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Geological and faunistic characterisation of differentially structured habitats in offshore areas of the North Sea

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I. Abbreviations

AUV	Autonomous Underwater Vehicle
AWI	Alfred Wegener Institute
BaSIS	Baltic Seafloor Imaging System
BfN	Bundesamt für Naturschutz
EEZ	Economic Exclusive Zone
EHSLR	Early Holocene Sea Level Rise
GUI	Graphical User Interface
IOW	Institut für Ostseeforschung Warnemünde
MIAS	Marine Image Annotation Software
PAPARA(ZZ)I	Program for Annotation of Photographs And Rapid Analysis (of Zillions and Zillions) of Images
PEV	Paleo Elbe Valley
PRIMER	Plymouth Routines In Multivariate Ecological Research
QGIS	Quantum Geographical Information System
SAC	Special Area of Conservation
SAR	Sylter Außenriff
SOR	Sylt Outer Reef
UNESCO	United Nations Educational, Scientific and Cultural Organization
WoRMS	World Register of Marine Species

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Abstract

Reefs are ecologically valuable habitats in coastal oceans, acting as ground for settlement, feeding, nursery and shelter for numerous species. Around 80% of the reefs worldwide are threatened by human activities. The reefs of the North Sea are mostly of geological origin. In the German Bight the rocky reefs are protected by the European Union as part of the Natura 2000 Network. In this study, the Sylt Outer Reef, located in the south-eastern part of the North Sea, was described geologically and faunistically using digital videos from a towed underwater camera. A methodology was established to evaluate the distribution of seafloor substrata and to identify the reef fauna. Additionally, the fauna was quantified and the relationships between geological and faunistic variables were explored.

A total of 11 video transects were analysed. At all stations, the benthic habitats were dominated by sandy sediment followed by lag deposit, while only small fractions of the seafloor were covered by stones. The sizes of the stones varied considerably within and between the stations with a maximum size of almost 60 cm. The benthic epifauna of the Sylt Outer Reef comprised 20 taxa (mostly species) from nine higher taxonomic groups. The Shannon-Wiener diversity of the epifauna varied between the stations from 0.69 to 2.01. The number of taxa at the stations depended on the habitat structure and declined with an increasing amount of the seafloor being covered by sand. Conversely, the number of taxa increased with stone size. Only the smallest stones were entirely uncolonized. In total, three different clusters of the epibenthic fauna could be distinguished inside the protected area of the Sylt Outer Reef. Although only a relatively small fraction of the benthic fauna can be captured by optical methods, the results generated by this non-invasive method allowed for a differentiated description of the epibenthic habitats of the reef areas of the Sylt Outer Reef.

Key words: reefs, image analysis, North Sea, benthos.

Resumen

Los arrecifes son hábitats de gran valor ecológico en los océanos costeros, ya que actúan como lugar de asentamiento, alimentación, cría y refugio para numerosas especies. Alrededor del 80% de los arrecifes de todo el mundo están amenazados por actividades humanas. Los arrecifes del Mar del Norte son, en su mayoría, de origen geológico. En la Bahía Alemana, los arrecifes rocosos están protegidos por la Unión Europea como parte de la Red Natura 2000. En este estudio, el Arrecife Exterior de Sylt, situado en el sureste del Mar del Norte, se describe geológica y faunísticamente utilizando vídeos digitales de una cámara submarina remolcada. Se establece una metodología para evaluar la distribución de los sustratos del fondo marino e identificar la fauna del arrecife. Además, se cuantifica la fauna y se exploran las relaciones entre las variables geológicas y faunísticas.

Se analizan un total de 11 transectos de vídeo. En todas las estaciones, los hábitats bentónicos están dominados por sedimentos arenosos, seguidos de depósitos residuales (*lag deposits*), mientras que sólo pequeñas fracciones del fondo marino están cubiertas por piedras. El tamaño de las piedras varía considerablemente en y entre las estaciones, con un tamaño máximo de casi 60 cm. La epifauna bentónica del Arrecife Exterior de Sylt comprende 20 taxones (en su mayoría especies) de nueve grupos taxonómicos superiores. La diversidad de Shannon-Wiener de la epifauna varía entre 0,69 y 2,01. El número de taxones en las estaciones depende de la estructura del hábitat y disminuye a medida que aumenta la superficie del fondo marino cubierta por arena. Por el contrario, el número de taxones aumenta con el tamaño de las piedras. Sólo las piedras más pequeñas están totalmente sin colonizar. En total, se pueden distinguir tres grupos diferentes de la fauna epibentónica dentro de la zona protegida del Arrecife Exterior de Sylt. A pesar de que sólo una fracción relativamente pequeña de la fauna epibentónica puede ser captada por los métodos ópticos, los resultados generados por este método no invasivo permiten una descripción diferenciada de los hábitats bentónicos de las zonas del Arrecife Exterior de Sylt.

Palabras clave: arrecifes, análisis de imagen, Mar del Norte, bentos.

1. Introduction

About 15 % of the world's coastlines are fringed by reefs (Roberts et al., 2002). These habitats act as a ground for settling, feeding, nursery and shelter for numerous species (Michaelis et al., 2019) and are, therefore, of significant ecological importance. In particular, one of the most biologically diverse ecosystems in the ocean are coral reefs, being considered biodiversity hotspots (Marchese, 2015). Reef ecosystems are characterised by a very low net productivity, implying slow accumulation of biomass and only little export thereof (Hatcher, 1990). Apart of their ecological importance, reefs also provide paleoclimatic information, protect coastlines from natural disasters, such as tsunamis, and provide economic benefits in terms of tourism, fisheries and coastal protection (Hoek & Bayoumi, 2017), among others.

Human activities are the major threat to coral reef, and round 80 % of the world's reefs are endangered because of those activities (Roberts et al., 2002). Growth of coastal cities, overfishing, inland and marine-based pollution as well as ocean acidification and global warming are some examples of factors threatening reef ecosystems around the world (Bryant et al. 1998). In acknowledgement of the risk of losing such important ecosystems, an extensive list of protection measures exists for reefs, from the local level up to the United Nations Educational, Scientific and Cultural Organization (UNESCO), including the nomination of the Great Barrier Reef as a World Heritage Site in 1981 and as one of the Seven Natural Wonders of the World in 1997 (*Great Barrier Reef Foundation*).

Reefs in temperate waters differ from coral reefs mostly in their formation and their characteristics. Most temperate reefs are of geological origin. For example, in the south-eastern part of the North Sea, reefs were formed after the Early Holocene Sea Level Rise (EHSLR) and the melting of glaciers, which transported and deposited moraine sediments (Schwarzer et al., 2019). The reef systems of the North Sea were formed only about 10,000 years BP and are, thus, relatively young. They are widely distributed along all costs of the North Sea (see Appendix Figure 1).

Reefs in the German Bight (SE North Sea) are protected by the European Union as part of the Natura 2000 Network (*BfN*, 2020). This Network is made up of Special Areas of Conservation and Special Protection Areas, under the Habitats and the Birds Directive (Natura 2000 Network, n.d.). The Sylt Outer Reef (SOR) described in this study is a

Special Area of Conservation (SAC). The European Directive requires regular documentation and assessment of the conservation status of the reefs. In Germany, the German Federal Agency for Nature Conservation (abbreviated 'BfN' for the German name 'Bundesamt für Naturschutz') is responsible for the accomplishment of these sovereign duties. The German reef systems are primarily monitored using towed underwater camera systems. This method is non-invasive and has a relative low cost compared with methods like divers or Autonomous Underwater Vehicles (AUV). Since 2011 the regular monitoring of the North Sea reefs is conducted by the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) (*BfN*, n.d.). The monitoring was initiated 10 years ago. The methodology is continuously being improved, however, there are still considerable gaps in the knowledge about the structure and the spatial extent of the local reefs.

In this thesis, the Sylt Outer Reef was studied to comprehensively describe the structure and status of the local reef habitats to support the national monitoring activities. New methods for the analysis of the video material were tested and evaluated.

1.1. Background

Reefs have been extensively studied all around the world because of the high ecological importance. Reefs in temperate waters, however, are yet less explored than tropical coral reefs. However, in order to meet the requirements of the European Union for efficient marine environmental protection, increasing effort is being made to explore and evaluate the environmental status of the reefs systems in the North Sea.

Maps created by Olsen (1883) show the presence of extensive reef areas in the southern North Sea. Diesing & Schwarzer (2006) identified the submarine hard-bottom substrates of the German North Sea and Baltic Sea EEZ using high-resolution acoustic seafloor imaging. Within the Sylt Outer Reef, a total area of 315 km^2 was mapped to explore the sediment distribution and the spatial heterogeneity of the seafloor. Clear distinction between coarse-grained sediment, fine-to-medium sand and boulders was done.

Coolen et al. (2015) compared the benthic biodiversity related to the sedimentology in habitats of the Borkum Reef Ground, another reef area off the Dutch and German coast. 193 taxa were observed combining four different methods, including image analysis.

Studies comparing the diversity between natural and artificial reefs are common in this area. The North Sea hosts numerous offshore platforms for gas and oil extraction as well as wind farms. Although offshore drilling often causes environmental damage, the steel structures act as a substratum for numerous sessile species (Bergmark & Jorgensen, 2014).

The advantages and weaknesses of optical methods to explore reefs have been evaluated. For example, Beisiegel et al. (2017) studied benefits and shortcomings of non-destructive benthic imagery for monitoring hard-bottom habitats.

1.2. Objectives

In this study, the Sylt Outer Reef in the North Sea was described geologically and faunistically using non-invasive underwater videos to address the following objectives:

- to establish an appropriate methodology, which allows the analysis of underwater images.
- to evaluate the distribution of seafloor substrata at selected reef stations.
- to identify and quantify the reef fauna.
- to explore relationships between both geological and faunistic variables.
- to classify reef habitats by their faunistic inventory.

2. Materials and methods

2.1. Study area

This study was conducted in the German Exclusive Economic Zone (EEZ) of the North Sea. The German EEZ has a total area of 32982 km^2. About 70% of it is located in the North Sea, whereas the minor fraction of only about 30% is located in the Baltic Sea. In the North Sea, the EEZ extends up to the 200 nautical miles, also referred to as the German part of the continental shelf. The data analysed in this study had been collected at the Sylt Outer Reef, which is located off the Isle of Sylt, in the north-eastern part of the North Sea-EEZ (Figure 1).

The Sylt Outer Reef (SOR) is a nature conservation reserve with an area of 5603 km^2. It is part of the Natura 2000 Network and comprises two areas protected according to the European Habitats Directive (DE1209301, Sylt Outer Reef) and to the European Birds Directive (DE1011401, Eastern German Bight), respectively. Two protected habitat types, “Sandbanks which are slightly covered by sea water all the time” (code 1110) and “Reefs” (code 1170), occur within the area of the Sylt Outer Reef. The formation of these two dominating habitat types of the Sylt Outer Reef is the result of the geological history of the region.

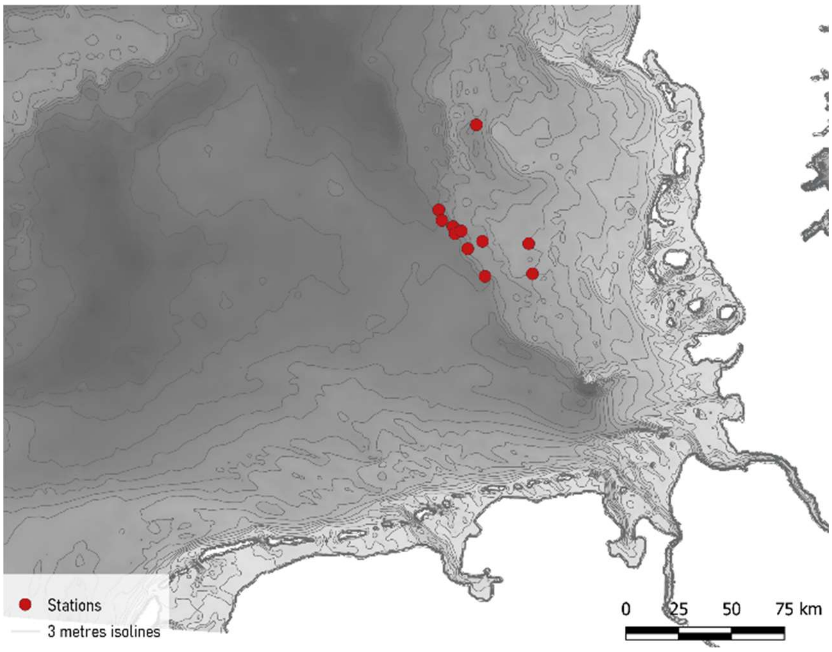

Figure 1. Study area with bathymetric isolines and stations position. The Paleo Elbe Valley can be observed as a darker (deeper) zone.

During the last glacial maximum (about 21,000 BP), the sea level was globally ca. 125 meters lower than present (Diesing & Schwarzer, 2006). Between 11,650 BP and 7,000 BP, the Early Holocene Sea Level Rise (EHSLR) took place, causing a rapid increase in the ocean volume, because of the continued increase in atmospheric temperatures and the resulting deglaciation. After the EHSLR period, the sea level rise continued until present but slowed down by about an order of magnitude (Smith et al., 2011). The southern North Sea is the youngest part of the North Sea, since it was the highest (now shallowest) area and was formed only about 10,000 years ago.

The sediments, which are now found in the study area, were terrestrial in the past. The meltwater from the glaciers of the last Glacial Period flowed in the past into a bigger glacier before entering the sea. This formed the palaeo-valley of the river Elbe, which is nowadays entirely covered by the North Sea. The ancient glacier valleys now form the modern rivers Ems, Weser, Elbe and Eider, which enter directly into the North Sea.

Due to its location in the south-eastern North Sea, the region of the Sylt Outer Reef is characterized by relatively nutrient rich waters. The freshwater inflow from the Elbe River in the south is mixed with the tidal currents of the Northeast Atlantic, entering the North Sea through the English Channel in the southwest. This induces upwelling processes, which supply nutrients and support the nutrition of a huge number of species. The Sylt Outer Reef area is home to various endangered species. For example, it harbours the largest, consistently recorded occurrence of harbour porpoises (*Phocoena phocoena*) in the German North Sea EEZ (Bildstein et al., 2017) and is an important feeding ground for endangered bird species such as the Kittiwake (*Rissa tridactyla*) and the northern fulmar (*Fulmarus glacialis*), which is considerably affected by plastic pollution (Van Franeker et al., 2011). The complete list of species inhabiting in this area permanently or temporarily can be obtained from the Natura 2000 viewer (https://natura2000.eea.europa.eu).

2.2. Underwater videos

The data presented in this thesis were generated from underwater videos, which were taken using a digital camera system during the expedition HE489 of the German research vessel Heincke in June 2017. The videos analysed in this thesis were taken on two sampling days: 10 and 11 of June 2017.

The underwater camera system (Baltic Seafloor Imaging System, BaSIS) was developed by the Leibniz Institute for Baltic Sea Research (abbreviated 'IOW' for the German name "Institut für Ostseeforschung Warnemünde") for operation in the Baltic Sea. It consists of a steel frame equipped with two simultaneously operating cameras, one looking downward and one looking forward (Figure 2). BaSIS was operated vertically below the ship allowing for the positioning of the camera from the ship-based GPS system. The camera system was equipped with four lasers, whereby only three of them were properly working during that expedition. From the distance between the parallel lasers, it is possible to calculate the visible area in each video. The target altitude of BaSIS above the seafloor was 1 m. However, movements of the ship and irregular seafloor morphometry resulted in constant variations in the total area captured. Moreover, at greater height above the seafloor, image quality was severely deteriorated by the amount of interfering particles in the water column, causing backscatter (Beisiegel et al., 2017). The position of the camera above the seafloor was controlled by the winch system of the research vessel.

During the recordings, the vessel was moving at a speed of 0.5 knots. The duration of the recordings varied between 12 and 27 minutes with an average (± SD) duration of 18 ± 4 minutes. The water depths of the video transects ranged from 23.2 m to 41.6 m, with an average depth of 35.6 ± 4.8 m.

The total area captured in still images taken from the videos was about 0.8 m^2 (Beisiegel et al., 2017), but the average final usable area for analysis was 0.47 ± 0.13 m^2 because only the central part of the image was sufficiently illuminated by the BaSIS spotlights.

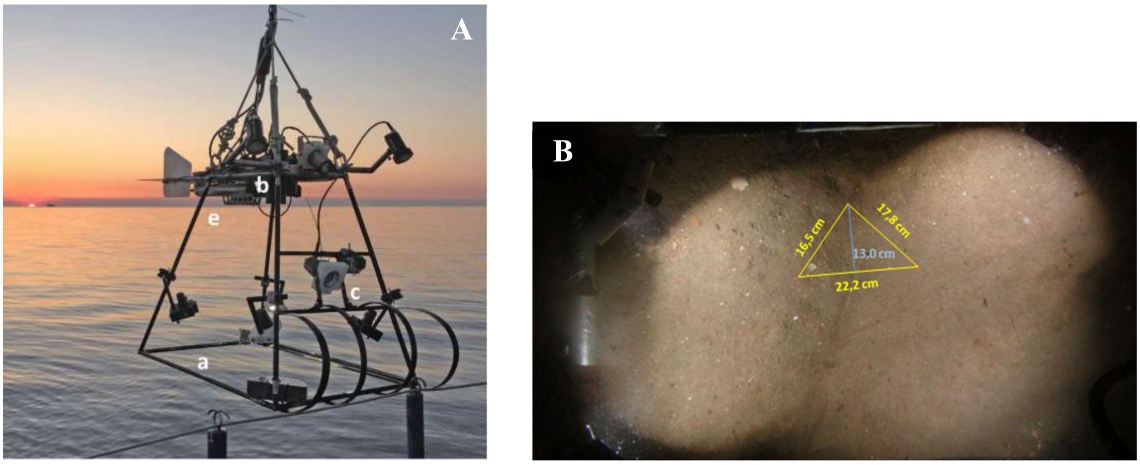

Figure 2. (A) BaSIS underwater camera system, a: steel frame, b: downward-looking camera, c: forward-looking camera, e: CTD for water quality parameters. (B) Sandy seafloor is seen through the down looking camera with the three parallel lasers. Distances between lasers given.

Videos were taken at a total of 11 stations, 10 of them in that part of the area which is protected (8 of them only protected according to the EU Habitats Directive and 2 also in the area, which is protected according to the EU Birds Directive). An additional station (SAR38) was located outside the protected area of the Sylt Outer Reef (Figure 3).

2.3. Image analysis

The forward-looking camera of the system was used only for orientation and not for quantitative assessment of benthic fauna. Accordingly, only videos taken by the downward looking camera were used. The images from the downward looking camera were more constant, the lasers were easily visible and interference with marine snow was minimal.

The videos were analysed using the software package PAPARA(ZZ)I (Marcon & Purser, 2017). The software works only with still images, so that the data had to be processed beforehand in order to generate static images, which can be analysed. For this, screenshots were made of every video. To avoid a handling bias, the screenshots were created automatically using the software Agisoft Metashape Standard (Agisoft LLC, 2020). A homogeneous database was compiled by extracting, from each video, frames at a frequency of 10 seconds. Accordingly, the final file with random screenshots did not discriminate between images showing abundant fauna on rocks and images showing sandy sediments.

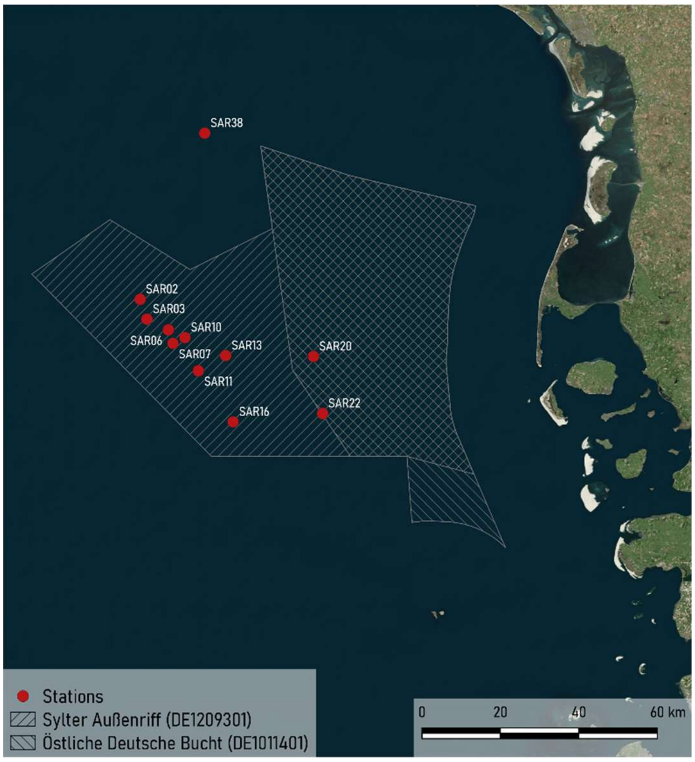

Figure 3. Position of the 11 stations within the marine protected area of the Sylt Outer Reef with the two sections protected according to the EU Habitats Directive and the EU Birds Directive.

This resulted in 74 to 162 images per station, depending on the length of the transect. Prior to image analysis, images were discarded if they were either of poor quality or if the observed surface was identical with the previous frame (because the camera did not move forward between two frames). The selection procedure resulted in an elimination of 54 ± 10 % of the initial images per station, leaving between 23 and 90 photos per station for analysis (an average of 51 images per station).

Before starting to study the images, a list was compiled of the species, which were expected to occur on the videos according to the results from previous video surveys in that region. A text file with the list was uploaded to the PAPARA(ZZ)I interface. During the analysis of the whole set of images, additional species were identified, which had to be added to the default list of species (see Table 2).

To facilitate species identification, a catalogue of the expected species with short descriptions and representative images was compiled beforehand, based on existing species lists from the subtidal reefs of the German North Sea. An abstract of this catalogue can be seen in Appendix 4. All species names were checked for validity in the World Register of Marine Species (WoRMS, date accessed: 27.08.2021). Most species could be identified at the species level, while some species could only be classified at a higher taxonomic level, such as class (e.g., Hydrozoa) or phylum (e.g., Bryozoa). A total of 20 attributes were used to analyse the fauna in the study area.

For the geological characterisation of the habitats, another table of attributes had to be created (Table 1). The seafloor seen at the different stations could be distinguished into three main types of geological structures. Stone is every sediment with a grain size ≥ 6.4 cm, according to Boedeker & Heinicke (2018). Sand generally has a grain size of 0.0625-2 mm, but in this study grain size of sand was not measured. The distinction among sand and lag deposit was done visually, classifying at first the lag deposit, seen as small stones (< 6.4 mm) and assigning the distinctive "sand" to everything smaller than that (Figure 4). The sizes of the geological structures were measured using the "Measure selected feature" function of PAPARA(ZZ)I. For stones, the faunal coverage was annotated, in a further analysis, according to the attributes given in Table 1.

Table 1. Table of attributes for geological characterisation of the habitats.

Stone	Minimum size of 6.4 cm.
Lag deposit	Coarse-grained sediment on abrasion surfaces, which have been formed by the selective abrasion of glacial till.
Sand	Fine-grained sediment.
Covered	Point on taxa covering a stone.
Uncovered	Point on uncovered surface of a stone.

For each image, the usable area was determined and selected with the "Select usable area" function in the PAPARA(ZZ)I interface, because in the images the steel frame of the camera system was visible and had to be excluded so that the calculated areas refer to what was actually seen. All options and functions can be seen in Appendix 2. The area was measured using the scale bar ("Draw scale bar" function) and the actual area was calculated from the known distance between the lasers as reference (see Figure 2B). Noting that the triangle formed by the lasers is not equilateral, always the same two points (upper and left one, with a distance of 16.5 cm) were used, so that the distance in the interface did not need to be changed between images. Subsequently, 100 grid points were laid over the selected area, using the option "Grid (100 Points)" in the "Generate points" function. To each grid point an attribute from the list was assigned, according to the species and sediment type hit by the point. Finally, the percentage coverage was calculated for each attribute as the fraction of grid points assigned to the attributes. Each grid point was defined by a faunistic and a sediment attribute to specify whether the identified organism was associated with a stone, with lag deposit or with sand. The option of PAPARA(ZZ)I for measuring the size of attributes was used to measure every potential stone to really confirm it as a stone (≥ 6.4 cm). The stone size provides additional habitat information, which can be useful in explaining the observed faunal community structure.

The annotations were downloaded as an excel file, which allowed for an easy identification of stones for re-analysis. The selected subset of images with stones was analysed again in PAPARA(ZZ)I for a more highly resolved estimation of the biotic coverage of each stone, using 25 grid points over the usable area of the stone. This time, each point was annotated as covered or uncovered, and assigned to the taxon by which it

Figure 4. Common substrate types on the seafloor of Sylt Outer Reef seen at the seafloor. 1: sand, 2: lag deposit and 3: stone (colonised by an actinia). Distance between lasers (16.5 cm) marked with red line.

was covered (using the attributes from Table 1). This output provided information for each station regarding the number of stones covered, the average percentage coverage of each stone and the colonization of the stones by different epifaunal organism.

Henceforth the data obtained from the 100 grid points will be the “Biotope data”, whereas the other data, from the 25 grid points and describing the stones will be the “Stone data”.

2.4. Descriptive and statistical analysis

The data were analysed using different software packages: Microsoft Excel, R Commander Version 2.7-1 (Fox & Bouchet-Valat, 2020), PRIMER v6 (Clarke & Gorley, 2006) and QGIS (version 3.18.2-Zürich).

Microsoft Excel was used to manage the PAPARA(ZZ)I output data. Every station was initially analysed independently. Subsequently, the data from all stations had to be combined in two larger data frames. All outputs for the Biotope data resulted in a table with 732 rows (each row represents the presence of a taxa in a screenshot) and 17 columns characterising every screenshot. The attributes of each entry were: station name, real time when the image was taken, time within the video, the screenshot number at station, the image file name, width and height of the usable area of the screenshot and the resulting usable area, taxon, higher taxonomic group, percentage coverage of the taxon, percentage coverage of sand/lag deposit/stones, latitude and longitude and the exact water depth where the image was taken.

For the Stone data, a similar data frame was created. In this case, there were only 316 rows, representing the presence of an organism covering a stone. The attributes for each entry were station name, real time when the image was taken, time within the video, the screenshot number at station, the image file name, the measured maximum length of the stones in metres and centimetres, the usable area in which the 25 grid points were overlaid, the taxon covering the stone, how many of these points were covered, uncovered, or placed on sediment, and a total degree of coverage.

For each station, the taxa were quantified according to their frequency of occurrence (%), which was calculated as the number of images on which a taxon occurred divided by the total number of images analysed for that station.

Various types of figures were prepared using Microsoft Excel: stacked columns for habitats, species-area curves and X-Y dispersions. Linear regression analysis was used to study the relationship between the percentage cover of each sediment and the number of taxa and between the sizes of stones and the number of taxa. Linear regression lines were described by the following equation:

$$Y = \beta X + \varepsilon$$

Y being the response variable (number of taxa), β the slope, X the independent variable and ε the y-intercept.

R commander is a graphical user interface (GUI) for the R programming language that enable the R tasks through menus. Apart from being a statistics programme, it is a strong tool for diverse plotting. All box plots and the plot showing the occurrence of stones along the videos were prepared with this programme.

PRIMER (Plymouth Routines In Multivariate Ecological Research) is a statistical software used for ecological community analysis. Cluster analysis, univariate community descriptors indexes and species-area curves were obtained with PRIMER.

The cluster analysis for comparison of species communities between stations were based on Bray-Curtis dissimilarity:

$$BC_{ij} = 1 - \frac{2C_{ij}}{S_i + S_j}$$

where C_{ij} is the sum of the lower quantity of the species present in both sites. S_i and S_j are the total numbers of species counted in sites *i* and *j,* respectively. Quantities of the species were the frequencies of occurrence.

Pielou's evenness and Shannon's diversity were calculated for each station based on the frequencies of occurrence. Shannon's diversity index takes into account absolute quantity but also the relative quantities (evenness) of the species, i.e. the proportion of species (*i*) relative to the total quantity of species (*Pi*).

Shannon's diversity index was calculated as:

$$H' = -\sum_{i=1}^{S} (P_i * \ln(P_i))$$

with the lower limit of 0 and the upper limit of $H'_{max}=S*ln(S)$ for each station. Shannon's diversity index increases with richness and evenness, so stations with higher H' values have a higher diversity.

Pielou's evenness is derived from Shannon's diversity index and refers to how equal a community is numerically. It was calculated as:

$$J' = \frac{H'}{\ln(S)}$$

having a value of 1 when all species are equally abundant.

The video transects were of different lengths. Moreover, different numbers of images have been analysed for the different stations. The number of species identified in an assemblage is directly dependent on the sampling effort, i.e. the number of images analysed. Accordingly, the number of species at the different stations might not be directly comparable. Since a considerable number of images was analysed at each station, it was likely that the species assemblages were covered entirely at each station. This was visualized by species accumulation curves that show how the number of species recorded increased with the number of images analysed, until reaching the maximum number of taxa per station (where an extra image gives no more information). The species-area curves allow to determine if the amount of images analysed was sufficient to properly comprise the communities (see Appendix 3). They were generated with the PRIMER software for each station from 999 random permutations of the single images counting the observations of taxa (S_{obs}) until the total number of taxa per station was reached. PRIMER provided the data (S_{obs}), and the curves itself were created with Excel.

All maps were created using QGIS (version 3.18.2-Zürich).

3. Results

3.1. Geological and sedimentological characterisation of the stations

The proportions of sand, lag deposit and stones varied between the stations (Figure 5). At all stations, sandy sediment was the major constituent of the seafloor habitat, followed by lag deposit. Only small fractions of the seafloor were covered by stones. The contributions of the different substratum types varied between 49.32 and 99.78 % for sand (mean ± SD: 78.42 ± 15.06 %), 0.22 to 48.34 % for lag deposit (21.12 ± 14.65 %), and 0.00 to 2.33 % for stones (0.46 ± 0.68 %). The proportion of sand was highest at station SAR 22, where the seafloor consisted of sandy sediment only. Similarly, at station SAR 06, the seafloor consisted almost entirely of sandy sediment with only minor fractions of lag deposit and stones. The contribution of lag deposit to the total seafloor structure was highest at stations SAR 13 (48.34 %) and SAR 10 (44.26 %), but only very low at stations SAR 22 (0.22 %) and SAR 06 (2.46 %). The contribution of stones was highest at stations SAR 13 (2.33 %) and SAR 03 (0.94 %). No stones were encountered at stations SAR 22 and SAR 38.

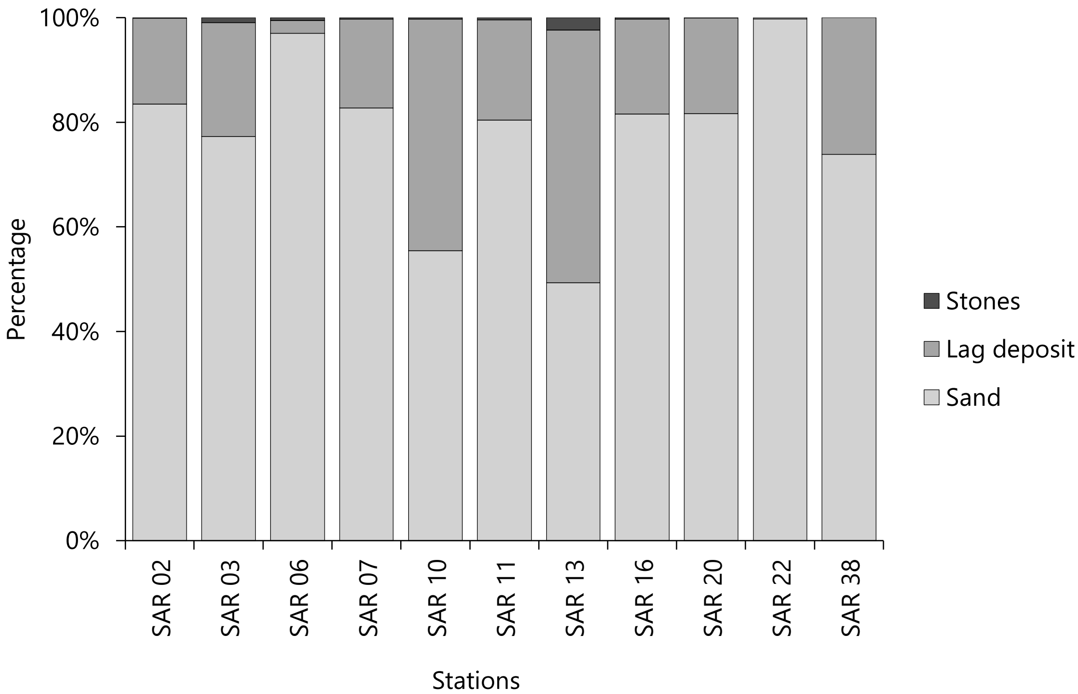

Figure 5. Proportion of sand, lag deposit and stones at the 11 stations in the Sylt Outer Reef, calculated as the mean percentage in each screenshot.

The stones were mostly irregularly distributed along the stations (Figure 6). According to the overall dominance of the sandy seafloor, extensive stretches of sand were interrupted by the occasional occurrence of stones. Stones occurred individually or in aggregates of up to 13 stones, as observed in station SAR 13. Similarly, aggregations of 2, 3 or 4 stones were commonly found. However, in stations SAR 02 and SAR 20, stones occurred only individually. Stones occurred at an average density of 2.41 ± 2.32 stones per image.

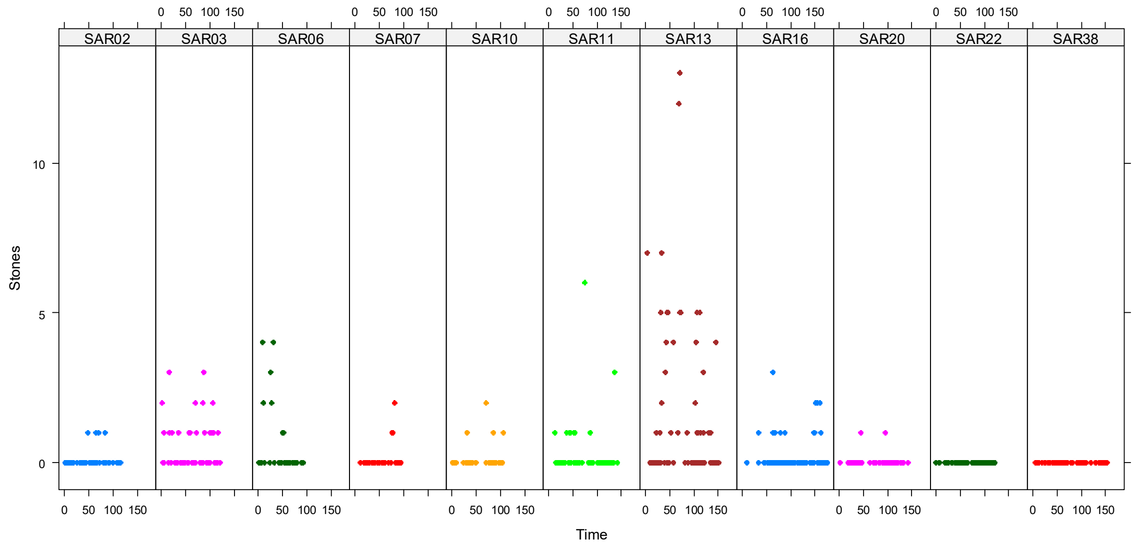

Figure 33. Occurrences of stones in videos taken of the seafloor at stations in the Sylt Outer Reef. Stations SAR 22 and SAR 38 did not have stones. Time in X axis as intervals of 10 seconds in the video. Beware of the different lengths of the transects.

The size of stones varied considerably within and between the stations (see Figure 7). The largest stones were observed on stations SAR 16 (58.86 cm) and SAR 03 (52.52 cm). The median stone size was highest on stations SAR 11 (median size: 22.87 cm) and SAR 03 (median size: 17.21 cm) and lowest on stations SAR 20 (median size: 7.12 cm) and SAR 02 (median size: 9.61 cm). The average (± SD) stone size over all stations was 15.75 ± 10.34 cm.

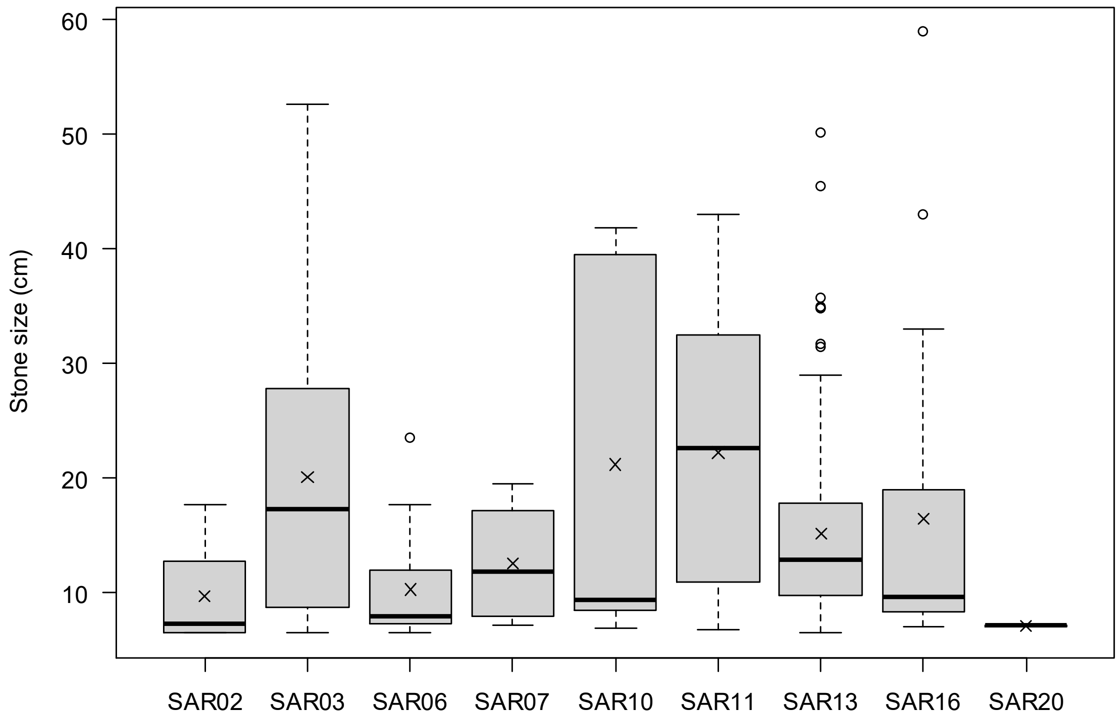

Figure 741. Stone sizes at stations of the Sylt Outer Reef. Stations SAR 22 and SAR 38 had no stones and are, therefore, not displayed. Medians are given as black lines, mean as crosses; boxes give the interquartile range, whiskers display 1.5 interquartile ranges; outliers are given as open dots.

3.2. Faunistic description

In total, 20 taxa (mostly species) from 9 higher taxonomic groups were identified on videos from the Sylt Outer Reef (Table 2). For each station, sufficient images were analysed to fully assess the entire spectrum of species that could be expected. The species area curves for all stations displayed the common initial increase. After variable number of images, all species were recorded and no further increase in species numbers was observed even when considerable numbers of additional images were analysed (Appendix 3). To identify all species at the stations, an average analysis of 18.45 ± 18.12 images (between 1 and 53 images) would have been sufficient. However, between 23 and 90 were actually analysed (an average of 51.18 ± 18.66 images per station). Accordingly, the species numbers from the different stations could be directly contrasted with each other in the following analyses.

The number of species varied between the stations, from 1 at station SAR 20 to 14 at station SAR 13. The most common species were the starfish *Asterias rubens*, which occurred at 10 out of 11 stations, and the Hydrozoa, which occurred at 9 out of 11 stations. The species with the highest frequency of occurrence within a single video was the polychaete *Spirobranchus triqueter*, which was encountered on 65.22 % of all images of

Table 2. List of all observed fauna, classified at the highest possible taxonomic level, as well as quantity of species per station, counted as the percentage of images in which each species was identified. Average percentage and standard deviation for each species in the different stations. Total images, total species, Pielou's evenness and Shannon's diversity indexes for each station.

Higher taxonomic group	**Taxa**	**SAR 02**	**SAR 03**	**SAR 06**	**SAR 07**	**SAR 10**	**SAR 11**	**SAR 13**	**SAR 16**	**SAR 20**	**SAR 22**	**SAR 38**	**Number of stations present**	**Average ± SD**
Porifera	encrusting sponge	0	0	0	0	0	3.03	1.45	0	0	0	0	2	0.40 ± 0.97
	Halichondria panicea	0	0	2.70	0	0	1.52	1.45	0	0	0	0	3	0.51 ± 0.93
Cnidaria	*Alcyonium digitatum*	0	18.52	2.70	8.70	3.13	9.09	4.35	1.11	0	0	0	7	4.32 ± 5.76
	Hydrozoa	4.00	35.19	8.11	13.04	15.63	13.64	8.70	26.67	0	0	1.96	9	11.50 ± 11.10
	Metridium senile	0	1.85	0	0	3.13	1.52	10.14	3.33	0	0	0	5	1.81 ± 3.05
	Urticina felina	0	24.07	2.70	0	9.38	9.09	40.58	8.89	0	0	0	6	8.61 ± 12.90
Crustacea decapoda	*Cancer pagurus*	0	1.85	0	0	3.13	1.52	4.35	0	0	0	0	4	0.98 ± 1.53
	Liocarcinus sp.	0	0	0	0	0	1.52	2.90	0	0	0	0	2	0.40 ± 0.94
	Pagurus bernhardus	0	0	0	0	0	0	0.00	1.11	2.17	0	0	2	0.29 ± 0.70
Annelida	*Spirobranchus triqueter*	2.00	12.96	5.41	0	0	0	65.22	3.33	0	0	1.96	6	8.26 ± 19.20
Bryozoa	Bryozoa indet.	0	3.70	0	0	0	0	0	0	0	0	0	1	0.33 ± 1.11
	Flustra foliacea	0	3.70	0	0	3.13	3.03	1.45	5.56	0	0	0	5	1.53 ± 1.99
Mollusca	*Aporrhais pespelecani*	2.00	0	0	4.35	0	0	0	0	0	0	0	2	0.57 ± 1.38
	Buccinum undatum	0	0	0	0	0	0	1.45	0	0	0	0	1	0.13 ± 0.43
Echinodermata	*Asterias rubens*	14.00	25.93	2.70	4.35	6.25	1.52	20.29	14.44	0	2.22	7.84	10	9.04 ± 8.49
	Astropecten irregularis	0	0	0	0	0	0	0	1.11	0	2.22	0	2	0.30 ± 0.71
	Echinus esculentus	0	0	0	0	0	0	7.25	0	0	0	0	1	0.65 ± 2.18
Tunicata	*Ascidiella aspersa*	20.00	7.41	2.70	8.70	0	0	7.25	16.67	0	0	1.96	7	5.87 ± 7.01
Vertebrata	*Agonus cataphractus*	0	0	0	0	3.13	1.52	0	0	0	0	0	2	0.42 ± 1.00
	Pleuronectes platessa	0	0	0	0	0	0	0	0	0	0	1.96	1	0.17 ± 0.59
	Total images	50	54	37	23	32	66	69	90	46	45	51		
	Total species (S)	5	10	7	5	8	11	14	10	1	2	5		
	Pielou's evenness (J')	0.77	0.84	0.94	0.95	0.89	0.84	0.73	0.80	-	1.00	0.86		
	Shannon's diversity (H')	1.23	1.95	1.83	1.52	1.86	2.01	1.94	1.85	0	0.69	1.39		

station SAR 13. Considerable frequencies of occurrence were also reached by the actinia *Urticina felina* (40.58 % at station SAR 13), the undetermined hydrozoans (35.19 % at station SAR 03), and *A. rubens* (25.93 % at station SAR 03). Rare taxa, occurring only on single stations, were plaice *Pleuronectes platessa* (1.96 % at station SAR 38), the sea urchin *Echinus esculentus* (7.25 % at station SAR 13), the dog whelk *Buccinum undatum* (1.45 % at station SAR 13), and the undetermined bryozoans (3.70% at station SAR 03). Characteristically, overall occurrences of species were highest on stations with the highest amounts of lag deposit and stones.

The Shannon-Wiener diversity varied between 0.69 at station SAR 22, which had only a single species, to 2.01 at station SAR 11. Among the stations with more than a single species, Pielou's evenness was highest at station SAR 22 (1) and lowest at station SAR 13 (0.73). The low evenness at SAR 13 was explained by the strong dominance of the faunal assemblage by *S. triqueter* and *U. felina*, which had their highest frequencies of occurrence at this station. For most species, the standard deviation was considerably higher than the average frequency of occurrence, demonstrating the very heterogeneous distribution of the species with high occurrence at only very few stations and relatively low occurrence or absence at most of the other stations.

Three different clusters of species assemblages were identified (Figure 8A). At a similarity of 0.26 %, SAR 20 separated from all other clusters, whereas station SAR 22 separated from the third cluster at a similarity of 9.31 %. The third cluster comprised all other stations, which were split into sub-clusters at different levels of similarity but could not be distinguished statistically (Clarke & Gorley, 2006).

The stations of the third cluster were mostly situated close to each other along the edge of the Paleo Elbe Valley (Figure 8B). Additionally, station SAR 38, which was spatially separated from the other stations, was assigned to the third cluster according to the composition of the benthic assemblage. Stations SAR 20 and SAR 22 were situated away from the edge of the valley and were well distinguishable from the other stations with regard the composition of the benthic assemblages.

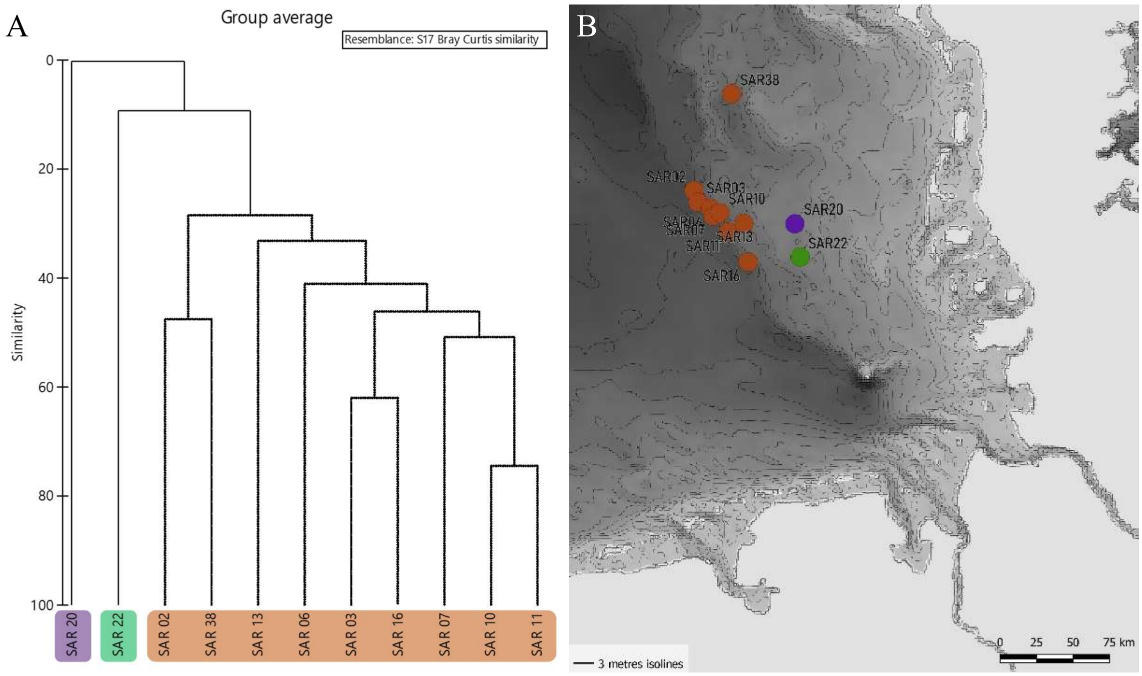

Figure 8. (A) Cluster dendrogram displaying similarity between clusters of species assemblages from the different stations at the Sylt Outer Reef based on frequencies of occurrence. Clusters that share the same colour are statistically not distinguishable from each other. (B) Map showing the distribution of the stations from different benthic assemblage clusters within the area of investigation. Stations from different clusters are given in different colours according to the dendrogram in panel (A).

The number of taxa found at the stations depended on the habitat structure. The number of taxa declined with an increasing amount of the seafloor covered by sand (Figure 9 Sand). The linear regression model explained 34 % of the variation in the data. According to the linear equation, the number of taxa declined by 0.15 taxa for each percent increase in sand cover. The situation was reverse for lag deposit and stones. For both substratum types the number of taxa increased with increasing cover of the seafloor (Figure 9 Lag deposit and Stones). The coefficients of variation varied between 0.31 for lag deposit and 0.57 for stones.

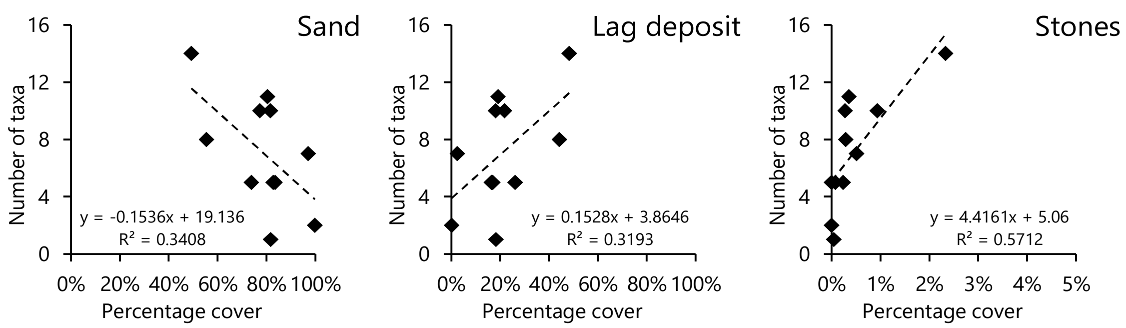

Figure 9. Relation between the cover of the seafloor by sand (left), lag deposit (centre) and stones (right) and the number of epifaunal taxa. Each point represents a station.

The percentage cover of the stones varied considerably within and between the stations (Figure 10). At most of the stations, the cover of the stones ranged from 0% to 100%, but the average cover was very different between the stations. At stations SAR 11 (55.77 %), SAR 07 (44.12 %) and SAR 03 (44.05 %) the average cover of the stones was highest, while the average coverage of the stones was lowest at stations SAR 20 (0.00 %) and SAR 02 (13.89 %).

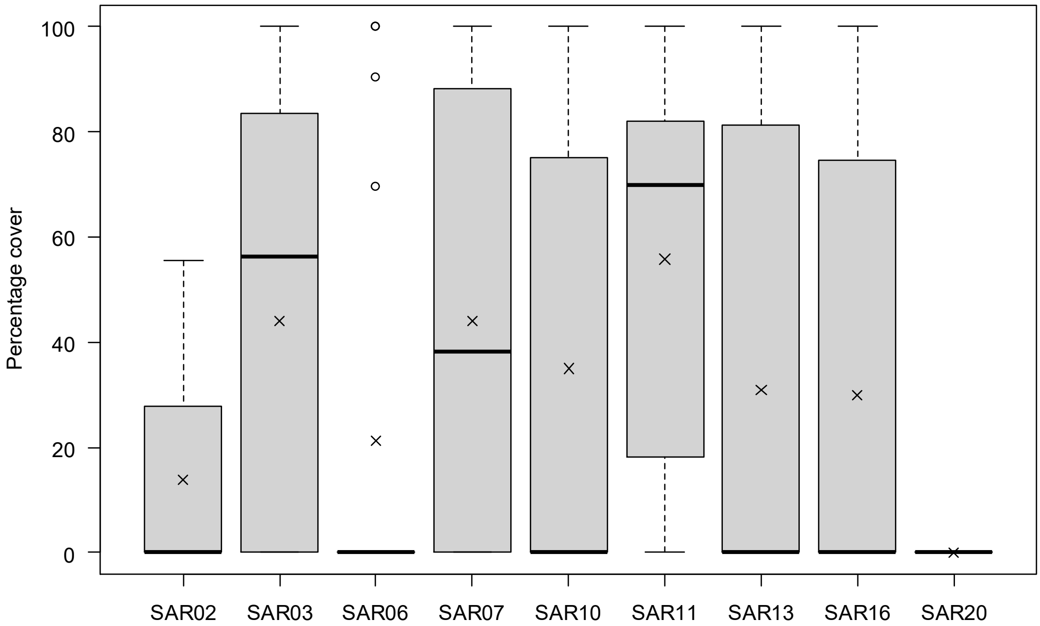

Figure 10. Percentages cover of stones at different stations at Sylt Outer Reef. Stations SAR 22 and SAR 38 are not displayed, because no stones were recorded. Medians are given as black lines, mean as crosses; boxes give the interquartile range, whiskers display 1.5 interquartile ranges; outliers are given as open dots.

The percentage cover varied considerably for stones of all sizes (Figure 11A). Numerous stones of all sizes were covered by 100 %. Similarly, a considerable number of stones was not covered at all (0 %). Characteristically, these were only smaller stones up to a maximum size of 21.57 cm demonstrating that only small stones were entirely uncolonized.

The number of taxa increased with the stone size but varied considerably among stones of similar size and of different size (Figure 11B). According to the linear function, the number of taxa increased by about 0.1 taxon per cm stone size. The linear regression model explained 56 % of the variation in the data. Similar as for the percentage cover, only small stones were not colonized. The highest number of taxa per stone was 5, which was counted on two stones with sizes of 38.68 cm and 58.86 cm.

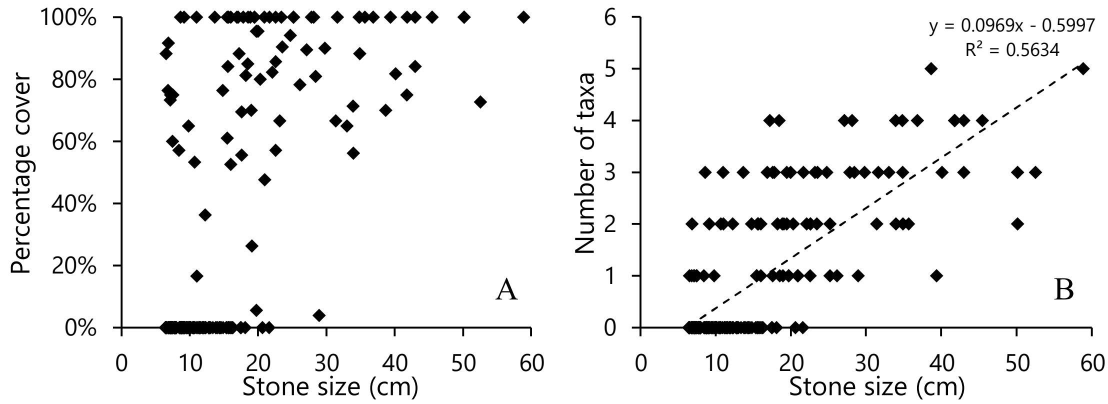

Figure 11. Percentage cover (A) and number of taxa (B) as functions of stone size.

4. Discussion

The video material analysed in this study allowed for the characterisation of seafloor habitats in the reef areas of the Sylt Outer Reef in the German North Sea. The seafloor was dominated by extensive stretches of sandy sediment occasionally interspersed by lag deposit or stones (either individually or in aggregates). The benthic epifauna varied among the stations along with the sedimentological characteristics. The fauna comprised primarily sessile species, which need hard substrates to live on. Accordingly, most organisms were recorded in areas with elevated stone cover. In total, three different clusters of the epibenthic fauna could be distinguished. Although only a relatively small fraction of the benthic fauna can be captured by optical methods, the data generated by this method allowed for a differentiated description of the benthic habitats of the reef areas of the Sylt Outer Reef.

4.1. Geological and sedimentological characterisation of the stations

With an average (± SD) percentage value of 78.42 ± 15.06 %, sand was the most common substratum type at all stations of the Sylt Outer Reef, followed by lag deposit and stones. Michaelis et al. (2019), who investigated several reef areas in the German North Sea, distinguish three spatial distribution patterns regarding the density of stones: solitary, mixed and full coverage. Although all three types were present in the Sylt Outer Reef, the mixed distribution was the most common pattern in this study as well as in Michaelis et al. (2019).

Lag deposit is a result of the loss and deposition of coarser particles during transport (Scott & Pain, 2009). It is left behind after finer particles have been removed by weathering. Lag deposit is a coarse-grained residue that can be angular to rounded in shape. According to Diesing & Schwarzer (2006), lag deposit is the most commonly found sediment type in the Darss Sill in the German Baltic Sea. Within the Sylt Outer Reef, Papenmeier et al. (2020) reported on the presence of lag deposit in the eastern portion of the Paleo Elbe Valley. This result matches with the cluster analysis made in this study, where all stations with elevated densities of lag deposit were also located at the edge of the Paleo Elbe Valley.

Stones were rare at all stations (Table 3) but varied considerably in sizes from the lower limit of 6.4 cm up to sizes of almost 60 cm in diameter. The average stone size was 15.10 ± 5.71 cm. Michaelis et al. (2019) classified the stones of the Sylt Outer Reef as cobbles (6-20 cm), boulders (20-63 cm) and large boulders (> 63 cm). Although this classification was not adopted in this study, similar results were obtained, with stones corresponding to the category of "cobbles" being the most common size class.

The stone density also varied within the Sylt Outer Reef. Stations along the edge of the Paleo Elbe Valley had a higher concentration of geogenic reef structures than those stations located closer to the shore (SAR 20 and SAR 22) or outside the protected area (SAR 38). Similarly, Boedeker & Heinicke (2018) describe the highest density of reef

Table 3. Summary of some analyses. For each station, total taxa found and percentage of substrate types, as well as average sizes, percentages cover and taxa for the stones.

	Habitats				Stones		
Station	**Taxa**	**Sand (%)**	**Lag deposit (%)**	**Stones (%)**	**Size (cm)**	**Cover (%)**	**Taxa**
SAR 02	5	83.45	16.47	0.08	9.61	13.89	0.25
SAR 03	10	77.31	21.76	0.94	20.02	44.05	1.63
SAR 06	7	97.02	2.46	0.51	10.25	21.18	0.65
SAR 07	5	82.76	17.00	0.24	12.52	44.12	1.00
SAR 10	8	55.45	44.26	0.29	21.16	35.00	1.00
SAR 11	11	80.44	19.20	0.35	23.72	55.77	2.10
SAR 13	14	49.32	48.34	2.33	15.07	30.97	0.72
SAR 16	10	81.60	18.13	0.27	16.42	29.96	1.00
SAR 20	1	81.65	18.30	0.04	7.12	0.00	0.00
SAR 22	2	99.78	0.22	0.00	-	-	-
SAR 38	5	73.88	26.12	0.00	-	-	-
Average	7.09	78.42	21.12	0.46	15.10	30.55	0.93
SD	3.96	15.06	14.65	0.68	5.71	17.03	0.64

structures at the Sylt Outer Reef at the edge of the paleo river valley and clearly fewer reef structures in other sections of the protected area.

Reef is a very broad term and, therefore, huge differences exist between reefs from different marine regions. The main distinction relates to the formation of the reef, which can be either biogenic (i.e., coral reefs) or geogenic (i.e., rocky reefs). Coral reefs are composed of live corals on top of an extensive fundament of calcareous skeletons of dead coral, which mostly need warm waters for formation but may also occur in cold waters (Nakamura & Nakamori, 2007). In temperate regions, rocky reefs are the most prevalent reef type. They are formed as a consequence of erosion of bedrock induced by submergence due to sea level rise and wave action (Msangameno, 2016). The formation of the Sylt Outer Reef, however, is related to moraine sediment deposition at the edges of the Paleo Elbe Valley (Schwarzer et al., 2019). It is thus characteristic for the shallow sediment-dominated basin of the southern North Sea, which have been formed after the most recent glacial period.

4.2. Faunistic description

Optical methods, such as underwater videos, can only capture larger organisms living on the surface of the seafloor, while small organisms as well as the benthic infauna remain largely undetected. Michaelis et al. (2019) found a total of 27 taxa at Sylt Outer Reef. Taking into account the difference in the amount of analysed images (930 images vs. 563 images analysed herein), a considerable fraction of species spectrum was identified also in this study. Ganz et al. (2017) encountered 19 taxa in a study of 13 stations of the Sylt Outer Reef. However, the focus of that study was primarily on sandy sediments and less on reefs. At Borkum Reef Ground in the SE German Bight, a total of 193 taxa were observed, using a combination of four techniques: box corer, airlift sampler, divers and a camera system (Coolen et al., 2015). Accordingly, that study considered also the infauna and smaller organisms of the epifauna, which cannot be detected with images taken by a towed underwater camera. A more extensive study applying different methods would probably have resulted in a bigger faunal spectrum at the Sylt Outer Reef.

Not all species were found at each station resulting in a spatial structuring of the benthic fauna. Using the frequency of occurrence of the taxa as quantitative measure, the stations SAR 20 and SAR 22 were distinguished from all other stations by a cluster analysis with regard to the composition of the benthic assemblage composition. However, the station SAR 38 was included in the cluster comprising all typical reef stations although it was spatially isolated and located at considerable distance from the edge of the Paleo Elbe Valley. Regarding its geological characteristics, station SAR 38 was more similar to the stations SAR 20 and SAR 22 (Table 3). However, its faunal composition rather characterises the station as a reef station indicating nearby reef structures that may have been missed by the towed video system, which captures only small sections of the seafloor.

4.3. Relationship between geologic structure and fauna

Stations with higher percentage of stones or lag deposit (SAR 13, SAR 11, SAR 03) characteristically showed the highest species richness. The presence of this substratum types in addition to sand increases the structural complexity of the habitat, providing diverse micro-habitats for a higher number of taxa than a comparatively simply structured sandy sediment surface (Tokeshi & Arakaki, 2012). The percentages coverage of the three different sediment types are directly complementary, i.e., an increase in percentage coverage of one sediment type occurs at the expense of the other. Similarly, stones can be placed either on sand or lag deposit, but they cover the underlying sediment. Most species were sessile and need hard substrate to settle on. Consequently, the number of epifaunal taxa increases when the percentage of the poorly colonized sand areas decreases as a consequence of elevated coverage of lag deposit or stones. Contrarily, the number of taxa decreased when the percentage of sand cover increased, which does not provide habitat for numerous epifaunal species. Accordingly, the almost complete lack of seafloor structures on the sandy sediments most likely explains the low species richness at stations SAR 20 and SAR 22, and their compositional distinction from the reef stations.

There was a positive relationship between both the percentage coverage of the sessile epifauna as well as the number of species and the size of the stones. Small stones may be less occupied by organisms because they are less stable than large stones. Occasional or frequent overturning of small stones induced by bottom-near currents may prevent the persistent establishment of species and may particularly affect organisms sensitive to mechanical forcing. Additionally, bottom-near transport of sand or shells may induce abrasion in the lower parts of the stones and may, thus, create a vertical boundary for colonization (Michaelis 2019). This will particularly affect the colonization of small stones whereas large stones may provide stable and undisturbed space for colonization also for mechanically sensitive species above the boundary zone. A linear regression model was used to describe the relationship between stone size and number of taxa covering the stones. The model explained about 56 % of the variation in the data. Fritsch (2017) fitted a logarithmic model to the relationship between these two variables for stones in the same region. Overall, the scatter in data was considerable and further investigations are needed to properly understand the relationship. Both models, however, consistently demonstrate the positive relationship between stone size and species richness of the colonizing epifauna.

Most sessile species, like the polychaete *Spirobranchus triqueter*, need hard substrate to settle on. Accordingly, this species was only found on stones and lag deposit irrespective of the substrate size. This annelid can even live on small stones that sometimes remain buried with sand. Apparently, the calcareous tube allows the species to withstand abrasion and temporary burial. Mobile species, such as sea stars, fishes and crustaceans were found on all types of substrates. Accordingly, these species are generalists with regard to habitat use. For example, the sea star *Asterias rubens* is very adaptive regarding its diet, allowing the species to exploit food resources in a wide range of habitats (Anger et al., 1977), including both sandy and rocky seafloor areas.

4.4. Methodology

The reef structure of the Sylt Outer Reef was described using underwater videos recorded with the help of a towed downfacing camera. This methodology implies some problems, which do not allow a comprehensive assessment of benthic ecosystems. First, videos provide only a 2-dimensional view of the seafloor resulting in a loss of information. Percentage cover can only be determined for organisms which are actually seen from above. However, organisms covered by other organisms remain undetected and are, thus, underestimated. Moreover, only the upper part of the stones and lag deposit was recorded, so that boarders of stones as well as vertical structures remain largely unexplored.

In the North Sea, the assessment of the benthic environment is also hampered by rough weather conditions, when high quantities of suspended sediment or organic matter affect the underwater visibility. Accordingly, only large organisms (megafauna) are identified and recorded at high reliability and with sufficient taxonomic resolution. Generally, however, low taxonomic resolution of the method leads to an underestimation of the diversity.

The methodology used for analysis was determined considering the type of data available. From each transect video, screenshots every 10 seconds were extracted. Not all screenshots made were later used, around half of them were discarded because of low quality or replication of information. In all these procedures, a considerable loss of information occurs, which could have been bridged by improving the camera quality or by using a system which allows video analysis. Nevertheless, the methodology used was easy and quick to learn, so not much time was spent in knowing how to run the analytical part of this study. For the same areas of study, other authors like Fritsch (2017) and Ganz et al. (2017) did not use a Marine Image Annotation Software (MIAS), what would have probably sped up the progress.

Apart from these disadvantages, imagery analysis is a non-invasive technique that allows the study of seafloor communities. It is an alternative to invasive methods like grab sampling, dredging, etc. especially in highly structured and sensitive habitats such as subtidal reefs. This is an important point, which has to be taken into account given the progressive degradation of reefs and marine ecosystems in general. Despite some methodological difficulties, it was able to describe and characterise all stations in the reef area geologically and faunistically, increasing the existing knowledge of reef habitats in the North Sea.

5. Conclusions

Underwater videos were successfully used to generate qualitative and quantitative data on the structure of the reef system of the Sylt Outer Reef and its faunal inventory. Different benthic habitats could be classified geologically and faunistically using descriptive and statistical analysis.

Sand was identified as the most common substrate. However, sandy substrata showed the lowest epifaunal species richness. Stones were only rare in the study area but provided settlement space for numerous species so that stones were the most species-rich habitat type. Hydrozoans was the most common epifaunal taxon, mostly covering stones and lag deposit. Similarly, *Asterias rubens* and *Urticina felina* were common, with the starfish being found on both stones and sand. Direct relationships were identified between the quantity of stones or lag deposit and the number of taxa, as well as between the number of taxa on stones and the stone size.

Although rocky reef structures found in the North Sea are not as species rich as biogenic reefs (e.g., coral reefs in tropical environments), they harbour different animal associations.

Methods like non-invasive underwater videos can be used to characterise and monitor these habitats, providing an important tool for their protection.

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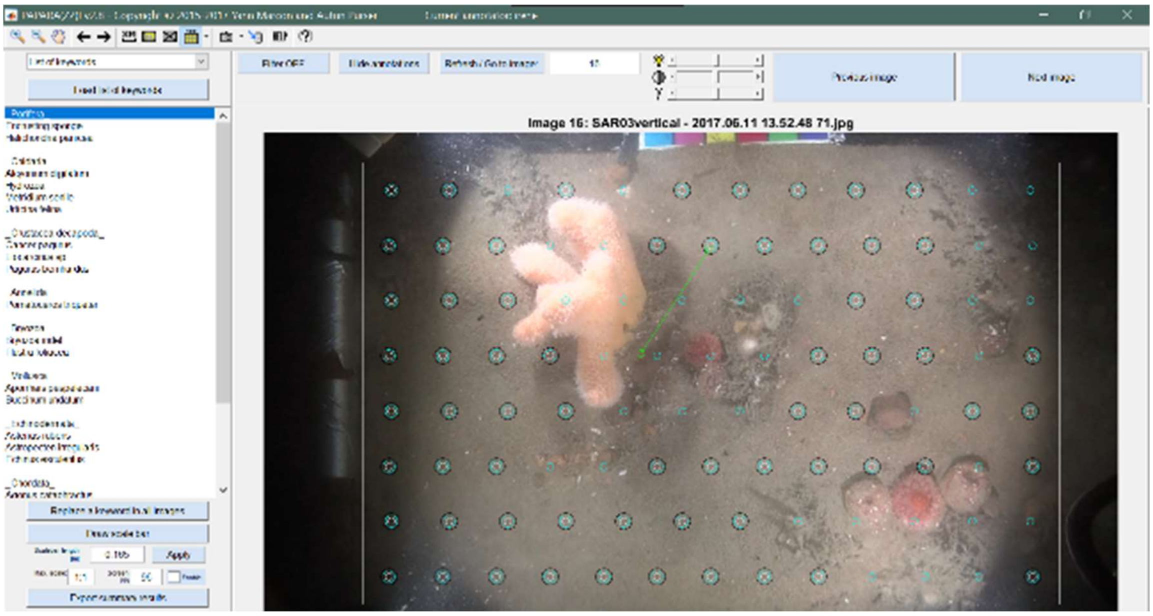
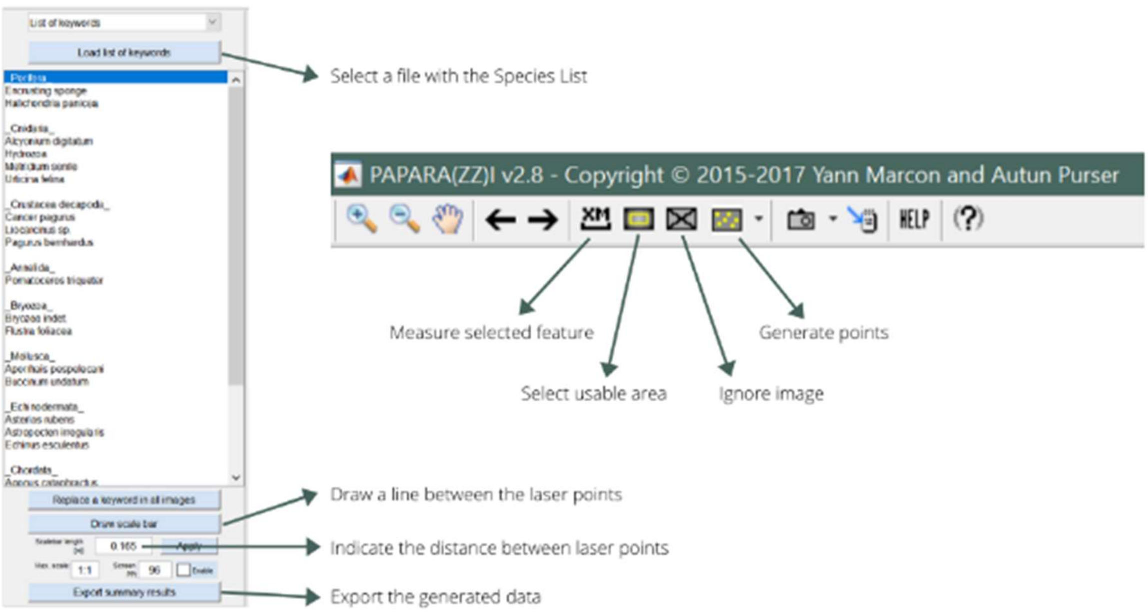
APPENDICES

Appendix 1. PAPARA(ZZ)I interface. A: general overview of the interface, with an example of screenshot and 100 points overlaid. B: detail of the functions for analysis.

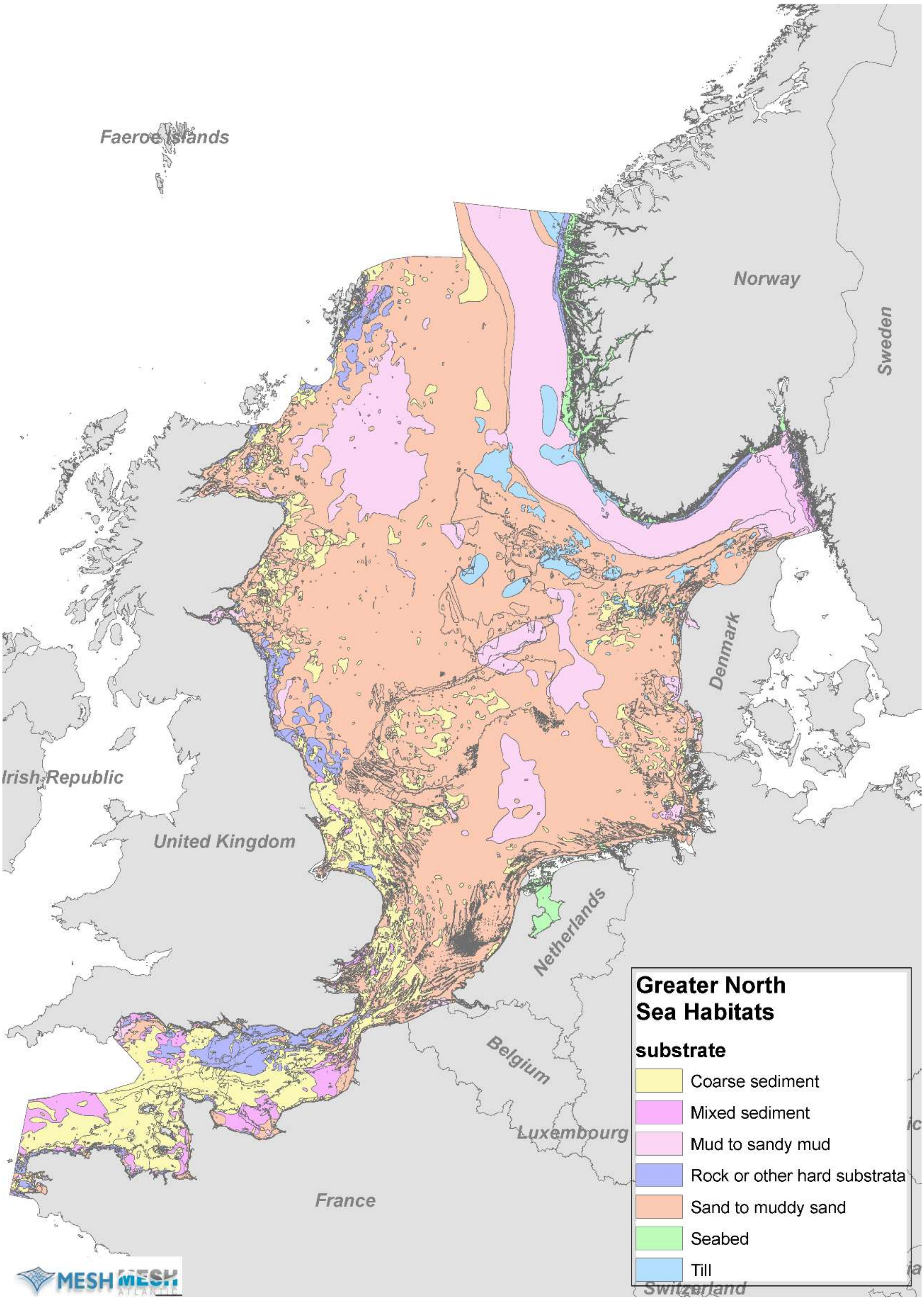
A



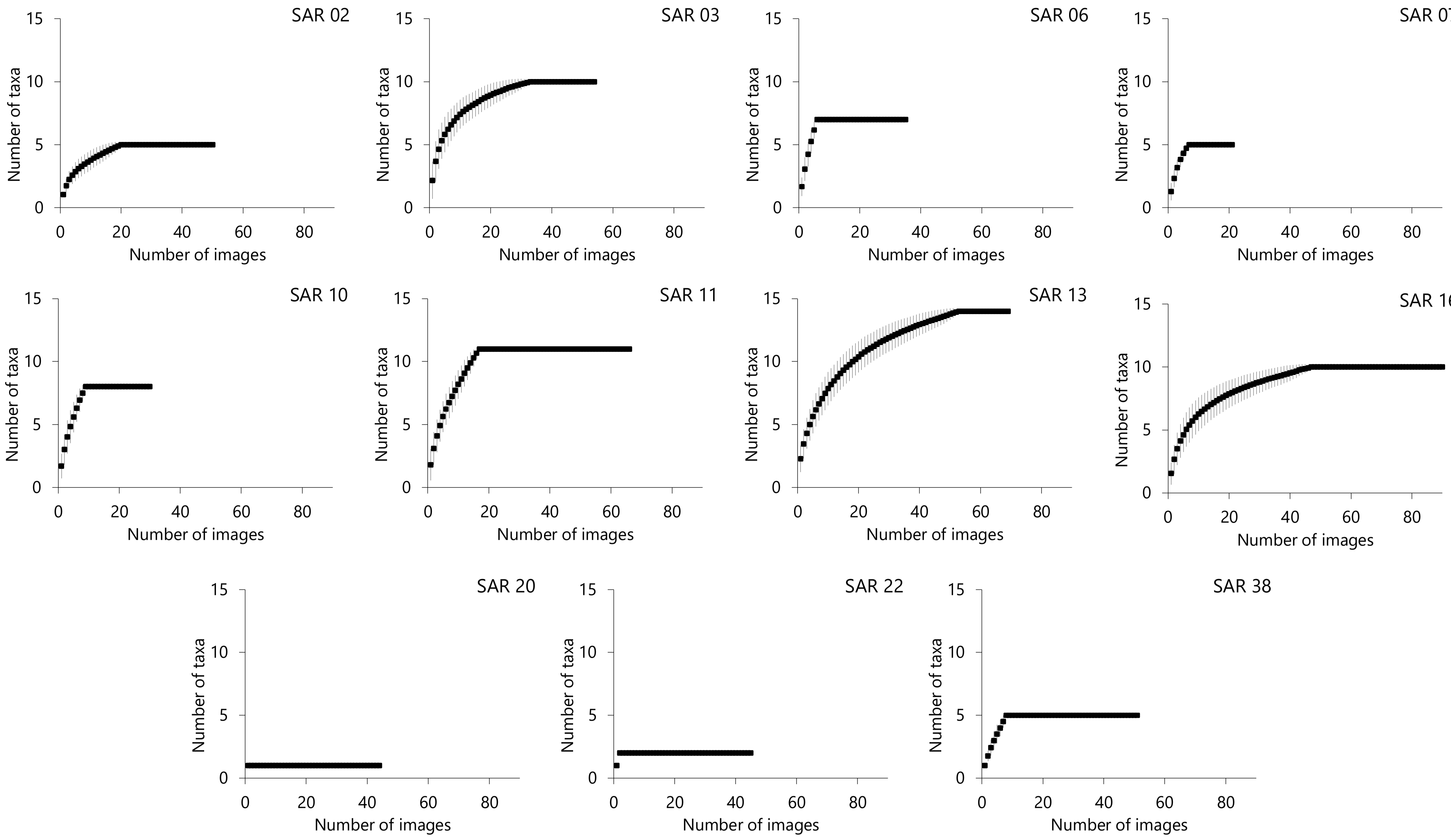
B



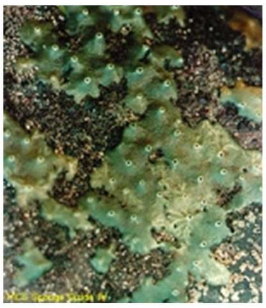
Appendix 2. North Sea Habitats. Taken from: International Council for the Exploration of the Sea.



Appendix 3. Species-area curves for each station.



Appendix 4. Catalogue for fauna identification. All images taken from WoRMS.



Halichondria panicea

Alcyonium digitatum

Metridium senile

Urticina felina

Cancer pagurus

Liocarcinus sp.

Pagurus bernhardus

Spirobranchus triqueter

Flustra foliacea

Aporrhais pespelecani

Buccinum undatum

Asterias rubens

Astropecten irregularis

Echinus esculentus

Ascidiella aspersa

Agonus cataphractus

Pleuronectes platessa