Helgolands ist das größte zusammenhängende Felsbiotop in der ansonsten von Weichböden geprägten südlichen Nordsee.

Luftaufnahme Helogoland

Foto: Roland Krone

Findling aus Fischereibeifang

Foto: Roland Krone

TIERE ALS BAUMEISTER

Die beschriebenen primären Hartsubstrate des Gezeitenbereichs und des Meeresbodens werden durch die vielfältige Gruppe der sekundären Hartsubstrate ergänzt. Da sie von Organismen gebildet werden, bezeichnet man sie auch als biogene Hartböden oder Riffe.

Manche als **bioherm** bezeichnete Organismen können den harten Untergrund selbst aufbauen - wie etwa die Steinkorallen der Kaltwasserriffe auf dem Schelf vor der französischen, irischen und norwegischen Küste. Diese erst seit Kurzem bekannten und sehr langsam wachsenden Riffe sind noch weitgehend unerforscht, aber bereits massiv durch die Grundschleppnetzfischerei bedroht. Andere **biostrome** Tiere können durch die Strukturen, die sie bilden, die Sedimentation in ihrem Umfeld erhöhen und auf dem emporwachsenden Haufen siedeln oder mit ihm in die Höhe wachsen. Es bilden sich riffartige Hügel. Solche als **Biostroma** bezeichnete Strukturen werden z. B. durch den Röhrenwurm *Sabellaria spinulosa* (früher fälschlicherweise als „Sandkoralle" bezeichnet) aufgebaut. Diese Riffe gelten heute zumindest im Nordseeraum als verschwunden. Auch die Europäische Auster (*Ostrea edulis*), die früher große Austernbänke gebildet hat, und von deren Beständen einst viele Fischer leben konnten, ist in der Nordsee nicht mehr oder nur noch als Relikt nachweisbar. Die ebenfalls biostromen Miesmuschelbänke (*Mytilus edulis*) des Wattenmeeres sind zwar noch in vielen Bereichen der Nordsee anzutreffen, werden aber seit einigen Jahren von der eingeschleppten und in den Austernzuchten Frankreichs erfolgreich kultivierten Pazifischen Auster (*Crassostrea gigas*) besiedelt. Noch ist unklar, ob die Miesmuschel nur bereichsweise verdrängt wird oder ob die fremde Auster durch die Ausbildung großer Bänke zu einer Gefahr für die Existenz der Miesmuschel wird. Die Ausbreitung und Vermehrung der Pazifischen Auster schreitet jedenfalls unaufhaltsam voran, und die Folgen dieser Entwicklung sind noch nicht absehbar.

Miesmuschelbank Foto: shutterstock

Foto: shutterstock

DER MENSCH – EINE BEDROHUNG FÜR DIE BEWOHNER DER HARTBÖDEN

Sowohl die primären als auch die sekundären Hartsubstrate sind vor allem in den vom Menschen intensiv genutzten Bereichen der Nordsee stark bedroht. Durch Überfischung, Schadstoff- oder übermäßigen Düngemitteleintrag wurden Muschelbänke dezimiert, geschädigt oder mit Sediment überlagert. Zusammen mit eingeschleppten Arten und Krankheiten führte dies sogar zum Aussterben einzelner Vertreter. Darüber hinaus werden weiterhin viele Bereiche zur Kiesgewinnung abgebaggert und unwiederbringlich zerstört.

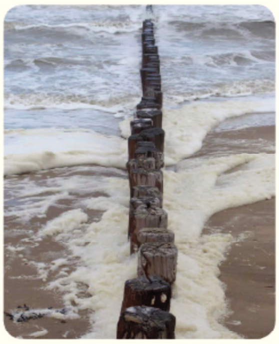
Durch die Europäischen Flora-Fauna-Habitatrichtlinie, die dem Schutz und der räumlichen Vernetzung besonders wertvoller Biotope dienen soll, sind „Riffe entlang der Felsküsten, als auch im offenen Meer [...] sowie Felsen, Felswatt, Geschiebe und biogene Bildungen, aber auch Steine und Blöcke auf submarinen Moränenrücken" als wertvolles Gut eingestuft worden, die es zu schützen und bei zukünftigen Eingriffen und Bewirtschaftungen des Europäischen Schelfmeeres zu berücksichtigen und zu schonen gilt.

Darüber hinaus zählen die Verbesserung der Wasserqualität z. B. durch verminderte Düngemittel- und Abwassereinleitungen, die Einrichtung von Fischereischutzzonen bzw. Meersschutzgebieten und die Begrenzung der Fangmengen zu den wirksamsten Maßnahmen zur Regenerierung der Meeresfauna.

KÜNSTLICHE HARTSUBSTRATE

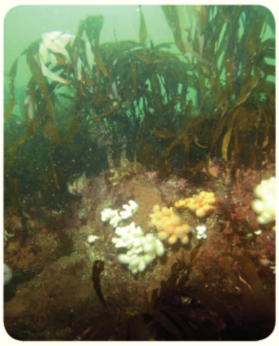
Neben den natürlichen Hartsubstraten finden wir entlang der gesamten europäischen Küste und auch auf der offenen See viele vom Menschen geschaffene Bauwerke aus Stein, Holz, Beton und Stahl. Falls sie als Imitate natürlicher Hartsubstratstrukturen absichtlich ins Meer eingebracht wurden, gelten sie als künstliche Riffe. Sie dienen mancherorts dazu Fische anzulocken und so die Freizeit- und Berufsfischerei zu unterstützen und als Attraktion für Sporttaucher.

Sekundäre künstliche Riffe sind Konstruktionen und Bauwerke, die kein Biotop imitieren. Sie stellen ungewollt, gewissermaßen als Nebeneffekt, einen Hartsubstrat-Biotop dar. Diese Hartsubstrate sind in der Nordsee in vielfältiger Form in großer Zahl vorhanden. Zu ihnen zählen z. B. Ölförderplattformen, Wellenbrecher und Hafenbefestigungen, Seefahrtszeichen, Schiffswracks und die Fundamente der Offshore-Windenergieanlagen.



Wellenbrecher

Foto: Michel.



Unterwasserlandschaft vor Helgoland

Foto: Carsten Wanke

LEBENSGEMEINSCHAFTEN AUF HARTEM UNTERGRUND

Hartbodenlebensgemeinschaften bilden sich sowohl auf natürlichem solidem Felsen, auf Geröllfeldern, auf einzelnen Felsbrocken, auf tierischen Bauwerken als auch auf künstlichen Bauwerken aus.

Der Untergrund muss dabei fest und möglichst lagestabil sein. Ein Kiesstrand etwa, dessen einzelnen Steinchen ständig durch Wellen umgelagert werden, ist gefährlich und kann praktisch nicht durch fest haftende (sessile) Arten besiedelt werden. In größeren Wassertiefen hingegen, bei geringer Wellenenergie und nur leichter Strömung, bleiben auch mittelgroße Kiesel dauerhaft liegen und bieten so ein Anheftungssubstrat für Hartbodenbewohner – sofern dieser Standort nicht von Sedimenten bedeckt wird.

Die Organismen, die den festen Untergrund besiedeln, werden häufig selbst noch von weiteren Tieren oder Algen besiedelt. Diese als Epibiose bezeichnete Besiedelung, führt zu einer Vervielfältigung der räumlichen Ausgangsformation. Hartsubstrate werden von schwimmenden, laufenden, kriechenden, sich fest anheftenden und sogar fest zementierenden Arten besiedelt. Die meisten Arten haben einen begrenzten Bewegungsradius (z.B. Miesmuscheln), besitzen gar feste Verstecke oder Brutplätze oder können sich, einmal festgesetzt, nicht vom Untergrund lösen (z.B. Austern). Deswegen verbreiten sich Hartbodenbewohner über größere Entfernungen überwiegend durch ein planktisches Larvenstadium. So können auch räumlich isolierte Felssubstrate besiedelt werden.

Der harte Untergrund kann als Verankerungsplatz oder seine Spalten und Höhlen als Versteck oder Brutplatz durch viele Krebs- und Fischarten genutzt werden. Schnecken und Seeigel weiden den Algen- und Detritusbelag von der Oberfläche ab. Wenige spezialisierte Arten wie der „Bohrwurm" (eine Muschel, *Teredo navalis*) und die Weiße Bohrmuschel (*Barnea candida*) können sich darüber hinaus in Holz und Gestein hineinbohren und dort die Nahrung aus dem vorbei fließenden oder in ihre Wohnröhre eingepumpten Wasser gewinnen. Sie nutzen also das Substrat als Wohnung.

Felsen und andere Hartsubstrate ragen meist über die lockeren Sedimente der Umgebung hinaus. Die darauf sitzenden Organismen können gut über der oft durch Wellenbewegungen und Strömungen aufgewühlten und trüben, manchmal sogar Sauerstoff verarmten Bodenzone gedeihen. Die Fangapparate filtrierender oder seiender Organismen bleiben von aufgewirbelten anorganischen, nicht verwertbaren Partikeln frei, und die Weideflächen der Pflanzenfresser verschlicken nicht. Viele Tier- und Pflanzenarten sind also auf festen Untergrund angewiesen und bilden darauf regelrechte Kolonien. Andere benötigen wenigstens eine kleine feste Fläche wie eine Muschelschale, um darauf zu gedeihen.

Foto: shutterstock

BODENHAFTUNG BEHALTEN IN DER BRANDUNGSZONE

Der Brandungsbereich mit seinen starken Staudrücken und Scheerkräften stellt an langsame, auf dem Substrat haftende und kriechende Organismen wie den Napfschnecken (*Patella vulgata*), den Miesmuscheln (*Mytilus edulis*) und den Seeohren (*Haliotis tuberculata*) ganz besondere Anforderungen: Um diesen Lebensraum besiedeln zu können, benötigen sie sehr stark ausgebildete Haftapparate wie Saugnäpfe, Haftfäden oder Haftkrallen. Tiere, die dauernd im Gezeitenbereich leben, sind noch weiteren starken Belastungen ausgesetzt. Sie unterliegen zeitweilig atmosphärischen Einflüssen und müssen deshalb spezielle Mechanismen z. B. zur Überdauerung von Hitze, Salzanreicherung, Aussüßung und Sauerstoffmangel besitzen.

Brandungszone, Miesmuscheln

photo : shutterstock

WEICHTIERE AUF HARTSUBSTRAT

Außer den **Einschalern (Monoplacophora)** und den **Kahnfüßern (Scaphopoda)**, die nur auf Weichböden vorkommen, sind alle Klassen der Mollusken in der Hartbodentiergemeinschaft vertreten.

Der Körper der **Käferschnecken (Polyplacophora)** ist perfekt an die schwierigen Bedingungen in Brandungszone angepasst. Mit der flachen Schale und dem breiten Fuß vermögen sich die Weidegänger eng an den harten Untergrund anzuhaften.

Schnecken (Gastropoda) kommen in vielfältigen Erscheinungsformen vor: So gibt es neben fast völlig sesshaften Arten, wie der Pantoffelschnecke auch frei schwimmende Arten wie der Seehase.

Muscheln (Bivalvia) verkitten sich entweder fest und unlöslich mit dem Untergrund (z. B. Austern) oder vertrossen sich mit Haltefäden (z. B. Miesmuscheln). Regelrechte Spezialisten bohren sich sogar in Holz oder Stein hinein.

Aus der Gruppe der **Kopffüßer (Cephalopoda)** bewohnen vor allem die Kraken (Octopusse) Hartböden, wo sie eine große Vielfalt an Beute und Verstecken finden.

bodenbiotope, mit typischen Lebensgemeinschaften, die schon über einen langen Zeitraum hinweg eine angenommene „reine“ Weichbodenfauna verfälschen.

Es könnte deshalb vermutet werden, dass die hinzukommenden WEA-Konstruktionen keinen nennenswerten weiteren Effekt haben. Bei einer differenziertere Betrachtung wird jedoch deutlich, dass im Unterschied zu Wracks, die stählernen Gründungsstrukturen der WEAs wie Felsen vom Meeresgrund in bis zu 45 Metern Tiefe durch die gesamte Wassersäule bis zur Oberfläche und darüber hinaus emporragen.

PROBLEMZONE: NEUER GEZEITENBEREICH

WEAs haben also einen Gezeitenbereich. Gerade dort siedeln sowohl auf natürlichen als auch auf künstlichen festen Untergründen spezialisierte Arten mit zum Teil hohen Biomassen. An der Forschungsplattform FINO1 sind es bis zu 65 kg pro Quadratmeter wovon rund 60 kg allein auf Miesmuscheln entfallen.

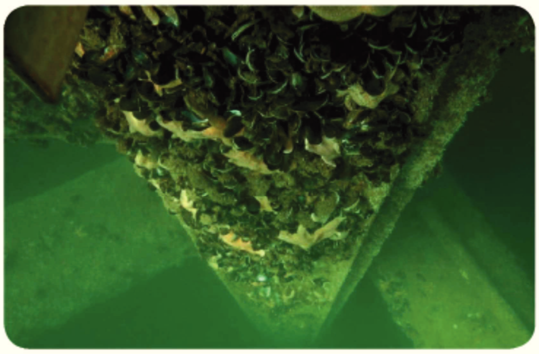
Gerade der Gezeitenbereich der Hartböden ist ein geeigneter Lebensraum für die sich immer weiter ausbreitende Pazifische Auster (*Crassostrea gigas*). Die Ausbreitung dieses Einwanderers (Neozoe) findet zwar auch ohne WEAs statt, könnte aber durch diese begünstigt werden. Der Gezeitenbereich fehlt anderen künstlichen Substraten wie Wracks und könnte als sogenannter „Trittstein“ für Neozoen des Gezeitenbereichs auf dem Weg von einer Küste auf die gegenüberliegende Seite genutzt werden.

Forschungsplattform FINO1 Foto: Emanuel Pundrich

Die tiefer liegenden Bereiche der Forschungsplattform werden von einer ähnlichen Tiergemeinschaft besiedelt, wie die der Wracks im selben Seegebiet. Das Vorkommen ortsuntypischer Arten zeigt aber auch, dass an den Konstruktionen tatsächlich zusätzliche Lebensgemeinschaften mit zusätzlicher Biomasse entstehen. Es werden also nicht nur einfach Krebse und Fische aus dem Umfeld angelockt und abgezogen.

Mindestens einen positiven Effekt werden die Anlagen bewirken: Zwischen den einzelnen Windkraftanlagen und in deren näheren Umfeld wird der Schiffsverkehr und so auch die kommerzielle Fischerei ausgeschlossen. Die wirbellosen Tiere und womöglich auch Fische werden von dieser Art Schutz profitieren. Gibt es doch in der Deutschen Bucht keinen gänzlich von den Schleppnetzen und Baumkurren der Fischer verschonten Meeresboden, auf dem sich eine Tiergemeinschaft ungestört entwickeln könnte.

Pfeiler von FINO1 mit Muschelbewuchs Foto: Lars Gutow



Getarnter Seebull an FINO1 Foto: Tanja Joschko

MUSCHELZUCHT AUF HOHER SEE – KÜNSTLICHE SUBSTRATE SCHAFFEN NEUE PERSPEKTIVEN

Die Züchtung mariner Organismen (Aquakultur) ist ein Handwerk, das von Menschen seit Jahrtausenden in vielen Teilen der Erde betrieben wird. Zu Beginn wurden meist Fische im Süßwasser kultiviert, später begann man auch mit der Kultivierung mariner Organismen, wie beispielsweise der Miesmuschel oder der Auster. Muscheln waren früher vor allem bei den ärmeren Bevölkerungsschichten als billige, eiweißreiche Kost beliebt und so wundert es nicht, dass die ersten geschichtlichen Überlieferungen von Muschelkulturen aus Europa bereits aus dem frühen 13. Jahrhundert von der französischen Atlantikküste datieren.

Miesmuschel Foto: shutterstock

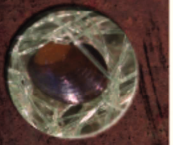
WIE KOMMEN DIE MUSCHELN ANS SEIL?

Die Muscheln vermehren sich getrennt geschlechtlich. Die Weibchen können im Schnitt etwa 5 bis 12 Millionen Eier in die Wassersäule entlassen. Im mittel- und nordeuropäischen Verbreitungsraum der Miesmuschel geben die geschlechtsreifen Weibchen im Frühjahr, wenn sich das Meerwasser erwärmt hat, ihre Eier fast zeitgleich ins Wasser ab. Durch die Eiabgabe werden auch die Männchen animiert ihre Spermien ins Wasser abzulassen. In der Wassersäule finden dann die Befruchtung und die anschließende Entwicklung zur Muschellarve statt. Das Entlassen der Samen und Eier nennt man Brutfall oder auch „Spawnen“. Das Spawnen kann mehrfach im Jahr stattfinden, wobei im Frühjahr die weitaus meisten Larven abgegeben werden.

Die Larven sind so leicht, dass sie im Wasser schwebend von den Gezeiten und der Strömung verdriftet werden (planktonisches Stadium). Nun beginnen sie einen geeigneten Untergrund für ihre weitere Entwicklung zu suchen. Jedes Hartsubstrat mit dem die Larve in Berührung kommt wird mit dem Fuß der Muschellarve auf seine Eignung als Ansiedlungsort untersucht. Ist ein passendes Substrat gefunden, vertrosst sich die Jungmuschel mit ihren Byssusfäden daran und die Umwandlung der Larve zur juvenilen Muschel beginnt. Binnen der ersten vier bis sechs Lebenswochen können die Muschellarven, falls die Bedingungen sich am gewählten Standort verschlechtern, die Vertrossung wieder lösen und sich erneut verdriften lassen. Danach ist die Larve irgendwann zu schwer und sinkt zum Boden ab.


Muschellarve


Muschelbyssus


Substrat bewachsen

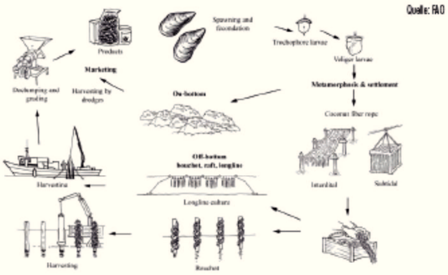
Fotos: Matthias Brenner

WER ZÜCHTET WIE?

Bei der Kultivierung von Miesmuscheln macht man sich das planktonische Stadium im Lebenszyklus der Muschel zu Nutze und bietet den umher driftenden Larven künstliche Substrate an, auf denen sie sich ansiedeln können. Die ersten französischen Züchter im Mittelalter nahmen dazu Hanfseile, die sie vor der Küste im Wasser aufspannten. Die Seile samt den darauf siedelnden Muschellarven wickelten sie anschließend um Eichenpfähle, die im Gezeitenbereich in den Meeresboden gerammt wurden. Daran wuchsen dann die Muscheln etwa zwei Jahre, bis sie groß genug zum Verzehr oder Verkauf waren. In leicht abgewandelter Form wird diese Pfahlkultur auch heute noch an der nordfranzösischen Küste praktiziert. Aufgrund dieser Form der Kultivierung nannte man früher die Miesmuschel auch Pfahlmuschel.

Vor allem in den Niederlanden, Deutschland und Dänemark, die durch das Wattenmeer über besonders geschützte Meeresgebiete verfügen, hat sich hingegen eine andere Form der Muschelkultivierung etabliert. Bei der sogenannten Besatzmuschelfischerei werden junge Saatmuscheln von wilden Muschelbänken mit Muschelkuttern abgefischt und anschließend in die geschützten ständig überflutete Bereiche des Wattenmeeres verbracht, wo sie auf Lizenzflächen bis zur Marktreife heranwachsen.

Eine entscheidende Weiterentwicklung der Kultivierungstechnik, die im Wesentlichen auf den Prinzipien der Pfahlkultur basiert, wurde vor etwa 40 Jahren eingeführt. Bei dieser sogenannten Langleinen-Kultivierung werden die für die Muschellarven so attraktiven künstlichen Substrate, auch Brutsammler oder Kollektoren genannt, senkrecht an eine an der Wasseroberfläche oder kurz darunter waagrecht verspannten Langleine befestigt. Die Langleine selbst wird mit Verankerungen am Boden und entsprechenden Auftriebskörpern am Verdriften bzw. Absinken gehindert. Im nordspanischen Galicien hat man diese Methode erfolgreich abgewandelt und lässt die Brutsammler statt von einer Leine von Holzflößen ins Wasser hängen.



Quelle: FAO

Kultivierungsmethoden ↑

Langleine, Korea ↓

Floßkultur, Galicien →

So unterschiedlich die Methoden der Züchtung im Detail sind, so ist ihnen doch seit je her eines gemein: Sie werden fast ausschließlich in geschützten und ruhigen Meeresbereichen durchgeführt. Mit den fortschreitenden Möglichkeiten der Technik hat sich daran bis vor kurzem wenig geändert, außer dass landgestützte Systeme hinzugekommen sind.

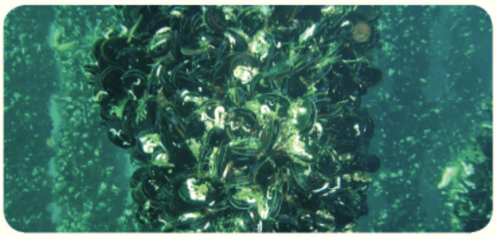


Foto: CIMM

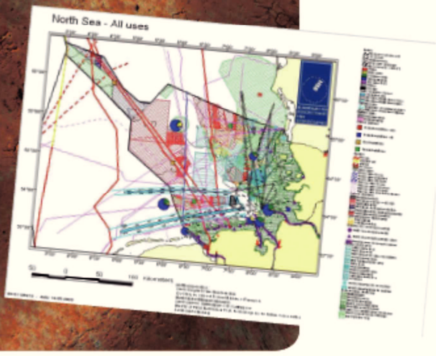
Foto: Matthias Brenner

AUSSICHTEN FÜR DIE DEUTSCHE MUSCHELZUCHT

An den deutschen Küsten der Nord- und Ostsee haben es die Muschelzüchter nicht leicht. Die Ostsee ist für viele Zuchtkandidaten wie Miesmuschel, Auster oder auch Makroalgen, die auf dem Markt hohe Nachfrage erzielen, nicht salzig genug. Zudem bilden sich im Winter recht häufig großflächige Meereiszonen, die die Zuchtanlagen zerstören können.

Der Bereich der deutschen Nordsee hat zwar einen ausreichenden Salzgehalt, kann aber aufgrund der sehr dynamischen Bedingungen (Tiden, Strömungen, Stürme, etc.) nur im Küstenbereich durch die Besatzmuschelfischerei genutzt werden. Der überaus größere Teil der deutschen Gewässer in der Nordsee wird traditionell lediglich befischt. Aufgrund der vielseitigen Nutzungsinteressen (Schiffsverkehr, Tourismus, Naturschutz, etc.) ist eine Expansion der Besatzmuschelfischerei nicht möglich. Im Gegenteil: Es ist ein kontinuierlicher Rückgang in der potentiell nutzbaren Fläche für die Muschelfischerei feststellbar, trotz der hohen Nachfrage nach Muscheln.

Zu den Raumnutzungskonflikten gesellen sich biologische Probleme, die starke Schwankungen des Ernteerfolges zur Folge haben und damit das wirtschaftliche Betreiben gepachteter Wattflächen problematisch machen. So siedelten sich in manchen Jahren trotz hoher Larvenkonzentration in der Wassersäule zu wenige Jungmuscheln auf den natürlichen Muschelbänken an (Larvenfall). Gründe dafür können sein, dass wetterbedingt die Strömungsbedingungen so ungünstig sind, dass ein Großteil der Larven ins offene Meer verdriftet wird, wo sie keine Möglichkeiten zur Ansiedlung finden und absterben. Eine andere Möglichkeit ist, dass, nach warmen Wintern die Freßfeinde der Miesmuscheln wie Seesterne in großer Zahl überleben, sich am Boden über die frisch angesiedelten Jungmuscheln her machen und so die Bestände drastisch reduzieren. Darüber hinaus sind die Erntemethoden (Dredgen und Schleppnetze) ökologisch überaus problematisch, da sie unselektiv sind, großen Beifang produzieren und eine Zerstörung der befischten Areale unweigerlich mit sich bringen.



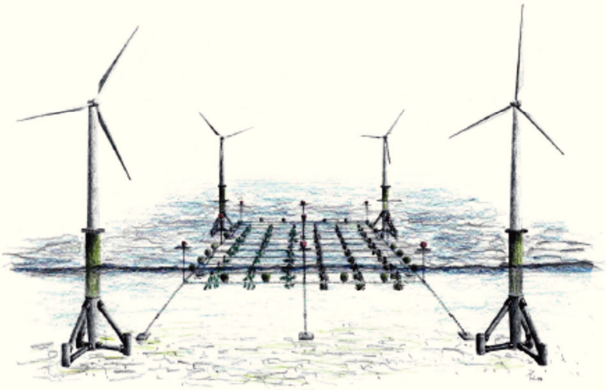
MUSCHELN AUS OFFSHORE-WINDPARKS?

Mit der Langleinen-Kulturtechnik können viele der erwähnten Nachteile reduziert werden. In der Wassersäule sind selbst in Jahren mit unzureichendem Larvenfall auf den Wildbänken immer genügend Muschellarven vorhanden, um die Kollektorflächen auszulasten und die Muscheln hängen für die auf dem Boden lebenden Räuber wie Seesterne zu hoch und für Muschel fressende Seevögel zu tief im Wasser. Außerdem ist auf hoher See die Konkurrenz um Raum wesentlich geringer als in Küstennähe. Dank des reichhaltigen Nahrungsangebotes, dass in der deutschen Bucht aufgrund der Eintragung durch die großen Flüssen eigentlich überall vorhanden ist, wachsen die Muscheln binnen 1,5 Jahren zur Marktreife heran.

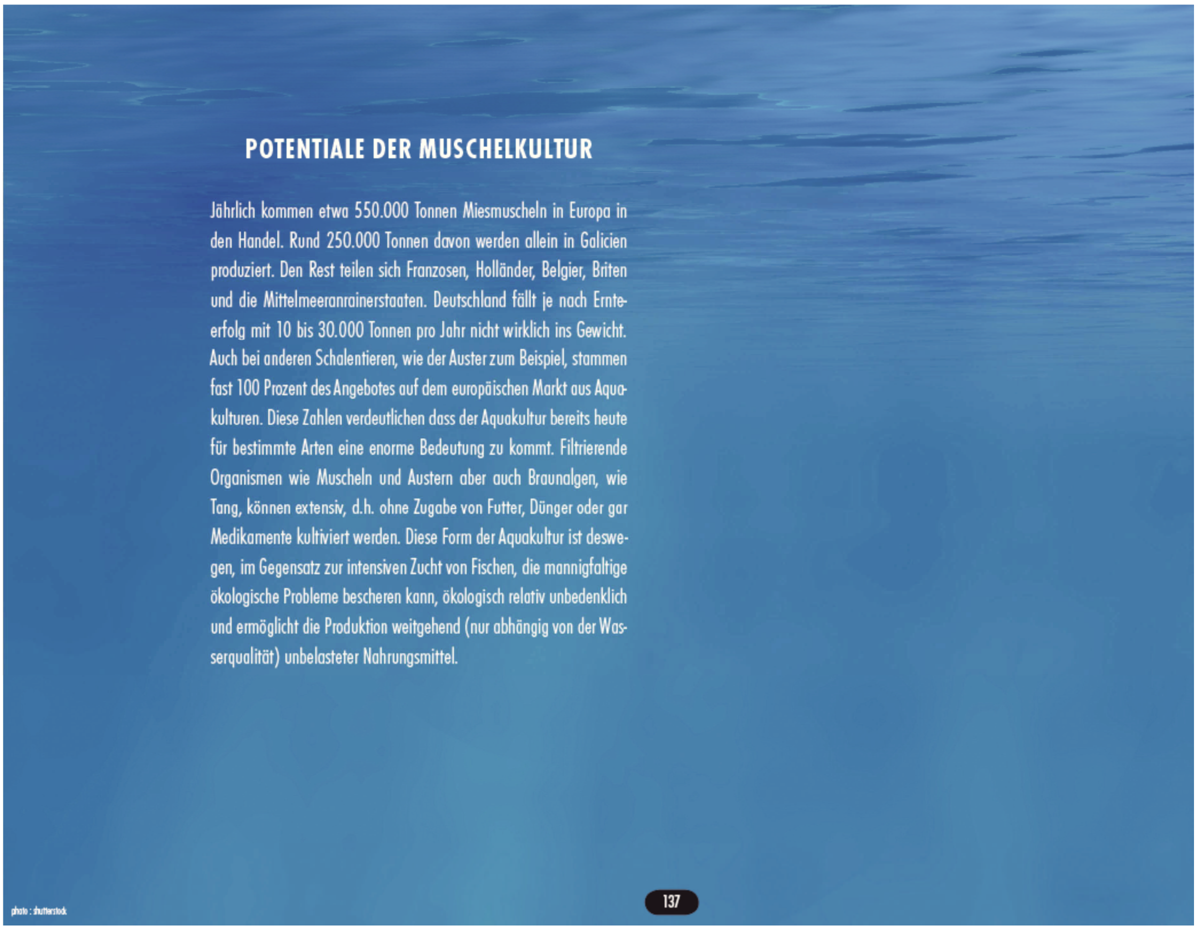
Geerntet werden können die Muscheln mit aus den Küstenbereichen bereits erprobten, bootsgestützten, weitgehend mechanisierten Methoden, die die Muscheln schonend von ihrem künstlichen Substrat lösen und gewährleisten, dass die Brutsammler wiederverwendet werden können.

Für den Einsatz im offenen Meer muss die Langleinentechnik angepasst werden. Das ganze System sollte ein paar Meter unter der Wasseroberfläche schweben, um der größten Wellenkraft zu entgehen, es muss stabil und gleichzeitig flexibel konstruiert sein und durch massive Verankerungen vor dem Verdriften geschützt werden. Klar ist, dass diese technischen Notwendigkeiten die Investitionskosten in die Höhe treiben. Deswegen kam die Idee auf, die massiven Verankerungen der geplanten Windkraftanlagen in der Nordsee sekundär zur Befestigung der Kultursysteme nutzbar zu machen.

Da die Windparks mit ihrer Realisation zu Sperrflächen für den übrigen Schiffverkehr würden, bieten sich diese riesigen Areale für die sekundäre Zucht von marinen Organismen geradezu an. Neben den bereits beschriebenen Miesmuscheln könnten in diesen Gebieten auch Braunalgen als industrieller Rohstoff mit vielfältigen Verwendungsmöglichkeiten oder auch Austern gezüchtet werden.



Zukunftsprojekt: Windpark mit Aquakultur Bild: Alexandra Haasbach



POTENTIALE DER MUSCHELKULTUR

Jährlich kommen etwa 550.000 Tonnen Miesmuscheln in Europa in den Handel. Rund 250.000 Tonnen davon werden allein in Galicien produziert. Den Rest teilen sich Franzosen, Holländer, Belgier, Briten und die Mittelmeeranrainerstaaten. Deutschland fällt je nach Ernteerfolg mit 10 bis 30.000 Tonnen pro Jahr nicht wirklich ins Gewicht. Auch bei anderen Schalentieren, wie der Auster zum Beispiel, stammen fast 100 Prozent des Angebotes auf dem europäischen Markt aus Aquakulturen. Diese Zahlen verdeutlichen dass der Aquakultur bereits heute für bestimmte Arten eine enorme Bedeutung zu kommt. Filtrierende Organismen wie Muscheln und Austern aber auch Braunalgen, wie Tang, können extensiv, d.h. ohne Zugabe von Futter, Dünger oder gar Medikamente kultiviert werden. Diese Form der Aquakultur ist deswegen, im Gegensatz zur intensiven Zucht von Fischen, die mannigfaltige ökologische Probleme bescheren kann, ökologisch relativ unbedenklich und ermöglicht die Produktion weitgehend (nur abhängig von der Wasserqualität) unbelasteter Nahrungsmittel.

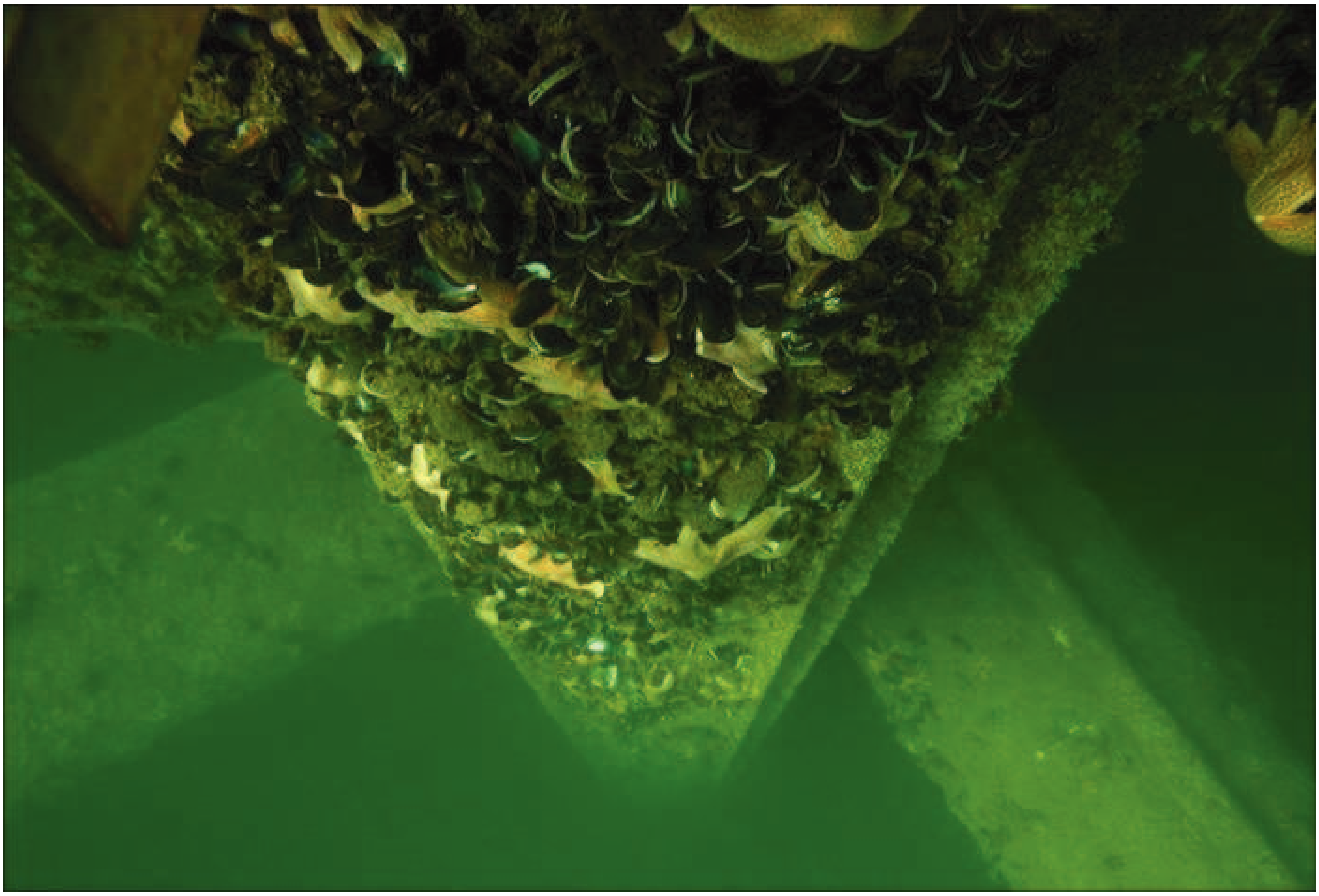
photo : shutterstock

PUBLICATION IX

Benthosökologische Auswirkungen von Offshore-Windenergieparks in der Nordsee (BeoFINO II)

Alexander Schröder, Lars Gutow, Tanja Joschko, Roland Krone, Manuela Gusky, Markus Paster, Michael Potthoff

BMU



Endbericht
November 2008

Benthosökologische Auswirkungen von Offshore-Windenergieparks in der Nordsee

BeoFINO II

Prozesse im Nahbereich der Piles

A. Schröder, L. Gutow, T.J. Joschko, R. Krone, M. Gusky, M. Paster & M. Potthoff

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16. Zusätzliche Angaben
Folgeprojekt zum Projekt FKz 327526: „Ökologische Begleitforschung zur Windenergienutzung im Offshore-Bereich auf Forschungsplattformen in der Nord- und Ostsee (BeoFINO II)"

17. Vorgelegt bei (Titel, Ort, Datum)

18. Kurzfassung

In der Nordsee wurden auf der Forschungsplattform FINO 1 Felduntersuchungen durchgeführt, um spezielle Fragen zu möglichen Auswirkungen von Offshore-Windenergieparks auf die marine Umwelt zu beantworten. Der Fokus war dabei auf die Konsequenzen für die Lebensgemeinschaft am Meeresboden gerichtet. Es wurden die benthosökologischen Prozesse im Nahbereich der Piles sowie die mittelfristige Entwicklung der Auswuchsfauna auf der künstlichen Unterwasserstruktur dokumentiert. Die Ansammlung pelagischer Fischen um die Plattform und der Export organischen Materials von der Plattform wurden quantifiziert. Die räumliche Ausdehnung und die Erheblichkeit von Auswirkungen auf die Lebensgemeinschaften des Meeresbodens wurden anhand mathematischer Modellierung abgeschätzt. Zusätzlich wurde die Anwendbarkeit der elektrochemischen Akretionstechnologie zur Schaffung naturnaher Kalksubstrate in der Nordsee getestet und geeignete Parameter für eine erfolgreiche Umsetzung unter Nordseebedingungen ermittelt.

Die auch 4 ½ Jahre nach Errichtung der Plattform noch ansteigende Artenzahl der Aufwuchsfauna lässt darauf schließen, dass der Sukzessionsprozess noch nicht abgeschlossen ist. Die stark vertikal zonierte Aufwuchsfauna auf der Unterwasserkonstruktion erreicht eine Masse von ca. 5 Tonnen mit ausgeprägten saisonalen Schwankungen. Anhand von echoakustischen Untersuchungen wurden saisonal auftretende Ansammlungen pelagischer Fische um die Plattform dokumentiert. Der Nahbereich der Plattform unterschied sich durch eine Schillauflage und eine räumlich und zeitlich sehr variable Sediment- und Bodenfaunazusammensetzung deutlich von einem unbeeinflussten Referenzgebiet. Eine konzentrische Zonierung mit unterschiedlich stark ausgeprägten Veränderungen der Bodenfauna lässt auf komplexe Veränderung des gesamten lokalen Nahrungsgefüges im Nahbereich der Plattform schließen. Anhand einer Modellierung konnte der Materialexport in die umgebenden Weichbodenbereiche für einzelne Piles und einen hypothetischen Windpark abgeschätzt werden. Die lokale Ausbildung einer hohen Biomasse auf der Unterwasserkonstruktion von WEA sowie der Export mit anschließender Sedimentation lassen zumindest lokal einen erheblichen Einfluss auf Stoff- und Energieflüsse erwarten.

19. Schlagwörter

Offshore-Windenergie, Forschungsplattform FINO 1, Auswirkungen auf die Umwelt, künstliches Hartsubstrat, Veränderung der Sedimentstrukturen, Lebensgemeinschaften des Meeresbodens, Benthos, Deutsche Bucht, Nordsee

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Hinweis für Bearbeiter/in:
Auf das Förderkennzeichen des BMU wird in Veröffentlichungen hingewiesen werden

Inhalt (unterstrichene Kapitel werden nachfolgend dargestellt)

1.4.9 Elektrochemische Akkretionstechnologie (EAT)

Die Schwerpunkte dieser Arbeit liegen in einer Machbarkeitsstudie zur **e**lektrochemischen **A**kkretions**t**echnologie (**EAT**) und der Erzeugung von Hartsubstraten mit Nordseewasser. Hierzu wurden verschiedene Versuchsreihen im Labormaßstab durchgeführt. EAT-Substrate sind feste karbonatische Platten oder Gitter, die durch die Präzipitation von Karbonaten auf einem als Kathode geschalteten metallischen Grundgerüst entstehen. Ihre bisherige Produktionen und Erprobungen erfolgten u. a. im Roten Meer (Sinai-Halbinsel) als Korallenriffprothesen (Abb. 1.4.20) (van Treeck & Schuhmacher 1999) und im Mittelmeer (Korsika) als Schwammaufzuchthilfen (Abb. 1.4.20) und als Seegraswiesenstabilisatoren. Aufgrund des hohen Mineralgehaltes von Meerwasser stellt die elektrochemische Akkretionstechnologie eine elegante Methode zur *in situ* Erzeugung von naturidentischen Kalksubstraten dar. Wird doch der Baustoff direkt aus dem Meerwasser gewonnen. Das Verhältnis der Hauptinhaltsstoffe variiert innerhalb der Weltmeere nur in sehr geringem Maße, sodass unter Einbeziehung gleicher Temperatur- und Druckverhältnisse potenziell eine weltweite Anwendung der Technologie möglich ist. In der hier durchgeführten Studie wurde die Anwendung der EAT-Technik erstmals in Nordseewasser getestet.

Abb. 1.4.20: EAT-Kalkgitter eingesetzt als Korallenriffprothese im Roten Meer (l.), in der Schwammaufzucht (mitte) und zur Seegraswiesenstabilisierung (r.) im Mittelmeer (Paster/ Eisinger).

1.4.9.1 Grundlagen der elektrochemischen Mineralakkretion

Die Festigkeit und somit auch das Mineralgefüge der EAT-Substrate hängen von vielen Faktoren ab. Bubner et al. (1988), Hilbertz (1988), Kolipara et al. (1984), Schuhmacher & Schillak (1994) sowie van Treeck (2001) beschrieben durch ihre Versuche zur elektrochemischen Mineralakkretion, das die wichtigsten Faktoren Stromdichte, Bildungszeit, Anoden- und Kathodenwahl sowie die Versuchsanordnungen zueinander sind. Auch Temperatur, Tiefe und somit der Druck am Entstehungsort sowie eine intermittierende Bestromung tragen zu einer bestimmten strukturellen und chemischen Zusammensetzung bei. Bei allen regional bedingten Unterschieden ist seit Langem bekannt, dass die Salze im Wasser aller Meere in fast identischen Anteilen vorliegen. Lediglich die Salinität variiert um 3,3 psu bis 3,8 psu in ozeanischen Regionen, Nebenmeere zeigen entsprechend höhere Varianzen auf.

Bei der Mineralakkretion im Meerwasser (Abb. 1.4.21) scheiden sich an speziell geformten Elektroden, an die ein Gleichstrom angelegt wird, die im Meerwasser gelösten Mineralsalze an der Kathode ab. Dies bedeutet, dass die Anionen unter Entwicklung von Chlorgas und Sauerstoff an der Anode oxidiert und die Kationen an der Kathode durch Reduktion und Freisetzung von Wasserstoff reduziert werden.

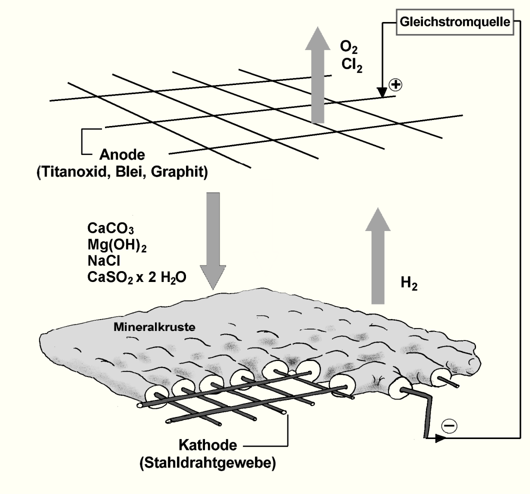

Abb. 1.4.21: Vereinfachte schematische Darstellung der elektrochemischen Mineralakkretion (aus: van Treeck 2001).

Durch diesen Prozess entsteht an den Kontaktflächen zwischen Matrixmaterial (Kathode) und Meerwasser eine Alkalisierung, die u. a. zur Abscheidung von Kalzium- und Magnesiummineralien führt. Durch diese Abscheidungen können harte Krusten entstehen, deren chemische Zusammensetzung und Materialqualität denen natürlicher Riffkalke sehr ähnlich ist (Meyer & Schuhmacher 1993). Neben Kalziumkarbonat, welches hier zumeist als Aragonit, einer rhombischen Form des $CaCO_3$ vorkommt, und Brucit ($Mg(OH)_2$), werden bei dem beschriebenen Verfahren noch geringe Anteile von Gips ($CaSO_4$ * $2H_2O$) und Halite (Steinsalze, NaCl) abgeschieden.

1.4.9.2 Steuerungsfaktoren der elektrochemischen Mineralakkretion

Die Zusammensetzung der Mineralschichten sowie die Bildungsgeschwindigkeit der Akkretion werden durch den pH-Wert im Grenzschichtbereich geregelt. Durch die Löslichkeitsprodukte der Hauptkrustenbildner und den Kationenkonzentrationen liegt der kritische Schwellenwert bei ca. pH 9,7 für Mg $(OH)_2$ und pH 8,7 für $CaCO_3$ (Menzel 1995). Die Messung des elektrischen Oberflächenpotenzials an einer Kathodenmatrix ermöglicht eine genaue Analyse der Bildungsbedingungen der Mineralakkretion und kann für die Entwicklung einer effizienten Regeltechnik herangezogen werden. Hierzu benötigt man eine Bezugselektrode, die die Spannung gegenüber der Kathode messen kann (Heitz & Kreysa 1977). Eine Abscheidung der Mineralien auf einer Kathodenmatrix beginnt in dem Elektrolyt „Meerwasser“ bei einem Oberflächenpotenzial von -980 mV gegenüber einer Kalomel-Bezugselektrode (Hg/Hg_2Cl_2). Bei diesen Oberflächenpotenzialen kommt es aber nur zu geringen Mineralschichtdicken. Geringere Oberflächenpotenziale von beispielsweise -1350 mV (Hg/Hg_2Cl_2) führen zwar zur Erzeugung von dicken Mineralschichten in sehr kurzer Zeit, verändern aber auch die Qualität (Zusammensetzung) der Mineralakkretion, da bei einem hohen pH-Wert und somit einer höheren Alkalinität höhere Anteile von Brucit präzipitieren. Brucit (Abb. 1.4.22) besteht aus einer lamellaren-foliaten Form mit nur sehr geringer Stabilität und ist somit für die Erzeugung fester Krusten unbrauchbar. Ein weiterer negativer Effekt ist durch die hohe Alkalinität von Brucit bedingt, die dieses Material für sessile Organismen besiedlungsfeindlich macht (van Treeck 2001).

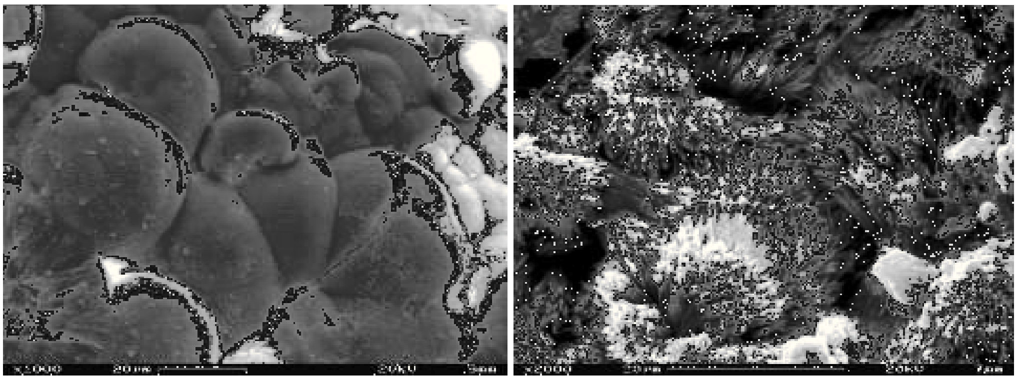

Abb. 1.4.22: Polsterförmige Brucit-Erhebungen (l.) und Aragonit-Nester (r.) (aus: Heesen 2002)

Der Aragonit (Abb. 1.4.22) hat durch die kristalline Form eine höhere Festigkeit als Brucit und ist durch die relativ geringe Alkalinität für die Erzeugung kompakter Mineralkrusten für konstruktive Bereiche sehr geeignet (Menzel 1995, van Treeck 2001). Alle Angaben zu Oberflächenpotenzialen stammen aus Laborversuchen, die den Einsatz der hoch sensiblen Kalomel-Elektroden möglich machten. Der Einsatz unter Freilandbedingungen stellt jedoch ungleich höhere Anforderungen an die Dauerhaftigkeit der Elektroden sowie Übertragung von sehr geringen Signalen im Millivolt-Bereich über zum Teil erhebliche Kabellängen, da die Experimente zumeist nicht direkt neben der eigentlichen Steuerelektronik stehen. Die Entwicklungen sowie Anwendung einer neuartigen Messelektrode konnte erstmals im Ramen des EU-Forschungsprojekts Development of non-degrading, NOvel MArine TEChnologies (NOMATEC 2001 - 2004) (NOMATEC 2004) durchgeführt werden (Paster 2006). Die ersten Ergebnisse zu dieser sogn. Referenzelektrode zeigte im Mittelmeer unter den dort herrschenden Freilandbedingungen eine gute Möglichkeit, die Akkretionstechnologie mit einer potenziostatischen Steuerung durchzuführen.

1.4.9.3 Stromversorgung und Steuerung der EAT-Versuchsanlagen

Als Stromversorgung wurden in dem Versuchszeitraum insgesamt drei verschiedene Netzgeräte verwendet (Abb. 1.4.23). Bei zwei Netzversorgern handelt es sich um selbst entwickelte sogn. „power supplys“, die im Rahmen des NOMATEC-Projectes erfolgreich eingesetzt werden konnten. Bei dem dritten handelt es sich um einen handelsüblicher Labornetzversorger der Firma IN-RIM, Modell 402 (Mannheim). Der Labornetzversorger und einer der mobilen EAT-Netzversorger konnten aufgrund der gering regelbaren Ausgangsleistungen hauptsächlich für die Bestromung von Experimenten in Kleinmaßstab eingesetzt werden. Das größere Netzgerät wurde aufgrund seiner hohen Ausgangsspannungen hauptsächlich für die Bestromung der etwas größeren Experimente eingesetzt.

Abb. 1.4.23: Übersicht der verwendeten elektronischen Netzversorger und Steuergeräte (v. l. n. r: 5 Kanal Netzgerät, EAT-Koffer, UVS und Trennverstärker, handelsübliches Netzgerät sowie Server für die internetbasierte Bildkontrolle).

Standort der einzelnen EAT-Stromversorger war die Hummeraufzucht-Halle der Biologischen Anstalt Helgoland (BAH). Um Störungen durch Spannungsspitzen des öffentlichen Stromnetzes zu vermeiden, wurden die Anlagen mit einem handelsüblichen Spannungsschutz versehen. Darüber hinaus wurde für den Fall eventuell auftretender kurzer Stromausfälle eine Strom-Back-up UVS Einheit (Firma APC) zwischen Überspannungsschutz und EAT-Netzgeräten installiert

1.4.9.4 Anodenmaterial der EAT-Versuche

Zur Bestromung der in dieser Arbeit dargestellten, relativ einfachen Kathodenstrukturen dient als Anode eine Titanode® (Heraeus Elektrochemie GmbH Hanau) in Streckmetall-Ausführung zur gleichmäßigen Stromverteilung. Der elektrische Anschluss wurde über ein an der Titanode® angeschweißten Kupferdraht und einer handelsüblichen Lüsterklemme realisiert. In den Rundbecken wurden korrosionsbeständige Trovidurklemmen oder PVC-Rohre als Abstandshalter an den Metallgittern befestigt. Mittels handelsüblicher PVC-Rohre wurden die Anoden entweder horizontal oder vertikal ausgerichtet.

1.4.9.5 Kathodenmaterial der EAT-Versuche

Als Kathodenmatrix ist ein spezielles blankes, d. h. nicht galvanisch verzinktes Schweißgitter (Maschendraht) verwendet worden. Die Vorteile dieses speziellen Gitters liegen in der Verarbeitungsweise des Einzeldrahtes, der an den Kreuzungspunkten jeweils punktverschweißt ist und somit im gesamten Gitter direkten elektrischen Kontakt hat (Abb. 1.4.24).

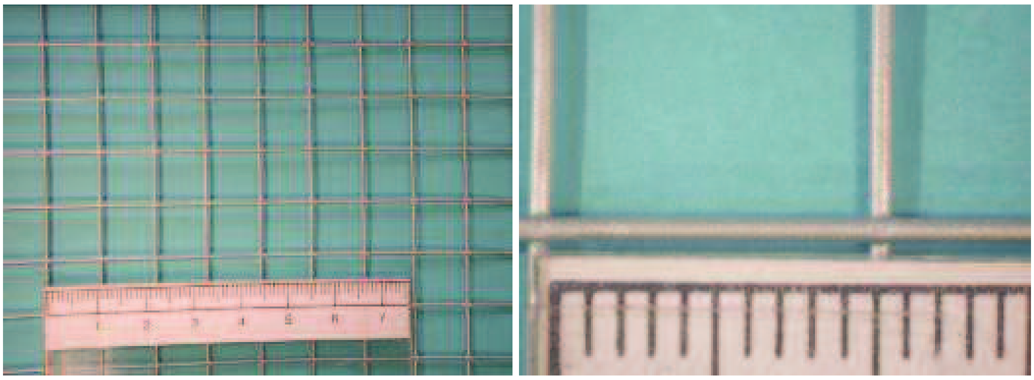

Abb. 1.4.24: Übersicht (links) und Detailaufnahme (rechts) des punktverschweißten EAT-Drahtgewebes.

Der Maschendraht wurde je nach Funktion bzw. nach dem notwendigen Design ausgeformt. Um einen einfachen und sicheren Kontakt des EAT-Gitters mit den Stromkabeln zu ermöglichen, wurden hier Anschlussklemmen verwendet, die einen Anschluss unter Wasser erlauben. Da die Kathode reduzierend beaufschlagt ist und Korrosion daher kaum eine Rolle spielt, ist die Konstruktion im Vergleich zur Anodenklemme relativ simpel. Diese Klemmen bestehen aus 2 Stahlplatten, wobei eine der Platten mit einer Lasche und Bohrung versehen wurde. Das Stromkabel wurde mittels einer Lötöse mit der Lasche verschraubt und durch einen mit handelsüblichem Sanitärsilikon eingespritzten Silikonschlauch gegen Wassereinbruch geschützt. Mit einer passenden Konterplatte (90 mm x 30 mm x 6 mm) kann somit die zwischen den Platten liegende Drahtmatrix fixiert und durch ein Verschrauben ein sehr stabiler sowie haltbarer Kontakt geschaffen werden.

1.4.9.6 Referenzelektrode

Die sogenannte Referenzelektrode (Abb. 1.4.25) wurde aus einem handelsüblichen Rohstab aus 99er Reinzink auf die Maße 20 x 16 mm gefertigt. Dieser wurde anschließend wasserdicht verklebt. Somit erhielt man an einem Ende des Stabes eine Kontaktfläche von ca. 2 cm^2 Größe. Diese Referenzelektrode wurde zum Schutz vor Wassereinbruch und mechanischer Beschädigung in einem PVC-Rohr (180 mm x 22 mm) mit Silikon vergossen. Zur Messung des Potenzials innerhalb des Potenzialmesskreises wurde ein Referenzanschluss aus einer Stahlplatte (100 x 30 x 6 mm) verwendet, der mit einer passenden Konterplatte (90 x 30 x 6 mm) an der Kathodenmatrix mit Schrauben befestigt werden kann. Der Kabelanschluss wurde, wie bei der Referenzelektrode, mit einer angeschraubten Lötöse und einem eingespritzten Silikonschlauch an einer Lasche der Stahlplatte gegen Wassereinbruch geschützt (Abb. 1.4.25).

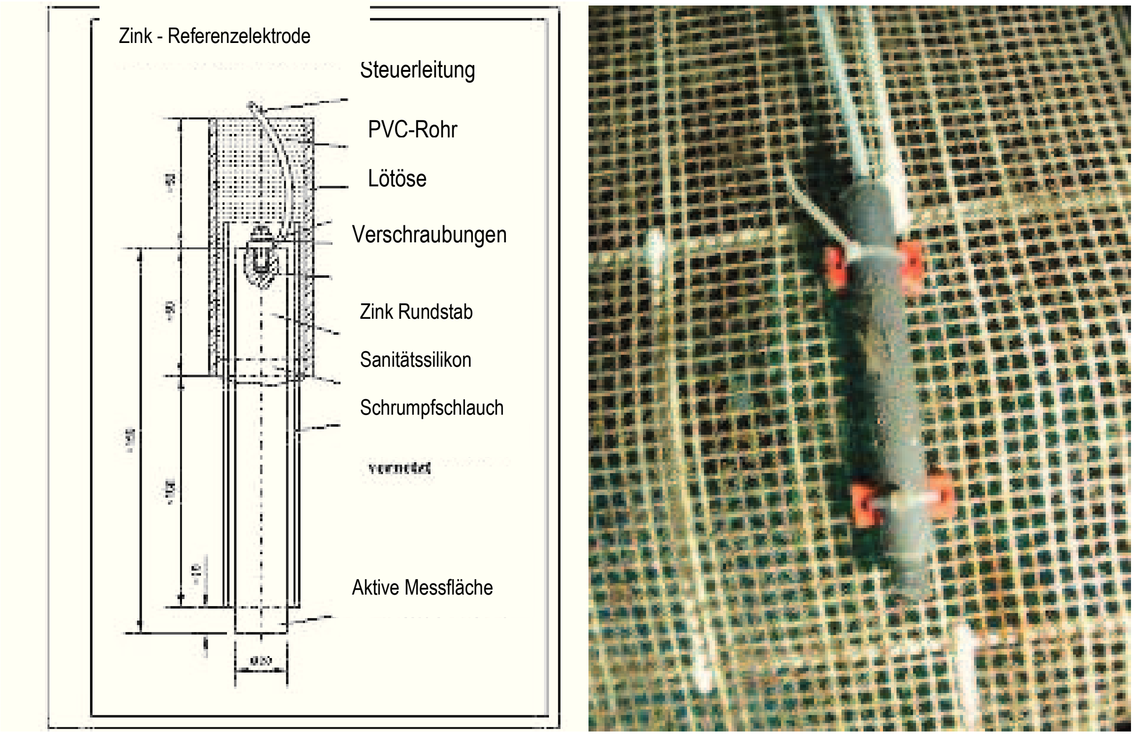

Abb. 1.4.25: Explosionszeichnung der Referenzelektrode (links) und Referenzelektrode mit Trouvidur-Abstandshalter auf einem EAT-Experiment (rechts).

Aufgrund des sehr geringen Oberflächenpotenzials (gemessen in Millivolt) ist eine Übertragung des Messsignals über ein Kabel auf wenige Meter beschränkt. Um nun eine Messung über längere Strecken zu ermöglichen, wurden Trennverstärker der Firma Schumann, Güglingen (Modell UT 1.14) so modifiziert, dass das mV-Signal des installierten Messkreises an den Experimenten vor Ort in Milliampere (mA) umgewandelt wird. Der Trennverstärker wird dabei extern über eine Messleitung (NYM 5 x 1,5mm^2) über zwei der 5 Kabeladern mit 24 Volt Strom versorgt. Das von dem Messkreis erhaltene Millivoltsignal (dritte Ader) wird anschließend in Milliampere umgewandelt und über die 4. Ader der Messleitung an die Erfassungseinheit geleitet (Abb. 1.4.26).

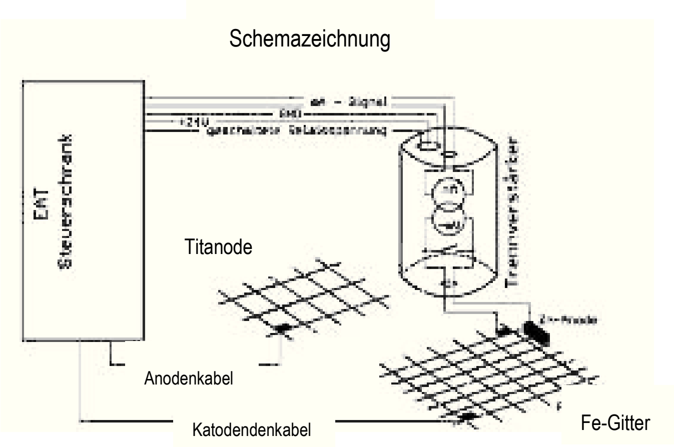

Abb. 1.4.26: Schematischer Aufbau einer EAT-Versuchseinheit mit Schaltkreis der Referenzelektrode und Detailbild der Trennverstärker-Box (aus Paster 2006).

An der Erfassungseinheit wurde das Signal wieder in Millivolt umgewandelt, an den Messinstrumenten angezeigt und digital abgespeichert.

1.4.9.7 Erprobung einer Fernüberwachungen der Experimente

Zur Einsparung von Reisekosten sowie zur zeitnahen Überprüfung der laufenden Experimente wurde nach Installation der ersten Versuchsanordnungen ein Videoserver (Convision V600, Braunschweig) mit handelsüblichen Webcams (Logitec Zoom, Germering) aufgestellt. Durch die Installation einer Remote-Software und dem AWI-Netzwerkzugang zum Datennetz der BAH war es möglich, die Bilder der Webcams automatisch auf einen FTP-Server der Universität Duisburg-Essen (UDE) zu überspielen (Abb. 1.4.28). Zur einfachen Kontrolle und Überprüfung ausgewählter Becken ist im Anschluss an die Installationsarbeiten an der UDE eine Internetseite (www.eat-nordsee.de) programmiert worden. Sie ermöglicht den einfachen Zugriff auf aktuelle Bilder der EAT-Versuche, die vom Messcomputer auf Helgoland in voreingestellten Intervallen automatisch nach Essen gesendet werden.

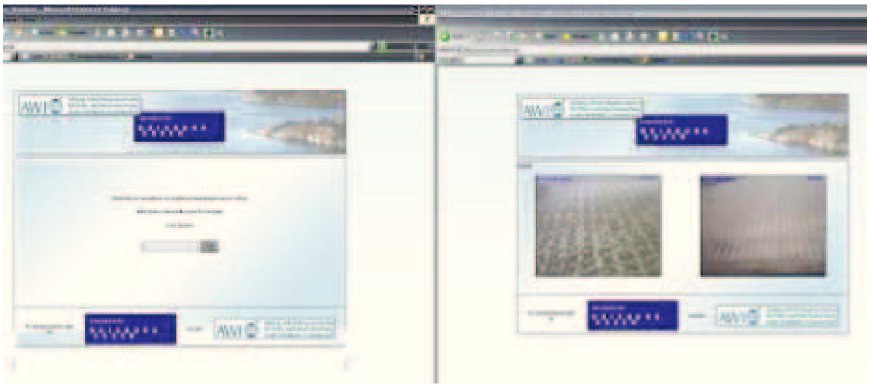

Abb. 1.4.27: Internetseite mit passwortgeschützem Login (links) und Webcambilder im geschützten Bereich (rechts)

1.4.9.8 Versuchsaufbau und Kathodendesign der EAT-Experimente

Die Überprüfung der möglichen Präzipitation wurde anhand realer Mineralakkretionsexperimente durchgeführt. Es wurden unterschiedliche Testmatten und Testkörper unter verschiedenen Stromregimen getestet. Insgesamt wurden 8 Versuchsansätze mit 6 verschiedenen Anordnungen der Messtechnik, des Substratdesigns und der Bestromungstechnik durchgeführt (Tab. 1.4.13). Aufgrund der begrenzten Verfügbarkeit fließenden Meerwassers sowie dem geringen Platzangebot in der Hummerhalle der BAH mussten Formen und Größen der einzelnen

Module sehr klein gehalten werden. Im Folgenden werden die wichtigsten Versuchsanordnungen vorgestellt und ihre Funktion steckbriefartig erläutert.

Folgende Seite:

Tab. 1.4.13: Kenndaten der einzelnen EAT-Experimente. * = durchschnittliche Durchflussrate ist wahrscheinlich geringer, da Wasserzufluss nicht immer permanent gegeben war.

	EAT-Versuch I	**EAT-Versuch II**	**EAT-Versuch III**	**EAT-Versuch IV**	**EAT-Versuch V**	**EAT-Versuch VI**	**EAT-Versuch VII**	**EAT-Versuch VIII**
Stromversorgung	Labornetzgerät	EAT-Koffer	5 Kanal-Netzgerät	5 Kanal-Netzgerät	Labornetzgerät	Labornetzgerät	Labornetzgerät	EAT-Koffer
Kabel	NEXANS Rhexflex	NEXANS Rhexflex	NEXANS Rhexflex	NEXANS Rhexflex	NEXANS Rhexflex	NEXANS Rhexflex	NEXANS Rhexflex	NEXANS Rhexflex
	5 G 1,5 VDE	5 G 1,5 VDE	5 G 1,5 VDE	5 G 1,5 VDE	5 G 1,5 VDE	5 G 1,5 VDE	5 G 1,5 VDE	5 G 1,5 VDE
Anodenmaterial	Titanmischoxid-Gewebe	Titanmischoxid-Gewebe	Titanmischoxid-Gewebe	Titanmischoxid- Gewebe	Titanmischoxid-Gewebe	Titanmischoxid- Gewebe	Titanmischoxid- Gewebe	Titanmischoxid- Gewebe
Anodenform	Flächig / L-Fom	Flächig	Zylindrisch	Zylindrisch	Flächig / L-Fom	Flächig / L-Fom	Flächig	Zylindrisch
Kathodenmaterial	EAT-Draht	EAT-Draht	EAT-Draht	EAT-Draht	EAT-Draht	EAT-Draht	EAT-Draht	EAT-Draht
Kathodenform	Flächig	Flächig	Zylindrisch	Zylindrisch	Zylindrisch	Zylindrisch	Zylindrisch	Zylindrisch
Kathodengröße (Gitterfläche) [m^2]	0,225	0,17	0,28	0,28	0,2	0,21	0,21	5,9
Kathodisch wirksame Metalloberfläche [m²]	0,135	0,102	0,168	0,168	0,12	0,126	0,126	3,54
Stromsteuerung	Galvanostatisch	Potentiostatische	Galvanostatisch	Galvanostatisch	Potentiostatische	Galvanostatisch	Galvanostatisch	Potentiostatische
Oberflächenpotenzial	Nicht gemessen	-140 mV_{Zn}	Nicht gemessen	Nicht gemessen	-110 mV_{Zn}	Nicht gemessen	Nicht gemessen	-125 mV_{Zn}
Bestromungsdauer (Monate)	8	8	6	6	11	11	12	7
Ampere pro m² kathodischer Oberfläche ($A/m^2_{Kath.Oberfl.}$)	2,9	3	3,5	3,5	2,6	2,5	2,5	2,4
Datenaufnahme	Protokoll	Digital	Protokoll	Protokoll	Digital	Protokoll	Protokoll	Digital
Beckenart / -volumen	Glas /	Glas	PVC /	PVC /	Glas	Glas	Glas	PVC /
Wasserdurchfluss l/min	5	4,5	4,5	3,5	3	3	3	6*
Überwachung	Webcam	Webcam	Manuell	Manuell	Webcam	Webcam	Webcam	Manuell

1.4.9.8.1 Versuchsanordnung I

Bei diesem Versuchsaufbau wurde ein Glasaquarium genutzt (Abb. 1.4.28). Die Ausgestaltung der Kathode wurde in Becken I als L-Form gewählt, um somit eine größere Drahtfläche zu erhalten und die Aspekte der eventuell vorhandenen ungleichen Präzipitation aufgrund von unterschiedlichen Entfernungen zur Anodenmatrix und damit zur Feldausprägung zu überprüfen. Der EAT-Maschendraht ist an der Unterseite auf kleine Trovidurplatten gelegt worden, um zu verhindern, dass der EAT-Maschendraht Kontakt zum Aquariengrund bekommt. Die Anodenmatrix ist kurz unterhalb der Wasseroberfläche befestigt worden. Aufgrund der sehr geringen Bestromung mit nur 0,4 A wurde hier das regelbare Labornetzgerät RIM 402 eingesetzt. Das Becken wird mit teilfiltriertem Wasser direkt aus der Nordsee bei einem Durchflussvolumen von ca. 5 l min^{-1} versorgt. Eine höhere Durchflussmenge war technisch leider nicht möglich.

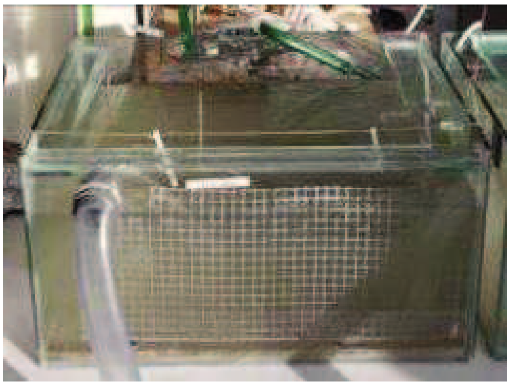

Abb. 1.4.28: Becken I mit Gitterfläche am Boden und Vorderseite als L-Form.

1.4.9.8.2 Versuchsanordnung II

Das Becken für die Versuchsanordnung II ist baugleich mit dem Becken I bei einer leicht veränderten Durchflussrate von ca. 4,5 l min^{-1} (Abb. 1.4.29). Die Anordnung der Kathoden- und Anodenmatrix ist wie in Becken I auch horizontal angelegt. Die Ausformung des Kathodendrahtes ist bei diesem Versuch jedoch als Platte gewählt worden, da der Schwerpunkt bei diesem Versuchsaufbau nicht auf der Kathodengestalt lag, sondern auf der Integration der potentiostatischen Messelektrode zur indirekten Steuerung der Stromversorgung zur Präzipitation. Die Bestromung dieses Experimentes erfolgte über den EAT-Koffer, der die Regel- und Steuereinheiten integriert hat. Aufgrund des noch nicht implementierten Regelchips zur automatischen Erhaltung eines Sollwert-Potenzial wurde das gewünschte Potential in regelmäßigen Intervallen manuell geregelt.

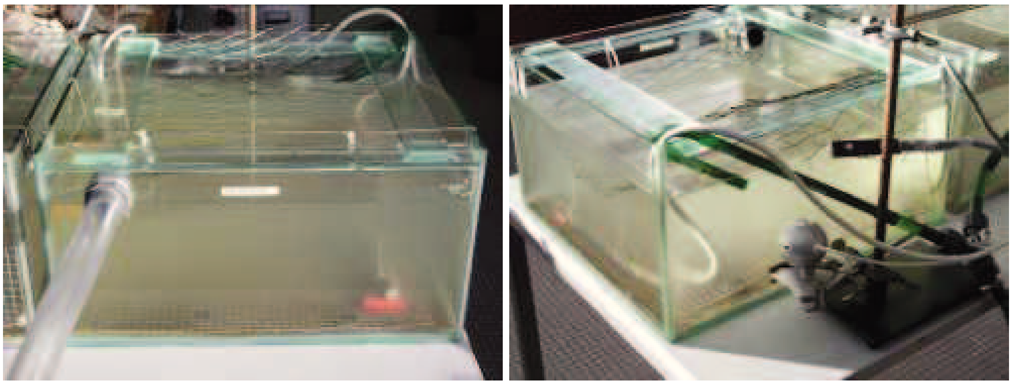

Abb. 1.4.29: Becken II mit Gitterfläche und Referenzelektrode am Boden und Wasserüberlauf (links). Rückseite des Beckens II mit Webcam (rechts).

1.4.9.8.3 Versuchsanordnung III und IV

Bei dieser Versuchsanordnung wurden Hummer-Aufzuchtfässer verwendet (Abb. 1.4.30). Im Gegensatz zu den Versuchsaufbauten I und II wurde dieses Becken (wie auch Becken IV) mit Brauchwasser aus der Hummeraufzucht gespeist. Die Anoden- und Kathodematrix wurde als offener Zylinder ausgeformt, um somit die geringen Volumina der Becken bestmöglich zu nutzen und große Kathodenoberflächen zu gewährleisten. Auf diese Weise kann gleichzeitig auch die einfache Erstellung von Röhren mittels der EAT-Technologie gezeigt werden. Die Anode wurde in einem Abstand von ca. 4 cm zur Kathode als Röhre ausgeformt und mittels der EAT-Klemmen mit dem Stromkabel verbunden. Aufgrund des sehr geringen Abstandes der Anode zur Kathode sind einfache PVC-Abstandhalter eingesetzt worden, die einen Kontakt beider Gewebe und somit mögliche „Kurzschlüsse“ vermeiden sollen. Das Becken IV war im Anoden- und Kathoden-Design identisch mit Becken III und als Doppelansatz zu werten. Beide Becken wurden über dieselbe Bestromungseinheit versorgt. Das Netzgerät hatte in seiner niedrigsten Einstellung dennoch eine zu hohe Ampere-Leistung, was bei der Einzelbestromung eine zu starke Präzipitation hervorrief. Daher wurden die Experimente in den Becken III und IV parallel mit einem Netzgerät versorgt. Hierzu sind die beiden Anoden- und Kathodenkabel der Becken parallel an die Stromausgangsbuchsen befestigt worden. Somit erhielten die beiden Versuche eine annähernd gleiche Bestromung.

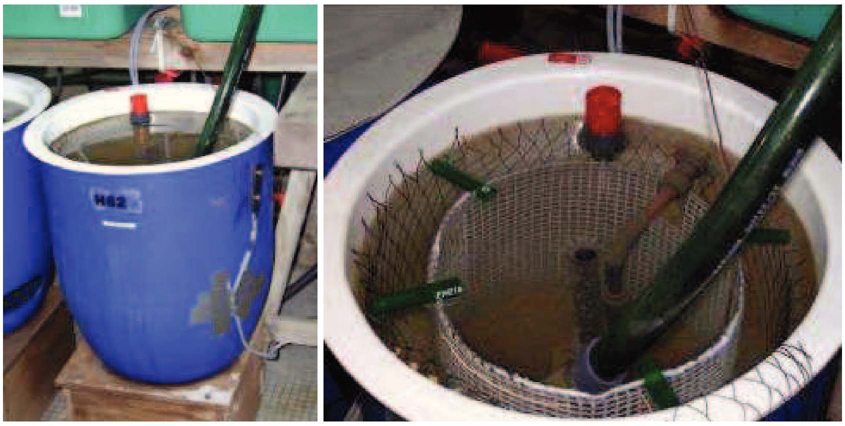

Abb. 1.4.30: Becken III mit innen liegender Kathode und außen liegender Anode (rechts), der grüne Schlauch ist die Wasserzufuhr aus den darüber liegenden Hummerbecken.

1.4.9.8.4 EAT-Versuchsanordnung VIII

Zur Herstellung von großflächigeren EAT-Hartsubstraten konnte ab 2007 ein größeres Rundbecken außerhalb der Hummeraufzuchthalle genutzt werden. Das Rundbecken hat einen Innendurchmesser von 2,5 m und eine Wasserhöhe von ca. 1,2 m. Zur optimalen Ausnutzung des Rundbeckens wurde ein EAT-Zylinder mit einem Gesamtumfang von knapp 6 m bei einer Höhe von 1 m erstellt und in dem Rundbecken positioniert. Die Titanode® wurde zentrisch auch als Zylinder in der Mitte angeordnet (Abb. 1.4.31).

Die Bestromung des Experiments erfolgte in 2007 mit dem EAT-Koffer. Für die potentiostatische Regelung wurde eine Referenzelektrode direkt am oberen Rand der EAT-Matrix angebracht. Alle zu- und abführenden Kabel wurden von dem Rundbecken zur Steuereinheit und dem Stromversorger in die Hummerhalle geführt.

Abb. 1.4.31: Aufsicht in das Becken V (2,5 m Durchmesser) mit der Kathode (Drahtmatrix) am Außenrand des Beckens (Bild links) und Aufsicht mit innen liegender Anode (rechts).

1.4.9.9 Analyse der mineralogisch-chemischen Zusammensetzung

Die mineralogisch-chemischen Zusammensetzung der EAT-Substrate wurde mittels Röntgenfluoreszenzspektroskopie (RFA) und Röntgendiffraktometrie (RDA) untersucht. Nach Auswahl geeigneter Probenbereiche der einzelnen Gitter wurden ausreichend große Gitterstücke aus dem Probengitter geschnitten, gemahlen und den Analysen zugeführt. Aufgrund der morphologischen Beschaffenheit der EAT-Substrate in Form von dünnen, teils foliaten Schichten war es nicht möglich, bestimmte Teilbereiche im Querschnitt des Substrates einzeln zu untersuchen. Aufgrund des von Bubner (1988), Meyer & Schuhmacher (1993) und Heesen (2002) beschriebene Phänomens der ungleichen Präzipitierung durch die Lage des Kathodenanschlusses sowie der Lage des Probenkörpers zum Wasser bzw. zu Sandflächen, wurden die Bereiche zur Analyse so ausgewählt, dass sie einem Bereich entstammen, der eine durchschnittliche Präzipitation aufweist oder es wurden sogen. Mischproben innerhalb eines Gitters der Analyse zugeführt. Hierzu wurden Probestücke entnommen und mittels der RDA-Analyse qualitativ untersucht. Mit dem RDA-Verfahren werden Kristallstrukturen anhand deren spezifischer Beugungsmuster für Röntengenstrahlung bestimmt. Die quantitative Untersuchung der gleichen EAT-Substratproben erfolgte unter Hinzunahme der elementspezifischen RFA-Analyse. Die Ergebnisse der Analyse entsprechen nicht linear proportional dem Gehalt der geröntgten Proben, da sie den Anteil des entsprechenden Oxids erfasst. Daher müssen die Ergebnisse im Verhältnis der Molekularmassen zwischen der gesuchten Mineralverbindung und dem der Oxide umgerechnet werden (Heesen 2002, Stirnberg 2002). Hierzu wurden aus der Berechnung der Molekülmassen der gesuchten Elemente folgende Verhältnisfaktoren zum entsprechenden Oxid ermittelt.

Für die CaO-Anteile gilt: F_{CaCO_3} = 1,78478,

für die MgO-Anteile der $F_{Mg(OH_2)}$= 1,02501 und

Halit der F_{NaCl} = 1,88589.

Bei der Multiplikation der gemessenen Werte mit den hier genannten Faktoren errechnet man unter der Maßgabe, dass die Elemente Kalzium und Magnesium ausschließlich in den beiden Mineralien Aragonit und Brucit vorliegen, die prozentualen Mineralanteile bzw. die absoluten Gewichtsanteile.

1.4.9.10 Besiedlungsversuch

Besiedlungsplatten wurden eingesetzt, um den Einfluss der Substratmaterialien auf die Zusammensetzung der Aufwuchsfauna zu untersuchen. Gleichzeitig sollte so die Eignung des in diesem Forschungsprojektes hergestellten Kalkmaterials (EAT Substrat) als Besiedelungssubstrat bestimmt werden. Es wurden jeweils 5 Platten (Replikate) aus angerautem PVC (15 x 15 cm), natürlichem Buntsandstein (unregelmäßige Größen ca. 14 x 17 cm), EAT-Substrat (14 x 17 cm), Beton (12 x 25 cm) und Spundwandstahl (14 x 17 cm) ausgebracht. Die Platten wurden in zufälliger Reihenfolge auf einem Gitter in Abständen von jeweils ca. 5 cm zueinander angeordnet und mit Kabelbindern fixiert (Abb. 1.4.32). Die Versuchsanordnung wurde für ein Jahr (Oktober 2006 bis Oktober 2007) nördlich von Helgoland auf dem Felssockel in 6 m Wassertiefe horizontal auf Grundgewichten montiert. Die Besiedelung der Platten wurde fotographisch nach 5, 7, 8, 9, 10 und 11 Monaten dokumentiert. Die prozentuale Bedeckung der unterschiedlichen Materialien durch Algen und Makrozoobenthosorganismen wurde für den 2. Oktober 2007, kurz vor der Entnahme der Platten, ermittelt. Hierzu wurde das Bild jeder Platte in dem Bildbearbeitungsprogramm Adobe Photoshop in Quadranten unterteilt. Für jeden Quadranten wurde anschließend die prozentuale Bedeckung durch Makroalgen und sessile Makrofauna am Bildschirm abgeschätzt. Die Ergebnisse der einzelnen Quadranten wurden auf die gesamte Platte aufaddiert.

Die Aufwuchsgemeinschaften wurden anhand eines MDS-Plots und einer ANOSIM-Gemeinschaftsanalyse (Clark & Warwick 2001) nach vorheriger Quadratwurzeltransformation der Daten miteinander verglichen.

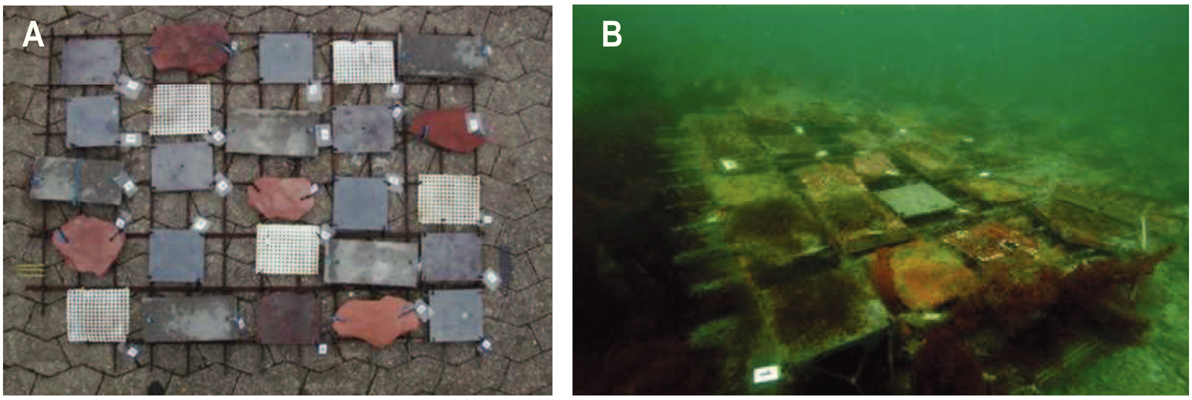

Abb. 1.4.32: Versuchaufbau Besiedelungsversuch. Installation der Bewuchsplatten aus 5 verschiedenen Materialien vor der Exposition (A). Das Versuchsgitter wurde ca. 40 cm über dem Boden auf Grundgewichten gegen Bewegung gesichert. Der Bewuchs nach acht Monaten der Exposition am 2. Mai 2007 (B). Die weißen EAT-Gitter sind zu diesem Zeitpunkt fast vollständig durch Rotalgen und Krustenrotalgen bedeckt.

2.7 *EAT-Produktion*

2.7.1 Qualitative Analyse der EAT-Substrate

In allen Proben konnten mit der Röntgendiffrakometrie (RDA) die Minerale Aragonit, Brucit, Kalzit, Kalzit mit Magnesiumanteilen ((Ca, Mg) CO_3) sowie Quarz nachgewiesen werden. Zur Veranschaulichung zeigt die Abb. 2.7.1 einen Graphen der RDA-Analyse der Gitterprobe I. Es sind die Minerale, die schon in früheren Untersuchungen in EAT–Materialien aus dem Roten Meer und Mittelmeer nachgewiesen wurden (vgl. Tab. 2.7.1). Alle Proben weisen vor allem die Minerale Aragonit und Brucit, Kalzit und Kalzit mit Magnesiumanteilen ((Ca, Mg) CO_3) in verschiedenen Konzentrationen auf. Das Brucit und das Aragonit konnten als Hauptminerale detektiert werden. Das vorkommende Kalzit sowie Kalzit mit Mg-Anteilen waren teilweise in höheren Mengen in einigen Proben vertreten.

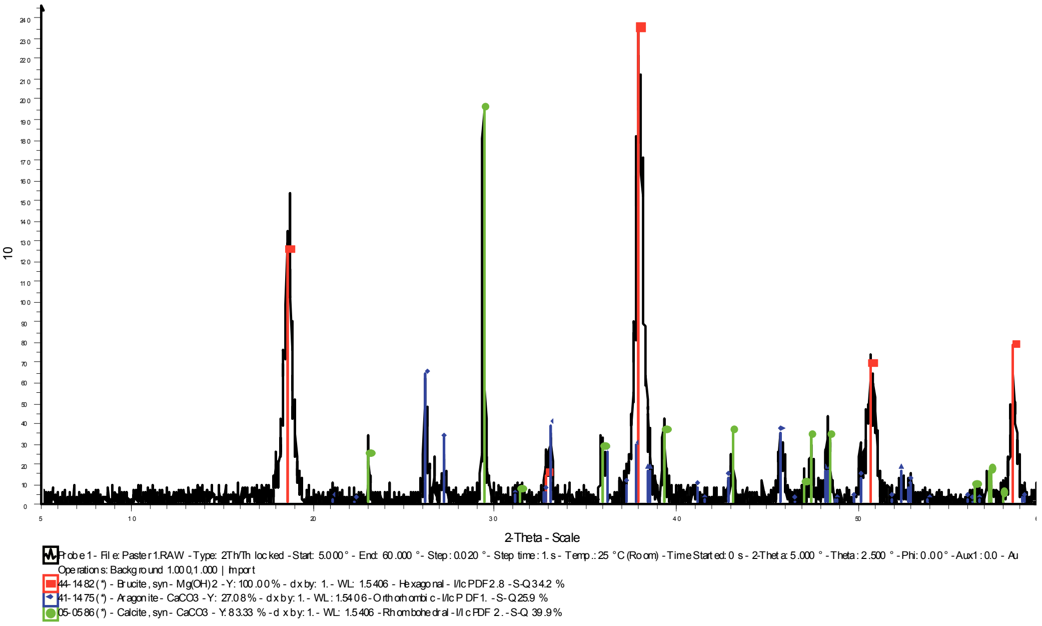

Abb. 2.7.1: RDA Spektrum von der EAT-Substratprobe Gitter I.

2.7.2 Quantitative Analyse der EAT-Substrate

Zur Berechnung der prozentualen Mineralgehalte der einzelnen EAT-Substrate wurden die ermittelten Röntgenfluorszenzspektroskopie (RFA)-Ergebnisse mit den in Kapitel 1.4.9.8 genannten Faktoren umgerechnet. Die Analyse beinhaltet die Hauptmineralbildner Aragonit, Brucit, Halit und Quarz. Die schon in der RDA-Analyse detektierten Minerale Kalzium und Magnesium wurden bei der Berechnung der RFA-Ergebnisse den Mineralien Aragonit und Brucit zugeordnet. Durch diese Aufrechnung liegen die Mineralgehalte von Aragonit und Brucit leicht über den tatsächlichen Gehalten. Der Halitgehalt entspricht dem tatsächlichen Wert, da keine weiteren Verbindungen des Elements gemessen wurden. Die prozentualen Angaben zum Quarz sind bei der RFA-Analayse direkt aus dem SiO_2-Gehalt berechnet worden. Aufgrund der methodischen Durchführung der RFA-Analyse werden die Elemente erst ab der Ordnungszahl 11 des Periodensystems, also ab Natrium, erfasst. Dieses bedeutet, dass die Messung mittels eines energiedispersiven Röntgenfluoreszenzspektrometers die Elemente der Ordnungszahlen 1 bis 10 nicht erfasst werden und somit ein Gesamtgehalt von 100 % nicht erreicht werden kann.

Die Analysen der hier dargestellten EAT-Substrate zeigen eine prozentuale Mineralverteilung (Tab. 2.7.1 und Tab. 2.7.2) von Aragonit von mindestens 30,3 % bis 71,4 %. Das Brucit weist einen Schwankungsbereich von 17,2 % bis 45,1 % auf, Halit ist in den Proben mit 0,9 % bis 1,1 % vertreten. Der Quarzgehalt ist bei fast allen Proben sehr gering bzw. in Spuren von <0,1 % bis 0,7 % vorhanden.

Tab. 2.7.1: Mineralgehalte (%) der RFA-Analyse ausgewählter EAT-Substrate und zwei Vergleichsproben.

	Aragonit [%]	**Brucit** [%]	**Halit** [%]	**Quarz** [%]	**Summe** [%]
Testgitter I	30,1	45,1	0,9	0,7	76,8
Testgitter II	29,5	40,9	1,0	0,5	71,9
Testgitter III	30,7	41,9	1,1	0,4	74,1
Testgitter IV	30,3	32,8	0,9	0,3	64,3
Testgitter Va (4 Monate)	42,2	34,8	1,0	< 0,01	78,0
Testgitter Vb (11 Monate)	**71,1**	18,4	1,2	0,1	90,8
Testgitter VIa (5 Monate)	47,7	24,3	1,2	0,8	74,0
Testgitter VIb (11 Monate)	**71,4**	**17,2**	1,1	0,5	90,1
Testgitter VII	**69,8**	17,7	1,1	0,6	89,1
Testgitter VIII	55,5	21,9	1,4	0,7	79,5
Testgitter NOMATEC	**72,1**	14,8	1,8	0,4	89,1
Naturkalk Helgoland	**97,8**	0,4	1,3	0,4	99,9

Die Mineralanalysen der EAT-Experimente Testgitter I bis IV zeigen ein sehr einheitliches Bild. Hier liegen die Anteile des Aragonits bei ca. 29,5 bis 30,3 % und des Brucits zwischen 32,5 und 45,1 %. Der geringste Aragonitanteil konnte im EAT-Substrat des Testgitters II mit 29,5 % bei einem Brucitanteil von 40,9 % nachgewiesen werden. Das von Aragonit:Brucit-Verhältnis lag somit bei 0,72 : 1. Der höchste Aragonitanteil wurde in der Probe des Testgitters VIb mit 71,4 % gemessen bei 17,2 % Brucit, was ein Aragonit:Brucit-Verhältnis von 4,2 : 1 ergibt. Ähnliche Werte weisen die Testgitter Vb und VIII auf. Hier erreichen die Aragonianteile 69,8 und 71,1 %. Der Brucitgehalt liegt in diesen beiden Proben bei 18,4 bzw. 17,7. %. Trotz der leicht unterschiedlichen Aragonit- und Brucitwerte sind die Aragonit:Brucit-Verhältnisse bei beiden mit 3,9 : 1 gleich (Tab. 2.7.2).

Bemerkenswert ist, dass das Vergleichsgitter aus dem Mittelmeer (NOMATEC 2004) gegenüber der hier genannten Probe Testgitter VIb einen nur geringfügig höheren Aragonitwert aufweist.

Der Quarzanteil ist in allen Proben sehr gering und wird durch die im zugeführten Meerwasser enthaltenen Sedimente bedingt. Bei Betrachtung der Aragonit- und Brucit-Werte der verschiedenen Experimente wird ersichtlich, dass es sich bei diesen beiden Hauptmineralien um gegenläufige Komponenten handelt. Schon Hilbertz (1988) und Menzel (1988) konnten durch ihre Untersuchungen zeigen, dass die elektrochemisch erzeugten Substrate mit einem hohen Aragonitanteil höhere Festigkeiten aufweisen. Somit ist ein hoher Aragonitwert auch eines der Ziele bei der Herstellung der Hartsubstrate. Die Betrachtung der mineralischen Zusammensetzung mit der bestromten Kathodenoberfläche in Ampere/m² Kathodenoberfläche (s. Kapitel 1.4.9.8, Tab. 1.4.13) zeigt, dass für das Experiment VIb der höchste Aragonitwert bei einer Bestromung von 2,6 A/m² Kathodenoberfläche ermittelt wurde. Hierbei handelt es sich im Vergleich zu den Experimenten von van Treeck (2001), Heesen (2002), Stirnberg (2002) und Paster (2006) um den zweithöchsten ermittelten Aragonitwert in einem EAT-Akkretionsversuch mittels der eingesetzten EAT-Technologie.

2.7.2.1 Schichtdicken und Oberflächenpotenziale

Betrachtet man die Schichtdicken der Testgitter im Zeitverlauf, so zeigen die Gitter III und IV die größte Schichtdickenzunahme von maximal 14 mm in 6 Monaten. Diese weisen aber einen relativ hohen Brucitgehalt auf (Tab. 2.7.2), der das Substrat als sehr weich und nicht dauerhaft haltbar erscheinen lässt.

Tab. 2.7.2: Mineralgehalte (%) der RFA-Analyse ausgewählter EAT-Substrate mit dem errechneten Aragonit:Brucit-Verhältnissen und den erreichten Schichtdicken der Präzipitate.

	Aragonit [%]	**Brucit** [%]	**Verhältnis** [Aragonit/Brucit]	**Schichtdicke** [mm]
Testgitter I	30,1	45,1	0,66:1	4
Testgitter II	29,5	40,9	0,72:1	3
Testgitter III	30,7	41,9	0,73:1	13
Testgitter IV	30,3	32,8	0,92:1	14
Testgitter Va (4 Monate)	42,2	34,8	1,2:1	4
Testgitter Vb (11 Monate)	**71,1**	**18,4**	**3,9:1**	6
Testgitter VIa (5 Monate)	47,7	24,3	2,0:1	7
Testgitter VIb (11 Monate)	**71,4**	**17,2**	**4,2:1**	8
Testgitter VII	**69,8**	**17,7**	**3,9:1**	8
Testgitter VIII	55,5	21,9	2,5:1	2
Testgitter Nomatec	72,1	14,8	4,9:1	6
Naturkalk Helgoland	97,8	0,4	245:1	-

Anhand der „Mohs'schen Härteskala“ (Wenk & Bulakh 2004) sind diese beiden Testgitter im feuchten Zustand der Härte I und somit „mit dem Fingernagel schabbar“ zuzuordnen. Das Testgitter VIb zeigt bei einem guten Aragonit:Brucit-Verhältnis von 4,2:1 zwar eine geringere Zunahme der Schichtdicke pro Zeit, doch ist das akkretierte Substrat im feuchten Zustand sehr viel härter und kann anhand der „Mohs'schen Härteskala“ in die Kategorie IV; „mit Messer gut ritzbar“ eingestuft werden. Ähnliche Werte zur Härte zeigen auch die Testgitter Vb und VII, die mit ihrem Aragonit:Brucit-Verhältnis von je 3,9:1 auch einen relativ hohen Aragonitgehalt erreichen.

Der EAT-Versuch VIII, der in dem Außenbecken realisiert wurde, zeigt entgegen den Aquarienversuchen bisher eine relativ mäßige Schichtdickenzunahme mit einem schlechten Aragonit:Brucit-Verhältnis. Die Gründe hierfür konnten noch nicht abschließend identifiziert werden. Wahrscheinlich ist aber, dass das Rundbecken im Verhältnis zum Gesamtvolumen eine zu geringe Wasserdurchflussrate hatte und somit nicht genügend „Frischwasser“ zur Versorgung mit Mineralien für die Akkretion zur Verfügung stand. Die erfassten Oberflächenpotenziale bei den EAT-Versuchen II, V und VIII bestätigen eine Verwendung dieser Messeinheit zur Steuerung der Akkretionstechnologie. Während Stirnberg (2002) bei seinen vergleichsweise kurzen Aquarienversuchen das optimale Oberflächenpotenzial -100 mV_{Zn} angibt, konnte Paster (2006) im Rahmen seiner *in situ* Experimente mit sehr großen Installationen im Mittelmeer einen optimalen Bildungsbereich von etwa -145 mV_{Zn} ermitteln. Unter Berücksichtigung der hier beschriebenen Experimente im Labormaßstab mit mittleren Expositionszeiten der Testgitter in Nordseewasser kann das optimale Oberflächenpotenzial mit etwa -110 mV_{Zn} angegeben werden.

2.7.3 EAT Besiedelungsversuche

Insgesamt wurden nach einem Jahr der Exposition im Helgoländer Sublittoral sieben Taxa identifiziert (Abb. 2.7.2). Tierische Aufwuchsorganismen waren Ascidien, Bryozoen und sessile Polychaeten der Gattung *Pomatoceros*. *Pomatoceros* spp. wurden ausschließlich auf Bewuchsplatten aus PVC gefunden jedoch mit relativ geringem Bedeckungsgrad (< 0,3 %) (Abb. 2.7.2 D). Auf allen anderen Substraten fehlte diese Gattung. Auf PVC-Platten wurden hingegen keine Ascidien beobachtet, die auf allen anderen Substraten wuchsen. Bryozoen bedeckten nur auf Buntsandstein und Beton Flächen von rund 5 bis 10 % (Abb. 2.7.2 B und C). Auf den anderen Substraten fehlten die Bryozoa nahezu vollständig.

Die pflanzlichen Aufwuchsorganismen wurden durch alle drei großen Makroalgengruppen repräsentiert. Grünalgen, Rotalgen und Braunalgen wurden auf allen Substraten angetroffen. Auch Krustenrotalgen, eine Untergruppe der Rotalgen, wuchsen auf allen Substraten. Die Bedeckung durch Rotalgen war auf dem anhand EAT-Technologie hergestellten Kalksubstrat mit durchschnittlich über 50 % besonders hoch (Abb. 2.7.2 A). Andere Substrate waren durchschnittlich zu 10 bis 20 % mit Rotalgen bedeckt. Auf Stahl betrug die Rotalgen-bedeckung sogar noch weniger als 10 % (Abb. 2.7.2 E). Im Gegensatz zu den Rotalgen wuchsen nur sehr wenige Braunalgen auf dem Kalksubstrat. Während Buntsandstein, Beton und PVC zu 15 bis 25 % mit Braunalgen bedeckt waren, bedeckte diese Gruppe auf Kalksubstraten nur rund 1 % der Oberfläche. Nur auf Stahl wuchsen vergleichbar wenige Braunalgen.

Generell war die Bedeckung mit Aufwuchsorganismen auf Stahl sehr gering. Die unbedeckte Fläche betrug durchschnittlich rund 80 %. Besonders wenig unbedeckte Flächen waren auf Kalksubstraten zu verzeichnen. Diese waren nahezu vollständig bewachsen, während die übrigen Substrate unbedeckte Flächen von 15 bis 20 % aufwiesen.

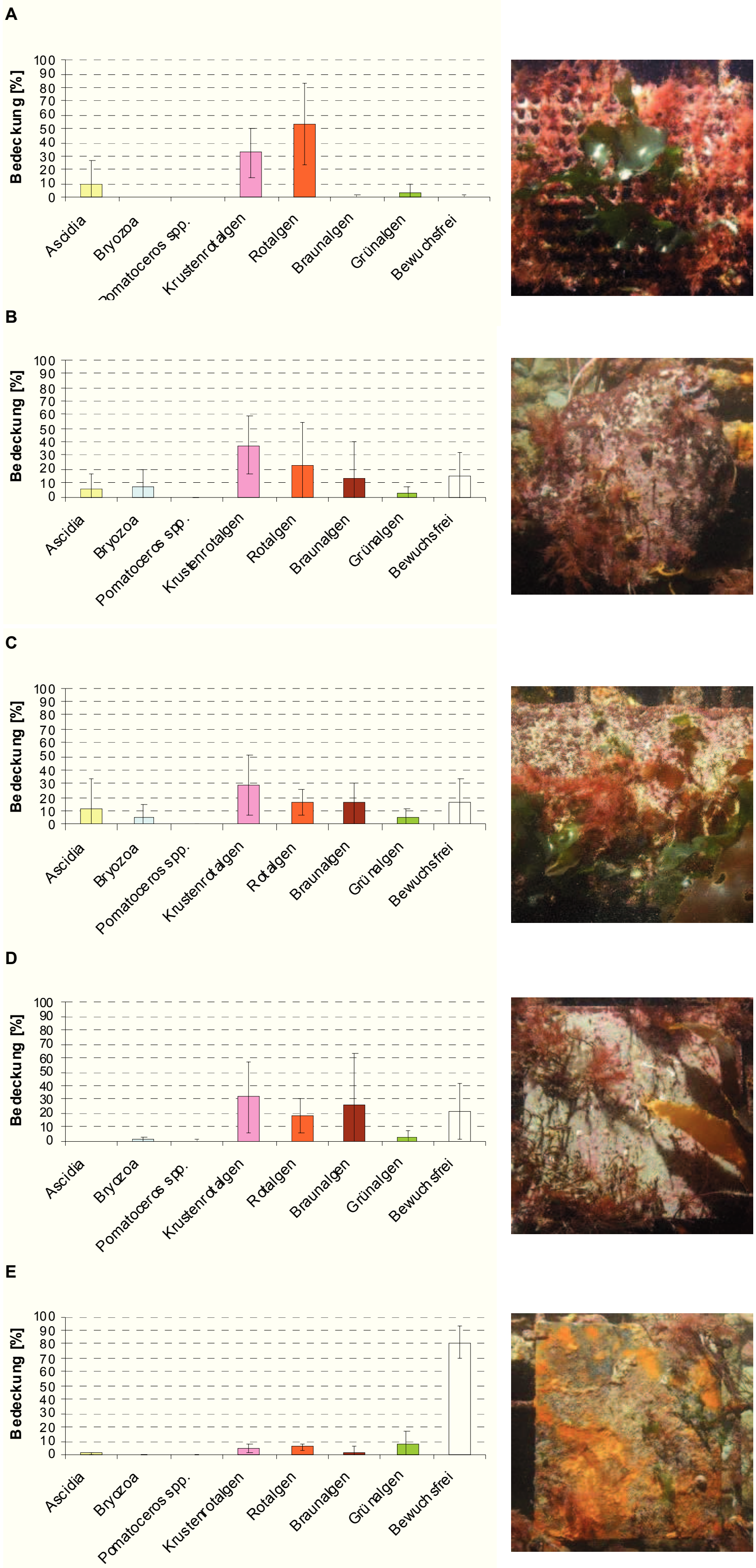

Abb. 2.7.2: Prozentuale Bedeckung (Mittelwert ± Stabw; N = 5) von Besiedlungsplatten aus anhand von EAT-Technologie hergestelltem (A) Kalk, (B) Buntsandstein, (C) Beton, (D) PVC und (E) Stahl nach einjähriger Exposition im Helgoländer Sublittoral auf 6 m Wassertiefe

Der Vergleich der Aufwuchsgemeinschaften der verschiedenen Substrate mittels MDS-Plot zeigte eine weitgehende Übereinstimmung der Gemeinschaften auf Buntsandstein, Beton und PVC (Abb. 2.7.3). Die Gemeinschaften dieser drei Substrate zeigen weitgehende Überlappungen. Negative R-Werte der begleitenden ANOSIM-Analyse zeigen auf, dass die Variation der Gemeinschaftsstruktur unter Substraten gleichen Materials größer ist als zwischen diesen drei Substraten (Tab. 2.7.3). Auch die Gemeinschaften der Bewuchsplatten aus EAT-Kalk zeigten Überlappungen mit den Gemeinschaften auf Buntsandstein, Beton und PVC, wobei die Aufwuchsgemeinschaft einer Bewuchsplatte aus EAT-Kalk im MDS-Plot deutlich von den übrigen abrückte. Diese Probe war durch einen nahezu vollständigen Bewuchs durch Rotalgen gekennzeichnet. Nach der ANOSIM-Analyse war die Trennung der Gemeinschaften auf EAT-Kalk von den Gemeinschaften auf Buntsandstein, Beton und PVC nicht deutlich. Dennoch waren die Unterschiede zu den Gemeinschaften auf Beton und PVC statistisch signifikant.

Die Aufwuchsgemeinschaft auf Stahl war im MDS-Plot deutlich von den Gemeinschaften aller anderen Substrate getrennt. Die entsprechende ANOSIM-Analyse bestätigte mit R-Werten von 0,524 bis 0,936 diese weitgehende bis nahezu vollständige Trennung der Gemeinschaft auf Stahl von den anderen Gemeinschaften.

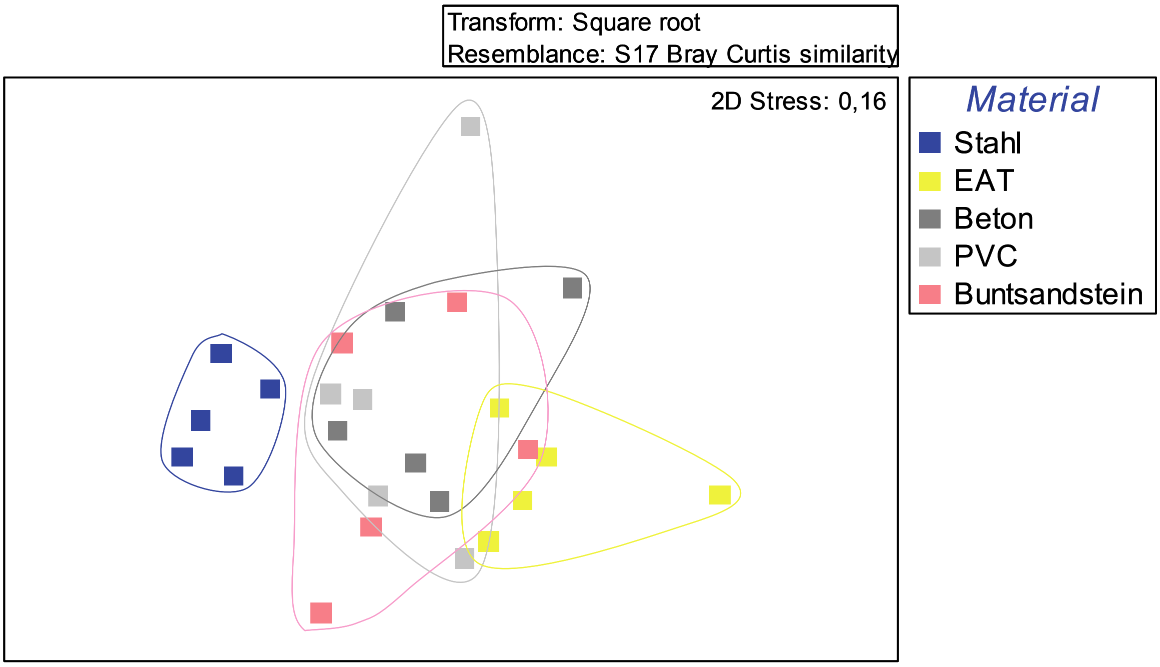

Abb. 2.7.3: MDS-Plot basierend auf Bray-Curtis-Ähnlichkeit nach vorheriger √-Transformation zum Vergleich der prozentualen Bedeckung von Bewuchsplatten unterschiedlicher Substrate nach einjähriger Exposition in 6 m Wassertiefe im Helgoländer Sublittoral.

Tab. 2.7.3: Ergebnisse der ANOSIM-Analyse basierend auf Bray-Curtis-Ähnlichkeit nach vorheriger √-Transformation zum Vergleich der Aufwuchsgemeinschaften auf Bewuchsplatten unterschiedlicher Substrate nach einjähriger Exposition in 6 m Wassertiefe im Helgoländer Sublittoral. Legende siehe Tab. 2.3.1.

Buntsandstein	0,120			
Beton	0,280*	-0,236		
PVC	0,268*	-0,200	-0,072	
Stahl	0,936*	0,608*	0,632*	0,524*
	EAT	Buntsandstein	Beton	PVC

3.1.5 Besiedelung unterschiedlicher Substrate

Die Besiedlung unterschiedlicher Substrate wurde in einem Feldversuch in Helgoland untersucht, um v.a. auch die Besiedlung der künstlich erzeugten Kalksubstrate (EAT) unter Nordseebedingungen zu beurteilen. Die Epifauna der Kalkgitter unterschied sich signifikant von der der Stahlplatten, der PVC-Platten und der Betonstücke. Zur Besiedlung des (Helgoländer) Buntsandsteinmaterials wurden demgegenüber keine signifikanten Unterschiede gefunden. Das EAT-Material hebt sich jedoch durch die beinahe flächendeckende Besiedelung der Oberfläche von allen übrigen Materialien ab, die zwischen 15 und 20 % unbesiedelte Stellen aufwiesen. Besonders die Rotalgen und die Krustenrotalgen dominieren das EAT-Substrat und auch Ascidien siedeln darauf mit vergleichsweise hoher Abundanz. Braunalgen fehlen weitestgehend. Unklar bleibt, ob diese durch die Rotalgen verdrängt werden oder ob das Substrat eine zu geringe Attraktivität für Braunalgen besitzt. Das EAT-Material wird wie im Mittelmeer (Schuhmacher & Schillak 1994) auch in der Nordsee als Besiedelungssubstrat akzeptiert und übertrifft gar den Buntsandstein im Bedeckungsgrad durch die Aufwuchsgemeinschaft. Beton und PVC werden weniger flächendeckend als das EAT-Material besiedelt. Im Gesamtvergleich weisen deshalb deren Aufwuchsgemeinschaften etwas geringere Unterschiede zum Buntsandstein auf als das EAT-Substrat. Dieser Pilotstudie zur Folge ist das EAT-Material in der Nordsee als Baustoff geeignet. Auf Grund der hohen Akzeptanz als Besiedelungssubstrat und der „Naturähnlichkeit“ des Materials könnte das EAT-Material für nichttragende Bauelemente im Meer in Bereichen, in denen ein dichter Aufwuchs zulässig oder erwünscht ist, eingesetzt werden.

Die exponierten Stahlplatten blieben zu 80 % unbesiedelt und können so nicht als naturähnlich betrachtet werden. Allerdings waren die hier verwendeten Stahlplatten ohne Korrosionsschutz installiert, so dass die Korrosion die Besiedlung behindert haben kann. Die Untersuchungen an der FINO 1 Plattform haben hingegen gezeigt, dass mit einem kathodischen Korrosionsschutz versehene Stahlbauten flächendeckend besiedelt werden können. Ein direkter Vergleich der Eignung als Substrat für Epifauna mit anderen Baustoffen ist daher anhand der Ergebnisse der Besiedlungsplatten nicht möglich.

3.5 EAT-Produktion

Das Ziel dieser Studie war der Testeinsatz verschiedener Stromsteuer- und Versorgungseinheiten zur Akkretionstechnologie sowie die Akkretion verschiedener Drahtkathoden zu Herstellung künstlich erstellter Hartsubstrate in Nordseewasser. Die hier vorgestellten Geräte und Materialien zeigten trotz der dargestellten Platzprobleme sowie zeitweise geringen Verfügbarkeit von Nordsee-Wasser eine gute Verwendbarkeit. Im Fokus zum Einsatz der „Technik“ stand die sogn. EAT-Stromversorgungs- und Steuereinheit (EAT-Koffer), die während der gesamten Laufzeit äußerst stabil lief und als Steuereinheit eingesetzt werden konnte. Auch die Datenerfassung der Stromdaten sowie der Millivolt-Messwerterfassung lief ohne größere Ausfälle und zeichnete kontinuierlich Daten auf. Die Referenzelektrode zeigte während der Einsatzphase eine gute Eignung. Ähnlich wie im Rahmen des EU-NOMATEC-Projekts (NOMATEC 2004) zeigten sich im Laufe der Einsatzzeit Ermüdungserscheinungen bei dem verwendeten Material zur Sicherung gegen Wassereinbruch. Die Gründe des Wassereinbruches konnten identifiziert werden. Somit können die Wassereinbrüche bei einem späteren Neubau der Referenzelektroden vermieden werden. Die hier dargestellten Untersuchungen und Ergebnisse basieren auf den Freiland und Laborarbeiten. Ziel dieses Projektes war es, die bisher im Roten Meer und Mittelmeer eingesetzten EAT-Technologie im kälteren und weniger salzhaltigen Meerwasser der Nordsee anzuwenden und erste Ergebnisse zu möglichen Bildungsraten von künstlichen Hartsubstraten zu erhalten. Es konnte anhand von verschiedenen Versuchen nachgewiesen werden, dass mit der EAT-Methode auch im Nordseewasser bei kälteren Wassertemperaturen sowie geringeren Salinitäten harte Substrate hergestellt werden können. Trotz der kleinmaßstäblichen Versuche zeigen die Bildungsraten pro Zeit ähnliche Werte wie die aus dem Mittelmeer. Es ist davon auszugehen, dass aufgrund der besseren Wasserversorgung bei *in situ*–Versuchen vor Helgoland wahrscheinlich gleiche Bildungsraten bei ähnlicher Stabilität und somit der Härte wie im Mittelmeer einstellen.

Die Anwendungsbereiche sind sehr vielfältig und reichen von der Restauration und Rehabilitation von Seegraswiesen, über Bauelemente in Aquakulturen (z. B. Schwammzucht) bis hin zur Schaffung künstlicher Strukturen und Biotope für die hartbodenassoziierte Fauna oder zur Verkleidung künstlicher Strukturen mit naturnahem Material. Die Eignung des EAT-Materials als Besiedelungssubstrat wurde in einer separaten Studie mit der anderer künstlicher und natürlicher Materialien verglichen (siehe Kapitel 3.1.5).

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PATENT I

Elektrochemisches Antifoulingsystem für seewasserbenetzte Bauwerke

Roland Krone & Markus Paster

(19) Deutsches
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(56) Für die Beurteilung der Patentfähigkeit in Betracht gezogene Druckschriften:

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US	**35 20 790**	**A**

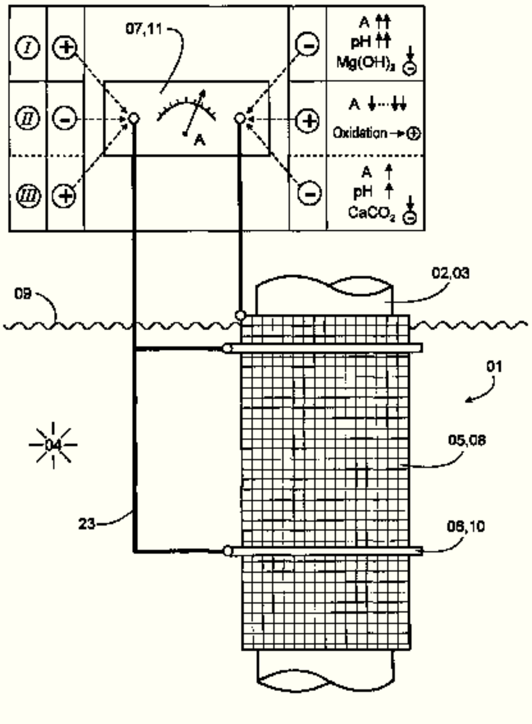
Hilbertz, W.H.: Electrodeposition of minerals in sea water: Experiments and applications. In: IEEE Journal of Oceanic Engineering, Vol. OE-4, 1979, No. 3, S. 94-113

Die folgenden Angaben sind den vom Anmelder eingereichten Unterlagen entnommen

Prüfungsantrag gemäß § 44 PatG ist gestellt.

(54) Bezeichnung: **Elektrochemisches Antifoulingsystem für seewasserbenetzte Bauwerke**

(57) Zusammenfassung: Das bekannte Antifoulingsystem weist eine Gitterstrukturelektrode, eine Gegenelektrode und eine einstellbare Stromquelle zur Elektrolyse auf. Die Gitterstrukturelektrode besteht aus einem biegeschlaffen Netz, das als Anode geschaltet und zur Korrosionsvermeidung sehr speziell aufgebaut ist. Die Stromeinspeisung erfolgt über die elektrisch leitende Oberfläche eines Wassereinlasskanals. Bei dem erfindungsgemäßen Antifoulingsystem (01) ist eine formstabile und aus einer einzelnen Metallkomponente bestehende Gitterstrukturelektrode (05) elektrisch gegenüber der Oberfläche (13) des zu schützenden Bauwerks (02, 03) isoliert, sodass dieses auch elektrisch nichtleitend sein kann und keinen Strom führt. Über eine Vorrichtung (11) können verschiedene Gebrauchsmodi eingestellt werden. Im Betriebsmodus I ist die Gitterstrukturelektrode (05) als Kathode geschaltet. Es wird ein hoher Strom erzeugt, sodass sich ein hoher pH-Wert ausbildet und weiches, schnell abscherendes Brucit ablagert, wodurch ein doppelter Foulingschutz gegeben ist. Zusammen mit den Möglichkeiten eines nachträglichen Anbaus und einer vollständigen Demontage durch Umpolung der Gitterstrukturelektrode (05) (Modus II) ist das Antifoulingsystem (01) damit besonders geeignet zum Foulingschutz unzugänglicher Offshorebauwerke.



(19) Europäisches Patentamt
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(72) Erfinder:
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  28203 Bremen (DE)
- **Paster, Markus**
  42551 Velbert (DE)

(54) Elektrochemisches Antifoulingsystem für seewasserbenetzte Bauwerke

(57) Das bekannte Antifoulingsystem weist eine Gitterstrukturelektrode, eine Gegenelektrode und eine einstellbare Stromquelle zur Elektrolyse auf. Die Gitterstrukturelektrode besteht aus einem biegeschlaffen Netz, das als Anode geschaltet und zur Korrosionsvermeidung sehr speziell aufgebaut ist. Die Stromeinspeisung erfolgt über die elektrisch leitende Oberfläche eines Wassereinlasskanals. Bei dem erfindungsgemäßen Antifoulingsystem (01) ist eine formstabile und aus einer einzelnen Metallkomponente bestehende Gitterstrukturelektrode (05) elektrisch gegenüber der Oberfläche (13) des zu schützenden Bauwerks (02, 03) isoliert, sodass dieses auch elektrisch nichtleitend sein kann und keinen Strom führt. Über eine Vorrichtung (11) können verschiedene Gebrauchsmodi eingestellt werden. Im Betriebsmodus I ist die Gitterstrukturelektrode (05) als Kathode geschaltet. Es wird ein hoher Strom erzeugt, sodass sich ein hoher pH-Wert ausbildet und weiches, schnell abscherendes Brucit ablagert, wodurch ein doppelter Foulingschutz gegeben ist. Zusammen mit den Möglichkeiten eines nachträglichen Anbaus und einer vollständigen Demontage durch Umpolung der Gitterstrukturelektrode (05) (Modus II) ist das Antifoulingsystem (01) damit besonders geeignet zum Foulingschutz unzugänglicher Offshorebauwerke.

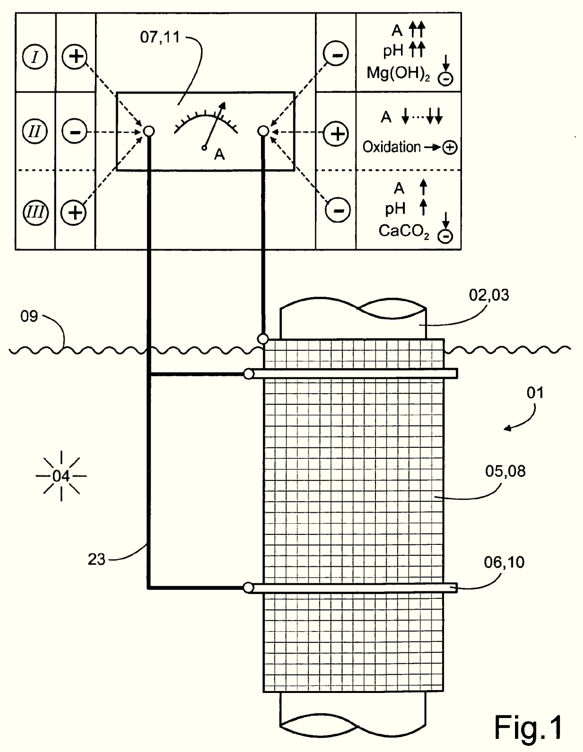

Fig.1

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(54) ELECTROCHEMICAL ANTIFOULING SYSTEM FOR SEAWATER-WETTED STRUCTURES

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(73) Assignees: **Stiftung Alfred-Wegener-Institut fuer Polar- und Meeresforschung**, Bremerhaven (DE); **Universitaet Duisburg Essen**, Essen (DE)

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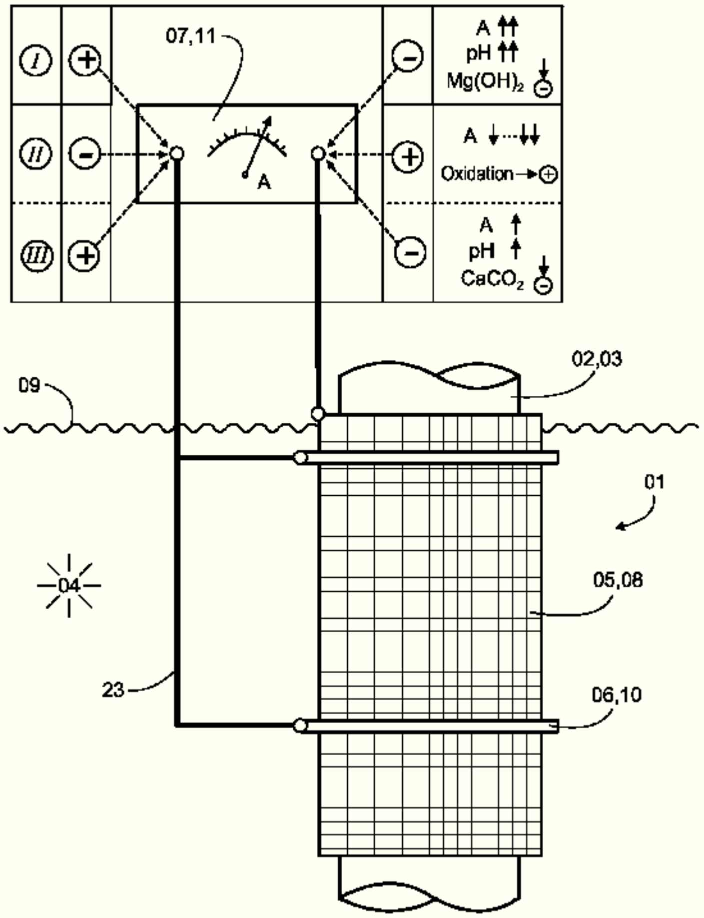
(57) ABSTRACT

An electrochemical antifouling system for preventing fouling organisms from adhering to seawater-wetted structures includes a direct current circuit for creating an electrolytic environment in seawater, the direct current circuit having an adjustable direct current source, a lattice electrode having a single metallic component so as to provide a dimensionally stable lattice structure, the lattice electrode electrically insulated from a surface of a seawater-wetted structure, at least one corrosion-resistant counter electrode having polarity opposite to the lattice electrode and disposed at a distance therefrom, and a switching device configured to alternatively switch the lattice electrode to (a) a continuous operating mode, and (b) a temporary depletion mode, wherein the lattice electrode is disposed in a distance range from the surface of the seawater-wetted structure so that the surface lies within an area of influence of an increase in pH value of the seawater caused by electrolysis.



PATENT II

Vorrichtung zur Habitaterschließung im Unterwasserbereich eines Offshore-Bauwerks

Roland Krone, Alexander Schröder & Philipp Krämer

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(72) Erfinder:
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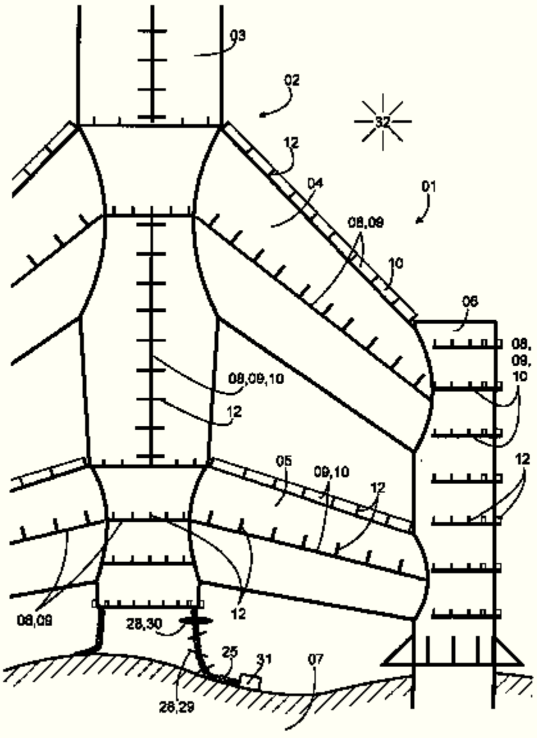
US	**2006 / 0 170 221**	**A1**
US	**6 089 191**	**A**
US	**5 799 752**	**A**
US	**5 860 392**	**A**
US	**5 807 023**	**A**
US	**5 836 265**	**A**
US	**5 564 369**	**A**
WO	**01/ 23 253**	**A1**
WO	**01/ 77 443**	**A1**
WO	**2006/ 080 721**	**A1**
WO	**2008/ 060 070**	**A1**
WO	**2009/ 064 085**	**A1**

(54) Bezeichnung: **Vorrichtung zur Habitaterschließung im Unterwasserbereich eines Offshore-Bauwerks**

(57) Zusammenfassung: Bekannte Vorrichtungen mit Steighilfen weisen keine ausreichende Attraktivität für laufende Hartbodentiere, wie beispielsweise Hummer und Krebse, auf. Die erfindungsgemäße Vorrichtung (01) weist deshalb Steighilfen (08) in Form von Leitprofilen (09) auf, die in vertikaler, horizontaler und/oder diagonaler Richtung abschnittsweise und/oder zusammenhängend am Offshore-Bauwerk (02) befestigt sind. Bevorzugt sind die Leitprofile (09) als rippenförmige Flachprofile (10) ausgebildet und von flachen Querprofilen (12), die auch der Horstschaffung dienen, weiter strukturiert. Die Flachprofile (10) können aus Baustahl bestehen und einfach an das Offshore-Bauwerk (2) bei der Herstellung oder Aufstellung angeschweißt werden. Die Leitprofile (09) können auch umlaufende einstückige oder mehrstückige Wendeln bilden. Es können auch Strukturmanschetten (17) mit zwischen zwei öffenbaren, ringförmigen Leitprofilen (15) angeordneten Netzen (18) oder Gittern (20) gebildet werden. Zusätzlich können Rohrelemente (24) und Verbindungselemente (25) zur weiteren Verbesserung der Attraktivität vorgesehen sein. Durch die Vorrichtung (01) nach der Erfindung können künstliche Offshore-Bauwerke (02), beispielsweise Windenergieanlagen, im Unterwasserbereich (32) als zusätzlicher Lebensraum für vagile Hartbodentiere nachhaltig erschlossen und effizient sekundär genutzt werden.



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(71) Anmelder *(für alle Bestimmungsstaaten mit Ausnahme von US)*: **STIFTUNG ALFRED-WEGENER-INSTITUT FÜR POLAR- UND MEERESFORSCHUNG** [DE/DE]; Am Handelshafen 12, 27570 Bremerhaven (DE).

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Veröffentlicht:

— *mit internationalem Recherchenbericht (Artikel 21 Absatz 3)*

[Fortsetzung auf der nächsten Seite]

(54) Title: DEVICE FOR DEVELOPING HABITATS IN THE UNDERWATER AREA OF AN OFFSHORE CONSTRUCTION

(54) Bezeichnung : VORRICHTUNG ZUR HABITATERSCHLIESSUNG IM UNTERWASSERBEREICH EINES OFFSHORE-BAUWERKS.

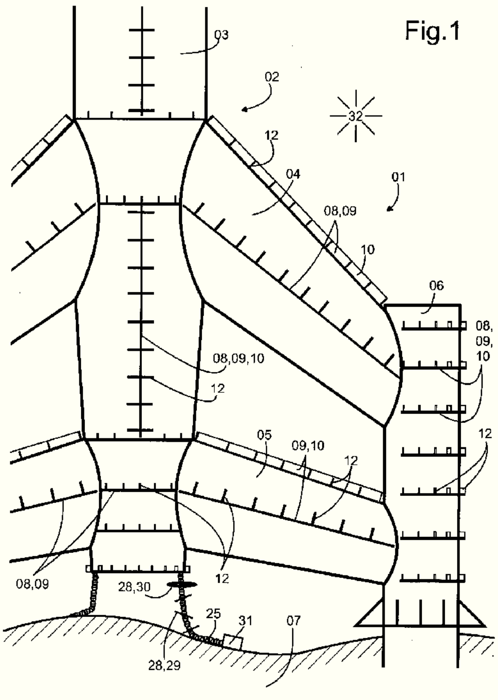

Fig.1

(57) Abstract: Therefore, the device (01) according to the invention has climbing aids (08) in the form of guide profiles (09), which are fastened to the offshore construction (02) in the vertical, horizontal, and/or diagonal direction at least in some sections and/or continuously. The guide profiles (09) are preferably designed as rib-shaped flat profiles (10) and further structured by flat transverse profiles (12), which are also used for making breeding places. The flat profiles (10) can be made of construction steel and are simply welded to the offshore construction (2) during production or installation. The guide profiles (09) can also form circumferential one-piece or multi-piece spirals. Structural collars (17) having nets (18) or grates (20) arranged between two openable annular guide profiles (15) can also be formed. In addition, pipe elements (24) and connecting elements (25) can be provided in order to further improve attractiveness. By means of the device (01) according to the invention, artificial offshore constructions (02), such as wind turbines, can be sustainably developed in the underwater area (32) as additional living space for vagile hard epifauna and efficiently used in a secondary manner.

(57) Zusammenfassung:

[Fortsetzung auf der nächsten Seite]

WO 2011/147400 A3

PATENT III

Vorrichtung zur Ansiedelung und Erntung von marinen Hartbodentieren

Roland Krone & Philipp Krämer

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(73) Patentinhaber:
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(72) Erfinder:
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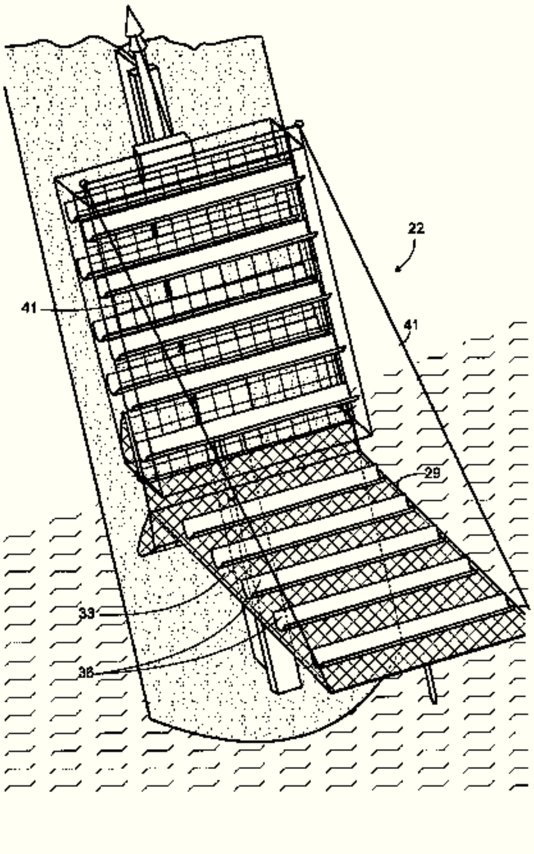
EP	**1 466 523**	**A2**
WO	**04/0 75 633**	**A1**

Buck, B.H.: Marikultur als Co-Nutzung in Offshore-Windparks: Status Quo, Probleme und Perspektiven. In: Meeresumweltsymposium 2006, Bundesamt für Seeschifffahrt und Hydrographie, Hamburg und Rostock 2007, S.167-179

(54) Bezeichnung: **Vorrichtung zur Ansiedelung und Erntung von marinen Hartbodentieren**

(57) Zusammenfassung: Offshore-Bauwerke werden gerne von Hartbodentieren besiedelt. Bekannte Einrichtungen zur zusätzlichen Besiedlung und Erntung werden jedoch nicht ausreichend präzise und immer in Abhängigkeit von den aktuellen Wetter- und Strömungsbedingungen ausgebracht. Ein bekanntes, an einem Pylon einer Windkraftanlage angebrachtes horizontales Schienensystem dient der wählbaren Umfangsanordnung einer Hebeeinrichtung für eine Netzeinrichtung. Die erfindungsgemäße Vorrichtung (28) weist zumindest eine vertikale Schieneneinrichtung (03) über die Höhe (05) des Unterwasserbereichs (06) bis oberhalb der Wasserlinie (07) auf, entlang der ein Bergeschlitten (08) und ein Habitatschlitten (22) sicher abgesenkt und wieder eingeholt werden können, wodurch sich eine präzise Positionierung ergibt. Der Habitatschlitten (22) umfasst einen Habitat- und Fangkorb (26) und vergrößert nach seiner Ausbringung die Ansiedelungsfläche auf dem Meeresboden (31). Das Einholen erfolgt über den getrennt absenkbaren Bergeschlitten (08), der fest, aber lösbar am abgesenkten Habitatschlitten (22) ankoppelt und anschließend über eine angekoppelte Hebeeinrichtung (44) zusammen mit dem Habitatschlitten (22) eingeholt werden kann. Durch die Erfindung können marine Offshore-Bauwerke (01, 02), z.B. Windkraftanlagen, eine Sekundärnutzung zur Ansiedelung und nachhaltigen Erntung von marinen Hartbodentieren (35) erfahren.



US 20110139083A1

(19) **United States**

(12) **Patent Application Publication**

Krone et al.

(10) **Pub. No.: US 2011/0139083 A1**

(43) **Pub. Date: Jun. 16, 2011**

(54) **DEVICE FOR COLONIZING AND HARVESTING MARINE HARDGROUND ANIMALS**

(75) Inventors: **Roland Krone**, Bremen (DE); **Philipp Kraemer**, Oldenburg (DE)

(73) Assignee: **Stiftung Alfred-Wegener-Institut fuer Polar-und Meeresforschung**, Bremerhaven (DE)

(21) Appl. No.: **12/964,860**

(22) Filed: **Dec. 10, 2010**

(30) **Foreign Application Priority Data**

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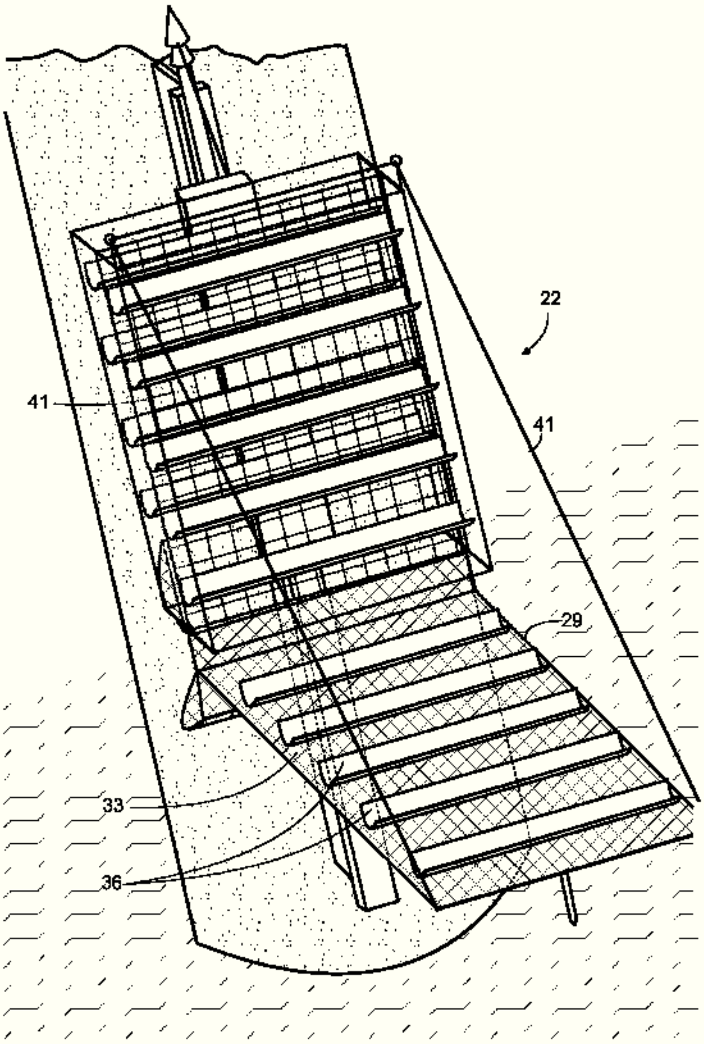
Publication Classification

(51) **Int. Cl.**
A01K 61/00 (2006.01)

(52) **U.S. Cl.** **119/200**

(57) **ABSTRACT**

A device for colonizing and harvesting marine hardground animals in an underwater region of a ground-based offshore edifice includes at least one rail device configured to extend vertically on the offshore edifice along a height of the underwater region to above a waterline. The device also includes a netting array including a habitat carriage having a habitat and trapping basket that is adapted to contain the hardground animals. A lifting device is configured to move the netting array along the at least one rail device. Additionally, the device includes a scavenging carriage including a basic unit and a running unit that is configured to detachably couple the scavenging carriage with the at least one rail device so as to be movable thereon. The scavenging carriage is configured to detachably couple with the habitat carriage and the lifting device.



PATENT IV

Transportierbare Vorrichtung zur Ansiedlung und Erntung von wirbellosen Tieren und Anwendung davon

Roland Krone & Philipp Krämer

(19) Deutsches
Patent- und Markenamt

(10) **DE 10 2009 049 083 B3** 2011.03.10

(12) **Patentschrift**

(21) Aktenzeichen: **10 2009 049 083.3**
(22) Anmeldetag: **07.10.2009**
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(45) Veröffentlichungstag
der Patenterteilung: **10.03.2011**

(51) Int Cl.^{8}: ***A01K 61/00*** (2006.01)
A01K 63/00 (2006.01)

Innerhalb von drei Monaten nach Veröffentlichung der Patenterteilung kann nach § 59 Patentgesetz gegen das Patent Einspruch erhoben werden. Der Einspruch ist schriftlich zu erklären und zu begründen. Innerhalb der Einspruchsfrist ist eine Einspruchsgebühr in Höhe von 200 Euro zu entrichten(§ 6 Patentkostengesetz in Verbindung mit der Anlage zu § 2 Abs. 1 Patentkostengesetz).

(73) Patentinhaber:
Stiftung Alfred-Wegener-Institut für Polar- und Meeresforschung, 27570 Bremerhaven, DE

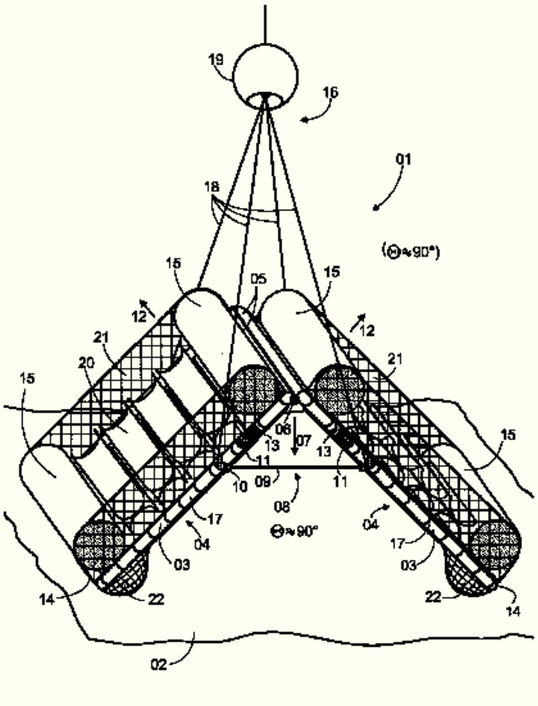
(72) Erfinder:
Krone, Roland, 28209 Bremen, DE; Krämer, Philipp, 26121 Oldenburg, DE

(56) Für die Beurteilung der Patentfähigkeit in Betracht gezogene Druckschriften:

DE	**101 61 174**	**C1**
FR	**23 45 914**	**A1**
US	**54 57 910**	**A**
US	**52 69 254**	**A**
US	**49 82 525**	**A**
US	**47 36 708**	**A**
US	**40 19 945**	
WO	**2008/0 77 562**	**A1**

(54) Bezeichnung: **Transportierbare Vorrichtung zur Ansiedlung und Erntung von wirbellosen Tieren und Anwendung davon**

(57) Zusammenfassung: Eine bekannte Vorrichtung besteht aus zwei Fangflächen aufweisende Rahmen, die über ein Zentralscharnier zusammenklappbar sind, und dient der Ansiedelung und Erntung von ortsfesten Schwämmen. Die bekannte Vorrichtung wird als Einzelelement nur in zusammengeklappter Form auf dem Gewässerboden ausgelegt, sodass dieser eben sein muss. Zur Ansiedlung und Erntung von vagilen benthischen Tieren, insbesondere Krebsen, auch auf strukturierten und unzugänglichen Gewässerböden, weist die erfindungsgemäße Vorrichtung (01) beiderseits des Zentralscharniers (06) zwei Nebenscharniere (11) auf, durch die die Rahmen (03) in unterschiedlichen Offnungswinkeln (Θ) der Vorrichtung (01) positionierbar sind, sodass die Vorrichtung (01) auch an strukturierte Gewässerboden (02) anpassbar ist. Hieven und Fieren der Vorrichtung (01) erfolgen in zusammengeklappter oder angeklappter Form, ausgelegt wird die Vorrichtung (01) in angeklappter oder vollständig geöffneter Form. Röhrenförmige Bauelemente (15) sorgen für einen verbesserten Abtrieb und eine besondere Attraktivität als Habitat für Krebse. Die Vorrichtung (01) nach der Erfindung kann somit als künstliches Riff zur Ansiedlung und als Falle zur nachhaltigen Erntung von Krebsen in der unmittelbaren Umgebung von Windkraftanlagen in Offshore-Gebieten verwendet werden.



(12) NACH DEM VERTRAG ÜBER DIE INTERNATIONALE ZUSAMMENARBEIT AUF DEM GEBIET DES PATENTWESENS (PCT) VERÖFFENTLICHTE INTERNATIONALE ANMELDUNG

(19) Weltorganisation für geistiges Eigentum
Internationales Büro

(43) Internationales Veröffentlichungsdatum
14. April 2011 (14.04.2011)

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(21) Internationales Aktenzeichen: PCT/DE2010/001146

(22) Internationales Anmeldedatum:
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(25) Einreichungssprache: Deutsch

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(30) Angaben zur Priorität:
10 2009 049 083.3
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(71) Anmelder *(für alle Bestimmungsstaaten mit Ausnahme von US)*: **STIFTUNG ALFRED-WEGENER-INSTITUT FÜR POLAR- UND MEERESFORSCHUNG** [DE/EC]; Am Handelshafen 12, 27570 Bremerhaven (DE).

(72) Erfinder; und

(75) Erfinder/Anmelder *(nur für US)*: **KRONE, Roland** [DE/DE]; Richard-Wagner-Strasse 28, 28209 Bremen (DE). **KRÄMER, Philipp** [DE/DE]; Jägerstrasse 60, 26121 Oldenburg (DE).

(81) Bestimmungsstaaten *(soweit nicht anders angegeben, für jede verfügbare nationale Schutzrechtsart)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Bestimmungsstaaten *(soweit nicht anders angegeben, für jede verfügbare regionale Schutzrechtsart)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ,

[Fortsetzung auf der nächsten Seite]

(54) Title: TRANSPORTABLE DEVICE FOR ESTABLISHING A COLONY OF INVERTEBRATES AND FOR HARVESTING SAME, AND USE OF SAID DEVICE

(54) Bezeichnung : TRANSPORTIERBARE VORRICHTUNG ZUR ANSIEDLUNG UND ERNTUNG VON WIRBELLOSEN TIEREN UND ANWENDUNG DAVON

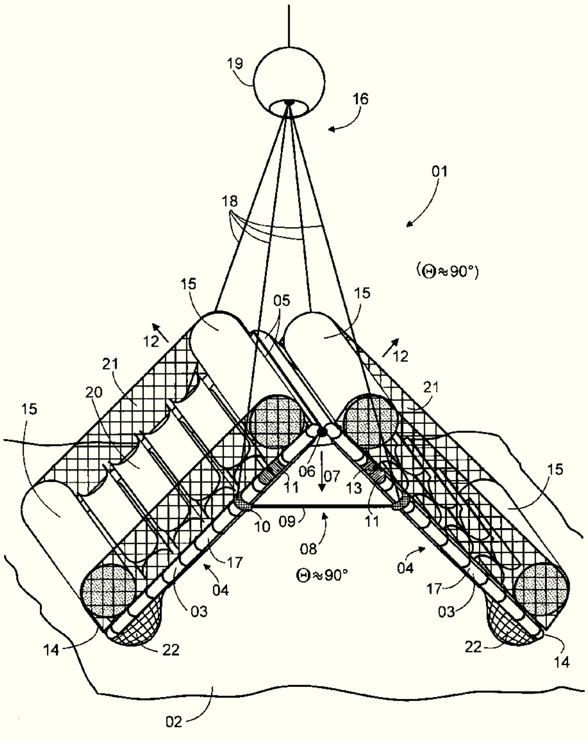

Fig.1

(57) Abstract: The aim of the invention is to establish a colony of and harvest vagile benthic animals, in particular crabs, including on structured and inaccessible beds of bodies of water. To that end, the device (01) according to the invention has either side of a central hinge (06) two auxiliary hinges (11) by means of which frames (03) can be positioned at different opening angles (Θ) of the device (01) such that it can also be adapted to structured beds of bodies of water (02). The device (01) is hoisted and lowered in the collapsed or folded form, and is laid out in the folded or fully open form. Tubular components (15) improve drift and are particularly attractive as a habitat for crabs. The device (01) according to the invention can thus be used as an artificial reef to establish a colony and as a trap for effectively harvesting crabs in the immediate surroundings of wind turbines in offshore areas.

(57) Zusammenfassung:

[Fortsetzung auf der nächsten Seite]

WO 2011/042003 A1

Office de la Propriété Intellectuelle du Canada

Un organisme d'Industrie Canada

Canadian Intellectual Property Office

An agency of Industry Canada

CA 2764735 A1 2011/04/14

(21) **2 764 735**

(12) **DEMANDE DE BREVET CANADIEN**
CANADIAN PATENT APPLICATION

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(86) **Date de dépôt PCT/PCT Filing Date:** 2010/09/24

(87) **Date publication PCT/PCT Publication Date:** 2011/04/14

(85) **Entrée phase nationale/National Entry:** 2011/12/07

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(87) **N° publication PCT/PCT Publication No.:** 2011/042003

(30) **Priorité/Priority:** 2009/10/07 (DE10 2009 049 083.3)

(51) **Cl.Int./Int.Cl.** *A01K 61/00* (2006.01), *A01K 69/10* (2006.01)

(71) **Demandeur/Applicant:**
STIFTUNG ALFRED-WEGENER-INSTITUT FUER POLAR-UND & MEERESFORSCHUNG, DE

(72) **Inventeurs/Inventors:**
KRONE, ROLAND, DE;
KRAEMER, PHILIPP, DE

(74) **Agent:** SMART & BIGGAR

(54) **Titre :** DISPOSITIF TRANSPORTABLE POUR LA COLONISATION ET LA RECOLTE D'INVERTEBRES ET SON UTILISATION

(54) **Title:** TRANSPORTABLE DEVICE FOR COLONIZING AND HARVESTING INVERTEBRATES AND ITS USE

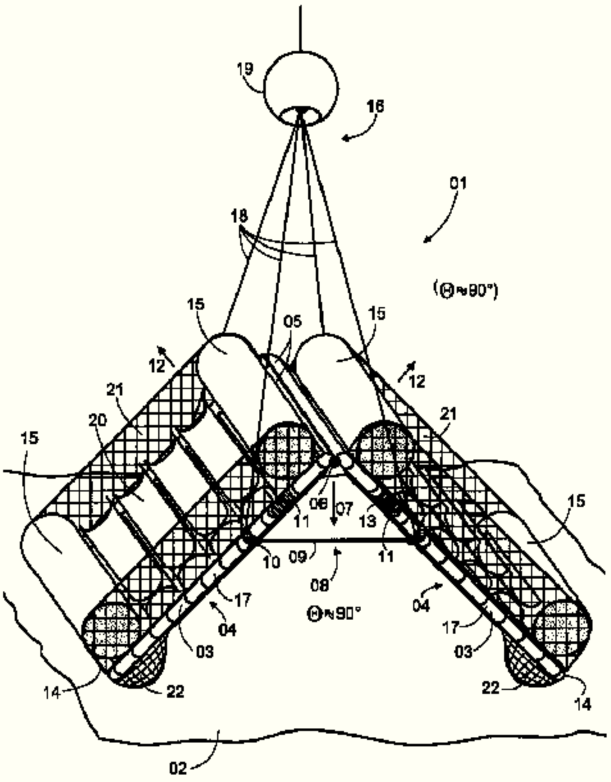


Fig.1

(57) **Abrégé/Abstract:**
The aim of the invention is to establish a colony of and harvest vagile benthic animals, in particular crabs, including on structured and inaccessible beds of bodies of water. To that end, the device (01) according to the invention has either side of a central hinge

Canada http://opic.gc.ca · Ottawa-Hull K1A 0C9 · http://cipo.gc.ca OPIC CIPO

OPIC · CIPO 191

PATENT V

Vorrichtung zur Nutzung von technischen Geräten im Unterwasserbereich

Roland Krone & Philipp Krämer

(19) Deutsches
Patent- und Markenamt

(10) **DE 10 2009 058 277 B4** 2011.12.01

(12) **Patentschrift**

(21) Aktenzeichen: **10 2009 058 277.0**
(22) Anmeldetag: **13.12.2009**
(43) Offenlegungstag: **16.06.2011**
(45) Veröffentlichungstag
der Patenterteilung: **01.12.2011**

(51) Int Cl.: ***B63C 11/52*** (2006.01)
F03D 11/04 (2011.01)
G21C 17/013 (2011.01)

Innerhalb von drei Monaten nach Veröffentlichung der Patenterteilung kann nach § 59 Patentgesetz gegen das Patent Einspruch erhoben werden. Der Einspruch ist schriftlich zu erklären und zu begründen. Innerhalb der Einspruchsfrist ist eine Einspruchsgebühr in Höhe von 200 Euro zu entrichten(§ 6 Patentkostengesetz in Verbindung mit der Anlage zu § 2 Abs. 1 Patentkostengesetz).

(73) Patentinhaber:
Stiftung Alfred-Wegener-Institut für Polar- und Meeresforschung, 27570, Bremerhaven, DE

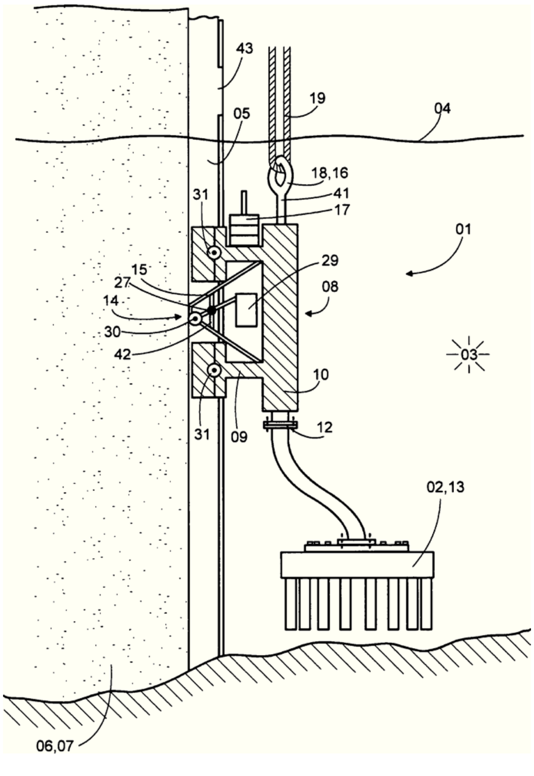
(72) Erfinder:
Krone, Roland, 28209, Bremen, DE; Krämer, Philipp, 26121, Oldenburg, DE

(56) Für die Beurteilung der Patentfähigkeit in Betracht gezogene Druckschriften:

DE	**102 22 472**	**A1**
DE	**199 21 312**	**A1**
GB	**2 270 664**	**A**
US	**2007 / 0 189 858**	**A1**
EP	**1 905 688**	**A2**

(54) Bezeichnung: **Vorrichtung zur Nutzung von technischen Geräten im Unterwasserbereich**

(57) Zusammenfassung: Bekannt ist eine Vorrichtung an einem wasserbenetzten Bauwerk mit einer vertikalen Führungsschiene, auf der ein Geräteschlitten läuft, der jedoch durch seinen Auftrieb im Wasser und durch Strömung und Wellendynamik leicht in der Führungsschiene verkantet. Die erfindungsgemäße Vorrichtung (01) weist Andruckeinheiten (14) am Geräteschlitten (08) mit einem drehbar gelagerten Hebel (28) mit einer Stützrolle (30) und einem Gewichtspaket (29) auf. Dabei ist die Abtriebskraft des Gewichtspakets (29) im Wasser größer als die Auftriebskraft des Geräteschlittens (08), sodass dieser an das Bauwerk (06) angedrückt wird und nicht längs verkanten kann. Weiterhin sind erfindungsgemäß am Geräteschlitten (08) zumindest zwei Abstandshalter (15) vorgesehen, die sich am Bauwerk (06) abstützen und der seitlichen Verkantung des Geräteschlittens (08) sowie übermäßig großer Krafteinwirkung auf die Führungsschiene (05) vorbeugen. Zum kontrollierten Ausbringen und Einholen des Geräteschlittens (08) ist eine koppelbare Fier- und Hieveinrichtung vorgesehen. Mit der Vorrichtung (01) nach der Erfindung können im Bereich von Bauwerken mit schwierigen Strömungsverhältnissen, beispielsweise Pylonen von Offshore-Windkraftanlagen, beliebige Geräte, beispielsweise Videokameras, Probennehmer oder Tauchausrüstungen, zuverlässig in den Unterwasserbereich verbracht und eingesetzt werden.



US 20110140059A1

(19) **United States**
(12) **Patent Application Publication**
Krone et al.
(10) **Pub. No.: US 2011/0140059 A1**
(43) **Pub. Date: Jun. 16, 2011**

(54) DEVICE FOR THE USE OF TECHNICAL EQUIPMENT UNDERWATER

(75) Inventors: **Roland Krone**, Bremen (DE); **Phillipp Kraemer**, Oldenburg (DE)

(73) Assignee: **Stiftung Alfred-Wegener-Institut fuer Polar- und Meeresforschung**, Bremerhaven (DE)

(21) Appl. No.: **12/964,843**

(22) Filed: **Dec. 10, 2010**

(30) **Foreign Application Priority Data**

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Publication Classification

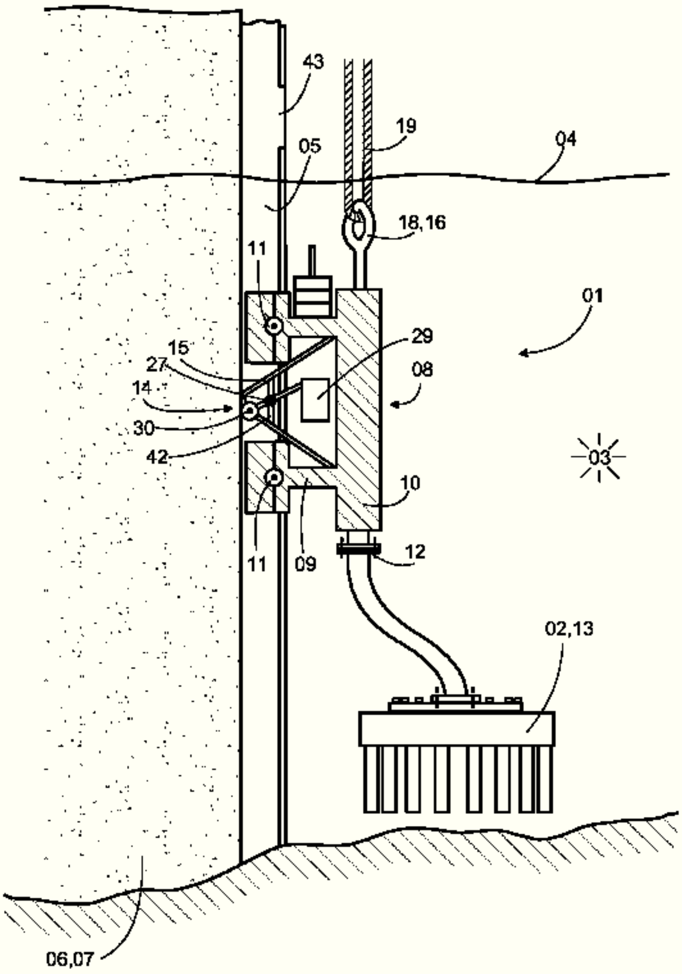
(51) **Int. Cl.**

B66D 1/60	(2006.01)
B66D 1/00	(2006.01)
B66D 3/18	(2006.01)

(52) **U.S. Cl.** **254/387**

(57) ABSTRACT

A device for using technical equipment underwater includes at least one guide rail configured to extend vertically underwater on an edifice from above a waterline. At least one device carriage is provided and includes a basic unit having a reception flange configured to couple the technical equipment thereto, and at least one running unit that abuts against the guide rail via guide rollers. A press-on unit is disposed on a first side of the device carriage and includes a lever pivotable on an axis of the device carriage so as to generate a pressing force of the device carriage against the guide rail. The lever includes a support roller at a first end and a weight packet at a second end so as to exert a downward drifting force underwater that is greater than a buoyancy of the device carriage. At least two spacers are each disposed at a first end on the at least one device carriage and abutting the edifice at a second end. A veering and hoisting device is detachably connectable with the device carriage via a coupling device, and is configured to control deployment and retrieval of the device carriage.



(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 2 336 429 B1

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(21) Anmeldenummer: **10075737.6**

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(51) Int Cl.:
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F03D 1/00 *(2006.01)*
B66B 9/187 *(2006.01)*
E06C 7/12 *(2006.01)*
B66B 9/00 *(2006.01)*
A47L 1/02 *(2006.01)*
E04G 23/00 *(2006.01)*

(54) Vorrichtung zur Nutzung von technischen Geräten im Unterwasserbereich

Device for using technical devices underwater

Dispositif d’utilisation d’appareils techniques dans le domaine sous-marin

(84) Benannte Vertragsstaaten:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR

(30) Priorität: **13.12.2009 DE 102009058277**

(43) Veröffentlichungstag der Anmeldung:
22.06.2011 Patentblatt 2011/25

(73) Patentinhaber: **Stiftung Alfred-Wegener-Institut Für Polar- Und Meeresforschung**
27570 Bremerhaven (DE)

(72) Erfinder:
- **Krone, Roland**
  28203 Bremen (DE)
- **Krämer, Philipp**
  26121 Oldenburg (DE)

(56) Entgegenhaltungen:
DE-A1- 1 634 211
GB-A- 796 365
US-B1- 6 170 613
US-B1- 6 640 934

Printed by Jouve, 75001 PARIS (FR)

PATENT VI

Künstliches Habitat in Polyederform für Krebstiere auf marinen Weichböden und Anwendung

Roland Krone

(19) Deutsches
Patent- und Markenamt

(10) **DE 10 2010 049 049 B3 2012.03.01**

(12) **Patentschrift**

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(51) Int Cl.: ***A01K 61/00*** (2006.01)

Innerhalb von drei Monaten nach Veröffentlichung der Patenterteilung kann nach § 59 Patentgesetz gegen das Patent Einspruch erhoben werden. Der Einspruch ist schriftlich zu erklären und zu begründen. Innerhalb der Einspruchsfrist ist eine Einspruchsgebühr in Höhe von 200 Euro zu entrichten(§ 6 Patentkostengesetz in Verbindung mit der Anlage zu § 2 Abs. 1 Patentkostengesetz).

(73) Patentinhaber:
Stiftung Alfred-Wegener-Institut für Polar- und Meeresforschung, 27570, Bremerhaven, DE

(72) Erfinder:
Krone, Roland, 28203, Bremen, DE

(56) Für die Beurteilung der Patentfähigkeit in Betracht gezogene Druckschriften:

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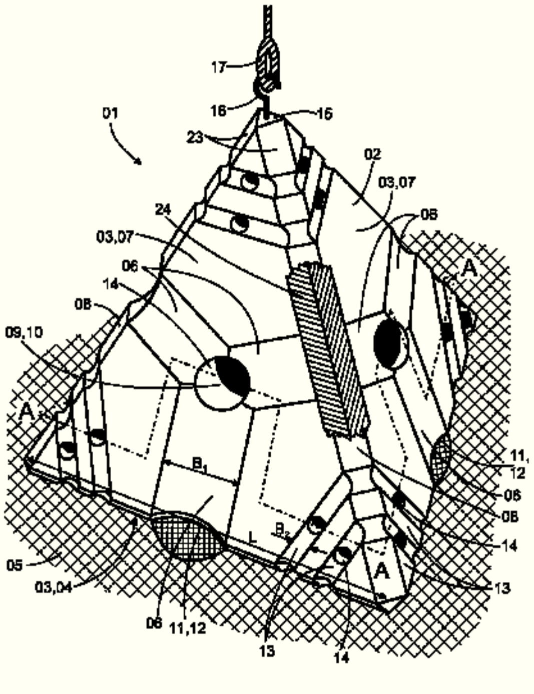
US	**6 896 445**	**B1**
US	**3 929 100**	**A**
US	**5 860 392**	**A**
US	**5 071 285**	**A**
US	**5 080 526**	**A**
US	**4 388 019**	**A**
US	**4 449 479**	**A**
KR	**10 0 913 808**	**B1**

(54) Bezeichnung: **Künstliches Habitat in Polyederform für Krebstiere auf marinen Weichböden und Anwendung**

(57) Zusammenfassung: Bekannte künstliche Habitate in Polyederform für Krebstiere auf aquatischen Weichböden mit einer eigenständigen Standfähigkeit und strukturierten Oberflächen weisen entweder keine oder eine extrem kleinteilige Strukturierung am Übergang zum aquatischen Weichboden auf. Krebse sind aber Hartbodentiere und siedeln in Weichböden nur unterhalb harter Komponenten. Das erfindungsgemäße künstliche Habitat (01) ist daher gekennzeichnet durch einen symmetrischen Vollkorper (02) in Tetraederform mit vier gleichen, jeweils eine mögliche Standfläche (04) bildenden Seiten (03), in deren Oberflächen (07) drei rinnenförmige Hauptgänge (06) mit einem Verlauf entlang der Seitenhalbierenden (22) von der Seitenkante (08) bis zu einem gemeinsamen Schnittpunkt (09) im Seitenschwerpunkt (10) angeordnet sind. Dadurch stellt der Vollkörper (02) in Tetraederform ein besonders attraktives künstliches Habitat (01) für Krebstiere dar, weil sich ihnen Hauptgänge (06) als Einstiegshilfen (11) und begonnene Höhlungen und ausreichend große Oberflächen (07) in den Seiten (03) des Vollkörpers (02) bieten, die sie für den Bau ihrer Höhlungen (12) unterhalb des massiven Vollkörpers (02) bevorzugt nutzen können. Durch Verbindungsgänge (19) können Materialersparnis, beispielsweise Leichtbeton, und bessere Handhabbarkeit, zusätzlich auch in Anwendungen als Fischereisperre oder Kolkschutz, erreicht werden.



GENERAL DISCUSSION AND CONCLUSIONS

This part of the thesis discusses how wind power foundations affect the marine ecosystem in the German Bight. Technical concepts on how to control and mitigate reef effects are presented based on my research. Major findings on reef ecology and reef effects are highlighted by text boxes. The first chapter summarises how offshore wind power reefs affect the North Sea ecosystem relating to biofouling (macrozoobenthos) and vagile demersal megafauna. The second chapter summarises the ecological functions of a tropical reef fish. The fish is used as an example to demonstrate the importance of a single species for reef development. The third chapter discusses how to manage the wind power foundations: How to enhance their function as reefs and how to mitigate the reef effects. Finally, I will outline questions which require further research.

How do offshore wind power reefs affect the ecosystem?

Biofouling induced reef effects

Earlier investigations into the impact of offshore wind power constructions on the ecosystem included the research into ship wrecks (Zintzen et al., 2006, 20082, 2008b), monopiles in shallow waters (Leonhard und Pedersen, 2006., Lindeboom, 2011) and offshore gravity foundations in Belgian waters (Degrear and Brabant, 2009; Kerckhof et al., 2010). These investigations focused on the first three years after construction. Samples for the present study were taken from the FINO 1 offshore research platform in the south eastern North Sea (Germany) over a period of five years after construction (Krone et al., submitted PUBLICATION VI). Biofouling quantifications were achieved with high resolution and in water depths comparable to the location of offshore wind power foundations. This allows estimations of the impact of biofouling on wind power foundations on the German Bight ecosystem. The biofouling (macrozoobenthos) mass at a jacket foundation was measured to be 4,300 kg on a foot area of ~1000 m². The soft bottom terrain usually provides an average of 122 kg macrozoobenthos per 1000 m². Hence the artificially introduced wind power foundations represent biomass hot spots inside the soft bottom terrain. Furthermore this means that 5000 foundations bring an additional macrozoobenthos biomass of 0.8 % to the North Sea soft bottom. The biomass means an increased secondary production and due to down falling biofouling compartments the adjacent benthic faunal community will change from a filter feeder dominated to a a scavenger dominated community (Schröder et al., accepted, PUBLICATION IX). How this agglomeration of biomass at the thousands of upcoming foundations will alter the food web remains unknown and requires more research.

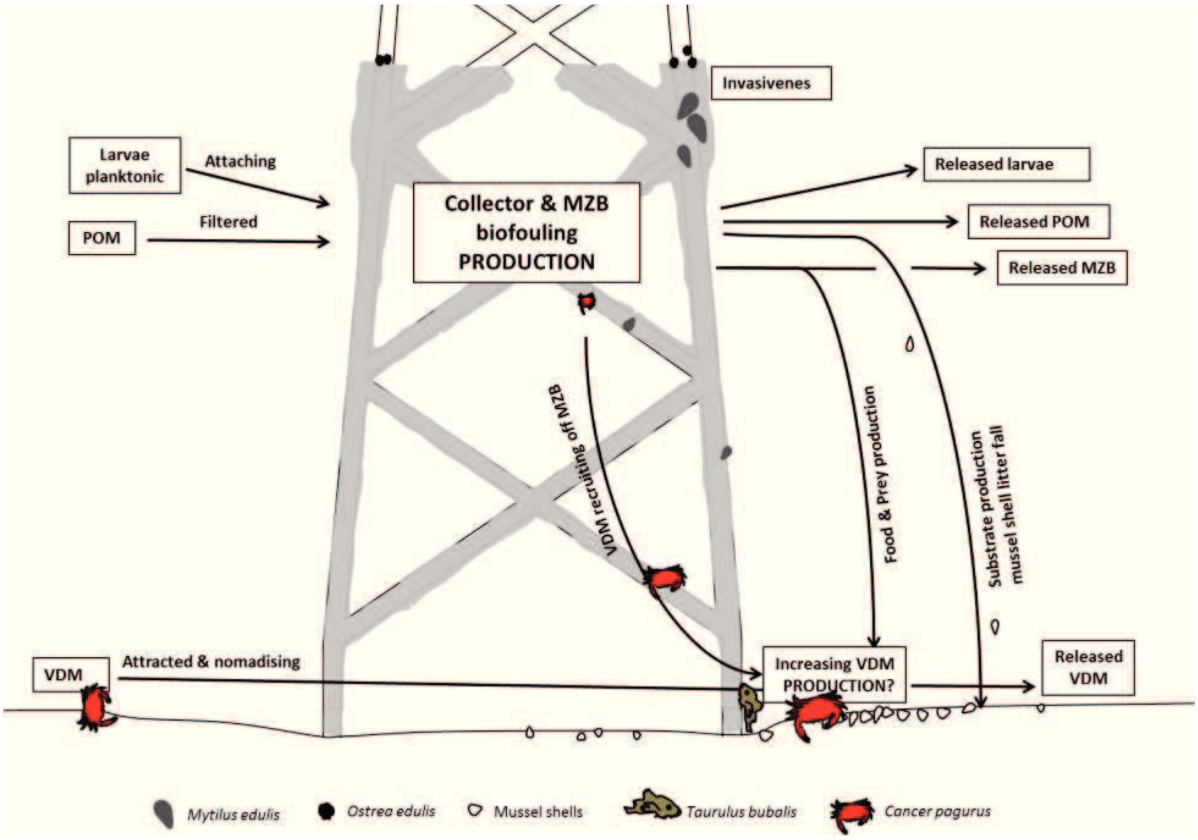


Fig. 11. Colonization processes and reef effects at a typical offshore jacket foundation in the North Sea. The biofouling (MZB = macrozoobenthos, biofouling ▒) plays a key role for reef effects (POM = particulate organic matter; VDM = vagile demersal megafauna = > 1cm). The sea scorpion (*T. bubalis*) and the brown crab (*C. pagurus*) which show much higher numbers at a foundation than on the soft bottom are used as examples for VDM. The grain size of the present soft bottom will become coarser due to massive mussel shell litter fall. Please note the thickness of the biofouling layer in the upper water level.

Five years after the construction of the FINO1 platform the biofouling community was still changing. However, the research revealed a clear depth zonation (Fig. 11). Fifty percent of the total biofouling masses of 4,300 kg wet weight grew in the upper 5 metres. The bivalve *Mytilus edulis* dominated this zone with approx. 90% of the biofouling mass. In the present project this species was not found deeper than 5 metres, whereas other investigations revealed depth proliferations down to 20 metres (Kingsbury, 1981; Whomersly and Picken, 2003). The water levels lower than 5 metres were dominated by anthozoans. It is believed that *M. edulis* compete with anthozoans for space (Kingsbury, 1981). Sea stars (*Asterias rubens*), which also occurred in 5 m depth, are the main predator of *M. edulis*. The *M. edulis* population is minimal in waters deeper than 5 metres where anthozoans and sea stars are abundant. As *M. edulis* is resistant to wave forces, the highly turbulent upper water levels may represent a spatial niche for this species (Gosling, 1992). Consequently, *M. edulis* is missing at fully submerged shipwrecks as these usually do not extend up to shallow water zones. The wrecks are often found to be densely colonized by anthozoans and sea stars (Zintzen et al., 2006, 2008a). Further investigations are needed to assess the depth proliferation of *M. edulis* and whether the biofouling masses remain stable. Altogether, the upper 5 metres were the most important foundation section in regards to biofouling mass production and for biofouling induced reef effects.

Lindeboom et al. (2011) suggested that the function of the wind power foundations as stepping stones will probably not exceed the stepping stone function of the many ship wrecks in the southern North Sea. However, the dense settlement of the native *M. edulis* on areas near the sea surface and their colonization by the exotic pacific oyster (*Crassostrea gigas*) clearly show that the construction of offshore foundations results in the development of a new habitat type. The future offshore foundations will add a significant amount of shallow water substrate to the open North Sea. These new zones will be colonized by new species which either stay at a particular foundation or move actively or passively between wind farms (box, compare Fig. 15). They potentially affect the North Sea through increased colonization pressure on autochthonous fauna communities. For example, the Korean sea squirt *Styela clava* was found in 2007 at the island of Helgoland - a long time after it had established itself along the North Sea main land coast (Krone et al., 2007 PUBLICATION V) where it dominates the fauna communities in some areas. A chain of wind power foundations in the North Sea may accelerate the proliferation of such alien “upper subtidal species”. The dark insides of the piles are linked with the open water and provide shelter against wave forces. Therefore I propose that foundations provide suitable conditions for the colonization and proliferation of high energy shallow water species such as *M. edulis,* as well as “calm shallow water species” such as *S. clava.* It is therefore important to include in the future this part of the piles when the stepping stone function of wind power foundations are investigated[1].

Shallow offshore stepping zones

With the introduction of wind power foundations into the sea, new hard substrate habitats and stepping stones are added to the offshore area in the German Bight.
The foundations are constructed in a way that they extend from the sea floor to near the water surface. So they provide shallow water attachment zones and can serve as stepping stones for species which are depth limited (e. g., *Mytilus edulis and Crassostrea gigas*). In comparison, the thousands of North Sea ship wrecks only provide fully submerged habitats.

The biofouling community of the offshore foundation FINO 1 is dominated by allochthonous hart bottom species. The three dominant taxa found at FINO 1, *M. edulis*, anthozoans and the amphipod *Jassa* spp., are also found on natural reefs and the artificial constructions at the island of Helgoland. However, the numbers are much lower (Anger, 1978; de Kluijver, 1991 Reichert and Buchholz, 2006; Reichert et al., 2008).The artificial reef fauna cannot

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[1] The inside of the main pylons of some foundation types are accessible e. g., for service purposes.

simply be interpreted as an amplification of the natural reef communities in the German Bight. Below a depth of 10 metres the FINO 1 and the many North Sea wrecks (Zintzen et al., 2008a, Krone not published) are densely colonized by anthozoans (anemones). The settlement of Anthozoa on natural hard substrates is much less in comparison to artificial hard substrates. This means that the anthozoan stocks in the North Sea will significantly increase with the introduction of wind power offshore foundations. As a result, the food demand may increase which can lead to heavy predation pressure on zooplankton, amphipods and fish larvae (Sebens and Koehl, 1984). This may significantly reduce the recruitment of certain species as observed for herring in the Kiel Bight (Möller, 1984; van DerVeer and Oorthuysen, 1985). The high number of 3.3×10^8 *Jassa* spp. individuals per foundation represents a substantial and valuable food resource for fish. In Belgium waters *Jassa* spp. was the major diet component of pout (*Trisopterus luscus*) at wind power foundations (Reubens et al., 2011). The high number of *M. edulis* attached to the FINO 1 foundation can also be seen as an easily available food source for different predatory species such as *Asterias rubens, Cancer pagurus* and *Necora puber.* It is believed that *M. edulis* will attract and feed these species (Wolfson et al., 1979; Freire and González-Gurriarán, 1995; see next chapter). The colonization on the research platform FINO 1 by *M. edulis* is a crucial example for an artificial stock enhancement of a single species. The future introduction of 5000 wind power foundations will increase the *M. edulis* population in the German Bight by approximately half of the population currently inhabiting the German Waddensea. For the potential reef effects of *M. edulis* stocks I propose the term *Mytilusation* (box).

Mytilusation

The presence of the blue mussel (*Mytilus edulis*) is limited in the German Bight by the lack of suitable hard substrate as habitat. The introduction of offshore wind power foundations into the open North Sea will significantly enhance the stock of this mussel and the *M. edulis* colonization on the foundations will affect the German Bight ecology in the following ways:

-Mussel shell litter fall will lead to coarser sediments in wind park areas and will favour the development of hard bottom communities on the sea floor.

-Increased filtration of the North Sea water by *M. edulis* leads to changing particle and nutrient fluxes as well as water clearance.

-Increased mussel stocks lead to stock enhancement of predators in offshore wind farms.

-Substantial release of planktonic larvae further increases the North Sea *M. edulis* stock and the Mytilusation.

The shift to coarser sediments (10,000 tons mussel shells are calculated to be produced annually) and the increased filtration of the North Sea water (the total effluent rate of the rivers Elbe, Weser, Ems, and Eider = 4.56×10^9 l h^{-1}) are, in my opinion, the major factors of Mytilusation. The future *M. edulis* stock may take on the ecological role of the former oyster banks (*Ostrea edulis*). *Ostrea edulis* used to be spread over vast areas in the North Sea and were able to produce hard substrate and contributed to the filtration of the water. There are large areas in the North Sea which used to be named after this mussel (Olsen, 1883; Franke, pers. communication), and the former existence of oyster banks was reported from around the island of Helgoland and the Northern Frisian coast until early 20th century (Caspers, 1950). The oysters formed biotopes which were inhabited by a specific oyster reef fauna. This fauna included for example the reef forming ross worm (*Sabellaria spinulosa*) which is now classified as an endangered species (Caspers, 1950, Rachor, 1998). The increasing *Mytilus*-stock (and secondary *Mytilus*-hard-substrate) will lead to a North Sea benthos which is again more dominated by mussels. To what extend Mytilusation will take place depends on two factors: The number of wind power foundations to be erected and the density of *M. edulis* on these structures. The results presented in this study are based on the data from a single research platform. Biofouling of other foundations may be different. More recent observations at other offshore wind power foundations such as the wind farm *alpha ventus* (in a distance of 500 metres to FINO 1) revealed a larger depth proliferation of *M. edulis* of up to 20 metres (Krone, not published). This means that the future population of *M. edulis* may exceed what is presented here.

Vagile demersal megafauna

About 1,300 ship wrecks are situated in the German Bight ecosystem for many decades and are a constituent of the ecosystem. Such artificial subtidal structures are densely colonized by the vagile demersal megafauna (VDM) and represent artificial biotopes with allochthonous VDM communities (Leewis et al., 2000; Zintzen et al., 2006; Zintzen and Massin, 2010). It is very likely that these communities affect the local ecology as many of the new “reef species” are predators of high trophic level and also represent important prey for top predators. What quality the thousands of future offshore wind power foundations will add to the underwater ecology was unknown. The FINO 1 foundation was used as a comparable measure to offshore foundations. It was found to be settled by the same species composition as found at ship wrecks (Krone et al., submitted PUBLICATION VII). Both kinds of constructions, wrecks and wind power foundations, were inhabited by species which are rarely or not at all found on soft bottom. Altogether, due to very high VDM abundances, the communities associated with the artificial habitats were significantly different to those which settled on soft bottom (Fig 12). However, abundances in the communities at the offshore foundation were six times less than at wrecks. The FINO 1 results show that, in contrast to biofouling, the shallow water zone of wind power foundations will add no significantly new VDM stock to the North Sea. This means that the shallow zone section of wind power foundations will be different from the wrecks in deep water and the bottom close construction sections with high VDM abundances. Typical hard substrate species such as the crabs *Necora puber* and *Cancer pagurus* showed very high numbers with 600 and 1,800 individuals per wreck. The stock of *C. pagurus* at ship wrecks is calculated to be 2.34 million. Such amounts may be the reason for frequent visits from the British *Cancer* pot fishery and may add significant commercial value to the German Bight area (Franke, pers. communication; Krone, pers. observation).

Although the food areas of ship wrecks and FINO 1-like foundations are of comparable size (1200 and 1024 m², respectively), foundations seem to be less attractive for typical hard substrate species (e.g., *N. puber*, *C. pagurus* and the sculpin *Taurulus bubalis*). Despite this, the high number of 5000 jacket foundations will add habitat for one million *C. pagurus*, one million *N. puber* and 200,000 *T. bubalis* to the North Sea. These predatory species are rare on the pure North Sea soft bottom[2] (Krone et al., submitted PUPLICATION VII). Their development in wind farms needs to be monitored as increasing stocks of predators may impact on the migrating and nomadic prey stocks moving through the parks. The reason for the low number of *C. pagurus* at the FINO 1 foundation may be the young age of the construction. I also suggest that the lack of structural diversity of offshore foundations plays a significant role in the relatively low abundances of such species. Abundances of reef fauna are positively related to structural diversity (Woll, 2003; Hunter and Sayer, 2009). The ship wrecks previously investigated are complex buildings and provide many hideouts and niches for organisms. The FINO 1 foundation, however, only provides minimal structural diversity as a significant part of the foundation is made up of naked tubes. Our research revealed that other construction elements such as cable ducts or sacrificial anodes were occupied by crabs or demersal fish (e. g., *T. bubalis*). This observation highlights the need to design hard substrate habitats to promote or discourage the settlement of VDM (see related chapter). It remains to be tested how the VDM at the future foundations will interact with the North Sea benthos. The questions are whether it will feed only on the prey which settles on the artificial habitats or whether, and to what extent, it will alter the prey spectrum of the surrounding sea floor. I assume that the FINO 1 fauna community functions as a self-containing biotope, comparable to the situation reported for a pacific offshore platform (Page et al., 1999). I also assume that the high load of organic matter in the eutrophic North Sea (Hickel et al. 1993; Ladwig, 2010) provides unlimited food for biofouling and therefore the basis for the “foundation biotope” (Kingsbury, 1981). Another effect of offshore constructions may be the

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[2] In 2007 not a single *T. bubalis*, *C. pagurus* or *N. puber* was found in 16 beam trawl catches performed in the FINO 1 area (Krone, not published).

provision of additional food for top predators such as the grey seal (*Halichoerus grypus*) which I saw on regular occasions in the vicinity of working wind turbines in the wind farm *alpha ventus* during the last three years. To what extent the VDM will be attracted to or is produced at the foundations and ship wrecks (Bohnsack, 1989; Page et al., 1999) remains unknown and cannot be answered as part of this study. Simple attraction will cause a redistribution of the taxa. Pure production (recruitment and growth at the construction) will enhance the stock of the relevant species (Bohnsack, 1989). It is likely that both mechanisms act simultaneously. Independent of whether the species are attracted to the site or whether they are produced there, foundations may provide significant benefits for them such as the provision of shelter and additional food. Such macrozoobenthos food variety is rarely available on soft bottom. This means that the increasing net production of the biofouling (prey species) masses at thousands of wind power foundations will result in a significant growth in predator numbers.

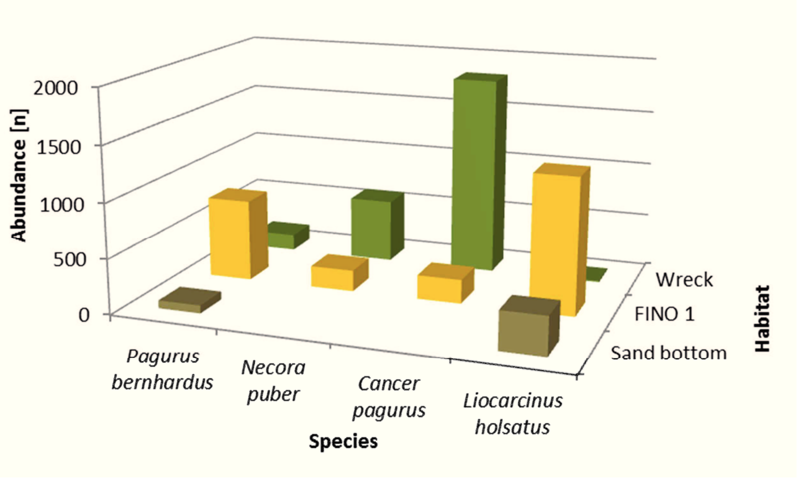

Fig. 12. Total abundance of crabs which contributed > 2% to the vagile demersal megafauna at three different habitats in the south westerly German Bight (wreck area 1200 m², soft bottom area 1200 m², area of the research platform FINO 1 1024 m²).

The example of *C. pagurus* shows that wind power foundations may exceed the effect of wrecks in terms of larval recruitment and therefore the production of VDM. A size analysis of *C. pagurus* revealed that the percentage of smaller individuals was higher at FINO 1 than at ship wrecks (Krone, not published) (Fig. 13). This might mean that wind power foundations will act as collectors for larvae, improving the survival rate of young *C. pagurus* and therefore enhancing the local production of this species. At FINO 1 the large adult individuals of up to 20 cm carapace width were restricted to the construction sections which are close to the sea floor (Fig. 14). The size of the individuals decreased with increasing distance from the sea floor. Large individuals are simply unable to climb up the construction and do not find appropriate hideouts in the very turbulent upper water levels.

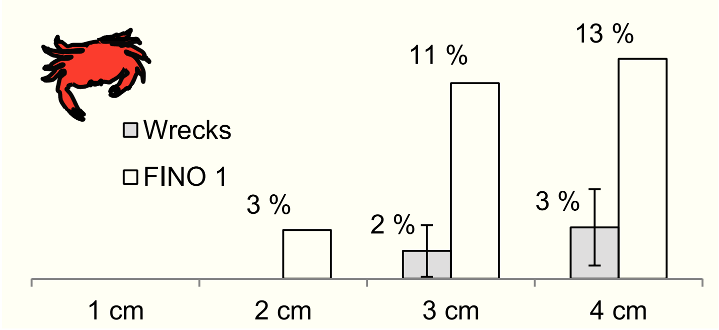

Fig. 13. Percentile share (±SD) of the 1-4 cm size group of the entire *C. pagurus* stocks at five ship wrecks (average carapace width of all measured individuals = 10.5±4.0 cm) and the research platform FINO 1 (average carapace width of all measured individuals = 10.0±6.0 cm) in the German Bight (FINO 1 data without SD because only this construction was sampled).

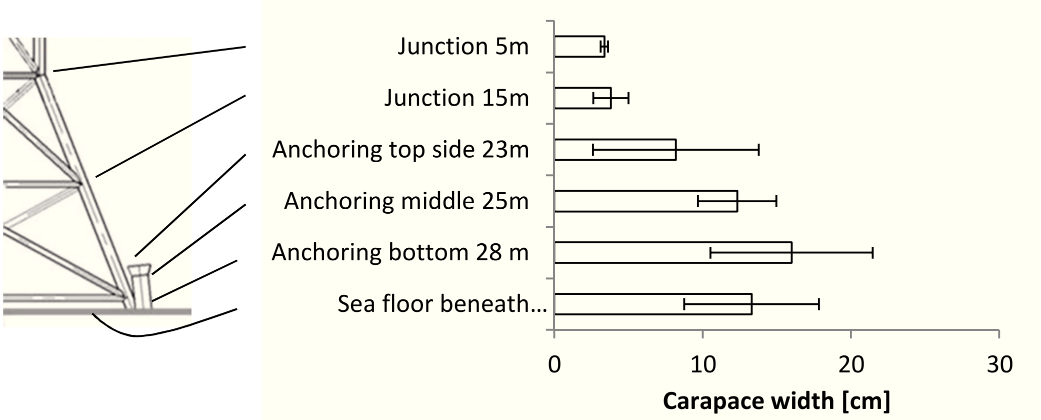

Fig. 14. Size of *C. pagurus* at the different sections of the construction and different water depths at the offshore research platform FINO 1.

Our research (Krone and Schröder, 2011 PUBLICATION VIII) clearly demonstrated the presence of the European lobster (*Homarus gammarus*) at wrecks in the German Bight. *H. gammarus* typically lives on rocky substrate, but individuals can also be found occasionally on soft bottom, dozens of kilometres away from rocks, probably searching for suitable hard substrate habitats. Most North Sea wrecks are within its range (Jensen et al., 1994). Therefore, wrecks may play a fundamental role in the spread of this rare species which, in the German Bight, was formally thought to be restricted to the island of Helgoland (Schmalenbach, 2009). Wind power foundations such as FINO 1 may not have the same qualities for lobster habitation as wrecks with their many caves and hideaways. Nevertheless, wind power foundations will probably also contribute to the population increase of lobsters by supplying food and habitat, and by functioning as stepping stones. Especially in the central German Bight where wrecks are rare, large wind power farms may enhance the spread of vagile megafauna like lobsters in the North Sea bottom terrains (Fig. 15). The design of some future wind farms entails the placement of bolder fields around the wind power foundation to prevent scouring. Such structural additions will enhance the suitability of the foundations for habitats for the VDM and improve the function of wind farms as stepping stones.

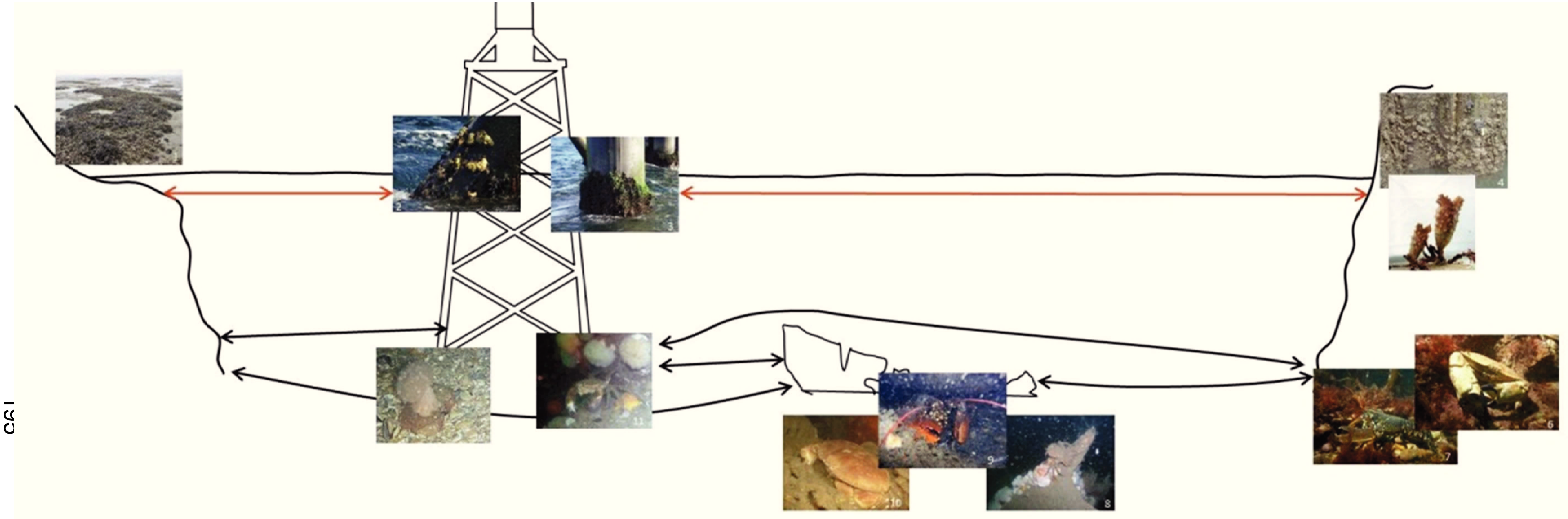

Fig. 15. Stepping-stone zones of wrecks and offshore foundations.

Shallow offshore stepping zones at foundations potentially enhance the spread of shallow water species in the North Sea and from coast to coast:
1 Banks of the invasive *C. gigas* in the North Frisian Wadden Sea (photo: Schmidt)
2 *C. gigas* at the offshore research platform FINO 1 in the North Sea (photo: Krone)
3 Large *M. edulis* stock in the intertidal at FINO 1 (photo: Schröder)
4 *C. gigas* at the Island of Norderney (photo Reichert)
5 The invasive sea squirt *Styela clava* at the Island of Helgoland (photo Krone)

Bottom close sections of offshore foundations are colonized by vagile demersal megafauna which is similar to those of wrecks. The introduction of thousands of wind power foundations into the North Sea will lead to an increased exchange between megafauna populations.
6 and 7 *C. pagurus* and *H. gammarus* at their preferred rocky habitat at Hegoland (photos Wanke)
8 – 10 *N. puber, H. gammarus* and *C. pagurus* inhabiting different ship wrecks (photo Krone)
11. and 12. *C. pagurs* and *N. puper* at the bottom area of FINO 1 (photo Krone)

Functional importance of vagile demersal megafauna – an example from a tropical coral reef

Coral reefs are one of the most diverse and complex ecosystems. Investigations into these reefs show that it is not only the number and biomass of species that is important to understand reef ecology and reef development, but also the behaviour and function of each species (Bellwood et al., 2004). As outlined earlier (Krone, 2005; Krone et al, 2006), behavioural studies on *Ctenochaetus striatus* (Acanthuridae) revealed that this fish has taken on a hitherto unknown ecological role as a reef sweeper. Other sediment-moving fish such as the reef scraping parrot fish (Scaridae) predominantly transport particles they have eroded from the reef surface (Bellwood, 1995), whilst *C. striatus* predominantly exports foreign lose sediments. The fish feeds on the sedimentary matter on top of reef patches or on the reef crest and then, at most times, defecates either on sandy bottom (Krone et al., 2008 PUBLICATIONI) or on the deep reef slope outside the fish’s browsing site (Krone et al., in preparation). Investigations in the Red Sea (Gulf of Aqaba, Egypt) showed that *C. striatus* exports at least 18% of the sediment which sinks on a coral reef on a daily basis (Fig. 16) (Krone et al., 2011 PUBLICATION II). Research into the Great Barrier Reef (Australia) also supports these finding and revealed that large *C. striatus* populations may be able to keep reef surfaces free of any sediment (Goatley and Bellwood, 2010). My investigations, however, reveal that the exported sediment also contains up to 13% of matter that *C. striatus* must have eroded themselves. This must be taken into considerations when interpreting the sediment balance of the Great Barrie Reef and others. At some reefs the *C. striatus* population can achieve bio-erosion rates which equal those of the sea urchin *Diadema setosum* (Krone et al., 2011 PUBLICATION II, Krone et al., 2006 PUBLICATION III, Schuhmacher et al. 2008a). *D. setosum* is an important reef eroder (Kroll, 1995). The severe deterioration of the reef in the Gulf of Aqaba must have taken place over many decades (Schuhmacher et al., 2008b PUBLICATION IV). To what extent the local *C. striatus* population has contributed to this erosion remains unknown. However, the numbers of *C. striatus* in the Red Sea are high. Whilst the global importance of reef sweeping for reef ecology (and geomorphology) needs further investigation, I suggest that *Ctenochaetus striatus* is only one among many important *reef sweepers*. The example of *C. striatus* shows how important it is to run basic behavioural investigations on the individual level, and it underlines that inconspicuous species are potentially very important for reef development.

Reef sweeper

The bristle tooth surgeonfish *Ctenochaetus striatus* is common throughout the Indo-pacific coral reefs. The fish uses its broom-like teeth to sweep lose substances into its mouth and defecates outside of the reef crest. It functions as a reef sweeper and helps to keep reef surfaces free of sediments. This is a key function for reef development as too much sediment prevents coral larvae recruitment at the reef crests and therefore the growth of coral reefs.

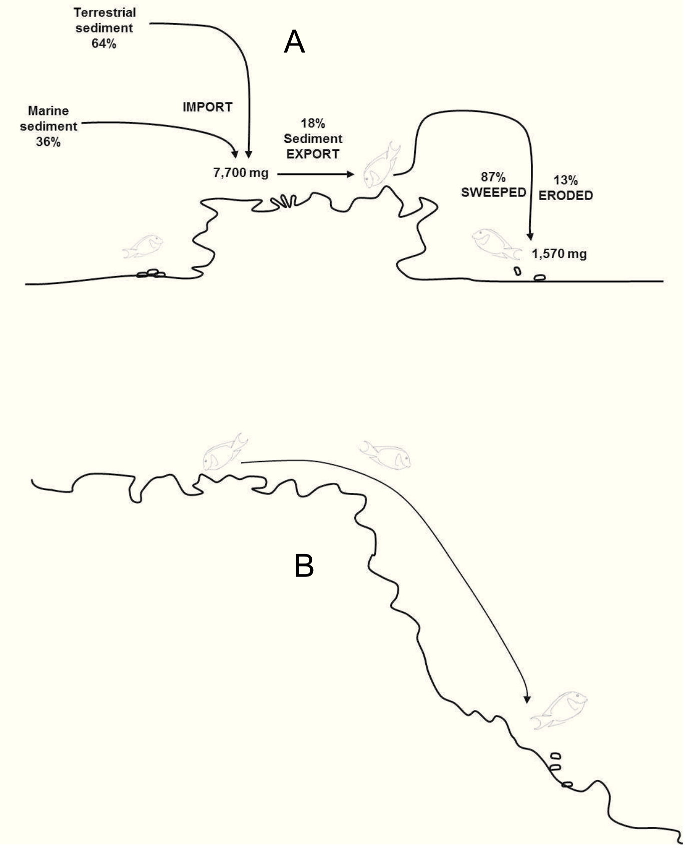

Fig. 16. The browsing and defecation behaviour of *C. striatus* in the Red Sea. It browses on top of reef patches (A) and on reef crests (B) where it ingests marine and terrestrial sediments. It also rasps and ingests calcareous reef rock. All ingested material is defecated around the reef and above sand bottom. When there is a lack of deep sandy places, the fish defecates at the deep reef slope away from its browsing site. In this way the fish transports sediments away from the upper reef zones.

Sediment removal and reef erosion do not play as big a role for wind power foundations. However, knowing the behaviour of the species at artificial reefs helps to predict and manage the fauna development. Field observations have shown how a reef must be shaped to become suitable for colonization by lobsters (Schmalenbach pers. communication; Jensen et al., 2000). This knowledge may be used in creating artificial reefs and wind power foundations which can enhance the local lobster stock. Species such as *T. bubalis* were detected at the wind power foundations on a regular basis, whilst they are rarely found on the autochthonous soft bottom. *In situ* behavioural observations may reveal whether the wind power foundations serve as mating sites for those species. If so, the foundations would enhance the distribution of *T. bubalis* by enabling the internal fertilisation and the release of the planktonic eggs (Lamp, 1966). Further studies should include the behaviour of *C. pagurus*. Large individuals of this species were found in high numbers at the anchoring of the FINO 1 platform (Krone et al., submitted PUBLICATION VII) and at the wind power turbines in the *alpha ventus* wind park (Krone and Krägefsky, submitted). It remains unknown, however, how they benefit from the constructions, what they eat and who their rivals are. *In situ* behavioural investigations at the coast of Norway (Woll, 2003) revealed that *C. pagurus* stay in the same shelter if it is a good hiding place. This highlights the importance of behavioural investigation for an understanding of the development of biotic communities in offshore wind power farms.

Managing reef effects

At the present time it is difficult to judge the ecological consequences associated with the introduction of the artificial reef type “wind power foundation” and its reef effects on fish and benthos. The question whether the impact is positive, negative or negligible remains unanswered and depends on the emphasis one places on the different implications of the reef effect. The present findings, however, enable the design of to increase or reduce biofouling and megafauna settlement at offshore wind power foundations. The reef effects as well as biofouling and the development of megafauna can significantly be reduced. This is what I name “reef passivation”. Alternatively, all potential reef functions could be activated if the development of a highly valuable artificial reef fauna is intended[3].

Reef passivation

If foundations are to have minimal impact on the benthic ecosystem, they can be modified in a way which mitigates biofouling and the accumulation of megafauna (Fig. 17). With the *electrochemical anti-fouling system for structures wetted by sea water* (PATENT I), biofouling at the foundations can be prevented. The advantage of this technique is that it is flexible: It can be added after the foundation has already been erected, and can be removed anytime. This technique can be applied to the entire foundation. However, to reduce the biomass accumulation and the spread of hard bottom species in shallow waters, it is particularly the top 5-10 metres of the construction which have to be protected from biofouling. The vagile

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[3] Physical disturbances as for example sediment re-suspension leeward the construction are not fauna induced.

demersal megafauna predominantly settle on the highly structured bottom anchorings (PUBLICATION VII). The EAT material was successfully tested and produced in North Sea water (PUBLICATION IX). The crevices at the foundations can be covered to mitigate the colonization by large species which require special hideouts. The material can also be successfully streamlined and used for scour protection and as a grid which further prevents sediment re-suspension. The advantage of the EAT material is that it is mostly made up of marine minerals and that it can be attached after the construction of the foundations and easily removed if necessary. For the inspection of the EAT structure a *device carrier for multiple use* (PATENT V) which is equipped with an underwater camera can be used. The device carrier can move up and down the piles and is a cost-effective way to check the EAT and other ecological and technical items.

Reef activation

Reasons to increase the artificial reef fauna community could be, for example, commercial use and species conservation. In this case the entire foundation could be made more easily accessible to certain species or could be constructed in a way which makes it more attractive for species. The *M. edulis* stock can be increased by keeping sea stars (*Asterias rubens*), the main predator, away from the settlement area. The *electrochemical antifouling system* (PATENT I) may be used as a barrier in deep water levels. In this way *A. rubens* can be prevented from climbing up the foundation and consuming the mussels. This would allow *M. edulis* to proliferate into deeper waters. The increase of *M. edulis* abundance in deeper waters would provide additional food for many predatory species and would result in increased Mytilusation through enhanced mussel shell litter fall. The number of predators of biofouling can also be increased by making the blank steel tubes of the foundation more accessible and habitable for megafauna. In this case a *device for developing habitats* (PATENT II) can be applied. These additional structures (sheets, steps etc.) do not affect the stability of the foundations and can be made out of the semi-natural EAT material (PUBLICATION IX) or steel. The scour protection made of EAT material can also be shaped similar to natural reefs, with crevices and holes for bottom species such as the European lobster (*Homarus gammarus*). The *device for the use of technical equipment* (PATENT V) can be used to lower the *device for colonization and harvesting* (PATENT III) along the piles down to the sea floor. *The colonization and harvesting device* has two purposes: It serves as habitat for commercially relevant crabs (e. g., *N. puber*) and as a harvester. When the device is pulled up along the piles, it may also collect part of the biofouling including *M. edulis* which also is of economic value (Dürr and Thomason, 2009; Krone and Brenner, 2009). A *transportable device for colonization and harvesting* (PATENT IV), similar to a trap, may be used as a transportable artificial reef and placed near the foundations. It must be identified by placing a buoy and can be pulled up to harvest the crabs inhabiting it[4]. To date, bottom trawling and fishery activity are prohibited inside wind farms for safety reasons and to protect the turbine foundations and the subsea-cables (BSH, 2012). In order to keep bottom trawling away from wind farms an artificial concrete ployhedron (*Künstliches Habitat in Polyederform*) (PATENT VI) may be used. This kind of barrier is designed to cut the fish nets in case the polyhedron is getting caught. The concrete ployhedron is also shaped in a way which allows crabs, and especially lobsters, to settle inside and to dig underneath. This lobster polyhedron can be placed along the cables in order to protect the cables and can also be placed in wind parks to prevent bottom trawling. The barriers can easily be produced using castings and simply be placed into the sea by dropping them.

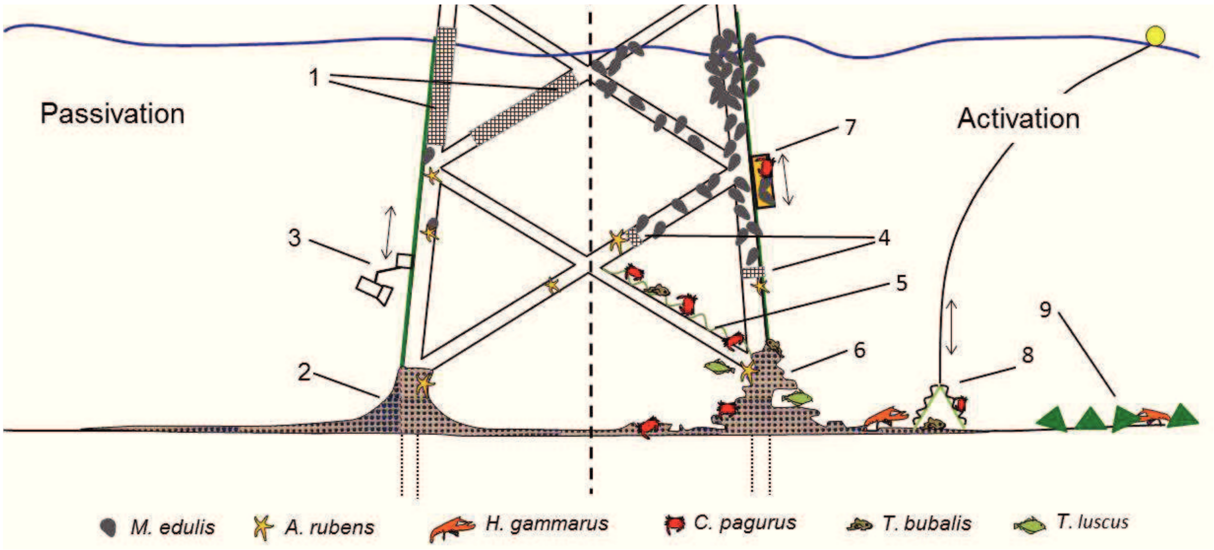

Fig. 17. Techniques for passivation and activation of wind power foundations and artificial reef fauna examples 1) *Electrochemical anti-fouling system for structures wetted by sea water*; 2) Calcareous *EAT-material* designed to reduce structural diversity and as scour protection; 3) *Device for using technical devices underwater*, equipped with a camera; 4) The *electrochemical anti-fouling system* applied to prevent sea stars (*A. rubens*) to climb up to feed on the Bivalvia *M. edulis;* 5) *Device for developing habitats in the underwater area of an offshore construction*, paths and hideouts for crabs and demersal fish; 6) *EAT-material* used to create reef-like structures to enhance the reef species; 7) *Device for colonizing and harvesting marine hard ground animals* such as *M. edulis* and large vagile megafauna; 8) *Transportable device for colonizing and harvesting invertebrates* in the vicinity of offshore constructions; 9) Artificial habitat in polyhedron shape used as a fishing net barrier which is at the same time habitable for lobsters.

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[4] Some crab species are found repeatedly to occupy almost every additional hard substrate that is placed close to the foundations (Krone, personal observation).

Outlook

The present study provides the most comprehensive data base for biofouling and megafauna on artificial offshore constructions in the south-eastern North Sea. It allows for impact scenarios related to the large-scale introduction of wind power foundations into the North Sea and for long-term studies in this context. However, the offshore wind power industry is at its very beginning and the present investigation as well as previous work undertaken in this area highlights the need for more research into this topic. It is important to conduct further investigations into biofouling and demersal vagile megafauna and to assess whether the findings published here can be generalised and to what extent the forecasted scenarios will occur. Some important questions identified during the investigation remained unanswered:

1) Operating wind power foundations vibrate and can, at the same time, attract and deter demersal fish. The questions remain whether the wind power foundations are colonised by the same vagile demersal megafauna community as the research platform FINO 1 and to what extent wind power farms increase megafauna stocks in the German Bight.
The current research project "*Untersuchungen der Effekte von Windenergieanlagen auf Fische und vagile Megafauna im Testfeld alpha ventus*"[5] is designed to answer these questions. The investigations focus on the megafauna development at the wind farm *alpha ventus*. For fauna quantifications at the foundations the scientific diving method is applied, which was first used at ship wrecks and the platform FINO 1 (Krone et al., submitted PUBLIKATION VIII). Preliminary results of that investigation have shown that a) wind power foundations of operating turbines will be colonized by a faunal community which resembles that detected at FINO 1, and that b) prior to the wind park construction some species such as *Taurulus bubalis* only occurred at the foundation of FINO 1 and not in the entire research area. This means that the wind power foundations alone are responsible for the *T. bubalis* community inside *alpha ventus*.

2) Not all offshore foundations will be built out of steel and placed in the same area. The questions remain what kind of biofouling community will develop on offshore foundations made out of other materials and built at other locations than FINO 1. Are these biofouling communities different in composition and biomass from those which settled on FINO 1?
To answer this questions the research project "*Ökologie Schwerkraftfundament - Windpark Albatros 1*" is being proposed in which the biofouling development at the first offshore gravity concrete foundations inside the German Bight will be investigated.

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[5] Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit, 2008-2012

3) To what extent will the process of Mytilusation take place?

To answer that question the project "*Auswertung digitaler Fotoaufnahmen des Meeresbodens im Offshore-Testfeld alpha ventus*"[6] is under way.

Photos of the sea floor will be taken close to a four year old operating wind power foundation as well as from a reference site. The photo analysis should allow for an assessment of possible substrate alteration due to mussel shell litter fall.

4) How does the vagile demersal megafauna of wind power foundations impact on the benthos of the surrounding sea floor?

To answer that question, *in situ* behavioural observations on the large and abundant predator *C. pagurus* should be performed at night when the crab is most active. Furthermore, the large scale moving and predation pattern in and around wind farms should be investigated. For this purpose, ultrasound-radio-telemetry (for moving detection) and behaviour loggers (e. g., to count claw action that indicates feeding) should be combined.

5) How will the locally increased biomass from future foundations in wind farms alter the energy balance of the ecosystem German Bight?

To gain first insights into this area, the FINO 1 biofouling data can be used to analyse the position as well as the trophic links of the heterotrophic fauna community of future wind power foundations within the food web and its importance to the German Bight.

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[6] Bundesverkehrsministerium, 2012-2013

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Eidesstattliche Erklärung Gem. § 6 (5) Nr. 1-3 PromO

Hiermit versichere ich, dass ich

1. die Arbeit ohne unerlaubte fremde Hilfe angefertigt habe.

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Roland Krone

Back cover:

The blue mussel colonizing a wind power foundation in wind farm *alpha ventus*, Krone.

The velvet crab at a ship wreck, Krone.

The striped bristletooth surgeonfish in a Red Sea coral reef, Kanstinger.

Roland Krone at a wind power foundation, Krone.